INVERSION TECTONICS IN THE CARBONIFEROUS BASINS OF NORTHERN ENGLAND:

With special reference to Northumberland.

Sarah Lesley Bower

Submitted in accordance with the requirements
for the degree of
Doctor of Philosophy

The University of Leeds
Department of Earth Sciences
Leeds LS2 9JT

October 1990

Abstract

The Northumberland basin is a member of the Carboniferous syn-orogenic complex that developed in the northern continental foreland of the Variscan orogeny. The basin occupies part of the Iapetus province, forming a generalised half-graben between the Southern Uplands and the Alston block. It straddles the Caledonian Iapetus suture, over lower Palaeozoic crust in the north and lower Palaeozoic and older crust in the south.

The basin was initiated in the Early Tournaisian by major extension along E/W normal syn-sedimentary growth faults. These dominated the southern margin of the basin where up to 6km of sediment accumulated. Fault activity was accompanied by localised dewatering and gravitational folding and slumping.

Basin asymmetry was maintained in the Late Carboniferous when the basin suffered inversion in the widespread Asturian compression event. Over 3km of pre-Permian erosion was achieved over the northern half of the basin compared with <1km in the south.

The inversion event is characterised by four structural elements: Reactivated basement controlled regional scale reverse fault bounded NE/SW to N/S anticlines (confined exclusively to the north): Minimal strike-slip reactivation and butressing around the southern margin and E/W faults: Positive flower structures associated with surface monoclines and original basin hinge-lines: Extensive transpressional deformation along the North Pennine Fault line.

A basin synthesis aided by palaeomagnetism suggests local dextral strike-slip modified NW/SE compression best explains the deformation. Basin modelling suggests mechanisms for the process e.g. thick skinned shortening for the north and foot-wall butressing against the southern margin. Modelling further indicated that subsidence was resumed after the onset of inversion prior to the intrusion of the Whin Sill.

Acknowledgements

The author would like to acknowledge the Natural Environment Research Council for the receipt of a postgraduate studentship and the University of Leeds, where the work was carried out. The following are gratefully acknowledged for assistance in providing data; G. Chisholm and D. Marsden of Amoco UK Ltd, J. Staffurth of Fina Exploration Ltd, Hurricane International, L. Knight of British Coal (Open Cast Executive). The following are also thanked for their various roles as advisers and sources of information at all stages of the project; E. Johnson (BGS Newcastle), J.Ward (Edinburgh Oil and Gas PLC), T. Evans (BGS Keyworth), Buffy McCelland (Oxford Uni.), and lastly to D. Robertson (Liverpool Uni.) for invaluable assistance in the palaeomagnetism pilot study.

I would like to thank all landowners who permitted access and drilling; including, the National Trust, the Northumberland National Parks Authority, the Buccleugh Estate (Langholm), Mr. Lammie of Preston Mill, Dumfries, Mr. S. Graham of Kirkbean, Dumfries, the Wood Hall Farm Estate (Cumbria) and the RSPB (Talkin Bird Reverse and Holy Island).

I would like to extend my thanks to all the warm and generous people of Northumberland who made my field seasons such a pleasure. I am grateful for having had the opportunity to roam at will in such a beautiful part of the country. Particular gratitude is extended to Jeff Metcalf (Warden, YHA Greenhead) and Edna Fairlam, Flynn and Cleo (The Old School, Paxton), even if dead mice at 6.30am is not my idea of breakfast!

To my long suffering supervisors many many thanks for their support, patience, advice and of course the odd pint... Mike Leeder (& Storm), Rob Knipe and Howell Francis... also to all my friends and colleagues who were regaled at one time or another with "tales of a basin". Apologies to you all, especially Sophie Bowtell, Carolyn Young, Ros and Steve Pike and "assistant driller" James Maynard; for the incessant chatter and thanks for your help. I won't forget the laughs, hangovers, cheesecake and bruises!

I wish to say a special thank-you to my parents for their enormous generosity, love and support; without whom I would have been penniless years ago! Last of all "slainte" to my dedicated proof-reader, Colin Sanderson, who saved this tome from its author's grammar (writes good I being a scientist am!) and provided Highland diversions when my enthusiasm waned.

This work is dedicated to the memory of Yvonne.

" A visitor to this quiet countryside might never suspect that it has passed through exciting and turbulent times..."
Bewcastle: A historical sketch (anon).

Cup and Ring markings (Bronze age), Doddington Law.

Table of Contents

List of Figures

Chapter One and Two

Chapter Three

Chapter Four

Chapter Five

Chapter six

List of Tables

List of Enclosures

Chapter One

PROJECT AIMS AND METHODOLOGY

1:1:0 Introduction

During the late Carboniferous, much of the northern foreland to the European Variscan orogeny experienced an uplift and deformation event. This event has been recognised as a widespread "inversion" phase in many Carboniferous basins, from the Moray Firth to the Midlands and southern North Sea (Besly 1987). The Northumberland basin, situated in the more northerly reaches of the Variscan foreland, is one such deformed basin. It occupies a unique position in Carboniferous studies, being one of the best exposed for its age and having an exceptional data base from which to conduct research. The basin has been part of the area available for onshore oil and gas exploration and has acreage over which seismic lines have been shot. There is a long history of publications concerning the basin, dating from the late 1800's and a similar history of mining activity (still active to the present).

In a regional context the Carboniferous basins of northern England can be usefully regarded as a suite of synorogenic basins. These include, not only Northumberland but also the Solway basin, the Vale of Eden, the Stainmore basin,the Bowland or Craven basin, the numerous basins of the southern Pennines, e.g. the Goyt and the Edale and Widmerpool basins, and also includes the Cleveland and Lancashire basins. This suite is represented both onshore and offshore.

1:1:1 Aims and Problems.

The aim of this thesis is to take the Northumberland basin as a case study and assess the late Carboniferous inversion event. The ultimate aim of the work is to integrate new information with available data for the basin to produce a logical and cohesive basin history that can be used to illuminate the regional geological evolution. Given that the basin was one of those to suffer Late Carboniferous inversion (Leeder et al 1989), the following questions have to be addressed; how was the inversion manifested and what were the ages and geometries of the structures produced? How does the previous extensional history affect subsequent deformation, and how much of this can be attributed to structures inherited from the original basin geometry or basement? In the wider aspect, how was this event related in time and space to the regional pattern i.e. other Carbonifeous basins in the same tectonic setting? How typical was this event of inversion in general and of late Carboniferous inversion specifically? Can the event be explained in local terms or is it related to regional scale tectonism, and perhaps most importantly of all, what does this event imply for other cases?

1:1:2 Approach and Data-base.

This study aims to answer the previous questions by an integrative multi-disciplined approach. At all times the province was considered utilising the Northumberland basin as a test case for previous interpretations and as a case history on which to base future research into Carboniferous basins and the basin inversion process. The subject area was approached initially with understanding of the regional Carboniferous events (tectonic, stratigraphic and palaeogeography). No models for the basin were assumed, either in terms of the extensional history or any subsequent deformation. Those theories already in the literature at the time were tested for their validity against field observations, using data sets including seismic, published work, BGS data and palaeomagnetism and against quantitative models of the basin.

Much of the Northumberland basin has been studied at different times and at the time of this work most of the detail was concerned with the extensional history. Northumberland is an ideal candidate for a detailed assessment of inversion processes because of the quality of the knowledge concerning the pre-inversion history.

The bulk of the study was based on detailed field work in selected areas. The regions selected were determined to be the most crucial in answering the problems of the basin. This selection was decided upon by constructing a regional structure map (1:625 000) for the British Carboniferous (see Chapter 7) and a detailed map (1:250 000) for the Northumberland basin (also chapter 7). The structure of the basin was cursorially interpreted to locate descisive areas, e.g. regions were fault bends or major lineaments would give interpretations specific to predictive stress systems and therefore support or refute a regional analysis (see intoduction to Chapter 4).

A pilot study in palaeomagnetism was conducted for the province around the Northumberland and Solway basins, to constrain any rotational history in interpretations. Lower Carboniferous lavas were tested against the early Permian Whin Sill to determine the amount (if detectable) of rotations about a vertical axis that may have occured in the province during the Carboniferous. The study was designed to be self-checking to indicate if strike-slip motions in the Iapetus suture zone province had played a role in the Carboniferous evolution of the area. The study utilised alternating field and thermal demagnetrometry techniques to assess the stability of the remanance in the rocks selected. The rocks were examined by Vibrating Sample magnetometry to determine the likely remanance carriers, indicated by published petrological studies.

As an introduction to the primary research conducted by the author, it is necessary to define the usage of the term "inversion", this is covered in the first half of chapter two: Following this the regional context will be discussed (Chapter two, part two) as the nature of the event is best considered in the broader context. The central part of this work will present new field data and interpreted seismic lines for southern basin margin (very generously made available by Amoco UK and Fina) in chapters four and five. Western Northumberland around the Brampton district and the North Pennine fault is dealt with in chapter four and North East Northumberland, from Berwick-upon-Tweed to Alnwick in chapter five. The latter half of this study is a chapter (six) on the modelling of the basin in quantitative terms. The seismic data was considered essential for a study of this kind to determine the structure and geometries of surface features at depth. By utilising seismic the beginnings of a 3D image of the basin can be constructed. The case study is synthesised in the concluding chapter seven, where primary interpretations are discussed.

The palaeomagnetic data, the seismic interpretation and the modelling are used in the concluding synthesis to facilitate a integrated three dimensional "picture" of the Northumberland basin's inversion event.

Chapter Two

PART 1: INVERSION

2:1:0 Introduction

The following discussion aims to introduce the terminology of "inversion" to the reader. The discussion opens with a review of the historical applications of the term and the general process implied by these applications. A definition of the term is not attempted until the second section because the historical applications have defined the modern usage of the term. Typical inversion produced structures and geometries are discussed following definition of the term and possible causes of the process are suggested.

2:1:1 History and Process:

The term "inversion" was introduced to geological communities amid considerable confusion and debate which is not fully resolved. Traditionally the term was used in seismic interpretation to describe uplift due to a compressional or transpressional event in an intracratonic extensional basin (Glennie & Boegner 1981). In hydro-carbon studies, inversion was deemed to be a process by which a reversal of hydrocarbon migration pathways occured(Dr.P. Jean pers. comm.), i.e. uplift. These were the first usages of the term inversion but their non specific definition led to a diversity of applications.

One of the first cases of inversion described was for the Sole Pit region of the southern North Sea (SNS) by Glennie and Boegner (1981), where uplift and fault reactivation produced antiforms and a discordance with sediments deposited after the event; which occoured during the Mesozoic. Such a process of deformation and intra-basin uplift had been recognised in the Weald of southern England as early as the 1920's (Lamplugh 1920) but it was not until "inversion" was coined in commercial exploration fields (Harding 1985) that the term was adopted in other disciplines. Unfortunately in the process a diversity of applications ensued, that began to obscure the term.

In the majority of published cases, it was implicitly recognised that reactivation of an existing fault or fault system was necessary to achieve the uplift and deformation identified (Bally 1984; Gillchrist, Coward & Mugnier 1987; Simpson, Gravestock, Ham, Leach & Thompson 1989). Over the past decade it has been tacitly assumed that the process reactivates original basin features (Wiltschko & Eastman 1983). Reactivated features include basin margin faults and intra-basinal highs (see figs. 1a & 1b). Inversion rapidly became synonymous with fault reactivation in some interpretations. Such faults had had their sense of motion partially or wholly reversed during the process concomitant with a reversal in the stress regime, i.e. extensional to compressional. If a fault had reverse motion superimposed on extensional geometry it was termed "positive inversion", vice-versa the term "negative inversion" was applied (Cooper & Mathews 1989). Dewey (1989) rejected the term "negative inversion" on the grounds that it was essentially basin formation or subsidence. By the mid-eighties the term "inversion"was far removed from its original basin context being applied to fault systems without discretion and thus was rapidly becoming redundant as a useful process name. Interpretations began to acquire genetic implications e.g. taking inversion to mean stress reversals and fault reactivations.

To the seismic interpreter and basin analyist inversion had continued to be applied to intracratonic basins suffering uplift (Gibbs 1983) since its introduction in the early eighties. By the late eighties such a dichotomy of interpretation between structural geologists (fault reversals) and exploration geo-scientists (basin uplift events) was confusing. It would seem logical to not use the term inversion at all when referring to reactivated faults (Needham 1987), as these can be accurately described by existing terminology as "reactivated" (Jackson 1980). This makes better science, avoiding genetic implications and cases where faults are not reactivated "in toto": It depends on the observer's position on the fault as to the degree of reactivation. Sibson (1985) calculated the stress ratios necessary for frictional reactivation of normal planar and normal listric faults. On mechanical grounds he determined that reactivation of listric faults was possible, but only at depth where the fault was less steeply inclined. Higher angle planar structures tended not to reactivate, in favour of structural short cuts which by-passed the original structures. This scenario leads to difficulties in calling the whole fault "inverted". It would be logical to identify reactivated or non-reactivated faults separately.

In the basin context, R.W.Murphy (1989) used the term when refering to mild deformation in basins governed by normal faults. Inversion in this case was thus the result of a compressional phase producing folding and uplift. The petroleum industry usage was strictly confined to intra-continental basins (Ziegler 1982), and such events were thought to occur more than once in some cases (Kent 1980). The process of inversion produced reverse motion on faults (usually original basin faults) and where this was not recognised, regions of folding and differential uplift. With the advent of transtensional and transpressional regimes being recognised (Sanderson & Manchini 1981) a fault bend for example in an oblique or pure strike-slip regime could produce localised deformation and/or inversion (Gillcrist et al 1987, apparently unrelated to the regional stress orientation (see figs 2 & 3). These narrow applications preclude that an identical set of structures in any other setting could not be called "inversion". There is no *a priori* reason to assume that inversion only occurs in intra-continental settings and necessarily requires a reversal of stress regime to occur. Similar events could no doubt be

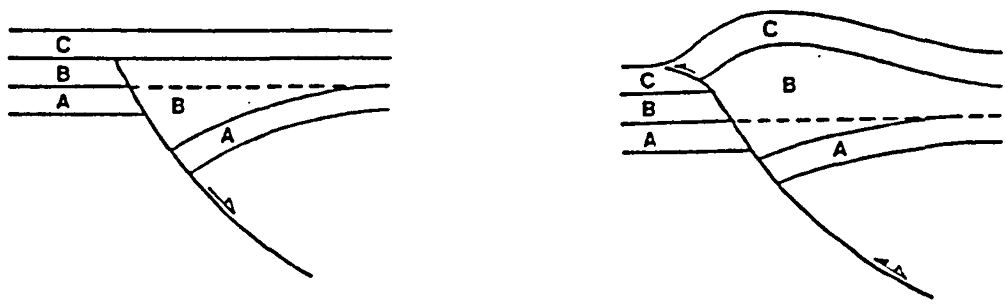


Fig. 1a) Schematic diagram of a classical inversion structure.
Where A,B & C are stratigraphical sequences, A = pre-rift, B = syn-rift and C = post-rift (after Williams et al 1989).

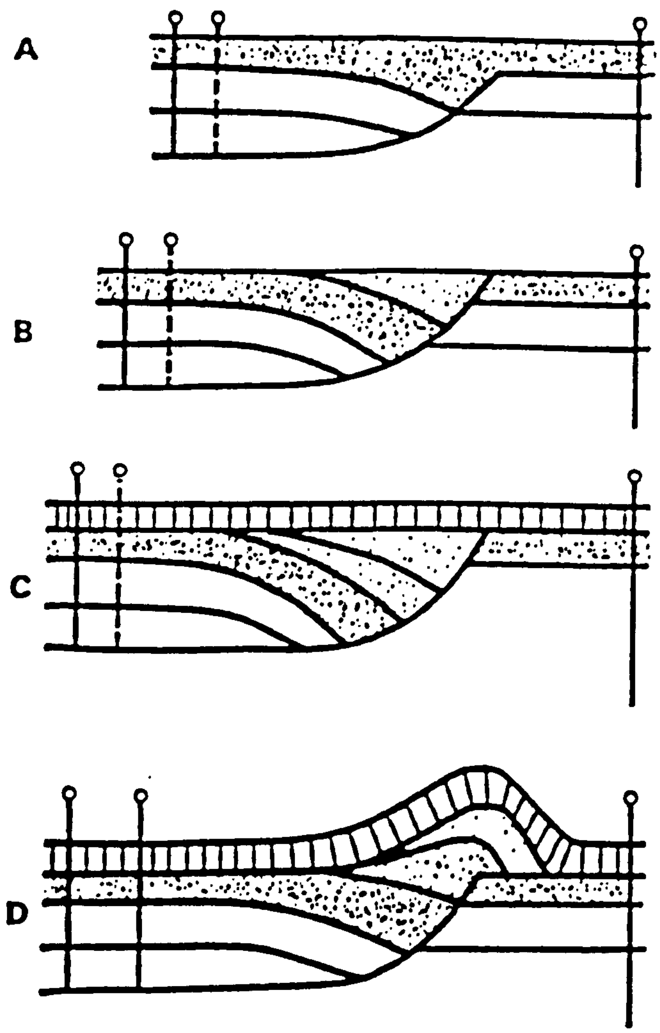


Fig. 1b) Schematic construction of a reactivated listric growth fault. A, B & C show progressive extension and deposition of syn-rift fill and D shows the consequences of inversion (after Hayward & Graham 1989).

identified in passive margins, foreland basins and strike-slip basins. Sense of motion reversal on faults does not inherantly require stress reversal (Ziegler 1982). To argue for inversion as being confined to intra-cratonic extensional settings, is to demand a special case and makes causal assumptions.

Dewey (1984) pointed out that inversion had been recognised in intra-cratonic areas e.g.north-west Europe, in back-arc areas (Ziegler 1982) e.g. Sunda arc, within mega sutures, e.g. Devonian basins in the Arctic-North Atlantic Caledonides and in passive margins e.g. Mid Norway basin (Bukowicz & Zeigler 1985). In these cases inversion was achieved largely through stress reversals but also in transpressional events. Both he (Dewey 1987) and Ziegler (1982) maintained that the term be reserved for the intra-cratonic setting. This application is far too restrictive and as previously mentioned it makes genetic assumptions concerning the tectonics governing the inversion process. In extending the application to potentially any basin however, care must be taken to distinguish the inversion from other deformation processes. In foreland basins, inversion may occur producing mild uplift and deformation, but if the basin is caught up in the orogen that caused the basin, any mild inversion events will be overprinted in succeeding deformation, i.e. incorporated into the advancing nappe pile. It would seem logical to refer to the deformation produced during basin inversion as that achieved during uplift and re-equilibration of the basin.Re-equilibration of a basin is the process of lithospheric re-equilibration that occurs after intial basin rifting. The basin may be formed by stretching or by erosion of a thermal dome. In the case of pure shear stretching (McKenzie 1978) lithospheric recovery can be achieved by thermal re-equilibration and sedimentation or by increasing crustal thicknesses e.g. in a thick skinned compressional event.

Once the basin has a re-equilibrated lithosphere it is no longer a basin because it ceases to operate as a depocentre and no further subsidence is apparent. It follows therefore that any further deformation cannot be basin inversion; since inversion is widely accepted as the term describing an event affecting a basin. Re-equilibration of a basin would prevent subsidence and so the previous depo-centre would cease to operate to control sedimentation. Though it must be stressed that it is not re-equilibration of a basin that causes inversion rather that inversion *could cause* re-equilibration. If epeiorogenic tectonism leads to later deformation of a basin after subsidence has ceased, this is also inversion but a special case as it will not be recognised in a geohistory analysis or time/depth curve for the basin's extensional history.

In the case of the foreland basin (Graciensky 1989), flexural loading is the cause of the subsidence and so here any reversal of basin structure can be said to be inversion. Once material becomes involved with the para-authocthon of the advancing nappe front, inversion no longer applies and deformation can be described in the conventional

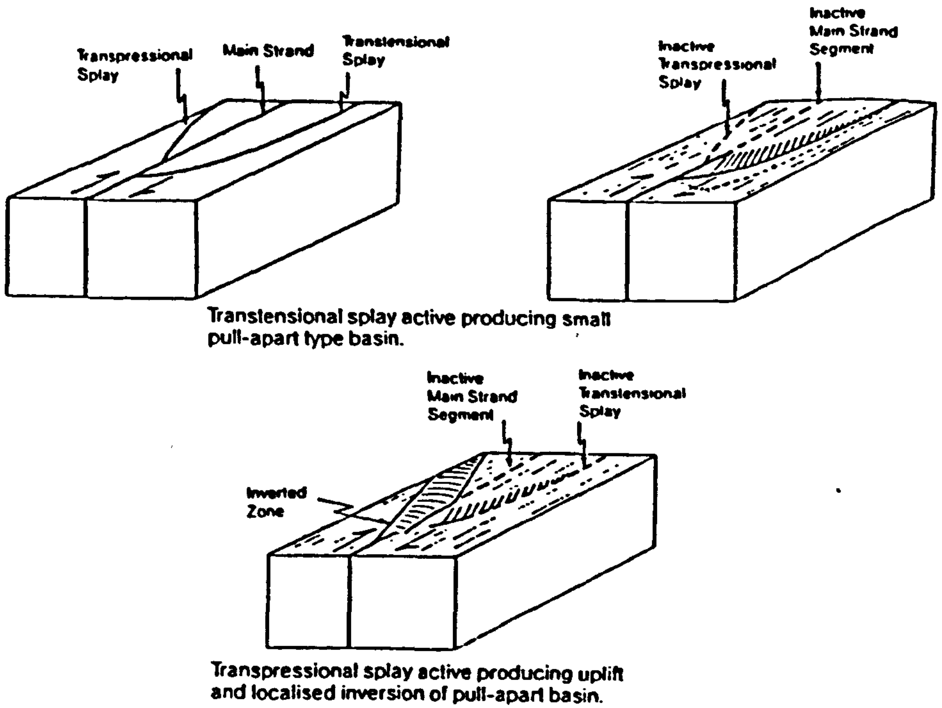
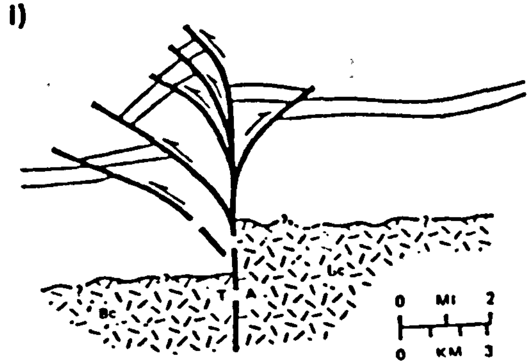


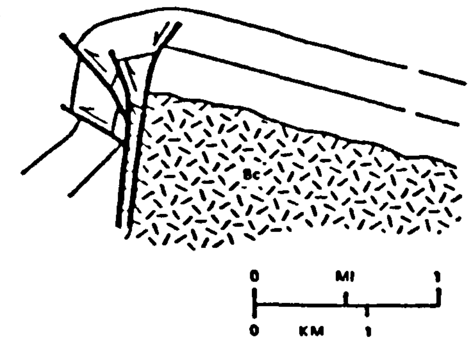
Fig. 2a) The development of inversion structures in a transcurrent fault zone (after Cooper et al 1989), producing b) structures i)-iii). where Bc is basement complex (after Harding 1984).

i)



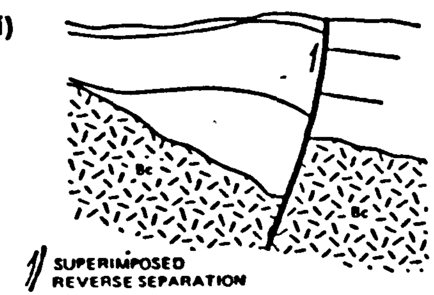
b)i) positive flower structure,

ii)



ii) contractional fault block,

iii)



iii) "positive" structural inversion,

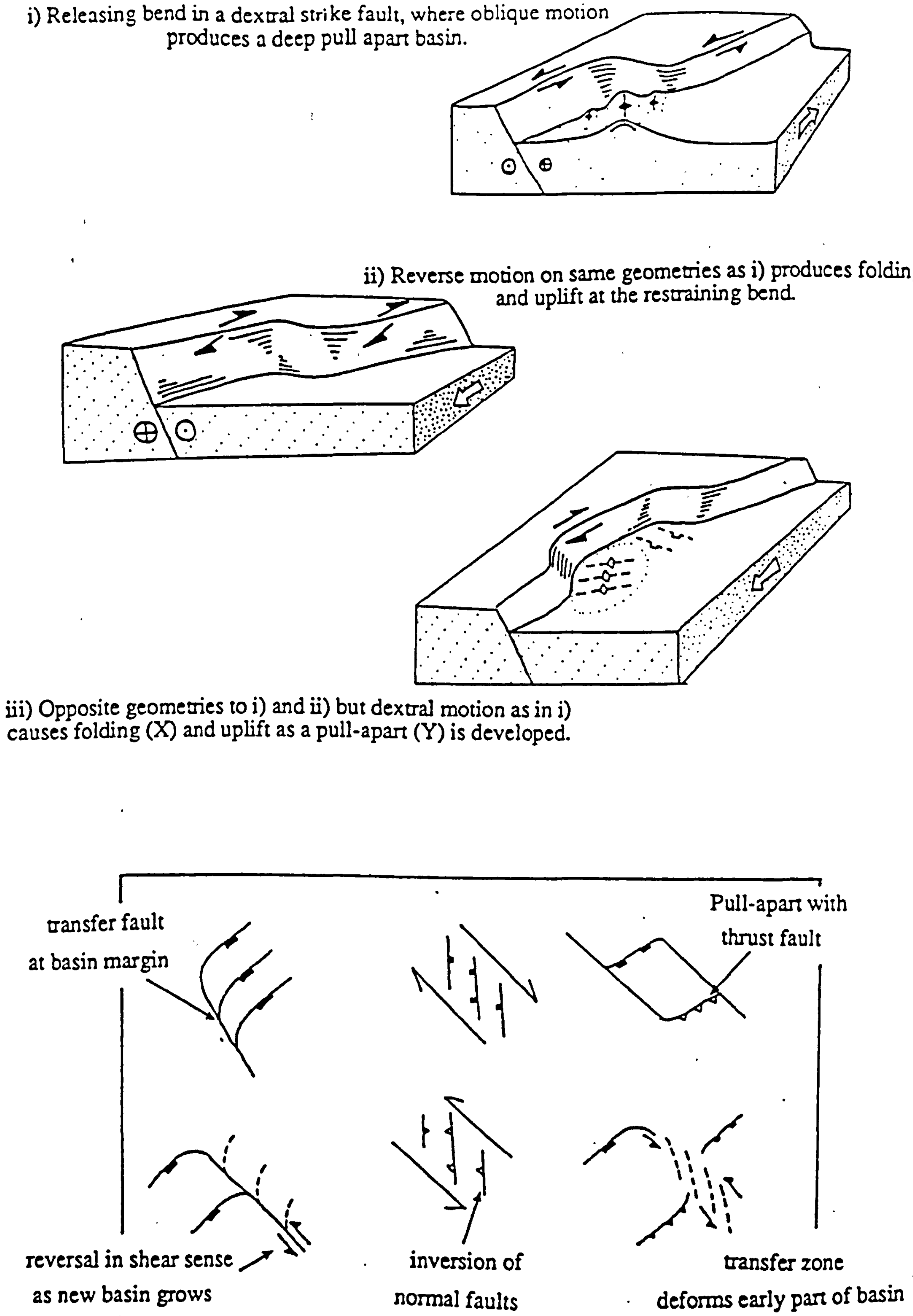


Fig. 3 Localised inversion in strike-slip zones. Inset: Inversion and reactivation in strike-slip zones (adapted from Gillcrist et al 1987).

terminology of thrust systems. It logically follows that if foreland basins are a special case of basins,then inversion in foreland basins is a special case of inversion.

To include basins other than intra-cratonic ones also avoids assumptions about the geodynamic environment. The term's broad application is of considerable use in understanding the processes of mild epeiorogenic deformation. This point was raised by P.C.de Graciansky (1989), who further suggested that the cut-off point for inversion deformation was when a basin became involved in a major orogeny.

Having discussed the application of inversion and its degree of deformation, it is necessary to define the term on the basis of its application.

2:1:2 Definition of terms.

Glennie and Boegner (1981) suggested that inversion was the conversion of a basinal area to a structural high. It was they who first introduced the senses of positive (uplift) and negative (subsidence) inversion. As both the former and latter terms are unnecessarily jargonistic, and historically have led to much confusion, it is proposed to not use these terms at all. Bally (1984) implied that the process was confined to extensional basins "inverted" to varying degrees by compressional forces re-utilising pre-existing basin faults (fig. 5). This approaches the sort of definition required but again makes genetic assumptions. Historically application of the term was imprecise because the very event had an imprecise definition. Harding (1985) in reference to flower structures, concluded that "positive structural inversion (was) a change in structural relief polarity". This is rather vague, but basically non-genetic, but uses the expression "positive inversion" which is redundant if no "negative inversion" is recognised i.e. is effectively subsidence.

On the basis of the historical applications of inversion discussed in 1:1:1 and the previous, Cooper and Williams (1989) suggested that inversion was "the change of regional and structural elevation by a later distinct phase of deformation, provided that the following are fulfilled;

1) deformation has a dip-slip component, 2) pre-existing faults are substantially reversed."

This is a vast improvement but assumes that all shortening or deformation was achieved via faults already in existence. This may not always be the case. Basin inversion need not necessarily occur through a stress reversal (Stonely 1989). Ideally the term should only be used when pre-fixed to "basin" to avoid confusion between disciplines. The term needs to be re-defined to avoid all genetic assumptions and include all geodynmic environments were basins are formed.

This author proposes that :
The term **inversion** be applied to a recognisable event in the history of a **basin** that produces both *uplift and deformation.* The processes giving rise to the deformation and uplift cause a *change in regional and structural elevation* by which the basin inversion event is recognised, and may include some or all of the following;

1) **Reactivation of pre-existing faults** (normal planar or normal listric), these may be: a) original faults formed during the formation of the basin, of any age and may include syn-rift syn-sedimentary faults. b) any set of faults not related to basin formation but present in the basin fill prior to inversion.

2)**Reactivation** (inheritance) of **basement features/structures** which may include: a) ancient lineaments, e.g. sutures or terrane boundaries. b) orogenic trends, e.g. fault and fold trends present in the basement of the basin and therefore older than the basin (Hills 1976; Jackson 1980; Dunbar & Sawyer 1988). These features are separated from the previous as existing *prior to the basin.*

The deformation will preferentially affect basin fill but not be exclusively confined to the basin. If the inversion is a regional event mild deformation should be expected over non-basin areas also.

In this definition it must be understood that a basement fault may be reactivated as a basin controlling structure and may subsequently be reactivated again in an inversion event. Such a fault can be described as a pre-existing basin fault and a reactivated basement structure.

Basin inversion is therefore an *event* in which deformation and uplift occurs in a basin setting; and is a *process* in which faults are reactivated, shortening occurs, and perturbation of heat-flow (the geotherm) may occur, which may ultimately lead to partial or full re-equilibration of the basin concerned. An inversion event can be recognised as a period of uplift or non-subsidence in time-depth history curves and as a hiatus or period of uplift in backstripped subsidence curves. The character of the event can be expected to vary with the initial conditions, i.e. the particular basin geometry considered and the relative importance of inherited structures. The mechanism of the event is described as the inversion process. Inversion can be expected to change regional elevation but there is no reason to assume that this will necessarily produce basin-wide expression. From the cases mentioned so far there is a tendency for inversion to be heterogeneous.

Inversion (the event) can occur in any basin but care should be taken to separate it from more general uplift and passive exummation of ancient basins. Regional uplift is a

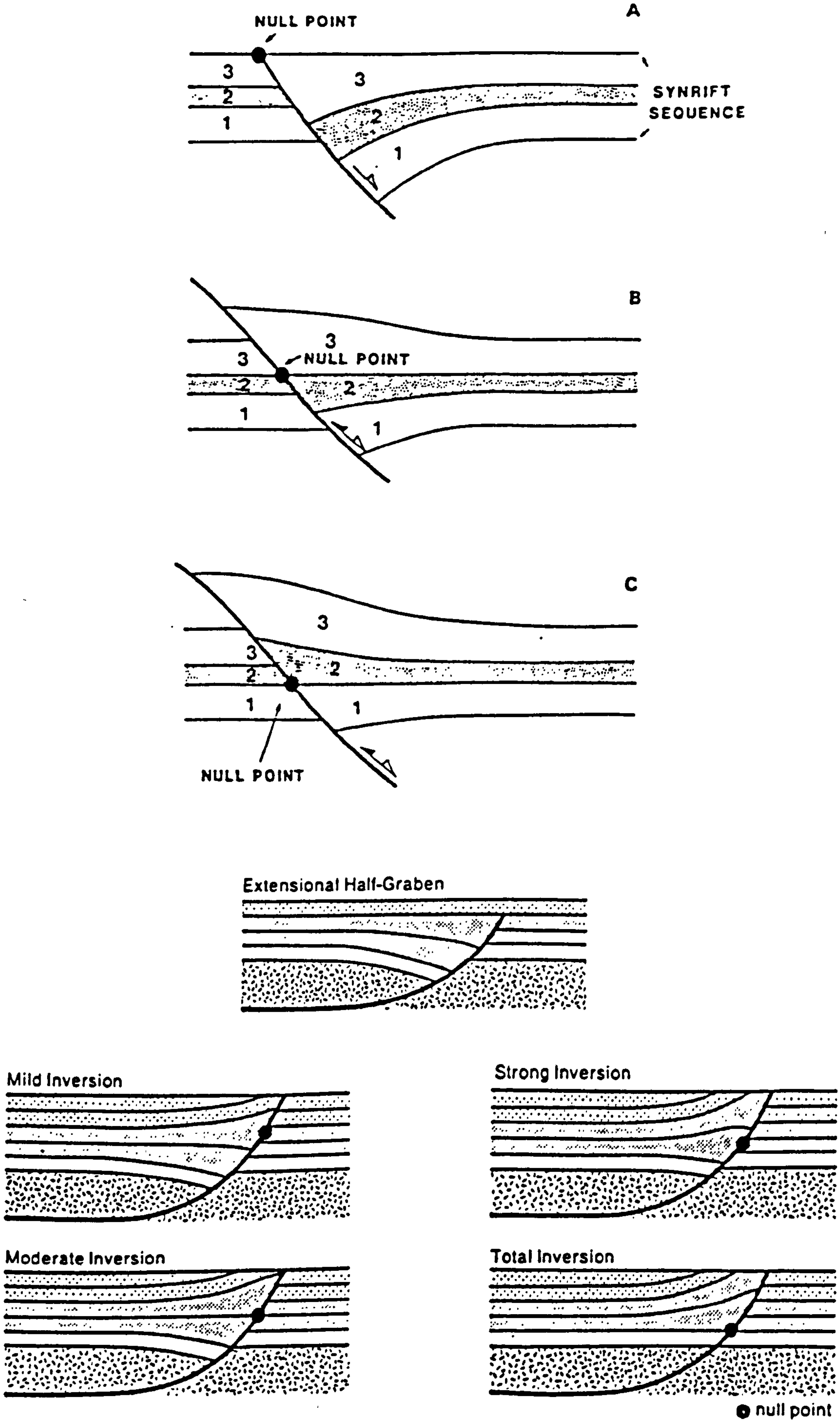


Fig. 4 Sequential diagrams to show the contractional inversion of an extensional fault. The null point moves progressively down the fault with increased contractional/reverse reactivation (adapted from Williams et al 1989 & Cooper et al 1989).

process by which the whole region is uplifted, basins and blocks alike by comparable amounts. This type of broad uplift is essentially a passive one not producing significant deformation or shortening over the region. Regional uplift is a process of vertical movement in continental areas that is not normally associated with crustal shortening. Explanations for this type of generalised uplift have been made (Gilbert 1877; Holmes 1964) and a detailed discussion of uplift mechanisms can be found in McCretchin (1980). In addition to those discussed by McCretchin, uplift due to lower crustal emplacement of basic magma has been envoked (McKenzie 1984), causing thermal doming and hence regional uplift. Regional uplift is not a shortening process, though shortening (crustal or thin-skinned) will cause uplift. The term should therefore also be kept distinct from orogenic deformation reserving it as an event affecting external orogenic zones (or unrelated to an orogeny altogether). To reiterate a point made in the discussion of 2:1:1 inversion usually occurs within the life-time of a basin although it may lead to total re-equilibration of the basin. Any subsequent regional uplift will produce erosion of the basin but should not produce new reactivation or deformation structures. If a basin has undergone significant deformation and uplift in one event and is later involved in another, old deep buried basins may experience renewed uplift along old inversion axes or over new structures. Care must be taken to distinguish between the two and identify each event correctly. For instance a second uplift event may not be a passive regional uplift but a weak widespread inversion event affecting a new basin system. To summarise the processes of crustal shortening, fault reactivation, thrusting and folding operate during a basin inversion event. This is to be distinguished from regional uplift or else any uplifted basin could be described as "inverted" (or more accurately, have suffered an inversion event), which is clearly ridiculous!

2:1:3 Recognition of basin inversion. Geometries and structures.

Basin inversion produces a change in structural elevation relative to the original positions of strata in a sedimentary basin or to markers in a fault system. Reactivation can be recognised in the hanging-wall of a fault where deformation produced a change in the geometry of the fault i.e. relative to a marker horizon. This is a common feature in inversion events. The consideration of marker horizons was expanded to a discussion of "null points" in recent work (Inversion Tectonics, Spec. Publn. Geol. Soc. 1989). The null point is the point on a fault in a sedimentary sequence where a bed is not offset from its time-equivalent, foot-wall counter-part (Williams 1989). Immediately after sedimentation the point is at the surface (see fig. 4) in a classic post rift sequence. If reverse reactivation of a growth fault occurs, then the null point migrates down the the

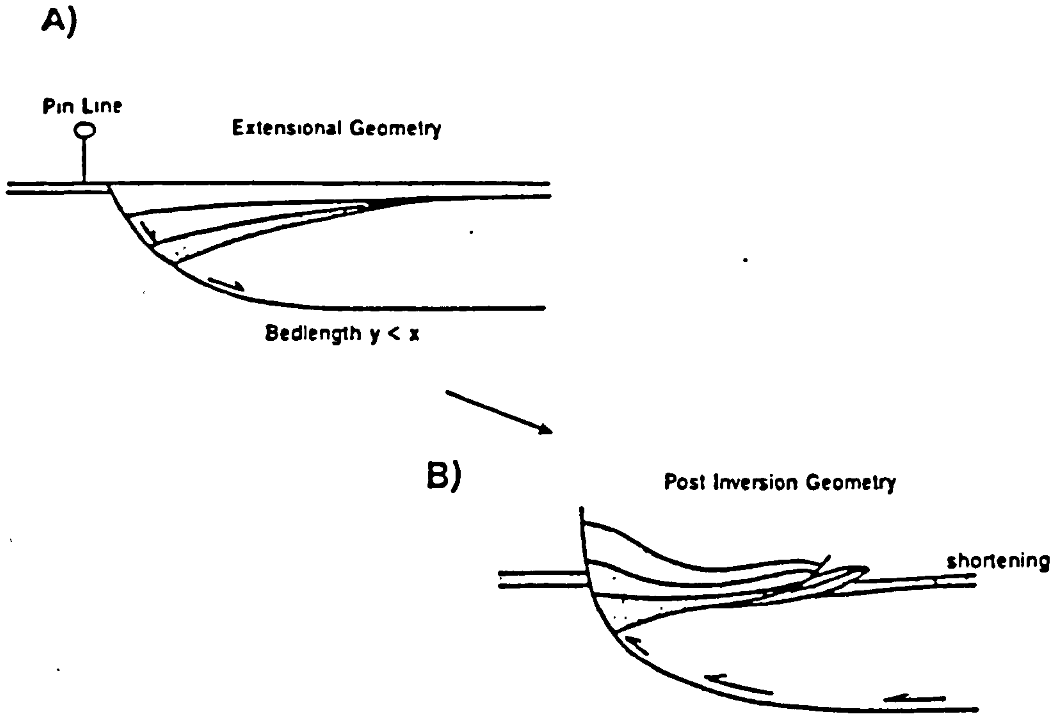


Fig. 5 Typical shortening accommodation structures in inversion. A - excessive bed length in the half-graben and B - the accommodation structures that develop (after Hayward & Graham 1989 modified from Bally 1984).

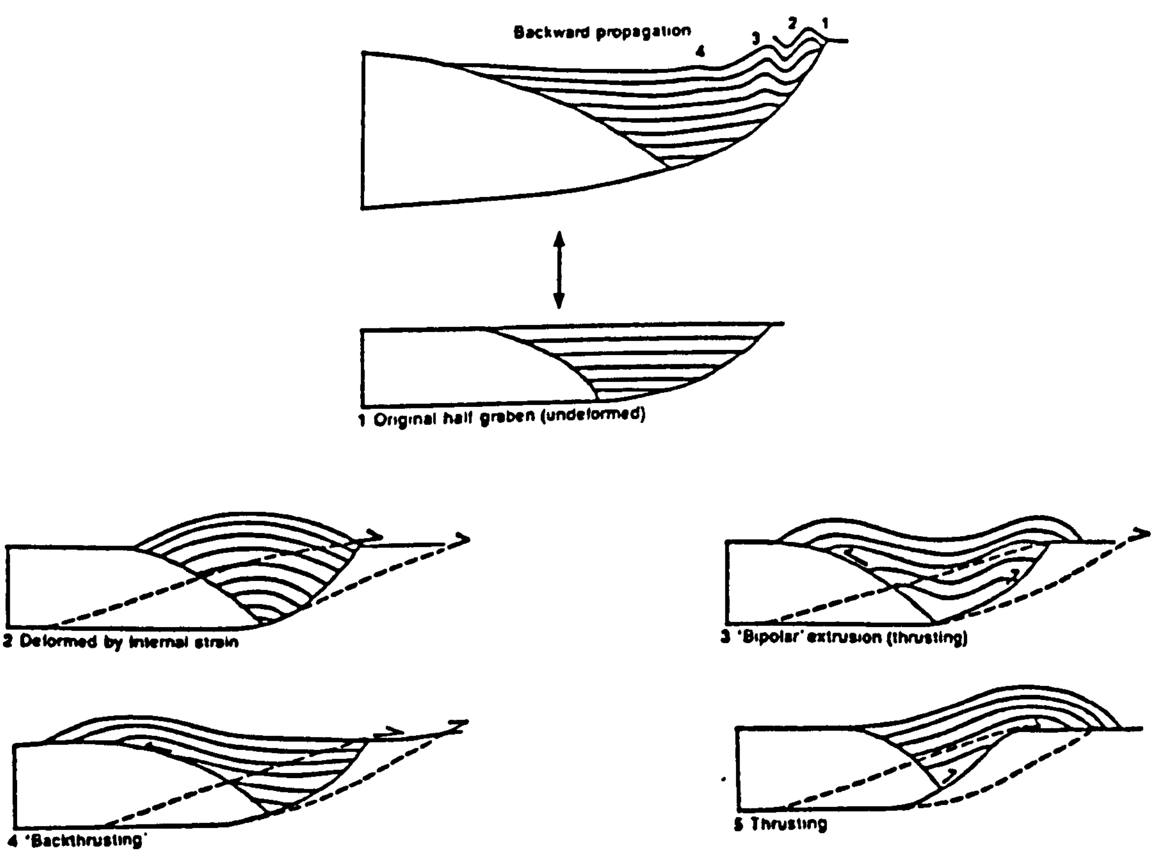


Fig. 6 The development of a backward propagating thrust sequence produced by butressing against the footwall fault block during inversion. Dashed line represents potential for late stage out-of-sequence thrusting (from Hayward & Graham 1989).

fault plane with time and continued reactivation. This assumes that a syn and post-rift sedimentary sequence can be identified and that the whole fault has been reactivated. Idealy complete reactivation of a syn-sedimentary fault will give one sense of motion for the post rift sequence (reverse geometry) and the opposite sense (normal geometry) for the syn-rift pile. If reverse fault geometry reactivation occurs in the above situation the result is often a characteristically asymmetric anticline (see fig. 5). If the system is by-passed during reactivation, short-cuts may be produced, (see fig.7). If total fault reactivation does not occur then shortening during inversion may produce 'back-thrusting' or butressing (fig. 6) against the foot-wall (Welbon 1988). Back-thrusts in an inversion system may be reactivated antithetics from the pre-existing extensional system (Gillcrist et al 1987).

Butressing is the process by which horizotal compressional stress (or thrust movement) is transfered into the hanging-wall of a fault. The fault is acting as a barrier to continued reactivation or thrusting. The butressing produces distributed deformation (folding, faulting) in the immediate hanging-wall to the fault concerned. The faults foot-wall acts as a rigid block so the hanging-wall deforms by internal shortening to accommodate the stress (Bartely & Gidon 1984; Welbon 1988; Butler 1989). Butressing or shortening against pre-existing faults gives rise to sites of upright folding and strain intensification (fig. 7b). Though areas of such deformation are not in themselves diagnostic of the presence of pre-existing faults, areas of increased strain may be expected in the hanging-walls of faults bordering stable "blocks" e.g. basin margins and are likely to be common features in basin inversions (Gillcrist et al 1987; Butler 1989).

Inversion frequently occurs at basin margins and as these are often controlled by major normal fault systems they are potential sites for reactivation (Etheridge 1986). In some cases intra-basinal grabens and horsts act as the focus for the inversion deformation, so basin margin reactivation cannot be used as an *exclusive* criterion for identifying an inversion event althougth it is generally very useful. Typical inversion structures are illustrated in figs. 1 to 7, but it should be emphasised the structures produced are a combined result of the cause of the inversion and the basin geometry.

Basin inversion can be suspected if some or all of the following are identified:

1) A hiatus or unconformity can be related to basin wide uplift, unexplained by normal basin processes.

2) Folding related to basin margins or confined to the basin fill: Deformation which is more widespread may be more intense in the basin than over surrounding inter-basinal areas.

3) Thrusting is found in the basin fill and particularly over the basin margins. Thickness and facies variations may prove difficult to correlate if facies distribution was controlled

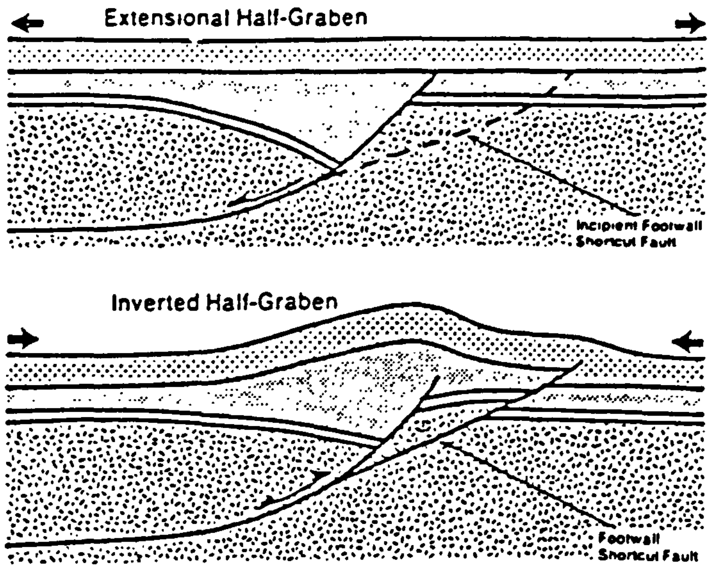
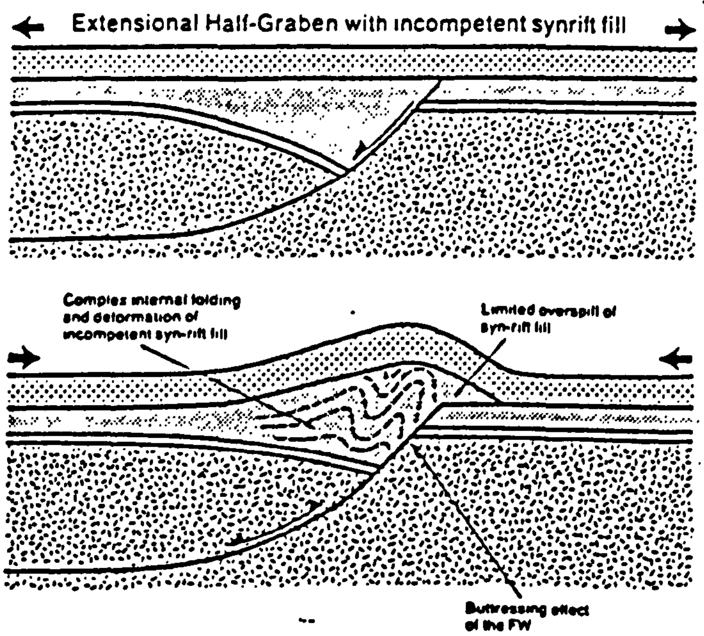


Fig. 7 a)Development of a footwall short-cut with a shallower dip than original structure during inversion of a listric fault (after Cooper et al 1989).



b) Butressing effect of the basement footwall (Cooper et al 1989).

by syn-sedimentary faults. Evidence for syn-sedimentary activity should be sought in the thrust pile.

4) In extreme cases of inversion cleavage development may be localised to the basin sediments.

5) Classical syn-sedimentary wedges are found with cut-offs against reverse faults.

6) New fault systems are identified in the basin unassociated with basin development in conjunction with 2) & 3)

7) Faults in the basin display complex histories and there is evidence for reversal of motions, especially associated with 1), 2) & 3).

8) Major uplift can be related to the distribution of recorded deformation otherwise unrecorded by an unconformity within the basin fill.

2:1:4 Causes of basin inversion.

Although frequently associated with continental compressional regimes the possible causes of the event are many and varied. They include the following adapted from Hinze and Gillcrist (Hinze, Braile, Keller & Lidiak 1980; Gillcrist, Coward & Mugnier 1987):

1) Regional temporal variations in inter-plate stress patterns.

These may be achieved through; a) plate boundary changes in the configuration and orientation of adjoining plate margins, producing compressional stress not directly related to orogenic processes; b) continental collision, following the subduction of oceanic lithosphere, the over-riding plate may enter regional compression (Jackson 1980) and the newly collided plate may change from extension produced by "trench-pull" to compression as the plates collide. Similarly the subducting plate may enter compression following "slab-pull" after the collision of the continental slabs; c) changes in rates of plate motion. A change in the rate of plate motion relative to surrounding plates may cause overall compression, being an indirect result of plate tectonics (Gillcrist, Coward & Mugnier 1987).

2) Intra-continental processes.

Inversion in basins has been associated with rifted margin break-up unconformities caused by the transition from rift-phase tension to "ridge-push" compression. Hence periods of inversion events could be related to global compression and tension during periods of stress change e.g. during major continental break-up.

3) Intra-plate variations associated with flexure.

Loading and de-loading of the crust in orogenic belts e.g. foreland basins and regions of high heat flow. The slow motion of semi-rigid plates over a non-uniform spheroid i.e. the Earth will produce periods of enhanced tension and compression (Beaumont 1978, 1981; Butler 1989; Royden & Karner 1984).

4) The gradual reduction of crust to lithosphere ratio, during slow extension can produce basin-wide uplift . This is not strictly inversion but is included for comparison with the 'active' process of basin inversion (Coward 1986).

5) Strike-slip processes.

a) Rotation of upper crustal blocks, horsts or graben in an overall strike-slip regime will produce changes in the stress systems and could lead to inversion, e.g. major strike-slip boundaries or inter-cratonic slip zones (Dewey 1975).

b) Localised uplift around individual faults. This is the case where oblique movement in a system may produce zones of compression or transpression at restraining fault bends (Reading 1980).

6) Passive effects caused by salt or mud diapirism.

This may produce structures very similar to inversion in basins, but are essentially upwelling processes not needing fault reactivation, They are included for completeness but fall into the realms of "salt tectonics" not inversion.

2:1:5 Timing of inversion.

Having defined the term, its application and causes, and discussed the characteristic geometries, it now remains to consider the effect of of the inversion event on a basin. The timing of the event relative to the basin's history is critical to the understanding of the whole. Only then can the consequences of inversion be allowed for in geologic reconstructions.

Theoretically inversion could occur at any time during the development of a basin and of course it need not occur at all! Taking the simple case of an extensional intracratonic basin undergoing subsidence by uniform stretching i.e. pure shear, a two phase development is recognised (McKenzie 1978). The initial rifting phase is governed by thinning of the continental lithosphere, followed by a recovery phase in which the thermally anomalous lithosphere recovers to re-establish equilibrium isostatically and thermally within the system. If it is assumed that the majority of inversion events involve crustal shortening during compression then it follows that lithospheric shortening will re-

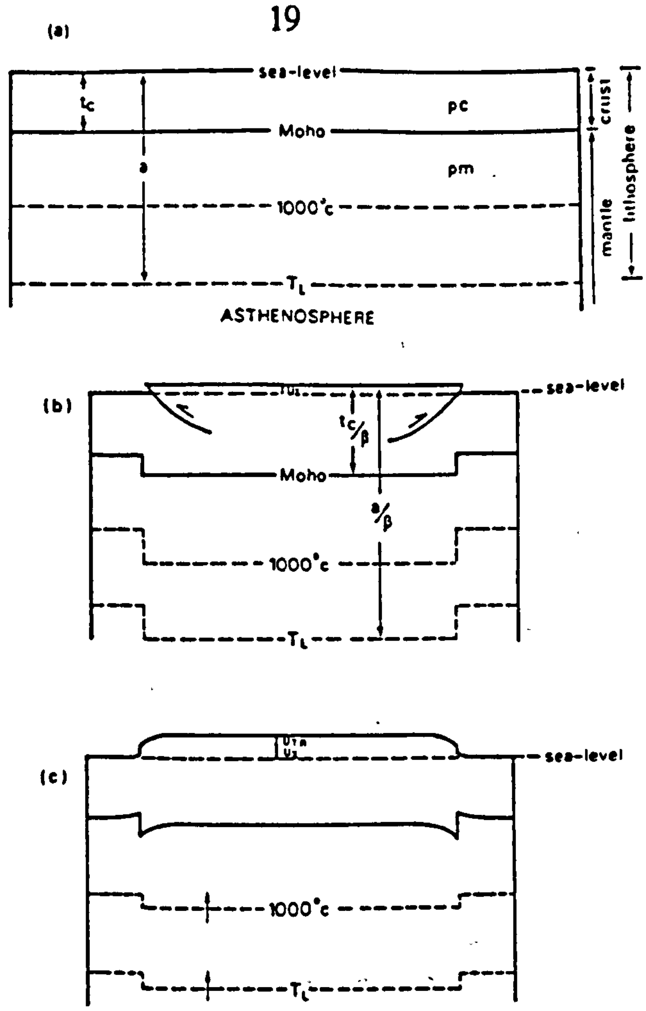


Fig. 8 a) The effect of uniform horizontal shortening on lithosphere a) isostatically balanced prior to shortening, b) after initial uplift and c) thermal equilibration (after Chadwick 1985).

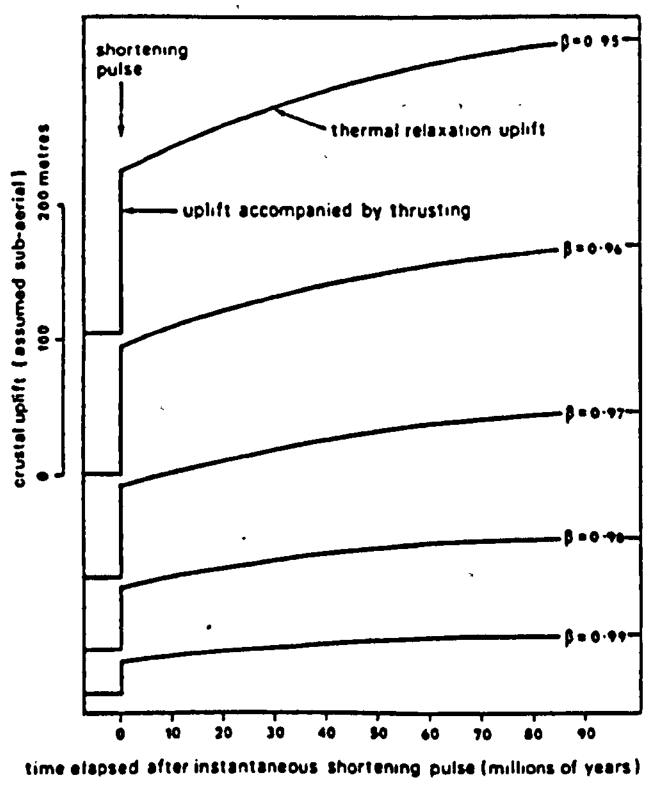


Fig. 8 b) Predicted uplift curves of sub-aerial crust for varying amounts of lithospheric shortening (after Chadwick 1985).

establish equilibrium after extension sooner than if inversion had not occured (please see chapter 6 for discussion).

The magnitude of the inversion event becomes important if the above is valid. If the inversion process is achieved through crustal shortening then the inversion could cause the basin to cease to exist! After complete equilibration no further subsidence would occur until the next rifting event. This is no doubt a rare event as the vast majority of documented events are within the life-time of a basin.

The duration of the event is less important than its timing relative to history of a basin. A long-lived event could uplift hydrocarbon (HC) source areas delaying their entry into the oil generating window. Similarly a long event could produce suitable HC traps above migration pathways whereas a short-lived event is less likely to produce major folding shortening and more likely to produce faulting and so is less attractive as a mechanism for trap creation.

2:1:6 Inversion Modelling; quantitative.

The modelling of the inversion event has been neglected in the literature. Whilst inversion can be recognised qualitatively from time-depth basin history curves it has received little quantitative analysis. Semi-quantitative data can be extracted from seismic and structural cross-sections. Individual faults can be analysed for their degree of reactivation although it is rarely that the 3-D geometry of the deformation is known.

Quantitative techniques for the assessment of basin inversion have been suggested by Chadwick (1985), in which he assumes that inversion is essentially the reverse of subsidence. He suggests that tectonic inversion develops as an isostatic response to the process of lithospheric shortening. He further assumes that shortening is instantaneous and following this there will be a phase of thermal relaxation uplift. In the model Chadwick assumes that inversion thickens the crust in a uniform manner, to greater than the pre-extension thickness (fig. 8a). This avoids difficulties with calculating the effects of inversion on renewed subsidence and recalculating the resultant geotherm. Chadwick offers a means to calculate initial shortening U_i and subsequent thermal relaxation uplift U_{TR}. Both of which can be derived in the same manner as subsidence in subsidence equations.

$$U = S\left(\frac{\rho_c - \rho_s}{\rho_c}\right)\left(\frac{\rho_c - \rho_s}{\rho_m - \rho_c}\right)$$

$$U_1 = \frac{a\left(1 - \frac{1}{\beta}\right)\left\{\frac{t_c}{a}\left(\rho_m - \rho_c\right)\left(1 - \frac{\alpha T_L t_c}{2a}\right) - \frac{\alpha \rho_m T_L}{2}\right\}}{\rho_m(1 - \alpha T_L)}$$

From these equations Chadwick plotted uplift curves for various values of β (or shortening factor), where β=2 shortening is 100% (fig. 8b). This is a useful point from which to calculated uplift due to inversion but it assumes homogeneous shortening. Chadwicks suggestion is valid only assuming the premise "Inversion is the opposite of subsidence" is a simplification taking no account of the shortening mechanism. Inversion is characteristically heterogeneous, a function of the mechanism, with non-uniform uplift. It is desirable to use another symbol for the shortening factor as β is well established to mean "stretching factor". Uplift will vary for values of shortening depending on the timing of the inversion event in the basin. 10% shortening in a young newly rifted basin will be unlikely to re-equilibrate the lithosphere and hence subsidence will continue after inversion, The same degree of shortening towards the final phases of thermal subsidence in a basin will have a greater effect, thickening to more than pre-extensional thicknesses and so producing Chadwick's two phase uplift, whereas the former case did not. The all assumes that the shortening is crustal. If it is not crustal, e.g. thin skinned then the uplift will be due to deformation alone and less than for either of the previous two cases (see chapter six for models).

A measure of inversion is therefore highly dependant on the mechanism of the inversion, i.e. it it dependant on initial conditions and therefore cannot be represented by a constant uplift relationship factor.

2:1:6 Inversion Modelling: Analogue.

As with quantitative models, analogue models of inversion in basins are scarce. Both Koopman and McClay and respective colleagues (Koopman, Specknijder & Horsfield 1987; McClay & Ellis 1987) have modelled extensional fault geometries using sand and mica box models. McClay (1989) used these as a starting point for inversion models. From the structures produced in sand-mica and sand-clay analogues, he concluded that inversion (shortening) of domino normal faults above a basal detachment produced reactivation of faults less than 60° to layering . With high contractional strains, faults were rotated and reactivation ceased. McClay confirmed that short-cuts tend to develop in the footwall of steep normal faults, whereas listric faults produce characteristic asymmetric uplift associated with the major detachment. Other models have achieved inversion by uplift or rotation of rigid fault blocks in sand boxes (Koopman et al 1987).

There is considerable room for future analogues, as McClay acknowledges "further research is needed to understand the geometries and kinematics of inversion systems."

PART 2: REGIONAL CONTEXT

Having established the criteria for recognising basin inversion and considered its potential in the history of a basin, these must now be applied to the Carboniferous basins of northern England. In order to understand the deformation in northern England, it is essential to have knowledge of the broad geodynamic setting of the basins and a general history of the region considered. To achieve this aim the pre-Carboniferous structure of the basement upon which these basins are sited is considered, since it has been established that this can play a crucial role in the inversion process. Following this the contemporaneous Carboniferous tectonic setting and general depositional system will be discussed. In chapter three these threads will be drawn together in the specific case of the Northumberland basin itself.

2:2:1 Caledonian Framework

In understanding the context for the Northumberland basin, the Caledonian framework must be explained. Since the study considers an event that may reactivate older structures, there is no reason to assume that these will all be Carboniferous in age (Variscan). It is widely recognised that Carboniferous subsidence patterns were controlled by Caledonian basement structure (Turner 1949; Wills 1978).

The general implications of gross Caledonian structure exerting an influence on future basin development was considered by Leeder (1982). In this work Leeder assessed the "inheritance factor versus contemporary orogenic processes" i.e.the Hercynian orogeny. Northumberland was classed as a basin sited initially by palaeo-plate features i.e. the Iapetus suture, and upper crustal Caledonian granites, but controlled by Hercynian factors, i.e. subsidence in a "retro-arc" position (Leeder and Hardman in press).

Northumberland straddles the site of the Iapetus suture, the faunal and crustal (?) junction between a northern (Scotland) and a southern continent (including the Lake District). The suture province is a narrow region between the Southern Uplands, the Lake District and the North Pennines. The tectonic grain in the Southern Uplands is predominantly NE-SW a product of subduction during the closure of the Iapetus ocean,

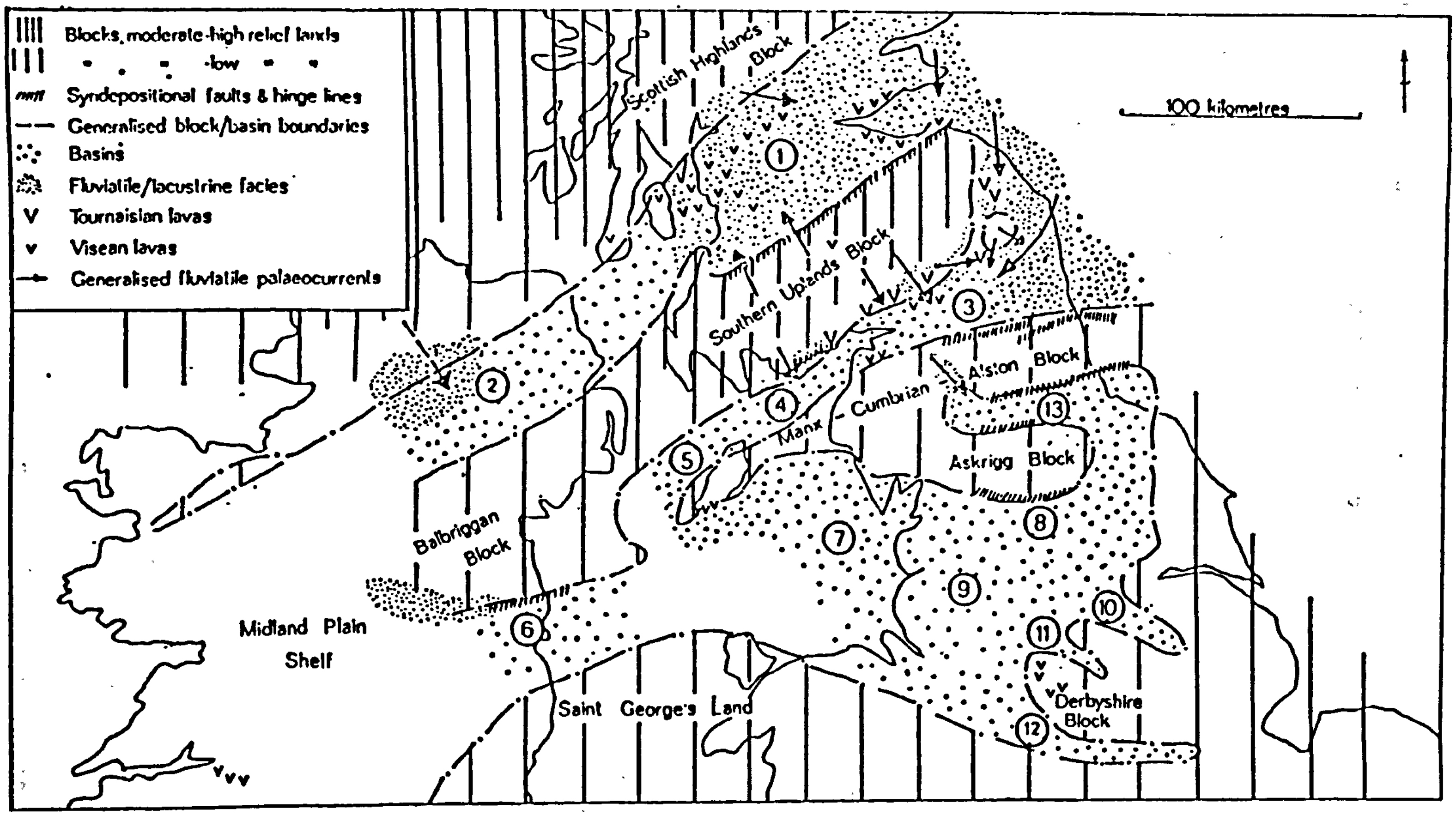


Fig. 9 Map to show location of Northumberland basin in the syn-orogenic basin complex of the northern Variscan foreland. Blocks apply to Tournaisian only. 1=Midland Valley, 2=Slieve Beagh, 3=Northumberland, 4=Solway, 5=Peel, 6=Dublin, 7=East Irish Sea, 8=Craven, 9=Bowland, 10=Gainsborough, 11=Edale, 12=Widmerpool, 13=Stainmore/Ravenstonedale (after Leeder 1976).

in the late Ordovician and Silurian. South of the province in the Lake District, Caledonian deformation is younger, currently believed to be early Devonian (Acadian after Soper, Webb & Woodcock 1987). Here the tectonic grain is arcuate, trending from NE-SW in the west (Appalachian trend) to ESE-WNW (Tornquist trend) in the east (Soper et al op. cit.). However there is no direct evidence for basement trends under Carboniferous Northumberland. The structure could be predicted from surrounding areas, but it is already clear that straightforward extrapolation could meet with difficulties in this province between deformation belts.

The Alston block, the northerly section of the Pennines (east of the Lake District) has an Upper Palaeozoic cover over a core of Lower Palaeozoic metasediments (very low grade) intruded by a late Caledonian (Devonian) granite. This is the Weardale granite (Bott 1966; Fitch & Miller 1965; Bott, Swinburn & Long 1982; Critchley 1984; Bott, Long, Green, Sinha & Stevenson 1985). The western margin of the Alston block is marked by the North Pennine Fault (NPF). This lineament connects with the Dent Line and fault system to the south on the western margin of the Askrigg block. Both the NPF and Dent systems are believed to have been active during the Lower Palaeozoic, though much of their older history is obscured by recent movements (Dunham 1933; Trotter & Hollingworth 1928; Underhill, Gayer, Woodcock, Donnelly, Jolley & Stimpson 1988). In the Pennines inliers of Lower Palaeozoic occur, e.g. Cross Fell, Ribblesdale and Howgill, all exhibiting a NW-SE structural trend. Just what that implies for the Alston block is debatable, especially if as suggested by Critchley (1984) the intrusion of the Weardale granite would have ammeliorated much of the structure. It seems that the pluton itself and the NPF system are the most reliable block features.

The Southern Uplands, the Lake District and the Pennine inliers are members of the Non-Metamorphic Caledonides (Dewey 1970). As there is no direct evidence for Northumberland basement it can only be tentatively inferred from the gross trends of surrounding areas. The Southern Uplands continues offshore into the NW of the Mid North Sea High as a persistent structural unit retaining its NE-SW trend (Glennie 1986). Further south in the North Sea the structural grain is N-S to NW-SE (Kent 1975). Extrapolation over the offshore Northumberland is supposition. Pharaoh (1987) suggested that on the basis of geochemical, isotopic, structural and geophysical data, much of eastern England is underlain by a concealed NW-SE trending Caledonian deformation belt. This apparently, is a mirror image of the NE-SW trending belt in Wales. The Midlands between these belts is underlain by the Midlands Microcraton. This is a wedge shaped area underlain by Precambrian crust exhibiting a N-S Charnian trend.

Pharaoh's work corroborates the arcuate trend proposed by Turner (1949), Smith (1987) and most recently by Soper and colleagues (1987). The arcuate trend for the

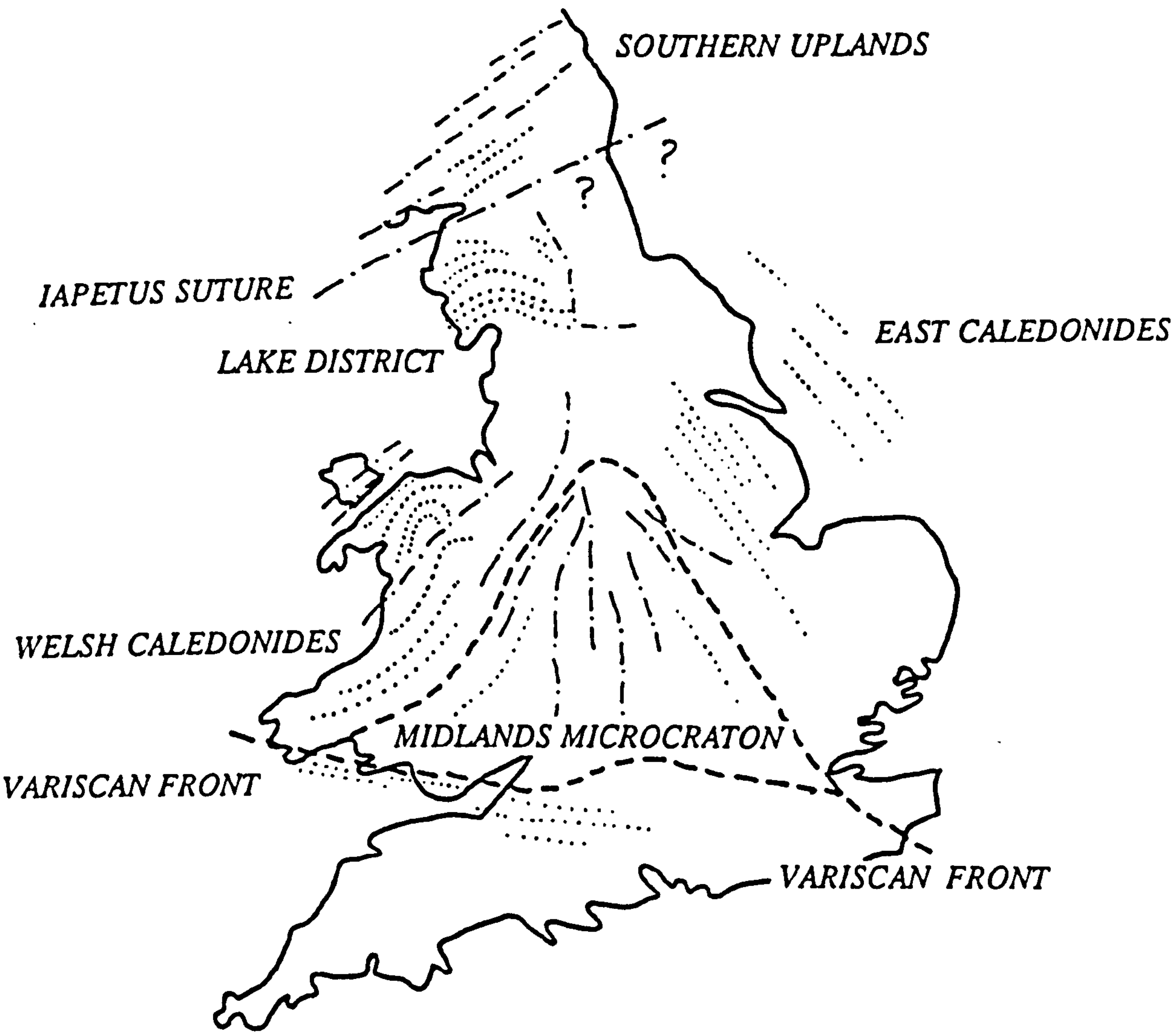


Fig. 10 Caledonian framework for the Carboniferous extensional basin complex. (adapted from Soper et al 1987 & Lee et al 1990).

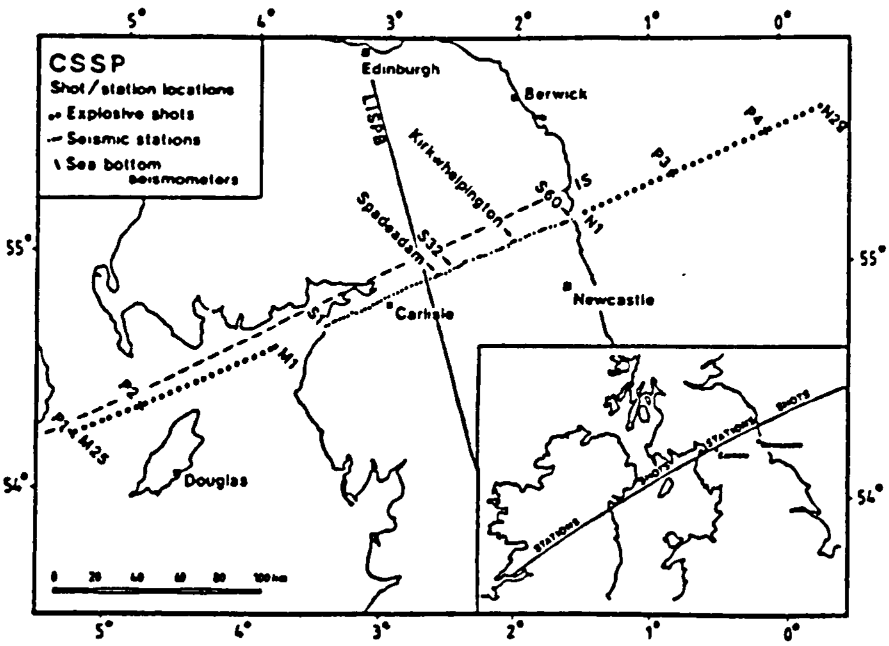
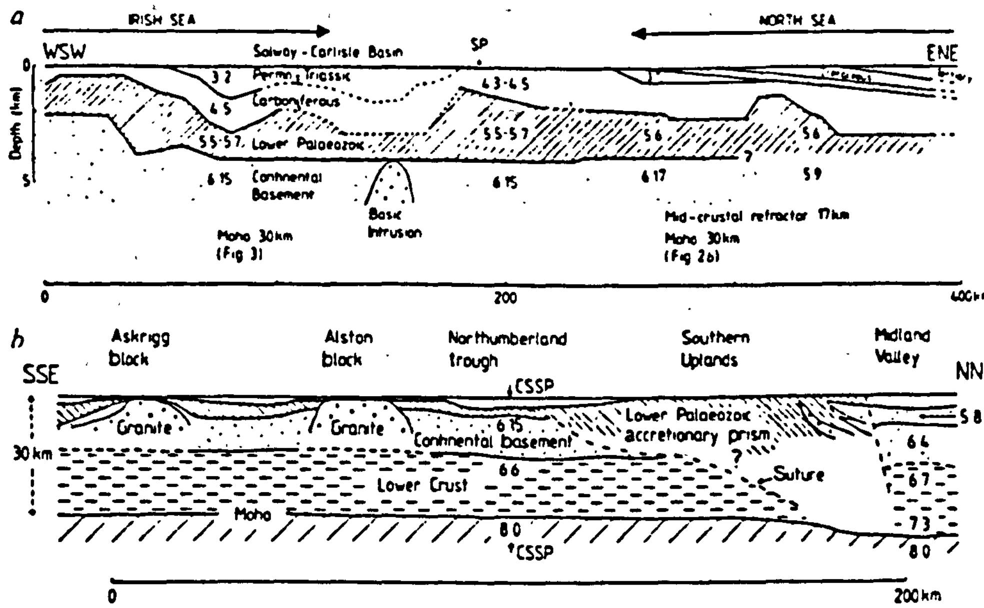


Fig. 11 Location map for the Caledonian Suture Seismic Project (CSSP) showing the lines in figs 12 & 13, where 12=Iapetus suture (Bott 1985) and 13=LISPB Bott 1979).

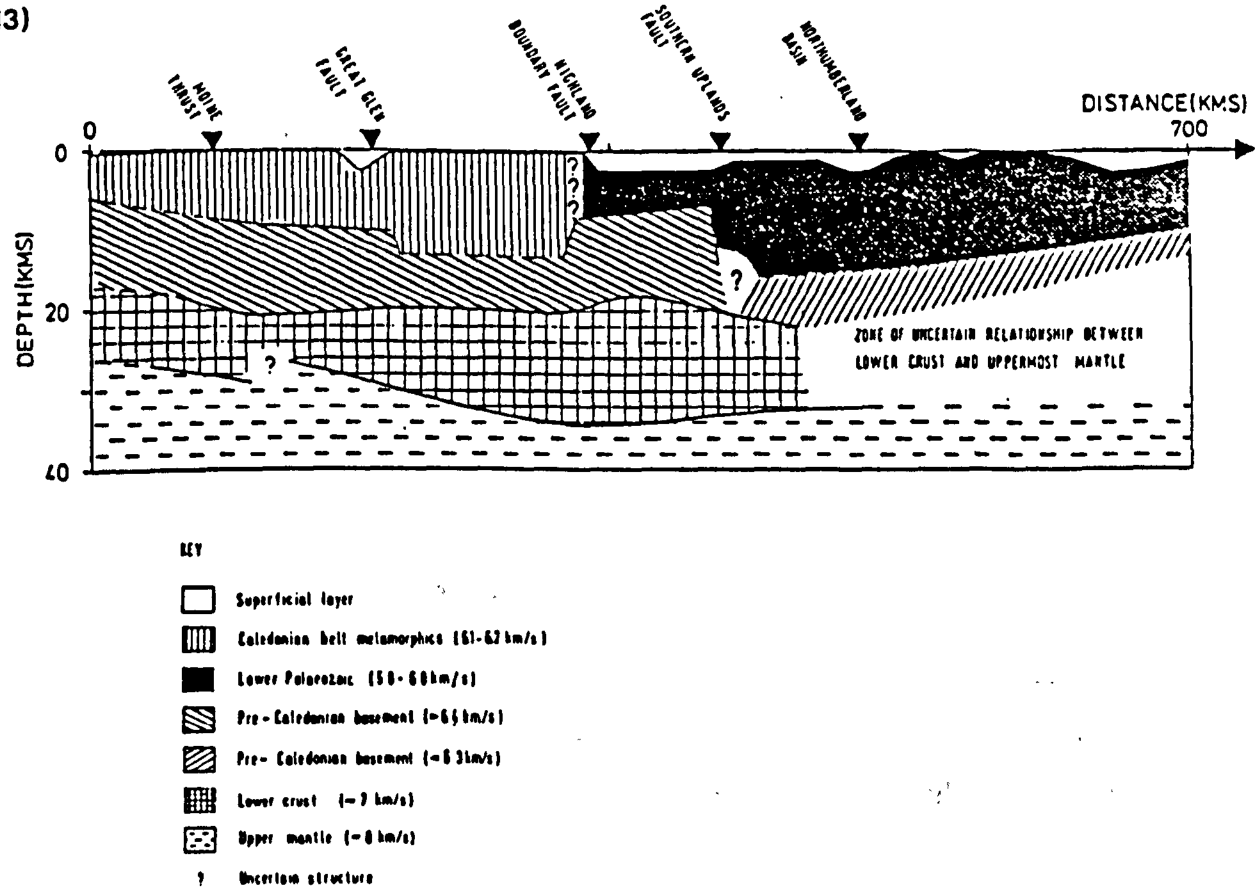
Fig. 12 CSSP line section along the Iapetus suture E/W and speculative section at right angles to this (Bott 1985).

Fig. 13 Schematic cross section interpretation of crust and uppermost mantle under northern Britain along the LISPB line (Bott 1979).

12)


a
IRISH SEA
NORTH SEA
WSW
ENE
Solway - Carlisle Basin
SP
Permo-Triassic
Carboniferous
Lower Palaeozoic
Continental Basement
Basic Intrusion
Moho 30km (Fig 3)
Mid-crustal refractor 17km
Moho 30km (Fig 2b)
Depth (km)
0
200
400km
b
Askrigg block
Alston block
Northumberland trough
Southern Uplands
Midland Valley
SSE
NNW
CSSP
Granite
Granite
Continental basement
Lower Palaeozoic accretionary prism
Suture
Lower Crust
Moho
30 km
0
200km

13)


MOINE THRUST
GREAT GLEN FAULT
HIGHLAND BOUNDARY FAULT
SOUTHERN UPLANDS FAULT
NORTHUMBERLAND BASIN
DISTANCE(KMS)
0
700
DEPTH(KMS)
20
40
ZONE OF UNCERTAIN RELATIONSHIP BETWEEN LOWER CRUST AND UPPERMOST MANTLE
KEY
Superficial layer
Caledonian belt metamorphics (6.1-6.2 km/s)
Lower Palaeozoic (5.8-6.0km/s)
Pre-Caledonian basement (~6.5 km/s)
Pre-Caledonian basement (~6.3km/s)
Lower crust (~7 km/s)
Upper mantle (~8 km/s)
? Uncertain structure

Caledonian creates difficulties for interpreting the Northumberland basin's basement; is it arcuate also, or more like like that of the Southern Uplands?

The Iapetus suture is no doubt in a critical position beneath the basin, but little is known or can be guessed at concerning its exact structure or role in the Carboniferous extensional province. Most recently the suture has been invoked as the main control for the siting of the basin as a extensional reactivation of the collision zone (Critchley & Holliday 1990). The authors present data to support their claims although the role of the suture has long been suspected (Leeder & Knipe pers. comm.) Critchley and Holliday make few interpretations about the basement and even assuming a simple NE-SW trends with some E-W arcing, the NPF appears anomalous with uncharacteristic trends.

Basement structure has been discussed in some detail by Lee and colleagues (Lee, Pharaoh & Soper 1990) utilising digital image processing techniques. These were applied to the regional British gravity and aeromagnetic data sets and a series of shaded relief and "illuminated" images were produced. These images show basement trends and depocentres very clearly. The arcuate English Caledonides are quite clear but trends are obscured for Northumberland by the thick cover of non-magnetic Carboniferous sediments. A number of NW-SE trends were seen but these correspond to known Tertiary dykes (and indicate the presence of others not previously recognised).

Geophysical techniques have been applied to the basin to determine crustal structure. Bamford (1978) constructed a cross-section based on the LISPB profiles conducted in 1974 (Bamford et al 1976). He identifies a layer at 6-14km depth under Scotland which he took to be Lewisian basement, and does not extend south of the Southern Uplands Fault. This indicates a fundamental deep crustal difference between Scotland and northern England, making extrapolation of Southern Upland trends into the whole of Northumberland dubious. Further studies for the crustal structure are summarised in figs. 12 & 13, confirming that there is L.Palaeozoic basement in northern England and indicating that it is thinner south of the suture over possibly Precambrian crust (Bamford et al 1978; Bott 1985). The crust immediately north of the suture is a thick stack of L. Palaeozoic with the Southern Uplands NE-SW trend. The trend of the thinner L.Palaeozoic south of the suture is unknown.

2:2:2 Hercynian Framework: Carboniferous Tectonics.

The extensional Carboniferous basins of northern England were developed in continental crust north of the penecontemporaneous Hercynian orogeny. This region is refered to as the Hercynian foreland (Hutton & Sanderson 1984) or stable northern craton (Francis 1988).

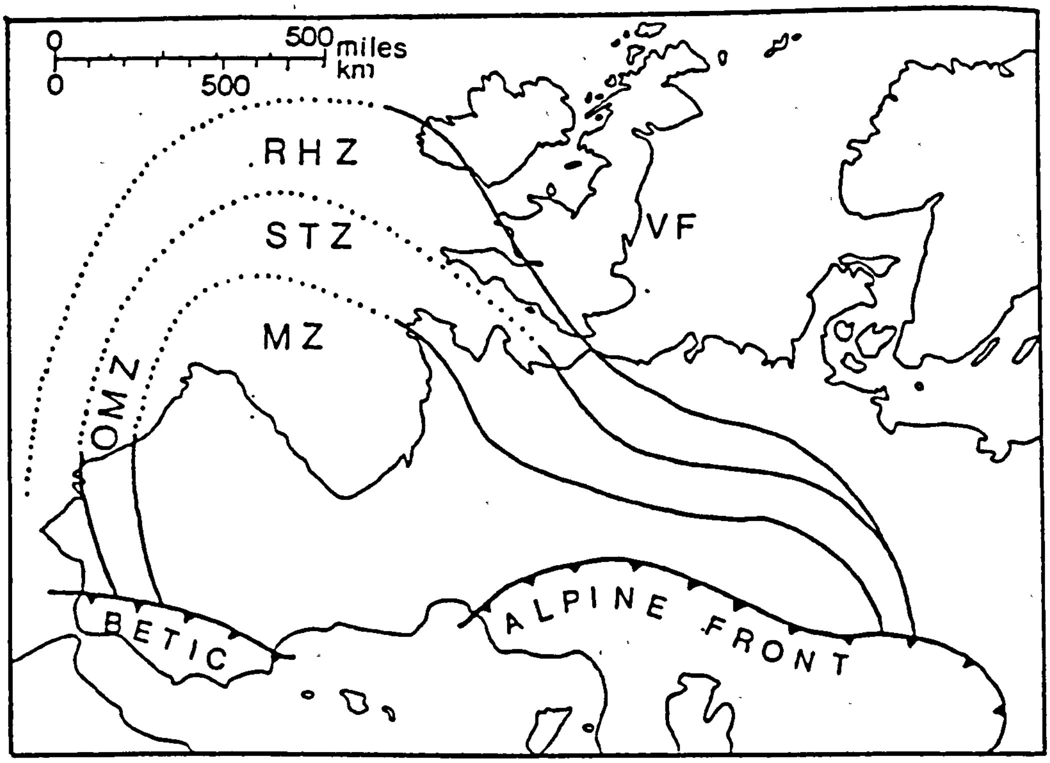


Fig. 14 Kossmatt zones for Hercynian western Europe. Where RHZ=Rhenohercynian zone, MBZ=Moldanubian zone, OMZ=Ossa Morena zone, STZ=Saxothuringinian zone and VF=Variscan or northern foreland (after Francis 1982).

The Hercynian orogeny occured from the middle Devonian to the early Permian, and forms an extensive orogen from North America to the Urals, across western Europe and NW Africa. The orogeny is known by different regional names such that several events are identified as occuring simultaneously but are now separated by subsequent plate motions. The Alleghenian is the Devonian/Carboniferous deformation seen in N.America, Appalachians and the Maritime province. The Mauritanides is the orogen in Africa and the Variscides is the orogen in Europe.

Kossmatt (1927) identified distinct zones of differing structural and metamorphic character in the Variscides of Hercynian Europe and proposed names that are still in use today. Hence the Variscides are divided into a central zone of supracrustal nappes with up to granulite grade metamorphism; the Moldanubian region. External to this is a zone of lower metamorphic grade, dominated by gravitational nappes and re-sedimented blocks; the Saxothuringinian zone. External to both of the former is a low grade metamorphic zone of intense folding and thrusting; the Rhenohercynian zone. It is the edge of the latter that is identified as the Variscan Front in the British Isles (fig. 14).

The Variscan Front runs approximately ESE through Southern Ireland, SW Wales and southern England to cross into Europe at the Dover Straits. This has been the accepted view for some years, but recent discussion has emphasised the term may have outlived its usefulness (Tectonic Studies Group special meeting, Tectonics of the British Isles, Durham, March 1990).

Sanderson (1984) suggested the Variscan front is best viewed as a transition from a more pervasive deformation occuring in the Variscan internides to heterogeneous deformation in the foreland. Shackleton (1982, 1984) argued that the present "front" was the northern limit of thin-skinned structures. South of the front he envisaged deformation decolling at depth, separating the sedimentary cover from the basement. North of the front, Shackleton maintained there was no decollment and deformation was influenced by basement structure. Certainly the state of deformation in the foreland is such that the front cannot represent the most northerly extreme of the Hercynian orogeny (Shiells 1964; Bluck 1978; Sanderson 1984).

Returning to the regional, Europe was dominated by a collisional orogenic belt in the Lower Carboniferous, represented by the Moldanubian region (the Ligerides),(Behr, Engel, Franke, Giese & Weber 1984). Although the development of the European orogen began with continental rifting in the early Palaeozoic about 450 Ma (Behr et al op. cit.), orogenic crustal shortening commenced with the closure of a Lower Palaeozoic ocean in the early Devonian with the Acadian event. This was the last event seen in the Caledonides of the British Isles (Weber 1984; Cogne 1976; Matte & Burg 1981; Brun & Burg 1982). Oceanic closure was caused by the collision of a N.European plate and

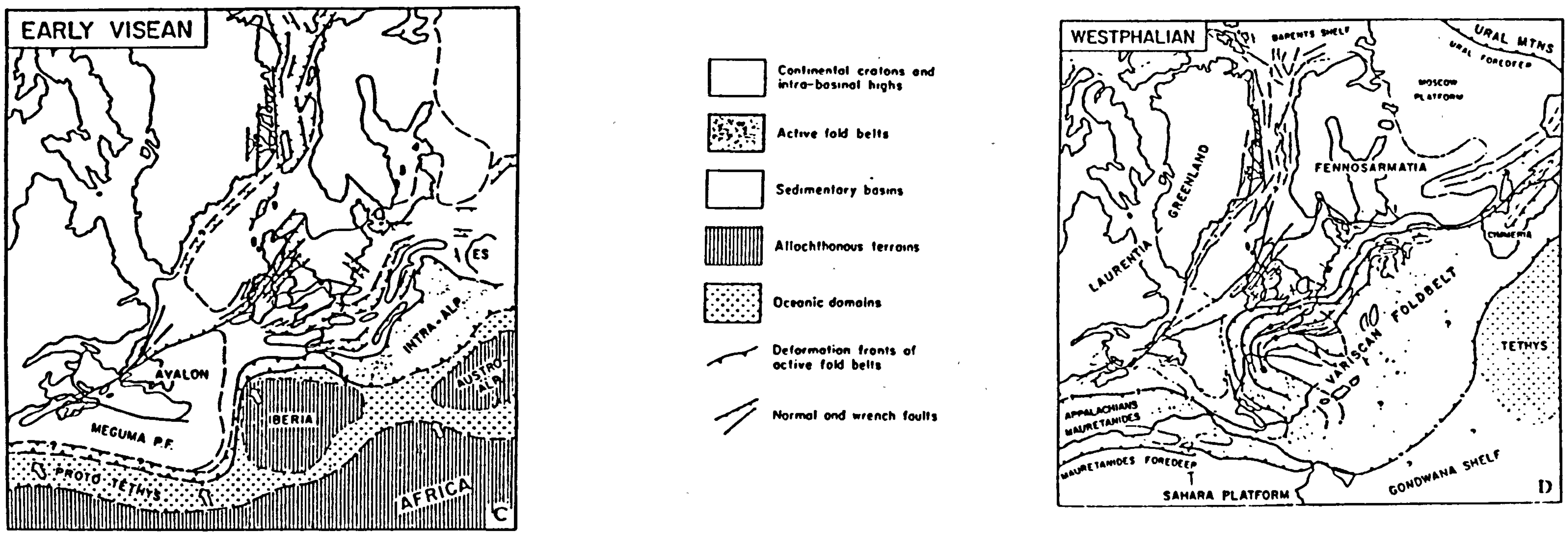


Fig. 15 Tectonic framework of the North Atlantic from the early Visean to Westphalian (after Ziegler 1984).

Gondwana with intervening microplates e.g. Armorica. The collision closed basins in Rhenohercynia, another in Saxothuringinia and a Mediterranean basin south of the microplates (fig. 15).

Subduction was broadly NE and S, a bilateral event around a central core region, Moldanubia (Behr et al op. cit.). The main Mediterranean seaway closed was the Mid European ocean or Proto-Tethys (Struth et al 1973; Glennie 1986). The orogen was essentially intracratonic with a central or dorsal axis and a fan-like shape verging to the west in the west and to the east in the east (Matte 1976). This central arc, convex to the west is the Iberico-Armorican region (Arthaud & Matte 1977). The orogen was summed up by Arthaud and Matte (op.cit.) as a "polyphase tectogenesis" that resulted in a complex series of folding events producing structures between 300 and 360 Ma .

a) Early Carboniferous to Late Carboniferous Orogenic phases.

The Variscan foreland was part of the northern paralic shelf on the margin of Hercynian Europe (Johnson 1978). This shelf was an archipelago of differentially subsiding basins and buoyant blocks (Bott 1967; Johnson 1978) during the early Carboniferous. The shelf developed whilst northerly subduction of the oceanic crust of Proto-Tethys was drawing Laurasia (N.America, Britain and Scandinavia) towards Gondwana (Europe and Africa) between 430-370 Ma (Cogne 1976; Matte & Burg 1978). By the late Visean (upper Carboniferous) continent-to-continent collision is believed to have commenced (Brun & Burg 1982; Glennie 1986) producing a new continental mass, Pangea (table 1). Stille (1951) proposed several phases of deformation within the orogeny although the phases are often based on local events e.g. unconformities, and so may not represent regional events (Simpson 1962), but are still used in the literature.

Phase	Timing
Pfalizic	Permo-Triassic
Saalic=Allenghenian	Early Permian (Rotliegendes)
Asturian	Westphalian C to Stephanian
Erzgebirgian	Namurian-Westphalian boundary
Sudetic	Visean to early Namurian
Bretonic	Late Devonian to early Carboniferous
Reussic (Acadian=Appalachians)	Early to middle Devonian

Systems			Eastern USA	Mid-continent USA	British Isles		International Systems			Belgium	Donets basin USSR
Permian										Autunian	Asselian
Carboniferous	Pennsylvanian		Dunkard	Wolfcampian (Permian)	Stephanian	D	Carboniferous	Silesian	Westphalian		
			Monongahelan	Virgilian		C B A				Gap	Agzhelian Kasimovian
			Conemaughian	Missourian		Cantabrian					
			Alleghenian	Desmoinian	Westphalian	D C					Moscovian
			Pottsvillian	Atokan		B A				B A	Bashkirian
			Pocahontasan	Morrowan	Namurian	Yeadonian Marsdenian Kinderscoutian Alportian Chokierian Arnsbergian Pendleian				Namurian	Serpukhovian
	Mississippian	Upper	Chesterian	Chesterian							
		Lower	Valmeyeran	Meramecian Osagean	Dinantian	Brigantian Asbian Holkerian Arundian Chadian		Dinantian		Visêan V 1, 2, 3	Visêan
			Kinderhookian	Kinderhookian		Courceyan				Tournaisian Tr 1, 2, 3	Tournaisian
Devonian											

Table 1 Correlation of Carboniferous chronostratigraphy for the Hercynian orogen (after Glennie 1986).

As far as the early Carboniferous of the Variscan foreland is concerned, no Sudetic phase is recognised, although a broad facies change (see 1:2:3) is seen over central Britain which is diachronous and not observed until later in Scotland and northern England.

There are several models for the collision of Laurasia and Gondwana e.g. LeFort and Van der Voo (1981), Badham (1982), Brun and Berg (1982).Continental collision is widely accepted to have occured in the early to middle Carboniferous. At this time the paralic shelf foreland was undergoing major extension and subsidence (Leeder 1982, 1987). The shelf was a series of active fault bounded basins, many typically half-grabens (Miller & Grayson 1978). These basins include those of the Midland Valley, the Solway basin, Northumberland, Stainmore etc. The foreland was an extensional province or suite of syn-orogenic basins that extended from the Moray Firth to the Southern North Sea.

The extension has been variously attributed to back-arc processes (although the arc is not readily identifiable); differential subsidence of sediment filled basins against buoyant granite cored blocks and upper mantle flow following equilibration after the Caledonian orogeny (Leeder 1982, 1987; Bott op.cit.). These processes may all account for the extension but regional extension on that scale must be linked to the orogeny in Europe. Extra-orogenic extension is a common feature of major collisions (Dewey & Burke 1973) and would seem appropriate for the British Carboniferous. Any models have also to take account of all of the above and also the patterns of volcanism through the foreland (Francis 1978). Other extension processes have been suggested including onset of early rifting in the North Atlantic (Russell 1974; Hazeldine 1984) and whilst these may have some validity, the effects would be minor in comparison with the Hercynian orogeny. The regional tension driving the extension is a product of plate processes. The tension could be achieved by trench suction of the over-riding plate during subduction (Leeder 1976) or lab-pull from the subducting plate, any roll-back of the subducting plate will also cause regional tension (Johnson 1978, 1981). As the subduction direction is still not wholely clear for the NW Variscides, it is difficult to say what the mechanism might be. If subduction is from the north (descending south) tension is due to trench pull or roll-back (Bott 1984; Weber 1984). However if subduction is down to the north, an interpretation favoured by Leeder (1982, 1987), then tension may be due to back-arc extension or roll-back (causing extension in the overiding plate).

By the middle Carboniferous activity in the foreland was limited to epeiorogenic events with the extensional province undergoing regional thermally driven subsidence (McKenzie 1978; Frazer 1989) occasionally interrupted by bursts of renewed activity

Permian		Series	Stage	Radiometric pick	Duration	Scale of Harland *et al.* (1982)
				300		
CARBONIFEROUS	SILESIAN	Stephanian	C		3	
			B			
				303		
			A		2	
				305		296
		Westphalian	D		3	
				308		
			C		3	
				311		
			B		4	
			A			
				(315)		315
		Namurian	C			
			B		4	
				319		320
			A		7	
	DINANTIAN			(326)		333
		Viséan	Br		*c.*9	
			As			
				(335)		
			Ho			
			Ar		*c.*15	
			Ch			
				(350)		352
		Tournaisian	Co		*c.*10	
				360		360
DEVONIAN						

Table 2 Absolute time picks on the Carboniferous chronostratigraphic scale (after Leeder & McMahon 1987).

(Leeder & McMahon 1988).This scenario of extensional basins in a syn-orogenic complex is discussed at length in Besly's 1987 paper.

In the middle to late Carboniferous strike-slip faults in Europe, Africa and N.America were active as part of a post-initial collision pattern of deformation as Gondwana and Laurasia continued to collide (LeFort & Van der Voo 1981). These events go unrecognised in the foreland except for minor deformation and folding in the Midland Valley (Read 1988), a postulated along strike continuation of the N.American province (Ziegler 1982; Leeder 1988). Such strike-slip motions have been forwarded on the basis of Palaeomagnetism data for sinistral motion between Mauritanian east N. Africa/Europe and America/Greenland for the mid.Carboniferous (Kent & Opdyke 1978; Van der Voo 1982). However such motions have received little supporting evidence from the North Atlantic (Smith & Watson 1983) and as Leeder pointed out (1988) there may be reason to doubt the age of the remnant magnetism on which the work is based.

The Erzegebirgian phase (Cloos 1948) is recognised in the foreland as a facies change from coarse clastics to coal producing delta facies: In Europe a broad north to south migration of deformation and metamorphic facies is recorded (Burg & Matte 1978) in association with the production of anatectic granites. These events are attributed (Pin & Peucat 1986) to major overthrusting in the late Visean with widespread thermal doming, i.e. continued collision 320-280Ma.

b) Late Carboniferous Deformation.

In the late Carboniferous a well documented Asturian phase (Engel & Franke 1983) occured, identified in the European orogenic front (a similar event seen in the Alleghenian is Stephanian to early Permian). An the event of this timing in the northern foreland caused a period of deformation resulting from regional compression. The extensional province that had previously characterised the lower Carboniferous experienced epeiorogenic deformation and uplift.

Johnson (1978) attributed this phase to the final plate collision and elimination of the Rheic ocean in the Westphalian. Badham (1982) believed that the final accretion of the European and African plates marked a phase of dextral shear and "instabilities" in Europe and east N. America. Though Badham does not specify what these instabilities are the implication is that he was referring to folding observed throughout the Variscan foreland. It is generally accepted (Leeder 1988) that the Asturian event was the indirect result of the final consolidation of Pangea.

The Asturian event occured in the foreland sometime during the late Westphalian and possibly early Stephanian, causing many of the Carboniferous basins of the previous syn-orogenic complex to be deformed and uplifted. This episode has lately been recognised as a widespread basin inversion event. Individual basins responded in unique ways producing a complex pattern of deformation across the foreland.

The late Carboniferous in Europe was marked by the northward migration of the Variscan foredeep ahead of a northerly advancing nappe pile (Hedemann & Teichmuller 1971; Bless et al 1977; Ziegler 1982). Ziegler linked the basin inversions to regional foreland compression during this late phase of nappe advancement. The Asturian manifests as thin-skinned imbricate thrust sequences in the Variscan externides e.g. Cornwall; although the foreland generally shows little evidence for thin-skinned deformation (see previous).Ziegler speculates that the entire late Variscan deformation (diastrophism)was associated with an active south plunging continent-continent subduction zone along the northern margin of the North German High. Such broad speculations are tentative at best.

Throughout the previously extensional province of the British Isles, basin inversion was remarkably widespread showing no temporal change with geography. Inversion is recorded as far north as the Orkney basin (Coward, Enfield & Fischer 1989)! Offshore, inversion axes include areas in the English Channel, SW Approaches, Bristol Channel and the Celtic Sea (Ziegler op. cit.; Tate & Dobson 1989). The degree of uplift is highly variable. In some places only a few tens of metres of Carboniferous are removed (Stainmore and Solway basins), whereas elsewhere even within the same basin (Northumberland, Cleveland and Solway basins) in excess of 2km may be missing. The deformation is not confined to the basins (although it much more intense here), but is also found on the intervening block areas e.g. the Cheviot (Robson 1977).

Many workers over the past 80 years of research have called the foreland deformation Variscan, but opinion is divided as to the orientation of the principal stress axes. Much work was conducted before oblique deformation style received attention and "transpression and transtension" became stress regimes in their own right. It is now widely understood that such deformation can produce radically different structural orientations in one area. It is not surprising therefore that there are difficulties relating spatially separate and geometrically distinct features over a single basin or a suite of basins in this case. In the Cheviot and S. Scotland, Robson (1977) related Variscan deformation to W-E compression but recently the same structures (inversion related folding) in the Midland Valley have been attributed to dextral transpression. The Westfield coal basin for example exhibits N-S folds and numerous related dextral strike-slip faults. In northern England late Carboniferous deformation was recognised as early as the first survey maps (Trotter & Hollingworth 1927; Dunham 1933). Robson re-iterated these observations in suggesting deformation around the NPF and the areas around Bewcastle and northern Northumberland were caused by W-E compression.

Since then in the Bellingham memoir the same basin, deformation has been attributed to N-S compression (Frost & Holliday 1980). The diversity of areas and interpretations are summarised in table 12 in chapter severn.

It is into this background of opinion that the case study of the Northumberland is introduced. The deformation and causative stress systems will be discussed in chapters 3,4 & 5 and summarised in chapter 7. The regional implications of the study will be discussed in the closing stages of this work. The interpretation of the region has not reached a consensus as yet, and clearly awaits future research applying modern structural techniques.

2:2:3 Regional Sedimentation over the Northern Foreland.

The pattern of Carboniferous sedimentation over the northern foreland was initially related to the final phases of the Caledonian Old Red Sandstone (ORS) continent palaeogeography. Britain was a series of uplands in the north with interior intermontane drainage basins and a coast/shoreline developed in the south of the ORS continent. Subsidence in the middle Devonian had been interrupted by a compressional episode but subsidence had resumed with fluviatile deposits which persisted until the Carboniferous (Anderton, Leeder & Bridges 1979, see table 2).

In the southern part of Britain, pelagic marine sedimentation commenced in the middle Devonian and continued until the Carboniferous: This was the "bathyl lull" referred to by Goldring (1962). It was while this facies was developing ahead of the the newly initiated Hercynian deformation front (fig.16), that differential sedimentation and subsidence was established in northern England (Leeder 1976). The bathyl lull facies advanced roughly northwards in Cornwall causing a major transgression in the Upper Devonian (a widely diachronous event). The progression of deeper water conditions from south to north has been referred to as an epeiorogenic down-warping (Johnson 1982) and the transition to the Carboniferous is seen as a gradual change from continental red beds to grey marine sediments. This transition worked its way north with time.

In northern England and Southern Scotland the earliest Dinantian (lower Carboniferous) sediments are marginal marine, lacustrine and fluvial facies, with fully marine environments developing later; first in the south and then in the west e.g.the first marine limestones in the Lake District are Chadian in age. In Northumberland the first marine limestones are Asbian and in the Midland Valley they are Brigantian (Edwards & Trotter 1954; Taylor, Burgess, Land, Mills, Smith and Warren 1971; Johnson 1982).

As Carboniferous facies became established across Britain it was recognised that this was related to differential subsidence between block and basin topography. Some of

Area:				South Isle of Man	Furness	West Cumberland	Alston Block	Brough-Ravenstonedale	North Cumberland	W & NW Northumberland	North Northumberland
Overlying beds:						Hensingham Group *First Lst*	Upper Limestone Group *Great Lst*	Millstone Grit Series *Great Lst*	Millstone Grit Series *Great Lst*	Upper Limestone Group *Great Lst*	Upper Limestone Group *Great-Dryburn Lst*
Lower Carboniferous or Dinantian	Viséan	P_2, P_1	D_2	Scarlet Volcanic Group • Black Limestones Poyllvaaish Limestones	Gleaston Group *Girvanella Band*	Chief Limestone Group	Middle Limestone Group *Smiddy Lst*	Alston Group	Upper Liddesdale Group *Low Tipalt Lst*	Middle Limestone Group *Oxford Lst* *Lower Bankhouses Lst*	Middle Limestone Group *Oxford Lst* Lower Limestone Group *Dun Lst*
		B_2	D_1	Castletown Limestones	Urswick Limestone		Lower Limestone Group *Melmerby Scar Lst*	*Great Scar Lst*	Lower Liddesdale Group *Naworth Bryozoa Band*	Lower Limestone Group *Redesdale Lst*	Scremerston Coal Group
			S_2		Park Limestone	*Seventh Lst* Cockermouth Lavas Basal Conglomerate •	Shales with Limestone	Orton Group	Upper Border Group *Clattering Band*	Scremerston Coal Group	
			C_2S_1	Basal Conglomerate	Dalton Beds Red Hill Oolite Martin Limestone Basement Beds •				Middle Border Group *Whitberry Band* Lower Border Group: Cambeck Beds	Fell Sandstone Group †	Fell Sandstone Group †
	Tournaisian	Strata not divided into zones					Basement Beds •	*Algal Layer* Ravenstonedale Group *Pinskey Gill Beds*	Lower Border Group: Main Algal Beds Bewcastle Beds Lynebank Beds *base not seen*	Cementstone Group Cottonshope Lavas • Lower Freestone Beds •	Cementstone Group Kelso Lavas •

• age uncertain   † both top and bottom of the Fell Sandstone Group are diachronous

Table 3 Summary of Lower Carboniferous stratigraphy in northern England (after Taylor et al 1971).

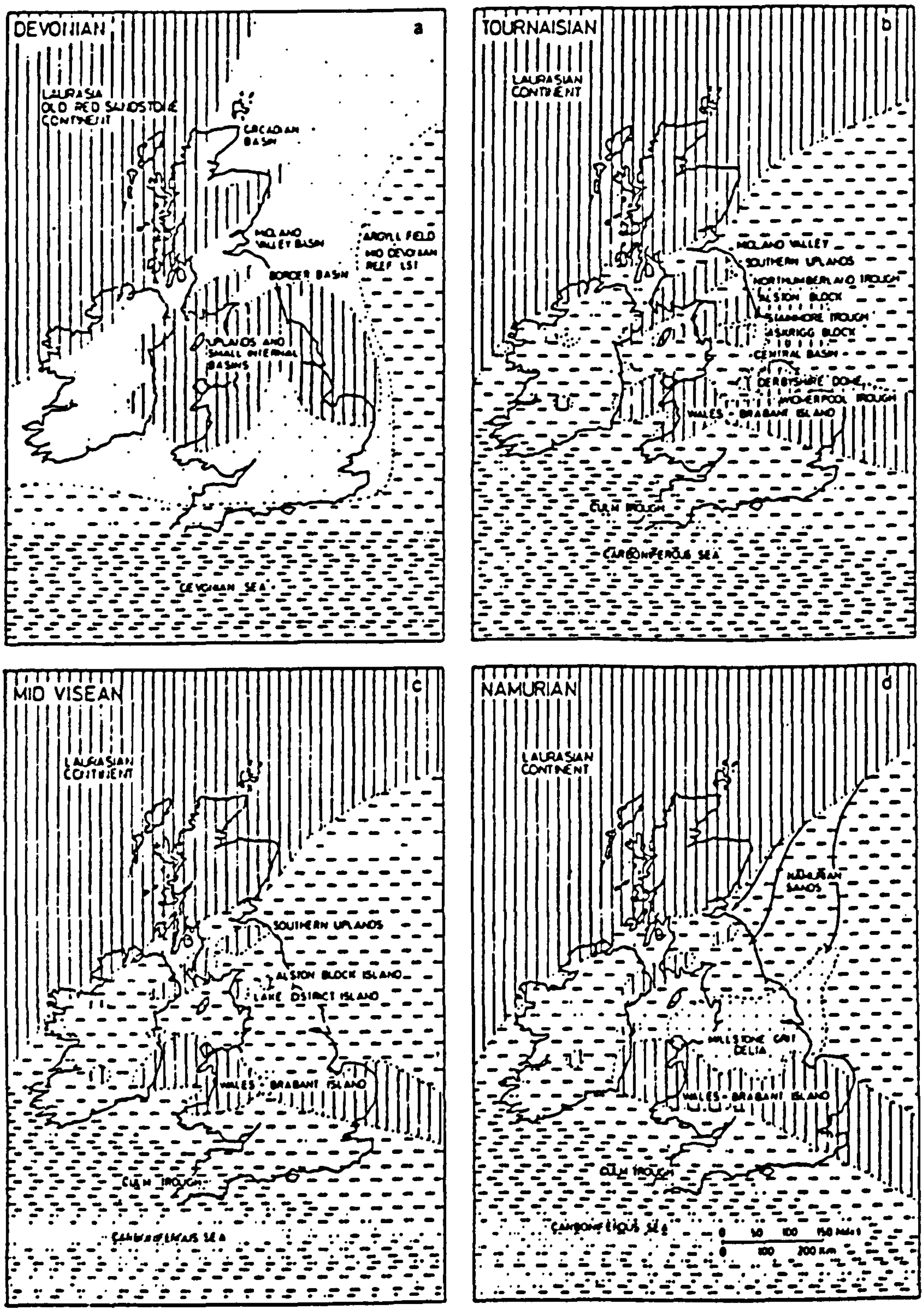
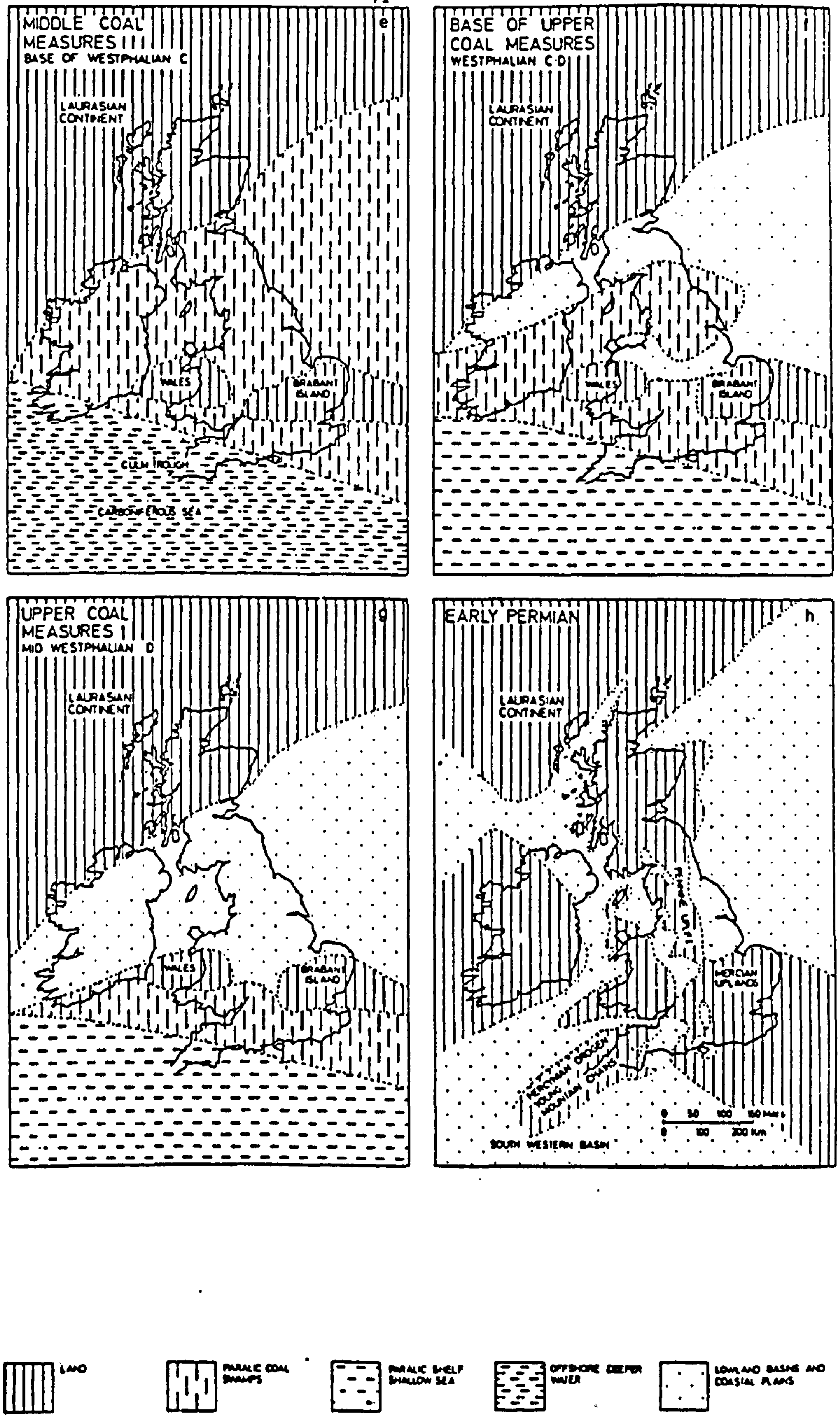


Fig. 16 Palaeogeographic reconstructions of the British shelf region from Devonian to Permian times (after Johnson 1984 modified from Anderton 1979, Calver 1969, Johnson 1967 & Ramsbottom 1969).


MIDDLE COAL MEASURES III
BASE OF WESTPHALIAN C
e
LAURASIAN CONTINENT
WALES
BRABANT ISLAND
CULM TROUGH
CARBONIFEROUS SEA
BASE OF UPPER COAL MEASURES
WESTPHALIAN C-D
f
LAURASIAN CONTINENT
WALES
BRABANT ISLAND
UPPER COAL MEASURES I
MID WESTPHALIAN D
g
LAURASIAN CONTINENT
WALES
BRABANT ISLAND
EARLY PERMIAN
h
LAURASIAN CONTINENT
MERCIAN UPLANDS
HERCYNIAN OROGEN
YOUNG MOUNTAIN CHAINS
SOUTH WESTERN BASIN
0 50 100 150 Miles
0 100 200 km
LAND
PARALIC COAL SWAMPS
PARALIC SHELF SHALLOW SEA
OFFSHORE DEEPER WATER
LOWLAND BASINS AND COASTAL PLAINS

these blocks are cored by Caledonian granites e.g. the Alston and Askrigg blocks by the Weardale and Wensleydale granites respectively. These granites retained their "buoyancy" until swamped by sedimentation in the Visean (Namurian). This trangression was D_1 on the Alston block (late Visean) and C_2S_1-S_2 (early Visean) for the Askrigg block. The Lower Carboniferous is generally represented by the Carboniferous limestone series though this is not developed in the more northerly basins.

Simplifying the facies, the main characters of the sedimentation in central England (Pennines and Derbyshire) are two environments developed over tilt blocks (Miller & Grayson 1986). The more stable block highs provided site for clear water carbonate dominated facies where thick well bedded limestones and shallow water lagoonal sediments occured with frequent dolomitic oolites and cherts. The open basin between the blocks were areas of argillaceous limestone sedimentation, with dark basinal shales and abundant fauna-rich marine bands. Along the edges of the blocks, reefs and sheets of reef debris developed including numerous reef knolls (Bond 1950).

Further north in the basins of northern England, the lowermost Carboniferous is represented by basal conglomerates of ORS material (and older) followed by shales and sandstones e.g. Roman Fell, Ravenstonedale and Pinskey Gill beds. Succeeding beds are rythmic sequences of mudstones and limestones with subordinate sands representative of shallow water fluvio-deltaic facies; with major sandbodies developed later (see chapter 2).

Under the extensional basin development basaltic volcanism occured in the Dinantian throughout the far north of England and in the Midland Valley of Scotland.The volcanism occured as the Birrenswark, Kelso, Clyde and Cockermouth lavas. Volcanism seems to have been absent for most of central England but does occur in Derbyshire. Volcanism occured immediately prior to the rifting of the Carboniferous Basins, and is believed to be typical of intra-plate igneous activity (Mitchell 1978: Macdonald 1984). The igneous activity of the Variscan orogeny can be divided into three volcano-tectonic provinces of which the northern foreland is one (Francis 1988). The volcanism is alkali basaltic indicative of production during extension of continental crust.

In late Dinantian times widespread deltaic and marine cycles became established over the foreland, with classic Yoredale cycles of sediment. Further north these cycles are slightly different and further south the facies were still mud dominated. Differential subsidence continued with 1600m of sediment already deposited in Northumberland before the Alston block was transgressed. In the Alston area 310m of sediment compare with 600m for the Stainmore basin, indicating continued differential subsidence. The deltaic cycles of the foreland persisted until the Namurian generally and until the late Namurian in the northern basins. The end of the deltaic cycles was marked by the sudden influx of a coarse clastic fluviatile facies; the Millstone Grit series (see table 4). In the

	MODERN CLASSIFICATIONS	OLDER CLASSIFICATIONS: Northumberland, East Cumberland and Durham	OLDER CLASSIFICATIONS: West and Central Cumberland
WESTPHALIAN (Coal Measures)	*LOWER COAL MEASURES* *Gastrioceras subcrenatum, Quarterburn or Swinstone Top Marine Band*	*LOWER COAL GROUP* *horizon of Ganister Clay Coal*	*PRODUCTIVE COAL MEASURES* *Harrington Four Foot Coal*
NAMURIAN (Millstone Grit Series)	*MILLSTONE GRIT SERIES* *Great Limestone*	*'MILLSTONE GRIT'* *UPPER LIMESTONE GROUP or 'CARBONIFEROUS LIMESTONE SERIES'* *Great Limestone*	*HENSINGHAM GROUP* *Great (First or Main) Limestone*
VISÉAN (Carboniferous Limestone Series)			

Table 4 Correlation of Namurian over Northern England (after Taylor et al 1971)

MAJOR DIVISIONS: Stubblefield and Trotter 1957	PLANT CLASSIFICATIONS: Heerlen Congress 1927	PLANT CLASSIFICATIONS: Miospore Zones	NON-MARINE BIVALVE ZONES	IMPORTANT MARINE BANDS
UPPER COAL MEASURES	Westphalian D	*Thymospora obscura*	*Anthraconaia prolifera* and *Anthraconauta tenuis*	
	Westphalian C	*Torispora securis*	*Anthraconauta phillipsii*	*Anthracoceras cambriense* (St.Helens, Down Hill)
—M—M— MIDDLE COAL MEASURES		*Vestispora magna*	—M—M— Upper *Anthracosia similis* and *Anthraconaia pulchra*	*Anthracoceras hindi* *A. aegiranum* (Bolton, Ryhope)
	—M—M— Westphalian B		—M—M— Lower *A. similis* and *A. pulchra*	
		Dictyotriletes bireticulatus	Upper *Anthraconaia modiolaris*	*Anthracoceras vanderbecki* (Solway, Harvey)
—M—M— LOWER COAL MEASURES	—M—M— Westphalian A	*Schulzospora rara*	—M—M— Lower *A. modiolaris*	
		Radiizonates aligerens	*Carbonicola communis*	
		Densosporites anulatus	*'Anthraconaia' lenisulcata*	*Gastrioceras subcrenatum* (Quarterburn)
—M—M— MILLSTONE GRIT SERIES	—M—M— Namurian		—M—M—	

(From Edwards and Trotter 1954, p.46, with additions and amendments)

—M—M— *marine band*

Table 5 Correlation of Westphalian (Coal Measures) over Northern England (after Taylor et al 1971) northerly basins the facies indicate delta top deposition giving rise to a paralic swamp, that spread southwards. Hence the earliest coals are found in Northumberland (Scremerston Coal Group see later). This system swept SW so that successively younger coals are found southwards; e.g. Lower Namurian on the Alston block, Upper Namurian on the Askrigg block and in the Craven (Bowland basin) the youngest coals are Westphalian (Johnson 1982).

Following the Namurian, the Westphalian Coal Measure (table 5) established delta top swamp facies. These gradually give way to a non-marine facies where coal facies are dominant over sandbody facies which become thinner and bound by erosion surfaces (Duff & Walton 1962; Reading 1971). By this time the foreland was subsiding regionally as differential subsidence had largely ceased. Maximum deposition was centered over central eastern England in the Westphalian, having migrated south with time (Dunham 1967). The thickest Westphalian is slightly south of the thickest Namurian (generally speaking) becoming over 1000m thick in the Bristol coal fields. Johnson (op. cit.) attributed the migration of the Carboniferous depocentre to the progressive seawards stablisation of a paralic shelf, though the development of a foreland deep due to Variscan nappe loading (to the south) may be a complimentary factor (Dewey 1982).

The distinctive cyclical sedimentation of the northern foreland has been the subject of much debate. Over the last three decades, cyclicity control has been attributed to autocyclic delta "switching", seasonal climatic variations, eustatic sea level changes and tectonic processes (Ramsbottom 1969, 1973; Broadhurst, Simpson & Hardy 1980; Fielding 1984; Hazeldine 1983; Gawthorpe 1986; Leeder & Strudwick 1987 and Collier 1988). A full discussion of the controls is inappropriate here but it likely that all these processes are involved.

The last Carboniferous facies developed were those of the Barren Coal Measures, a sequence of red beds thought to be Westphalian C to possibly Stephanian in age. These are found over the Midlands (Etruria formation), in the SW Peninsula (Pennant Group) and are also recorded in the North Sea and northern England (Canonbie coalfield). These beds herald a change to semi-arid climatic conditions and most recently have been found developed in areas of inversion axes (Besly & Turner 1983; Besly 1987; Leeder & Hardman in press).

This is the framework for the case study of the Northumberland basin, its tectonic setting, its sedimentational background and its relationship to the other basins of the synorogenic complex prior to the late Carboniferous (Asturian) basin inversion event.

Fig.18 Geological map of Northern England. 1 = Llandovery, 2 = Wenlock & Ludlow, 3 = Llandeilo & Caradoc, 4 = Andesite (L.ORS), 5 = Granite (L.ORS), 6 = Upper Devonian, 7 = L. Carboniferous lavas, 8 = Lower Border Group/Cemenstones, 9 = Middle Border Group/Fell sandstone, 10 = Upper Border Group/Scremerston Coal, 11 = Lower Limestone Group, 12 = Middle Limestone Group, 13 = Upper Limestone Group, 14 = Longhoughton Grits (ULG), 15 = L. Coal Measures, 16 = U. Coal Measures, 17 = Coal Measures (Cumbria), 18 = Whitehaven sst, 19 = Permian, 20 = Trias (Lower), 21 = M. Trias, 22 = U. Trias, 23 = Lower Lias. 24 = Whin Sill.

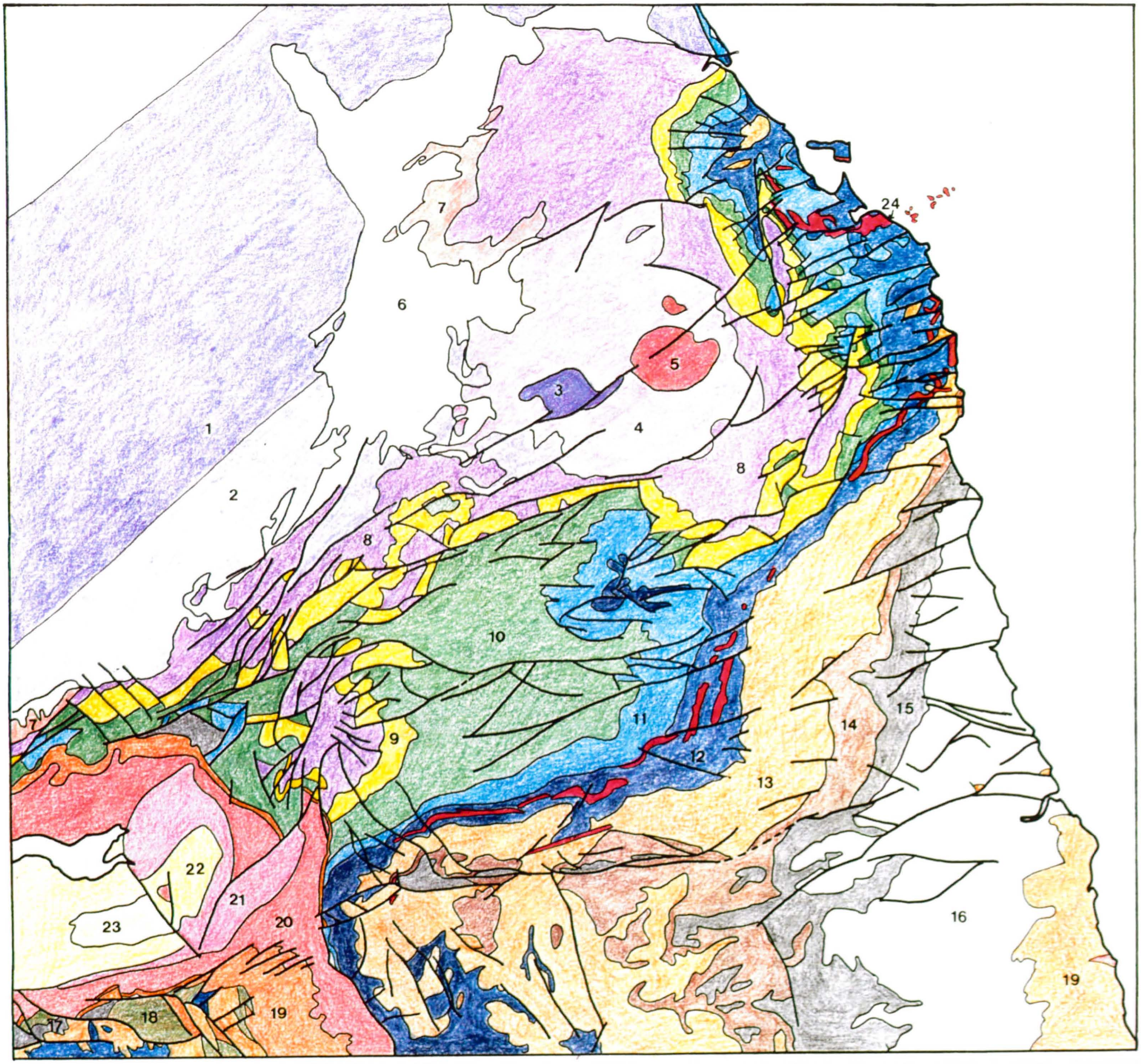


Fig.18 Geological map of Northern England. 1 = Llandovery, 2 = Wenlock & Ludlow, 3 = Llandeilo & Caradoc, 4 = Andesite (L.ORS), 5 = Granite (L.ORS), 6 = Upper Devonian, 7 = L. Carboniferous lavas, 8 = Lower Border Group/Cementstones, 9 = Middle Border Group/Fell sandstone, 10 = Upper Border Group/Scremerston Coal, 11 = Lower Limestone Group, 12 = Middle Limestone Group, 13 = Upper Limestone Group, 14 = Longhoughton Grits (ULG), 15 = L. Coal Measures, 16 = U. Coal Measures, 17 = Coal Measures (Cumbria), 18 = Whitehaven sst, 19 = Permian, 20 = Trias (Lower), 21 = M. Trias, 22 = U. Trias, 23 = Lower Lias. 24 = Whin Sill.

Chapter Three

THE NORTHUMBERLAND BASIN

3:0:0 Introduction

The case study for this work is the Northumberland basin, which occupies most of Northumberland and the extreme north-east of Cumbria. The basin is largely Carboniferous, situated immediately south of the Southern Uplands. Carboniferous outcrop occurs over the area from the southern uplands to the Lake District, Carlisle area and the Vale of Eden. The Northumberland basin extends from uplands north of Bewcastle and Langholm, eastwards over the Borders into Scotland near Windy Gyle and Carter Bar and the Cheviots. The basin extends to Berwick-upon-Tweed in the north east and its margin in the south is along the edge of the Pennines, the northern edge of the Alston block. To the west the basin passes laterally into the Carlisle area where the Carboniferous Solway basin exists under a Permo-Triassic cover. The western margin of the basin lies approximately along an imaginary extension of the Vale of Eden escarpment on the extreme west of the Pennines/Alston block separating the Canonbie coalfield from the Northumberland basin. To the east the extent of the basin is much less easy to define as it passes offshore under the Permo-Trias in the North Sea (fig. 18).

The original shape of the basin was determined by BGS land survey geologists (Goodchild 1920; Garwood 1931; Trotter & Hollingworth 1932). The name "the Northumberland basin" is the final evolved label from a series that began with the "Northumbrian trough" (Trotter & Hollingworth 1932). This became the "Northumberland trough" in the 1950's (Rayner 1953) and recently the "trough" was dropped in favour of dividing the basins south of the Southern Uplands into two separate basins, the Solway and Northumberland basins (Leeder 1974, 1976, 1982; Johnson 1985).

The following chapter is a review of the basin. The geometry of the basin will be outlined in the geophysics section and will lead into a summary of the geological history with special reference to possible subsidence mechanisms. The later history of the basin deals with the inversion event and its pattern of deformation over the basin. Finally the tectonic history of the basin is summarised distinguishing between basin formation and evolution related deformation and subsequent inversion and later events.

PART 1: The Extensional Basin History

3:1:1 Geometry and Geophysics

The Northumberland basin can be simply described as a half-graben bounded by major normal faults along the southern margin adjacent to the Alston block (Trotter &

Hollingworth 1932). The basin is the most northerly of a series of grabens with intervening horsts or blocks of the English suite in the Variscan foreland complex. The Stainmore basin, for example is the half-graben to the tilted block of Askrigg (Johnson 1967). The simple pattern of rotated blocks and basins breaks down to the south in the complex basins, sub-basins and highs of the Bowland district and Central Pennines. However a sequence of rotated blocks is a useful concept with which to regard the basins of northern England.

The southern margin of the Northumberland basin was first identified as a "hingeline" in 1911 (Kendall), trending E-W along the edge of the Alston block (Trotter & Hollingworth 1932: Dunham 1933). The "hingeline" coincides with the positions of the Stublick and 90 Fathom faults identified at the present day surface. These faults have long been recognised as growth faults. In particular, the Stublick fault in the west of the basin has a thick succession of Lower Carboniferous in its hanging wall which is not recognised on the Alston block (Trotter & Hollingworth 1928). At the present day there is between 150 and 530 metres normal fault geometry separation along the Stublick-90 Fathom systems (Johnson 1984). The two systems are en-echelon with a dextral overlap i.e they are oblique to one another, overlapping to the right. This relationship may not be the original since post-Carboniferous movement has occured on both fault systems.

Early gravity studies (Bott 1961, 1967) determined the broad asymmetry of the basin. This generalised half-graben aspect places the deepest sections of the basin against the Alston block, with up to 4km of sediment in the basin compared with 1.5km - 2km on the block. Along the opposite margin no such major thickness changes have been identified. Several subsiduary depositional lows have been recognised within the basin. These are believed to be bounded by normal faults, e.g.the Antonstown and Harrets Linn faults where the Lower/Middle Border group is nearly twice as thick as elsewhere (Day 1970).

To NE the main basin merges with the Tweed sub-basin; here Dinantian strata decrease in thickness in the Cheviot Alnwick area from 2000m to 550m, increasing in the Tweed area to 1500m. The thinning of the Dinantian is due in part to the Cheviot block (Johnson op. cit.) where shallowing of the basement has recently been proved (L.Palaeozoic and Devonian igneous material) extending E/W from the Rothbury area to the coast near Alnwick (Leeder, Fairhead, Lee, Stuart, Clemmey, Al-Heddaheh & Green 1989). Both the Cheviot and Alston blocks are cored by Caledonian granites. In the former the granite is exposed at the surface surrounded by a series of andesitic lavas. These were exummed in the Devonian since Upper ORS conglomerates contain fragments of granite and andesite e.g. the Roddom Dene conglomerate.

The Alston block to the south of the Northumberland basin was long suspected to be cored by a granite (Marr 1921, Dunham 1933). This suspicion was vindicated when the Weardale granite was proved in the Rookhope borehole in the early 1960's (Dunham, Bott, Johnson & Hodge 1961; Dunham, Hodge & Johnson 1965). The granite

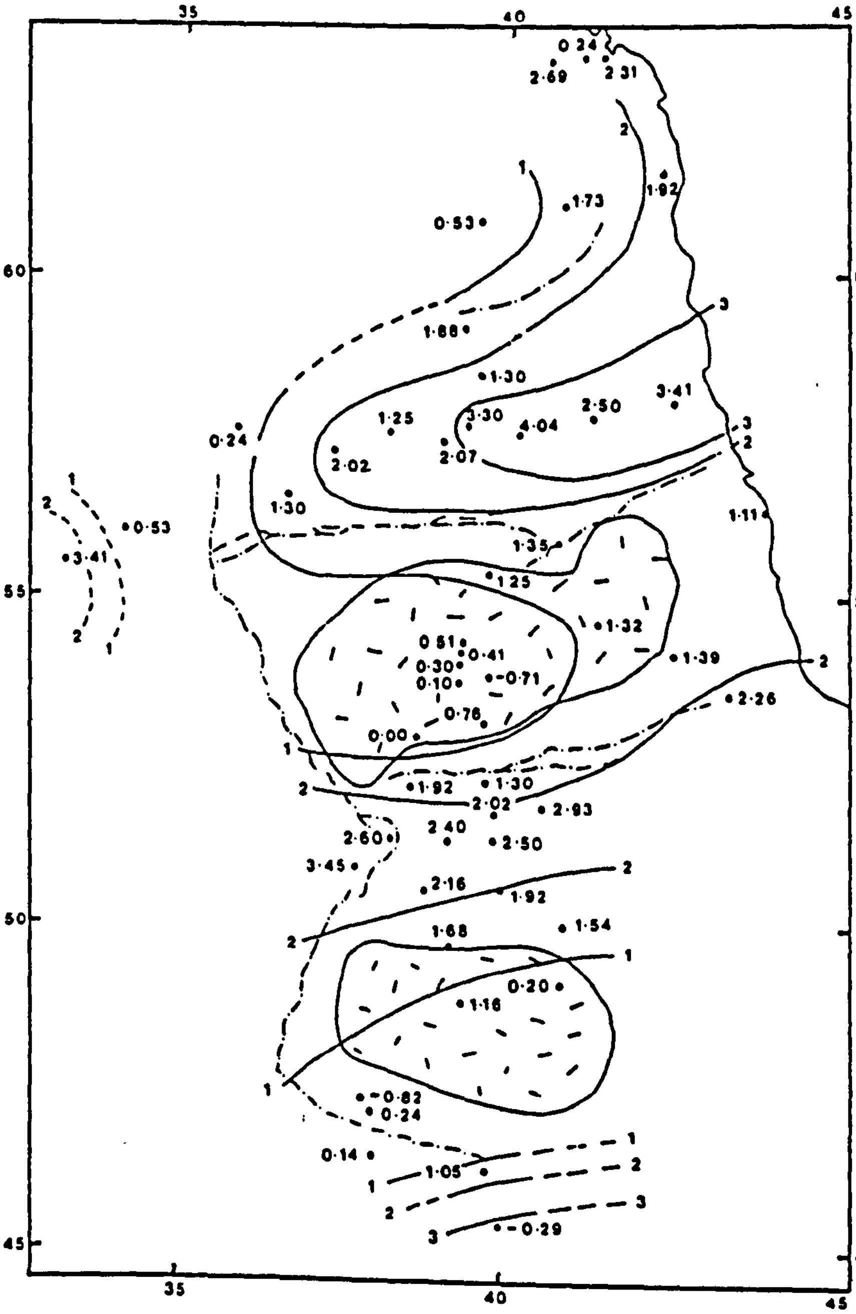


Fig. 19 Map showing the depth to seismic basement beneath northern England determined using quarry blasts. Circles are shot and station positions with the depth to basement in kms below O.D. assuming a cover velocity of 3.7km s^{-1} (after Bott et al 1984).

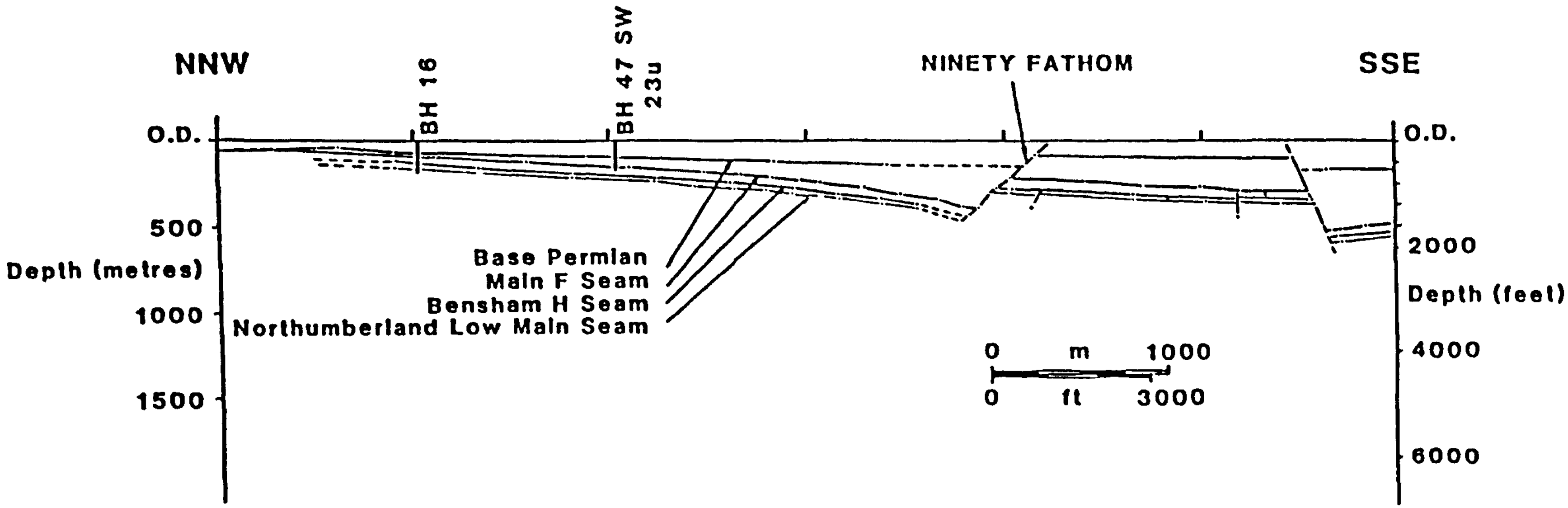


Fig. 20 Cross-section across Ninety-Fathom Fault in the Tynemouth area from structure contoured coals (taken from Collier 1989).

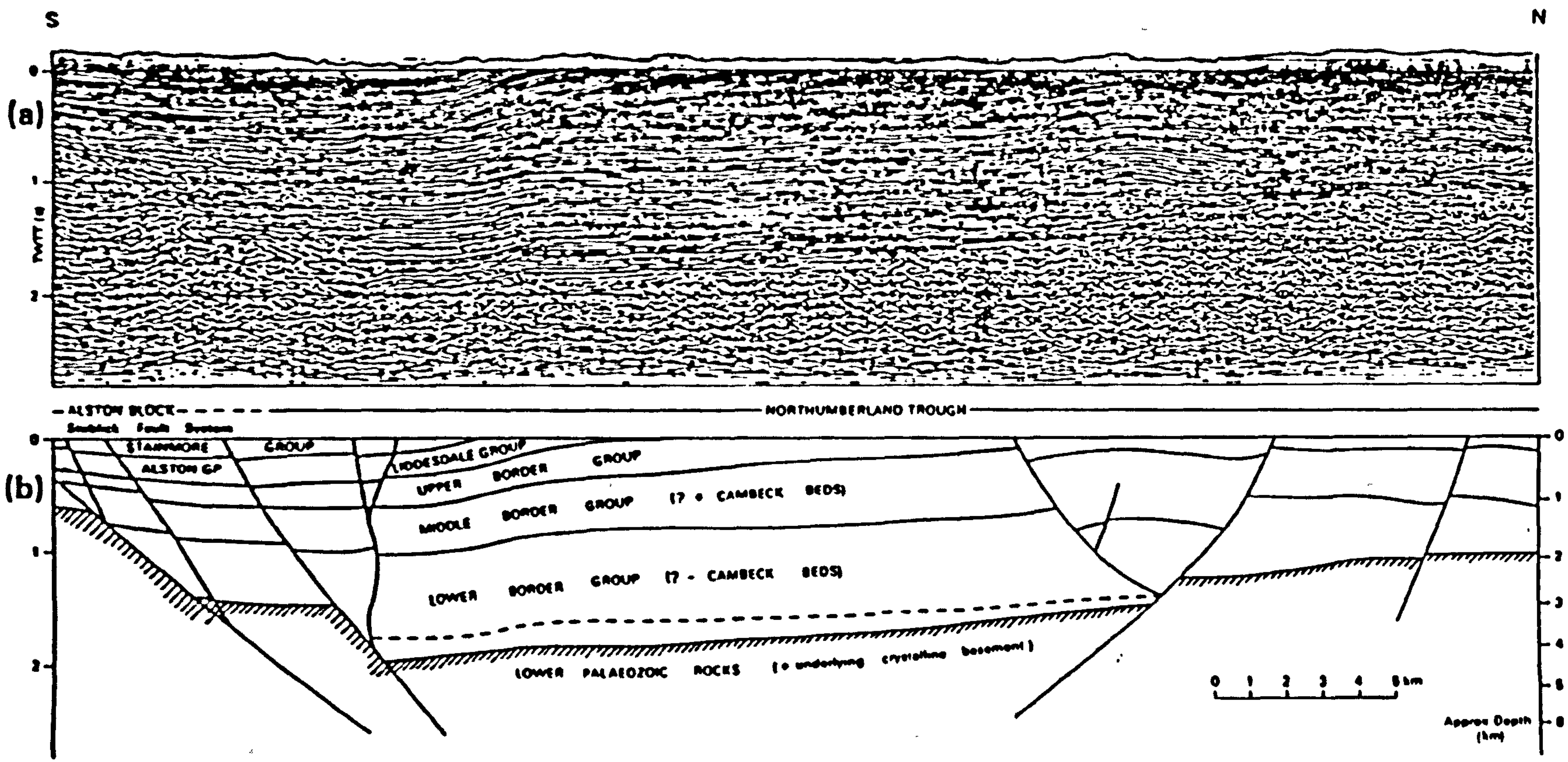


Fig. 21 Cross-section across the Stublick fault system from published BGS line 86-02 seismic interpretation data over western Northumberland (taken from Kimbell et al 1989).

has been dated at approximately 390my (Fitch & Miller 1965).

Geophysical surveys of the southern margin of the basin (Bott 1961,1967) determined major thickening of Lower Carboniferous sediments along the line of the Stublick fault and in the vicinity of the 90 Fathom fault. This early impression has been confirmed (Leeder et al 1989) proving the Stublick fault is the original basin margin, but is a step faulted margin with extensive normal fault reactivation (see later sections on early and late fault activity in the basin). In the same study (Leeder et al op.cit.) the 90 Fathom fault is displaced south of the original basin margin, judged from the position of the maximum sediment thickness. The 90 Fathom's position is thought to reflect a post Permian fault nucleated at depth on the original Carboniferous margin (Leeder et. al. op. cit., Collier 1989, see figs. 20 to 22).

The Stublick and 90 Fathom faults are orientated E/W to ENE/WSW, parallel to the axis of the basin. There are numerous faults of a similar orientation e.g. the Antonstown and Harrets linn faults that are also associated with sedimentary thickness variations (see previous, Day 1970).

Seismic refraction studies (Bott, Swinburn & Long 1984) interpreted the basin as 3-4km deep and clearly indicated the thickest developments of sediment were in the south and to the south-east, where thicknesses gradually increasing towards Newcastle (see fig 19).

As part of the Caledonian Suture Seismic Experiment of 1982, Bott and co-workers (Bott, Long, Green, Lewis, Sinha & Stevenson 1985) interpreted data from a line running E/W across the basin. A high was recognised at the junction of the Northumberland and Solway basins (see fig. 12). Bott concluded that the fundamental structure of the crust varied from south to north under the Northumberland basin (see fig. 13), agreeing with Bamford's interpretation of the LISPB data (Bamford et al 1979). The broad half-graben form was also determined in 2D current geomagnetic variation models (Banks 1986). In Bank's study a northwards dipping, E/W orientated slab was suggested to explain the results and identified with the Iapetus suture zone. The zone was an area of higher conductivity, either due to enhanced fluid flow or a relic of subducted oceanic crust. The latter view is unlikely since no gravity studies (Bott et al 1985, Bamford et al 1979) have identified such a feature.

In recent years geophysical techniques have been reapplied to Northumberland (Leeder et al 1989) and finer details have emerged. The main points of relevance here that Leeder and collegues concluded, are;

a) The southern margin of the basin stands out as an ENE-SSW gradient which doesn't appear to be related to the shape of the Weardale granite (in the block).

b) The margin is step-faulted in both the Stublick fault and 90 Fathom regions.

c) In the west over Bewcastle a major anticlinal feature (see later 2:1:3) is related to shallow basement that extends into the area around Kershope and the Border.

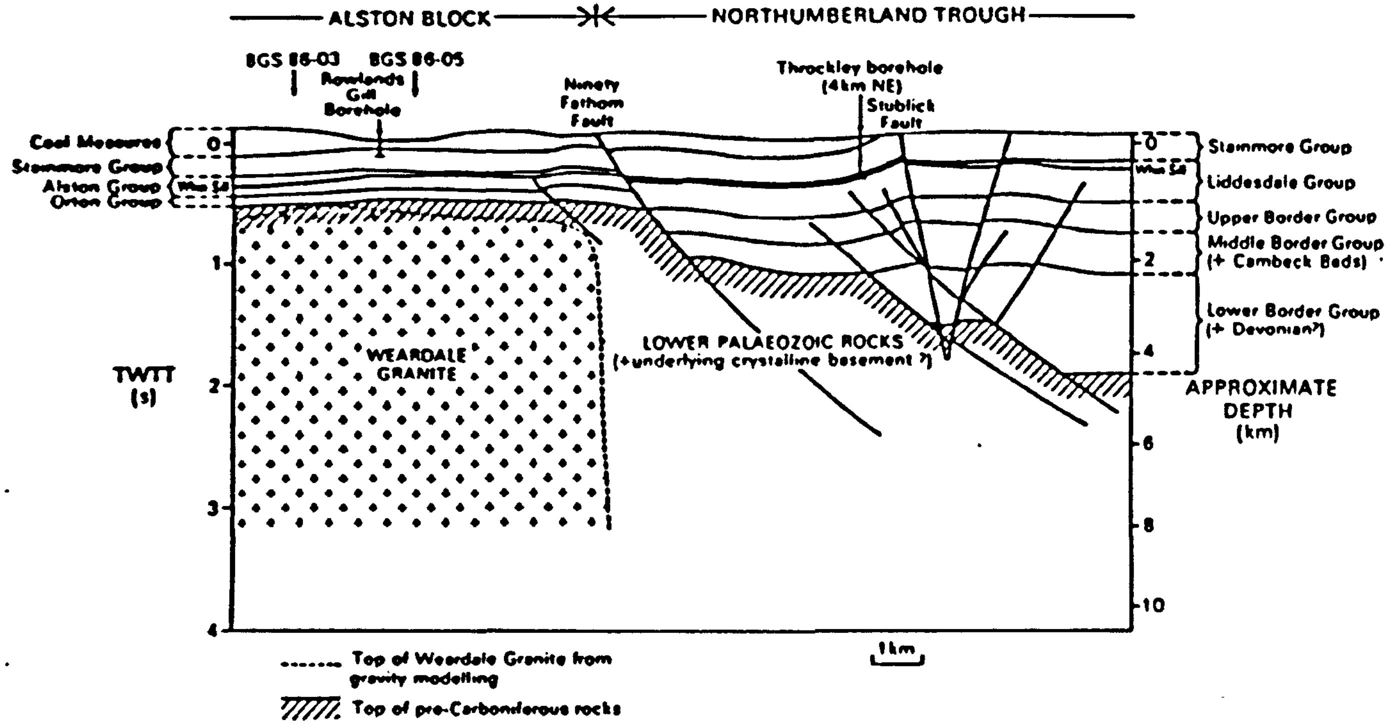


Fig. 22 Detail cross-section over the Stublick fault from published BGS seismic interpretation, where The system overlaps with the Ninety-Fathom system (taken from Kimbell et al 1989).

d) The sedimentary succession in the area of c) appears to thin eastwards (see also later 2:1:2).
e) The Lemmington anticline (as Bewcastle see 2:1:3) is related to shallow basement extending towards the Simonside/Rothbury area, the same basement high that extends to the coast at Alnwick.
f) The third major anticline in the basin at Holburn shows no association with shallow basement.

The main structures of the basin discussed in this section are summarised in chapter severn (for a fuller explanation see Leeder et al 1989).

Magnetic data from the basin (Leeder et al op. cit.) has indentified Tertiary dykes trending WNW-ESE to ESE. The Whin Sill, a major intrusive body running from the south west to the north-east and was observed (Francis 1982) and its associated dykes. These trend ENE (High Green echelon, see 2:3:1) to NE. The NE trend appears to be related to basement "features" (Leeder et al op.cit.). Extrusive lavas and vents of the Lower Carboniferous, are prominent magnetic features (Leeder et al 1989) e.g. the Birrenswark lavas in the west and the Kelso lavas in the west Tweed area.

A geophysical survey conducted by the BGS (Evans, Roberts & Bateson 1989) identified magnetic features in the Brampton and Alston districts (see fig. 23). These are linear NE-SW anomalies thought to be structural axes. The anomalies were distinguished from those known to be caused by the Whin sill and are either (unexposed) sill horizon changes or represent a persistent structural trend, possibly a branch to the Stublick fault system. The authors (Evans et al 1989) note that this trend is a continuation of a LandSat imaged, mineralised lineament extending over the basin to the NE coast.

Geophysical and geomagnetic studies have been invaluable in determining the sub-surface structure of the basin. Not only has the broad geometry been determined but important details like the positions of syn-sedimentary highs and lows and hence likely syn-sedimentary faults. Unfortunately the basement structure cannot be directly observed but its general character is expressed in the basin's geometry and structural character.

3:1:2 Subsidence and sedimentation

The basins of the Carboniferous syn-orogenic complex (Besly 1986) underwent initial rifting between the late Devonian and the early Carboniferous (Gawthorpe, Gutteridge & Leeder 1989). The Northumberland basin is believed to have been initiated during the early Carboniferous, in the Tournaisian (fig. 24). The earliest known sediments are those of the Lower Border Group (partly equivalent to the former Cemenstone Group, Leeder et al 1989) preceeded in the SW and the NE by alkali basaltic lavas (Leeder 1971, 1974, 1976). The erruptives are the Birrenswark and Kelso lavas respectively. The lavas are alkali basalts, typically intraplate in character (Macdonald

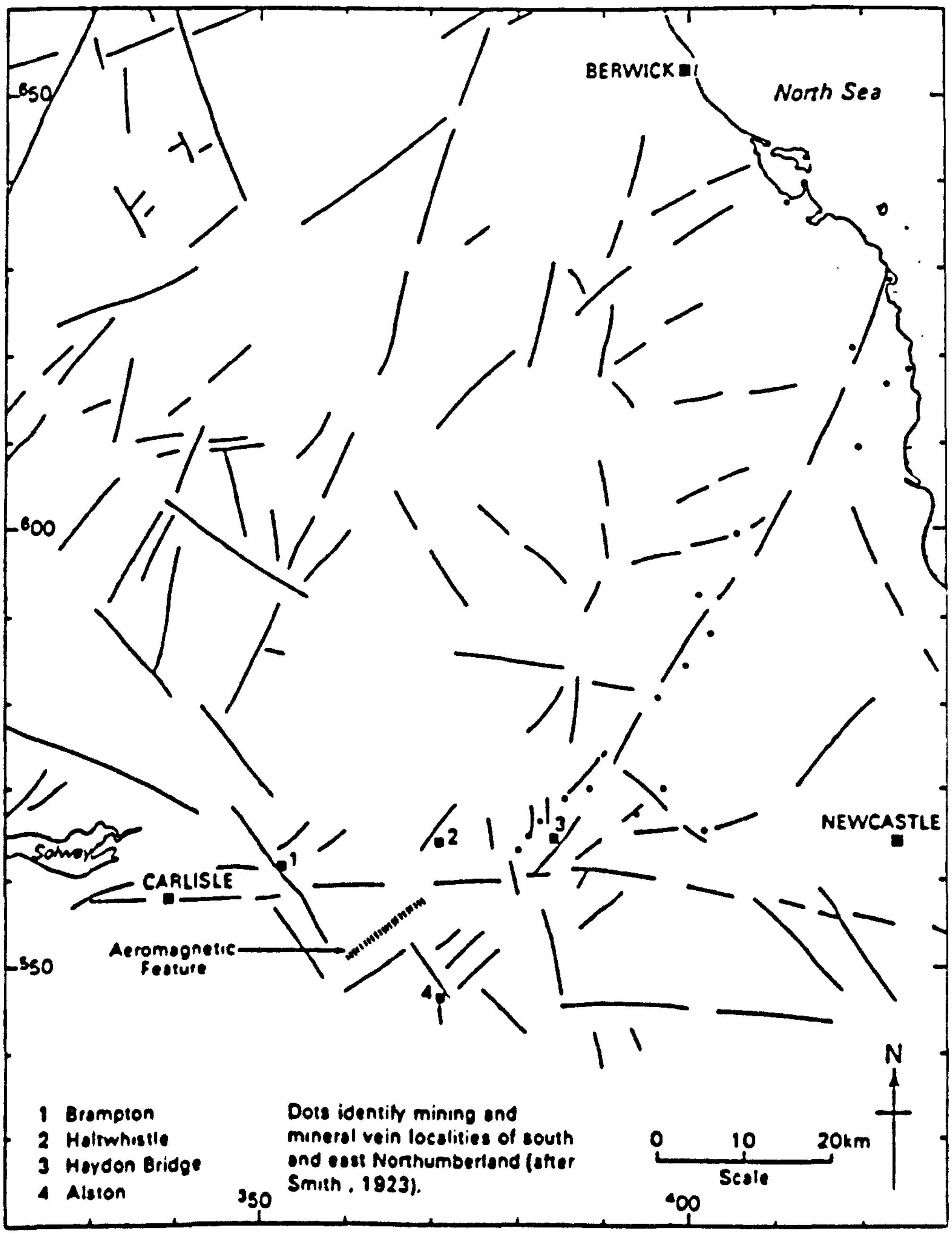


Fig. 23 Main structural elements in Northumberland from Landsat imagery, showing region around Brampton and aeromagnetic feature mentioned in text (Evans et al 1989).

1984). They are associated with numerous vents and necks, scattered throughout the borders up to late Visean in age (Leeder 1974). No central vent has been identified and so it seems likely that the extrusivs were issued from fissures or "strings of vents", rather than a central caldera (Leeder 1974).

The lavas were errupted over a sequence of Upper Old Red Sandstone (ORS), taken to be pre-rift because palaeocurrent data indicates NE drainage systems were operating depositing material in intermontane continental basins (Leeder 1973). These show no sign of the ENE trending structure of the Carboniferous basin (see 2:1:1). The Devonian basins are termed "molasse" basins and are surmised to have been formed by the structural collapse of the Caledonian orogen (Dewey 1986).

The Lower Border Group (LBG)

The Lower Border Group (see table 6) is exposed in an arcuate outcrop from the west, north-east and to the north of the basin. This pattern is due to later asymmetric uplift of the basin (see part 2:2). The group can be picked on seismic reflection lines (Kimbell et al 1989) adjacent to the footwall of the Stublick fault system (see chapter 4 seismic lines A1 & A2).

During rifting predominantely E/W or ENE/WSW syn-sedimentary normal faults were active (Gawthorpe, Gutteridge & Leeder 1989). In the north and south the Southern uplands (Cheviot) and the Alston block were emergent uplands, probably acting as local sediment sources for alluvial systems along the developing footwalls (Leeder et al 1989). The LBG varies between 100m and 600m thick but there are greater thicknesses in the unexposed southern parts of the basin (Kimbell et al 1990).

The former Cementstone Group (in north-east Northumberland) is a thick sequence of grey shales, thin limestones and sandstones that develop up sequence into channel sandbodies. In the upper parts of the group thicker limestones are developed with a high algal content (Johnson 1984). These sequences are freshwater-brackish water deposits with evidence for occasional hypersaline conditions (Leeder 1974; Scott 1987). The LBG is generally a mixed fluvio-lacustrine facies types with cementstone lithotypes e.g.dolomitic carbonates, sandbodies, lacustrine and floodplain muds and silts.

The Cementstone facies is well developed in the Tweed area which during LBG times was a separate depocentre from that of Northumberland. The Cementstone facies is thin over the Cheviot area (Robson 1952) thickening in the south and west into the Northumberland basin.

The Tweed basin was partially isolated from the main Northumberland basin in the Dinantian and the LBG here has a Tournaisian age (Anderton 1985).In Berwickshire deposition was on alluvial plains and in lacustrine environments. The facies include a unique shallow lake deposit, the Foulden Fish Bed. Marine waters are believed to have flooded into this basin from time-to-time driven by storm winds from the south, perhaps from the main Northumberland basin (Anderton 1985).

Table 6 Subdivisions of Carboniferous stratigraphy in the Northumberland basin (after Johnson 1984).

West — NORTHUMBERLAND TROUGH — East							
SOLWAY BASIN		NORTHUMBERLAND BASIN					
BRAMPTON. TROTTER & HOLLINGWORTH, 1932	LANGHOLM & BEWCASTLE. LUMSDEN et al. 1967 DAY, 1970	ROTHBURY & NORTH TYNE. FOWLER 1936 & 1966	TYNEMOUTH. LAND, 1974	BELLINGHAM. FROST & HOLLIDAY, 1980			
	Upper Coal Measures Shafton Marine Band		Upper Coal Measures Down Hill Marine Band		? Stephanian		SILESIAN
					Westphalian D		
		Coal Measures: Upper Group High Main Coal	Middle Coal Measures		Westphalian C		
Middle Coal Measures Low Main ≈ Brockwell Coal	Middle Coal Measures Queenslie Marine Band	Coal Measures: Middle Group Brockwell Coal	Harvey Marine Band		Westphalian B		
Lower Coal Measures	Lower Coal Measures	Coal Measures: Lower Group	Lower Coal Measures Quarterburn Marine Band		Westphalian A		
	Millstone Grit Series	Millstone Grit	Millstone Grit Series	Stainmore Group	Yeadonian G_1, Marsdenian R_2, Kinderscoutian R_1, Alportian H_2, Chokierian H_1, Arnsbergian E_2, Pendleian E_1	NAMURIAN	
Upper Limestone Group Great Limestone	Catsbit ≈ Great Lst	Upper Limestone Group Great Lst	Great Lst	Great Lst			
Middle Limestone Group [illegible] ≈ Smiddy Lst	Upper Liddesdale Group Low Tipalt Lst	Middle Limestone Group Oxford Lst		Upper Liddesdale Group Low Tipalt ≈ Peghorn Lst	Brigantian	VISÉAN	DINANTIAN
Lr. Limestone Group Naworth Lst	Lr Liddesdale Group Naworth Bryozoa Band	Lower Limestone Group Dun Lst Redesdale Lst		Lr Liddesdale Group Redesdale Lst	Asbian		
Birdoswald Limestone Group Lanercost Lst	Upper Border Group	Scremerston Coal Group		Upper Border Group Kingbridge Lst			
Craighill Sandstone Group Kingwater Lst	Clattering Band						
	Middle Border Group Whitberry Band			Middle Border Group	Holkerian		
Fell Sandstone Group		Fell Sandstone Group			Arundian		
Cementstone Group	Lower Border Group Birrenswark Lavas	Cementstone Group		Lower Border Group	Chadian		
					Courceyan (Tournaisian)		

In the extreme west thick sandstone formations exist e.g. the Whita and Annan formations. It has been suggested that these were controlled by deposition adjacent to active faults, the Kirkhill and Arnton faults (Gawthorpe, Gutteridge & Leeder 1989). The LBG represents deposition in an interior fluviatile and coastal plain environment (Johnson 1984; Leeder et al 1989). The Whita sandstone formation shows evidence for southerly drainage from the Southern uplands, depositing fluviatile sediments along the northern margin of the newly initiated basin (Johnson op. cit.). The climate was typified by high seasonal temperatures and extreme aridity as Britain occupied tropical equatorial latitudes (Johnson 1982; Leeder et al 1989). The river channels and lakes were periodically infilled by crevasse mouthbars and cut by new channels disrupting the haline environment. This led to the "schizo-haline" environment described by Leeder (Leeder et al 1989). During periods when the fluvio-deltaic system was absent, diverse shallow water carbonate facies developed (Anderton, Leeder and Bridges 1979; Johnson 1984).

The Cementstones in the west of the basin around the Bewcastle district are of a different facies; containing limestones and shales with fully marine faunas (Garwood 1931; Day 1970; Ramsbottom 1977) of Chadian age. The LBG in the west of the basin is a thick Chadian to Holkerian sequence where deltaic facies alternate with marine sub-tidal carbonates (Armstrong & Purnell 1987).

Palaeocurrent data indicates that the drainage patterns in the Northumberland basin in the LBG were distinct from the ORS pre-rift sequence (fig. 25), flowing from the NE to the SW and laterally to this (Leeder et al 1989). This pattern is suggestive of drainage governed by a hanging-wall dip-slope to active normal faults i.e. the Stublick fault system (Leeder & Gawthorpe 1987).

In the Bewcastle area the LBG passes into the succeeding group the Middle Border Group (MBG) above the base of the Whitberry band (Day 1970). Elsewhere the the base of the following group is a diachronous boundary with the former Fell Sandstone Group (Leeder et al 1989).

The Middle Border Group (MBG)

This group is partly equivalent to the former Fell Sandstone Group, though as previously mentioned the base of this group is diachronous over the basin rising to the south and west (Johnson 1984). The MBG is difficult to correlate but recent biostratigraphy based on conondant zones has suggested a Holkerian age for the group (Armstrong & Purnell 1987).The MBG is exposed in a similar arcuate fashion to the LBG and is between 100m and 600m thick (see fig.26).

Within the MBG there is evidence of igneous activity. The Kershope olivine alkali basalts were errupted in the north-west around Langholm (Lumsden et al 1967). The Kershope lavas are petrographically related to the basal Carboniferous basalts of the LBG and by inference are of a similar intraplate tectonic setting.

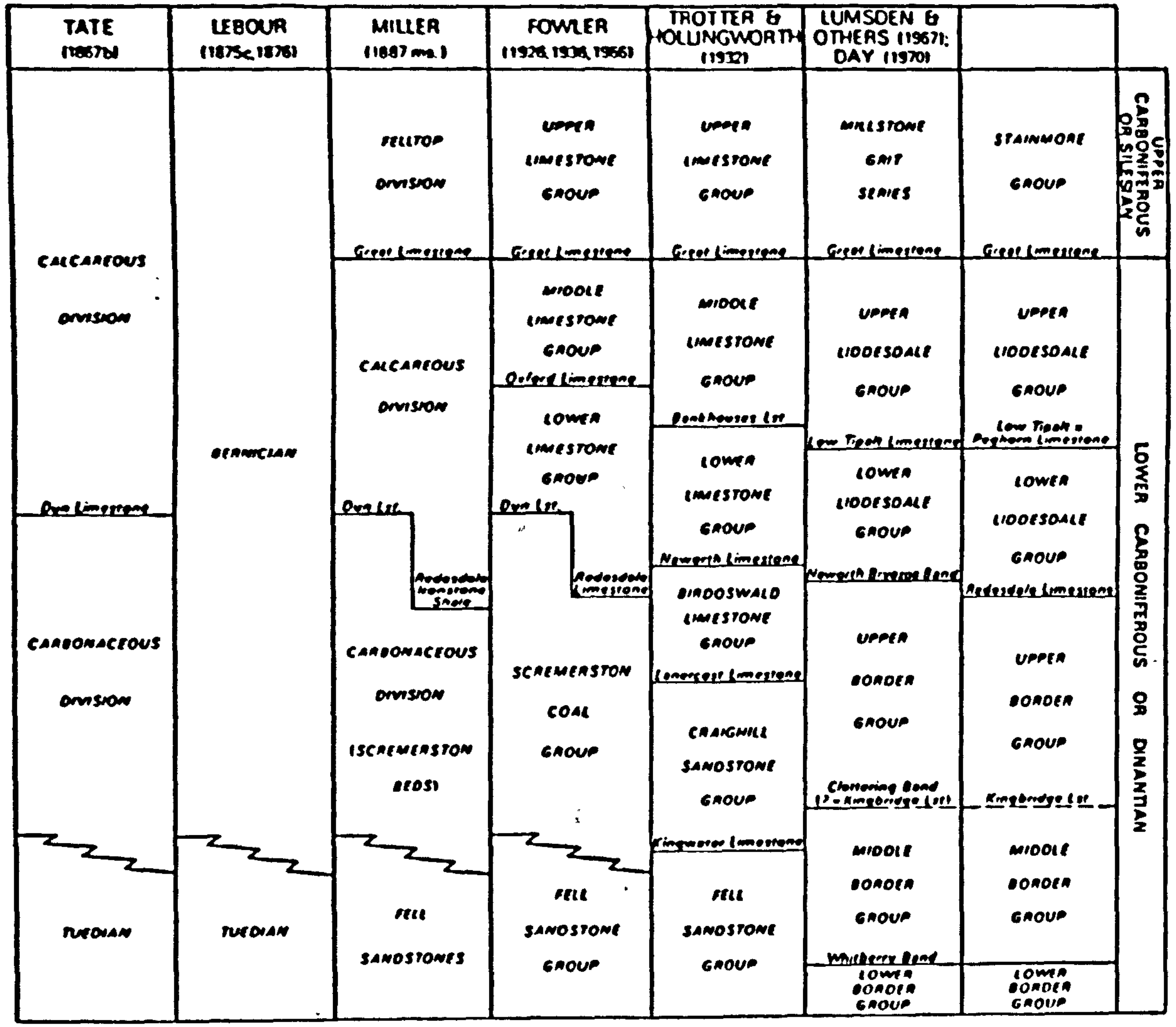


Table 5 Correlation of Carboniferous stratigraphy over Northumberland, showing current and older classifications (after Frost & Holliday 1980).

The Fell Sandstones are generally massive, medium to coarse white-red sandstones interbedded with grey and black shales. In the middle of the basin around the North Tyne and Lyne Rivers (Fowler 1966), the group is 300-400m thick and lithogically similar to the upper parts of the LBG in this region (the Cambeck beds, Day 1970) above the Whitberry band (containing *Rugoschonetes cumbriensis-Muirwood*). Sandbodies are uniformly well developed from Redesdale northwards through Rothbury and to Berwick-Upon-Tweed where the group is 240-300m thick. The sandstones are fine-grained quartzites with occasional thin pebble beds, mud partings and thin coals in the lowermost part of the group. Cross-stratification is very common with numerous examples of catastrophic dewatering and foundering structures.

The MBG is dominated by multistorey sandbodies which may be up to 40m thick. They were deposited in a braid-plain channel system (Hodgson & Scott 1970; Hodgson 1978) and according to Leeder and co-workers (1989) boreholes have penetrated red mudstones and pedogenic calcrete horizons between the sandbodies. Such mudstones occur in outcrop where the Fell Sandstone lithofacies are not so pronounced e.g. Keilder district. Here the mudstones are red-purple to brown, with minor grey and green beds (Fowler 1966).

The Fell Sandstone lithofacies inter-digitates in the Bewcastle area with a fossiliferous marine facies (Day 1970; Leeder et al 1989) containing less sand and more shale/mudstones. This E-W change is a progression from fluvial braid-plain facies to delta-top and delta-front deposition (Leeder et al 1989; Johnson 1984).

Palaeocurrent data from the MBG indicates an axial drainage system along the basin, feeding from the NE turning axially SE into the basin (Leeder et al 1989).

The Upper Border Group (UBG)

The Upper Border Group (UBG) is the partial equivalent of the former Scremerston Coal Group (Tate 1867) whose type locality is at Scremerston, south of Berwick-Upon-Tweed and crops out across the basin in an arcuate fashion (see fig. 27). The UBG is difficult to correlate and date but taken to be lower Asbian in age (Leeder et al 1989). Early in UBG times there were a number of subaerial pyroclastic eruptions producing tuffs and lavas. These include;

a) the Glencartholm volcanics in the river Esk region of western Northumberland and north Cumbria (Lumsden 1967).

b) the Oakshaw Tuff in north Cumbria (Taylor, Burgess, Land, Mills, Smith & Warren 1971).

c) numerous volcanic plugs and agglomerate vents in the Borders of approx. 330my (De Souza 1978).

The UBG is quite variable and Leeder et al (1989) clarified the understanding of this group by dividing it into three broad facies belts. This is the convention followed here.

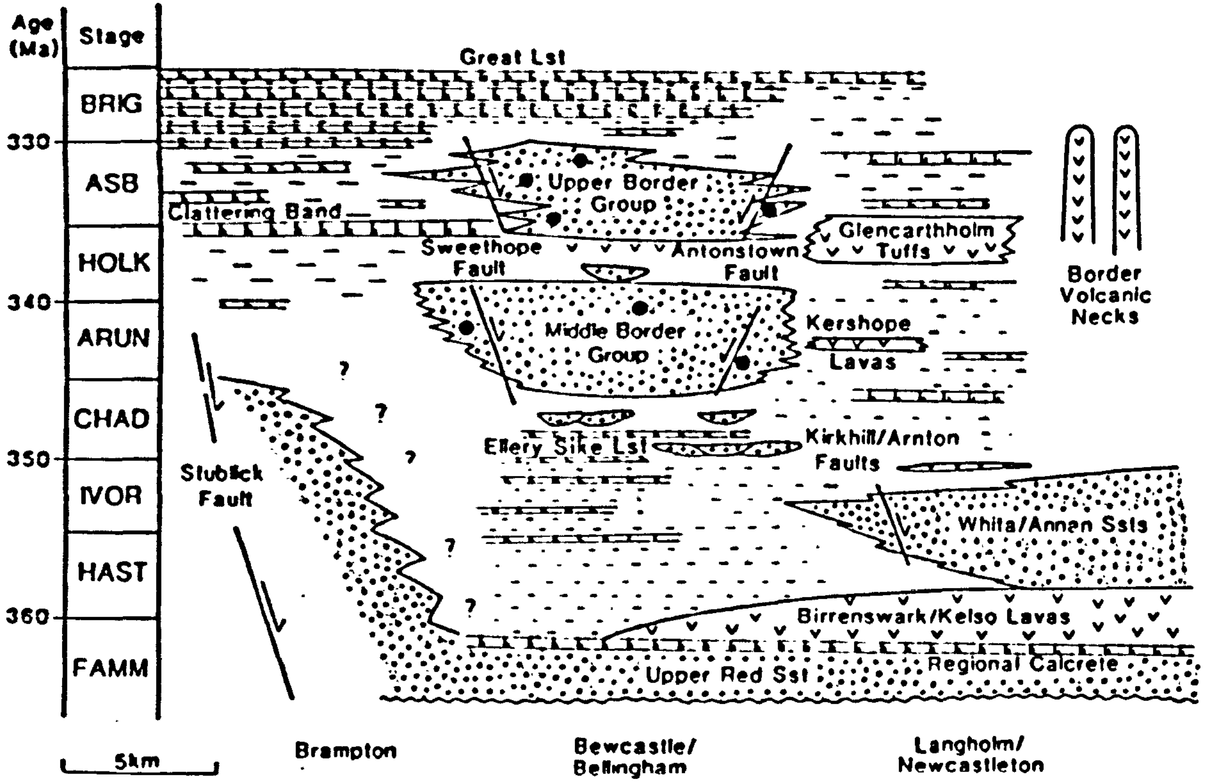


Fig. 24 Upper Devonian/Lower Carboniferouschronostratigraphic and semi-structural section across Northumberland. FAMM= Fammenian, HAST= Hasterian, IVOR= Invorarian, CHAD= Chadian, ARUN= Arundian, HOLK= Holkerian, ASB= Asbian, BRIG= Brigantian (taken from Gawthorpe et al 1989).

a) North and North-east Northumberland.

The UBG here is a sequence of sandstones, shales, seatearths and workable coals. In the lower part of the group there are thin argillaceous limestones containing ostracods. The succession is regarded as starting at the first limestone above the Fell Sandstone lithofacies. The top of the group is the base of the Redesdale limestone in the Tynedale region but around Rothbury (Coquetdale) and the north-east the top is taken at the Dun limestone some 70-100m above the Redesdale limestone. This has arisen because the Redesdale limestone appears to die-out northwards. The group is between 90-150m thick but increases in thickness towards the coast at Berwick-Upon-Tweed to 275m (Taylor et al op.cit.).

The UBG is dominated by mudstones of a delta-plain swamp facies with crevasse channels and bay or lake fill coarsening upwards sequences. These are interrupted by rare marine limestones. The Dun limestone (= Ladies Wood = Denton Mill lmsts) is the first marker horizon that correlates between the main Northumberland basin and the Tweed sub-basin (Johnson 1984). The Cheviot-Alnwick ridge seems to have been a shoal between the two of reduced sedimentation (Johnson 1984). The Dun limestone is thought to be equivalent to the basal part of the Melmerby Scar limestone on the Alston block (Frost & Holliday 1980) making it the first horizon of more uniform and synchronous deposition over the basin and its surrounding blocks (see table 7).

The north and north-east region was an area of low subsidence rates possibly isolated from the main fluvio-deltaic sand dominated system of the UBG seen in other areas (Leeder et al op. cit.).

b) Central Northumberland

This region covers the area from northern Bewcastle to Bellingham. The UBG here is very thick, ranging from 600-1600m and is predominantly a succession of sandstones (Day 1970; Frost & Holliday 1978, 1980). The base of the group is the Kingsbridge limestone in the Bellingham region (Frost & Holliday 1980) and the Clattering Band in the Bewcastle district (Day 1970).

The UBG can be divided into three main facies associations (Frost & Holliday 1980);

1) a marine cycle with occasional seatearths and coals. Clastics are present with erosion surfaces, large and small scale trough cross bedding. They are interpreted as tidal flats in a shallow sea with local back-swamp development.

2) a coarsening upwards sequence of shelly muds and sands with a marine limestone at the base. These are similar to the Yoredale cyclothems of the Pennines and are thought to be a deltaic complex prograding into a marine environment (Leeder 1974; Elliot 1975).

3) a fining upwards sequence from erosive sandstones to silts and shales. Occasionally this association has marine fossils in the upper shaley parts and is therefore taken to

represent interdistributory bay cycles and fluvial flood-plains (Leeder 1974; Frost & Holiday 1980; Leeder et al 1989).

In the Bellingham district the group is Asbian in age (Westoll 1955; George 1976) possibly lower B_1 zone. The group is about 600m thick but to the north in the North Tyne catchment between the Antonstown and Harret's Linn faults, the UBG is as much as 1800m in thickness (Day 1970). The UBG shows a dramatic change in thickness across the former suggestive of active syn-sedimentary control at the time (Leeder 1987). From Bewcastle to Bellingham fault patterns form a series of oblique ENE-WSW en-echelon "rhomboids" which may represent original intrabasinal grabens (Frost and Holliday 1980).

The UBG shows much variation in facies and thickness over the areas and contains abundant catastrophic dewatering features (Leeder 1987). The facies in the lower part of the group are highly laterally variable. The group is a series of impure (sandy, argillaceous and ferruginous) limestones and calcareous sandstones, silts and shales. Some of the thicker sandstones are single or multistorey sandbodies with palaeocurrent indicators showing ENE-WSW axial directions. Higher in the succession the main limestones and sandstones are traceable across the region (Frost & Holliday 1980).

c) West Northumberland

The Bewcastle UBG is similar to the previous area being of non-marine carbonaceous backswamp facies. These are predominant in the south and west but a marine deltaic and bay facies is dominant in the north-east (Day 1970). Catastrophic dewatering structures are common suggesting contemporaneous fault activity (Leeder 1987). In the Bewcastle district volcanic rocks (Oakshaw Tuff) are thought to be attenuated representatives of the Glencartholm volcanics Langholm (Day 1970). The subaerial alkali basaltic extrusives were fed from short-lived centres, part of a broad N-S change from calc-alkaline - tholeiitic - alkaline volcanism. This is related to the evolution of the whole Variscan orogen from a destructive margin through a back-arc into a continental situation (Floyd 1982). The volcanics in Northumberland are the continental representatives (Francis 1988) and show no trends in composition directly related to plate subduction.

Lower and Upper Liddesdale Groups (Lower and Middle Limestone Groups)

The Lower and Upper Liddesdale Groups are the current group names equivalent to the Lower and Middle Limestone groups (and in places to the upper parts of the Scremerston Coal Group). This study follows the convention set by the Geological Survey of Great Britain (as per Bellingham sheet memoir 13, 1980).

The Lower and Upper Liddesdale groups (L&ULiG) are Asbian-Brigantian in age i.e. top Dinantian (Frost & Holliday 1980). During these groups sedimentary facies were more uniformly established over the basin (fig. 28), however correlation problems still exist. The Melmerby Scar limestone splits NE from the Alston block into the Northumberland basin but (Frost 1984) makes a poor marker horizon. The first reliable marker horizon is the Denton Mill limestone close to the base of the Lower Liddesdale group (LLiG). This limestone is the lateral equivalent of the Ladies Wood and Dun limestones (Frost & Holliday 1980). The Denton Mill limestone is the top of the former Scremerston Coal Group (SCG) in central areas. In Bewcastle the base of the LLiG is the Naworth Bryozoan Band (for full correlations see table 7). Around the North Tyne this band is not present and the Reddesdale limestone is taken as the local base (Dun limestone in NE Northumberland). Higher in the LLiG & ULiG correlation is easier where extensive and laterally persistent marine limestones are present e.g. the Four Fathom and Great limestones.

Sediment thicknesses on the Alston block are only half as thick as th . in the basin (Johnson 1967; Frost 1984) implying continued fault movement along the southern margin.

By the Brigantian the Cheviot-Alnwick shoal had all but disappeared as had the Southern Uplands axis north of the Tweed so that the Hardraw Scar limestone can be correlated with the Jew and Oxford limestones of Northumberland and with the Hurlet transgression of Southern Scotland (Gun 1898; Johnson 1959).

The cycles of sediment established in the Liddesdale and Limestone groups are termed "Yoredale" as they bear a strong resemblance to the Yoredale cyclothems of the southern Pennines (Gardiner 1983). The cycles are thick 12-70m repetitions of clastics derived from a river dominated deltaic environment. The cycles include pro-delta muds, mouth-bar sandbodies, crevasse spill-over sands, distributary channel sands and back-swamp muds occasionally of the oil-shale type. The cycles contain thin coals 5-15cm and are usually capped by 1-20m thick limestones e.g. Scar and Eelwell limestones (Carruthers, Dinham, Burnett & Maden 1927; Carruthers, Burnett and Anderson 1930; Trotter & Hollingworth 1932; Strudwick 1987).

Palaeocurrent information derived from the channel sandstones shows a NW-SE flow direction swinging NE-SW over south-western areas. This pattern is interpreted as axial funnelling of the fluvio-deltaic system along the hanging-wall of the Sweethope fault (running ESE-WNW).

The top of the Middle Limestone and Upper Liddesdale groups is the Great Limestone, a thick (20m) distinctive marine limestone. It is taken to be the base of the Namurian in Northumberland.

Upper Limestone Group (Millstone Grit Series or Stainmore Group)

The Upper Limestone group (ULG) occurs over much of the area e.g. Brampton, Berwick-Upon-Tweed and Alnwick districts. But elsewhere the equivalent is the Millstone Grit Series (Land 1974) around Tynemouth or the Stainmore group around Bellingham (Frost & Holliday 1980).

The Great limestone is an excellent stratigraphic marker that can be traced throughout northern England. In the Northumberland basin the Upper Limestone group (ULG) continues the Yoredale cyclothemic deposition typical of the upper Dinantian although the limestones tend to become thinner up- succession where marine mudrocks become more developed. Limestones with fully marine faunas occur up to Arnsbergian times. Above this shelly marine bands persist up to the base of the Westphalian.

The cycles in the ULG are the result of deposition in river dominated, interdistributory bay sequences (Elliot 1976). The group shows major cycles and minor cycles (Johnson 1984). The major cycles are frequently marked by a marine limestone but the irregularity of the minor cycles has led to much mis-correlation over the basin. This has been exacerbated by the intrusion of the Whin Sill at the end of the Carboniferous (early Permian) which frequently changes its intrusion horizon. The minor cycles have been attributed to fine tectonic control and/or compactional effects when the basement was relatively stable (Johnson 1960; Frost 1984). The lateral impersistance of the minor cycles (Frost 1984) produced simultaneous deposition of coals, seatearths and limestones over relatively small areas, the source of the mis-correlations, and are best developed at the top of the MLG (Brigantian). In the ULG in south-west Northumberland (Trotter & Hollingworth 1932) the minor cycles are sequences of marine bands, limestones or sandy limestones, shales, sandstones and seatearths with occasional coals. The marine horizons and coals are frequently absent. The cycles can be correlated with the thickest parts of the ULG and are absent on inter-basin blocks (Frost & Holliday 1980; Johnson 1984).

The onset of the ULG represents the start of a gradual marine regression with clastics assuming increased dominance in the group. Depositional thicknesses in the basin were about twice as thick as on the Alston block at the beginning of the Namurian. By end Namurian times subsidence was approximately equal over both block and basin (Johnson op.cit.). In the north-east a thick 150m development of multistorey sheet sandstones, the Longhoughton Grits were deposited. These were derived from a fluvial braid-plain and are exposed on the coast near Alnwick. Here the grits are slightly unconformable on the shales over the Upper Foxton limestone. The unconformity is marked by a thin conglomerate and south of Longhoughton this cuts out the Upper Foxton limestone completely. The Longhoughton Grits are a series of coarse clastics interbedded with occasional shales, seatearths and minor coals (Carruthers et al 1930; Leeder et al 1989).

The Coal Measures (Westphalian A-D)

The Westphalian in Northumberland crops out principally in the south of the basin and south-east adjacent to the southerly faulted margin. It is part of the Northumberland and Durham Coalfields (Smith & Francis 1967; Land 1974). There is virtually the same thickness of Westphalian either side of the 90 Fathom fault (Johnson 1984; Leeder et al

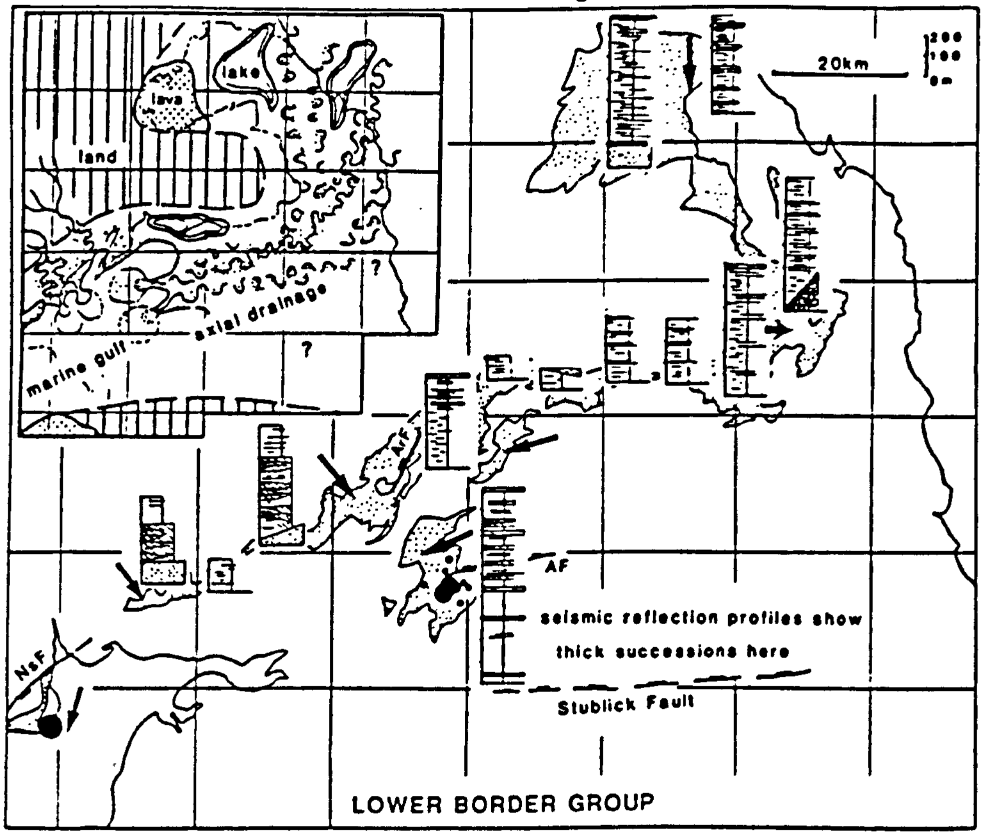


Fig. 25 Map of Lower Border group in Northumberland and local palaeogeography. Arrows indicate palaeocurrent trends and solid circles indicate sites of abundant soft-sediment deformation structures (Leeder 1987). Suspected growth faults are also shown where AF= Antonstown fault, ArF= Arnton fault and NSF= North Solway fault (taken from Leeder et al 1989).

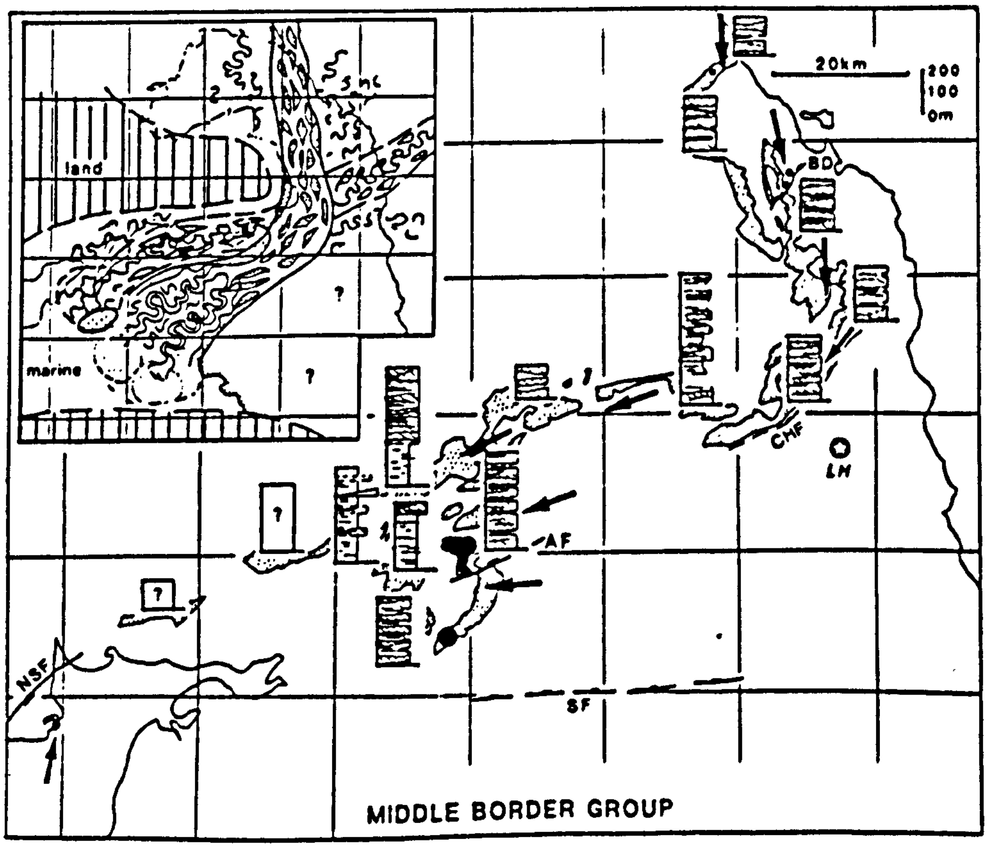


Fig. 26 Map to show Middle Border Group in Northumberland and local palaeogeography. LH= Longhausley wildcat, AF= Antonstown fault, CHF= Chartners fault, BD= Bowden Doors fault, SF= Stublick fault and NSF= North Solway fault (Taken from Leeder et al 1989).

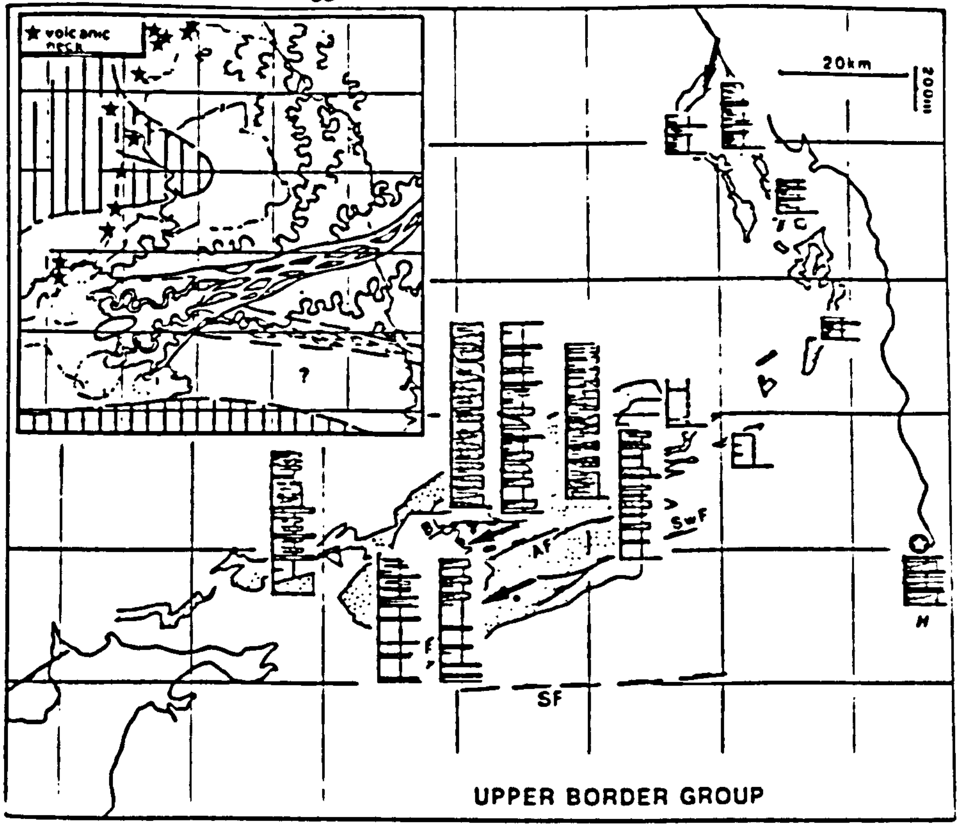


Fig. 27 Map to show Upper Border Group and local palaeogeography in Northumberland. Where BL= Beckhead/Lewisburn faults, AF= Antonstown fault, SwF= Sweethope fault, SF Stublick fault (taken from Leeder et al 1989).

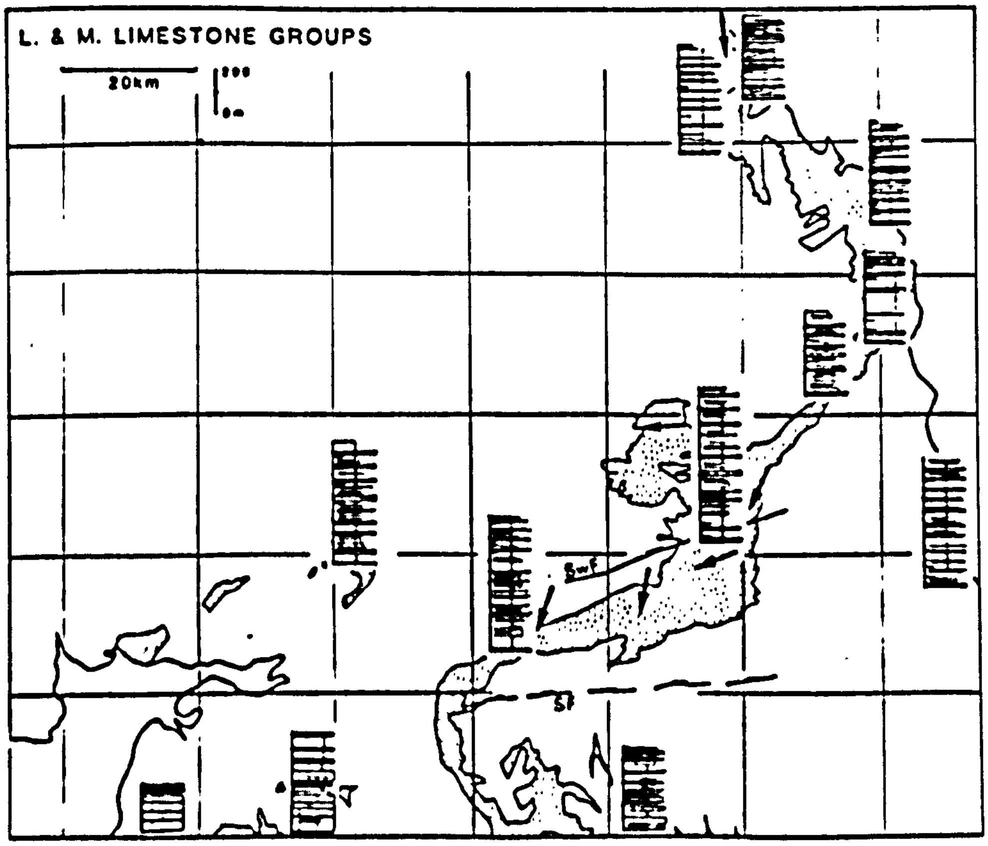


Fig. 28 Map to show Lower and Middle Limetsone and Liddesdale Groups in Northumberland. Symbols as for fig.** (taken from Leeder et al 1989).

1989) though this relation cannot be proved adjacent to the Stublick fault in the Midgeholme Coalfield (Trotter & Hollingworth 1932) where there is only 210m of Westphalian A and B and none on the immediate foot-wall. Westphalian A,B,C occur in the south-east but the latter is incomplete due to erosion prior to the Permian unconformity.

The Westphalian is much thinner in Northumberland than elsewhere in northern England, up to 600m, generally thinning northwards so that there may be some doubt as to the extent of Westphalian cover over the Southern-Uplands (Francis pers.comm.) but Westphalian strata occur in the Thornhill and Sanqhuar inliers in the western Southern Uplands. The Westphalian sedimentation continues the cyclicity seen in previous groups but its facies are distinctly different with two broad associations;
1) lower delta plain and 2) upper delta plain. The former is represented by lacustrine, lake crevasse splay and minor mouth bar deposits. The latter being that of a distributory channel facies association (Hazeldine 1984, 1984; Fielding 1982, 1986; Leeder et al 1989).

The Westphalian B represents a coastal plain of subdued relief with sediments deposited from fluviatile, muddy deltas feeding into shallow freshwater lakes (Hazeldine 1984). The fluviatile sandbodies form channel belts over wide areas (up to 5km) and Hazeldine suggested that coal seam splits and sand body trends are related to tectonically controlled topography. Recent compaction modelling (Collier 1989) has shown that seam splits and facies distributions can be controlled by differential compaction over dormant or extinct faults. Land (1974) mapped sandbody distribution in the north-east coalfield and demonstrated a regional N-S palaeoslope with local E-W and W-E flow.

Westphalian cyclicity has been attributed to auto-cyclic processes but as Leeder (Leeder et al 1989) indicated the repetitions of marine band transgressions in the Lower Westphalian A and later parts of the Westphalian B, could be due to glacio-eustatic controls.

3:1:3 Basin Subsidence

Several mechanisms have been suggested to explain subsidence in the Northumberland basin. One of the earliest mechanisms was the "mantle-flow" hypothesis (Bott 1964, 1965). In this hypothesis, regional tension is created by upper mantle flow, southwards from the Caledonian massif (Scotland) as a mechanism of isostatic compensation response to the stabilisation of the massif. Leeder (1974) suggested that partial melting of the upper mantle during "mantle-flow" could account for the volcanism in northern England, provided it was sufficiently localised. He observed no widespread volcanism like that of the Midland Valley and the Iapetus province, further south (with the exception of Derbyshire, MacDonald 1984).

The regional thinning of the crust above upper mantle flow was refined with a mechanism for differential subsidence; this was the "wedge subsidence" model, where areas of stable, granite cored crust were buoyant relative to other areas (Bott 1976; Leeder 1976). However not all areas identified as blocks are granite cored, though this was an attractive proposition for Northumberland.

Leeder (1982) attributed Upper Carboniferous (Silesian) subsidence to thermal subsidence according to McKenzies (1978) uniform stretching theory. McKenzie suggested that instantaneous rifting of the lithosphere, raised crustal temperatures (elevated the geotherm) as asthenosphere rose to shallower levels in compensation. Subsequent regional subsidence occured as the thermal anomaly decayed. Whilst the lithosphere cooled and thickened to its pre-rift state, and sedimentation occured at the surface in the rift basin created. Bott (1984) suggested a modification of the previous for Northumberland, placing emphasis on crustal and lithospheric stretching with subordinate thermal effects. Bott estimated 50% stretching or using McKenzies (1978) theory a stretching factor of $\beta=1.5$ for northern England. Bott (1984) estimated a maximum thermal subsidence of 3km (including sediment loading) over a period of 50my after rifting. He suggested also that stretching was heterogeneous; being greater in the lower lithosphere based on his assumption of continued tension and Upper lithospheric "resistance" to Hercynian subduction in Variscan Europe. Bott also maintained that this was reasonable as no evidence for upper crustal extension was evident, i.e. the surface rocks showed no signs of the 50% extension envisaged. Bott's hypothesis is to be doubted on this evidence as McKenzie's (1978) theory requires extension in the crust not in the sedimentary fill of the rift basin. Bott's theory (1984) envokes southerly subduction for southern England, though European geologists prefer a northerly directed subduction scenario (Leeder pers.comm.).

Leeder and McMahon (1987) proposed that following Leeder's (1982) suggestion of a McKenzie type mechanism, subsidence was due to regional tension and post-rift subsidence. Silesian subsidence curves for northern England were presented (see fig. 30) and interpreted as the result of thermal subsidence. Leeder and McMahon (1987) assumed that only extension drove the subsidence and hence derived values of $\beta=1.7$ to 2 for northern England. Northumberland was calculated at $\beta=1.7$ (max.). Leeder suggested that the shape of the subsidence curves were indicative of thermal subsidence occasionally interrupted by pulses of active rifting and mild inversions, e.g the Bowland basin and the Canonbie Coalfield respectively. This suggestion is similar to Bott's (1984) continued tension theory of subsidence; although wedge subsidence appears to be unnecessary as a mechanism. Granite-cored blocks acted as sites for the location of major extensional faults, with block rotation over the entire foreland province producing differential subsidence (Leeder 1982).

McKensie's theory (1978) was taken as the starting point for subsidence modelling in Northumberland by Kimbell and co-workers (Kimbell et al 1989). Kimbell pointed out that Leeder & McMahon's (1987) subsidence curves were only part of the basin's subsidence history, approx. 25-30 my of post-rift thermal subsidence.

Kimbell and colleagues (1989) presented subsidence curves (sediment loaded and deloaded basement subsidence plots) for the Northumberland (fig. 29) basin and determined that instantaneous rifting was improbable: Rifting was active in the basin from the LBG to the MBG. Kimbell invoked Cochran's (1983) modelling of non-instantaneous lithospheric extension and lateral heat transfer during extension, as a means to determine β values for the basin. Using Cochran's model of a 2D basin 80km wide rifting over a period of 25my (fig. 31 & 32), Kimbell derived a value of β=1.30. This value corresponds closely with calculated values, assuming estimated post-rift subsidence based on 600m of Westphalian cover (Kimbell et al 1989). If greater thicknesses of Westphalian are assumed, then subsidence as Kimbell suggests, must have increased in the late Carboniferous due to;

1) Renewed extension in the late Carboniferous (Leeder & McMahon 1987; Kimbell et al 1989).

2) Peripheral thermal subsidence from a) lateral offsetting of crustal and sub-crustal extension in a simple shear type model (Wernicke 1985; Buck, Martinez, Steckler & Cochran 1988), or b) a thermal event i.e. partial melting in the Upper Mantle (this might explain the Whin suite intrusives).

Kimbell and co-workers (1989) used fault restoration techniques from regional seismic lines to estimate upper crustal extension of between 1.15 and 1.19. The discrepancy between these values and the β=1.30 for the whole crust could be due to;

1) Non-uniform stretching of the lithosphere (Hellinger & Sclater 1983; Bott 1984).

2) Under-estimation of extension due to non-imaging of normal faults on seismic (up to 20% error).

Leeder (1989) suggested that active basin extension occured throughout the Dinantian up to the early Namurian i.e. up to 30my after initiation of the basin.

Jarvis & McKenzie (1980) remodelled subsidence extension assuming finite extension rates. The authors concluded that if duratiion of rifting was less than 20my, Mckenzie's (1978) simple model was applicable provided that $\beta \leq 2.0$. Above this rifting time subsidence would be under-estimated and extension over-estimated. For Northumberland a simple McKenzie type model yields a β=1.7 (Leeder & McMahon 1987) and a Cochran (1983) non-instantaneous rifting model value of β=1.3. If 1.7 is too high assuming a rifting event of 25-30my, and a value of 1.3 is a minimum, extension in Northumberland lies between these.

Subsidence in Northumberland is generally agreed to be the product of extension driven by regional tension, under slab-pull according to Bott (1984) or trench-pull according to Leeder (1982), or back-arc/retro-arc extension during Variscan subduction (Leeder & Hardman in press).

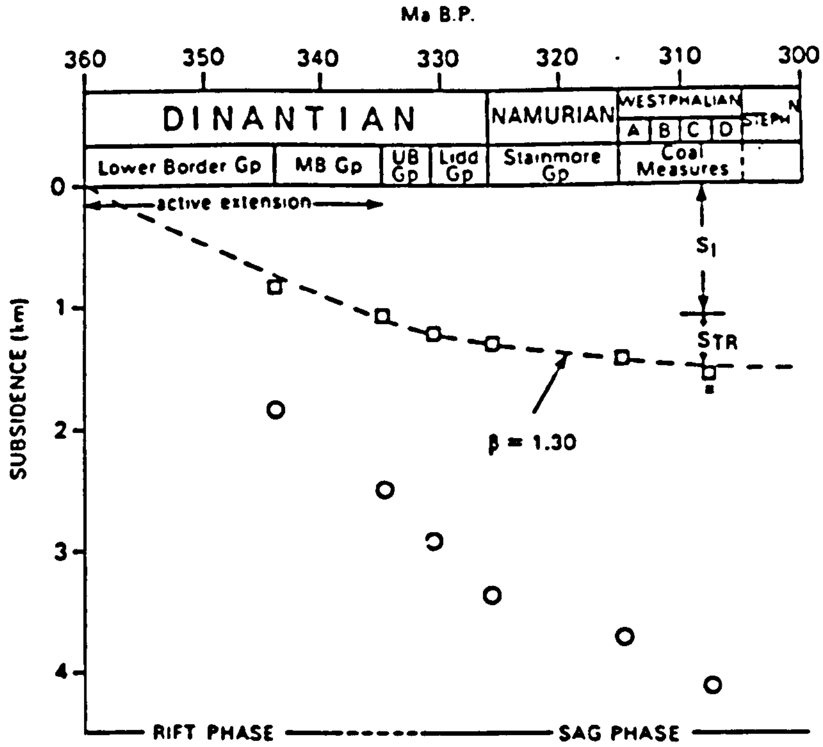


Fig. 29 Basement subsidence plot for Northumberland. Circles= decompacted sediment-loaded subsidence; squares= sediment-straved subsidence where cross indicates thicker Westphalian estimate; dashed line= modelled subsidence; S_I-isostatic subsidence, S_{TR}-thermal relaxation subsidence (after Kimbell et al 1989).

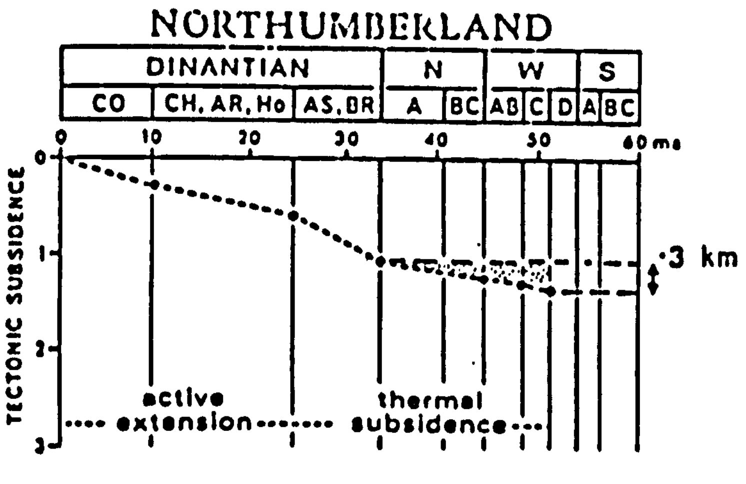
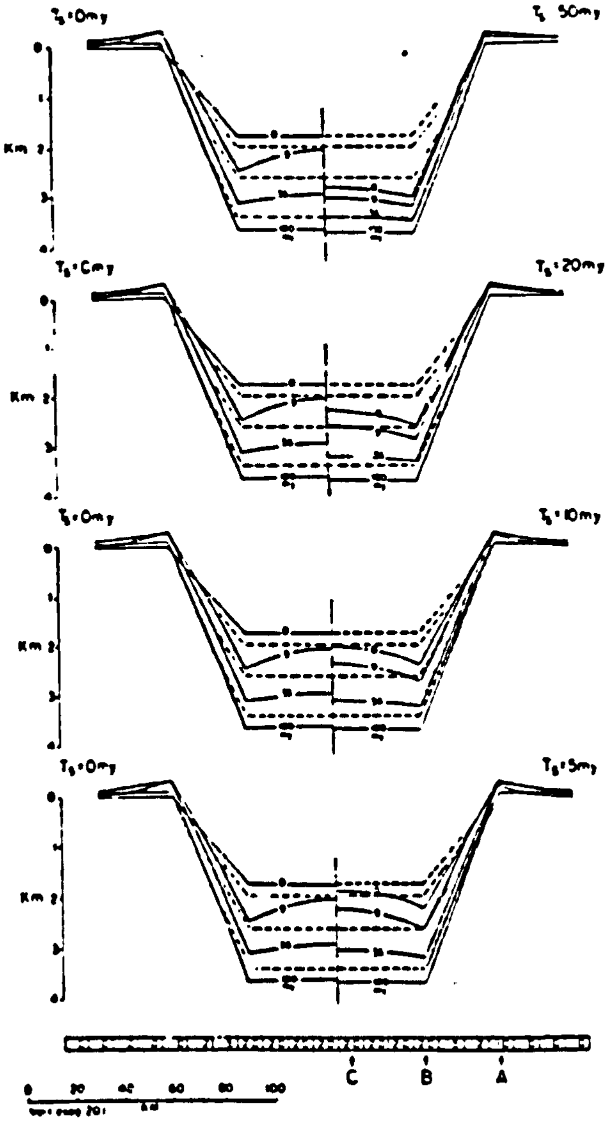


Fig. 30 Thermal subsidence versus time plot for Northumberland, assuming decompaction and local Airy isostatic unloading (after Leeder & McMahon 1987).

Fig. 31 Tectonic subsidence in a simple basin of a finite-length rifting event. The left hand side in the same in each case and shows the development of the basin for instantaneous rifting, the right hand side shows results for different rifting times T_S. The numbers below the sections are β values and A,B and C are positions in the rift (taken fron Cochran 1983).

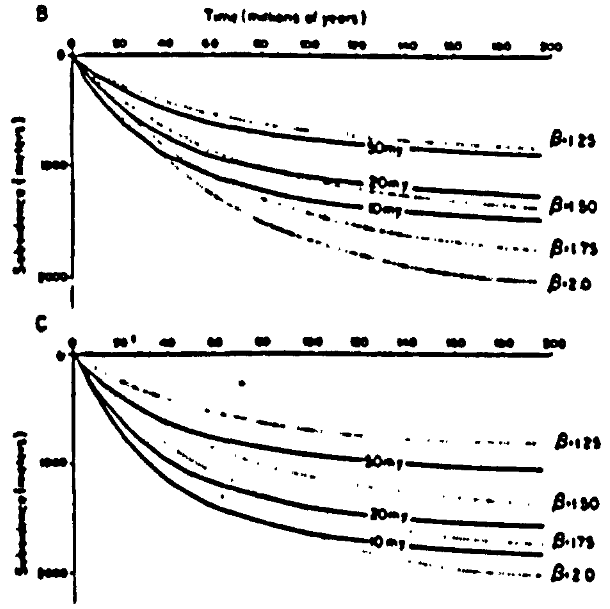
Fig. 32 Post-rift subsidence curves for locations B and C of the basin shown in Fig.31 for extension times of 10, 20, and 50 m.y. (solid lines) compared with subsidence curves resulting from the instantaneous one-dimensional model (dotted lines). Taken from Cochran 1983.

fig. 31



POST-RIFT SUBSIDENCE

fig. 32



Rifting was up to 30my in duration and may have been locally augmented by renewed tension (Leeder & McMahon 1987; Collier 1989). Thermal subsidence was interrupted by a basin inversion event in the Late Carboniferous, followed by renewed rifting in the Permian (Collier 1989) associated with the onset of rifting in the North Sea basin.

Chadwick and Holliday (1990) suggest that the extensional evolution of the basin was due to reactivation of the Caledonian thrust zone (Iapetus suture zone). This might suggest a simple shear type model of extension (Wernicke 1985) which would produce a radically different syn-rift and post-rift sedimentary accumulation. Distinguishing between the two models of pure shear and simple shear (as Chadwick and Holliday's model implies) has been attempted for the North Sea (White 1989). White used the geometry of the post-rift thermal subsidence to determine the model appropriate and concluded that for the same basin the post-rift thickness is an order of magnitude greater for a pure shear interpretation than for a simple shear model.

The post-rift geometry of the Northumberland basin and its surrounding blocks is not known in sufficient detail to be able to assess the validity of the two models.

Part 2: The Basin Inversion History

3:2:0 Introduction

It has long been understood that the Northumberland basin was deformed and uplifted prior to the deposition of Permian sediments e.g. the Yellow Sands in Tynemouth (Land 1974) and the Mid-Permian sandstones in the Brampton and Bewcastle districts (Trotter & Hollingworth 1932; Day 1970).

The deformation was described in early BGS memoirs as folds, faults and "crushes" but it was only recently that these were thought of as products of basin inversion (Leeder et al 1989). Attempts have been made to link the deformation structures with the history of the basin (Collier 1989) but no comprehensive basin wide structural analysis has been conducted until now, though some very detailed work has been undertaken for parts of the basin (Shiells 1962).

The succeeding sections intend to summarise previous work concerning the late Carboniferous (Asturian) deformation as an introduction to the work conducted by the author in the remaining chapters.

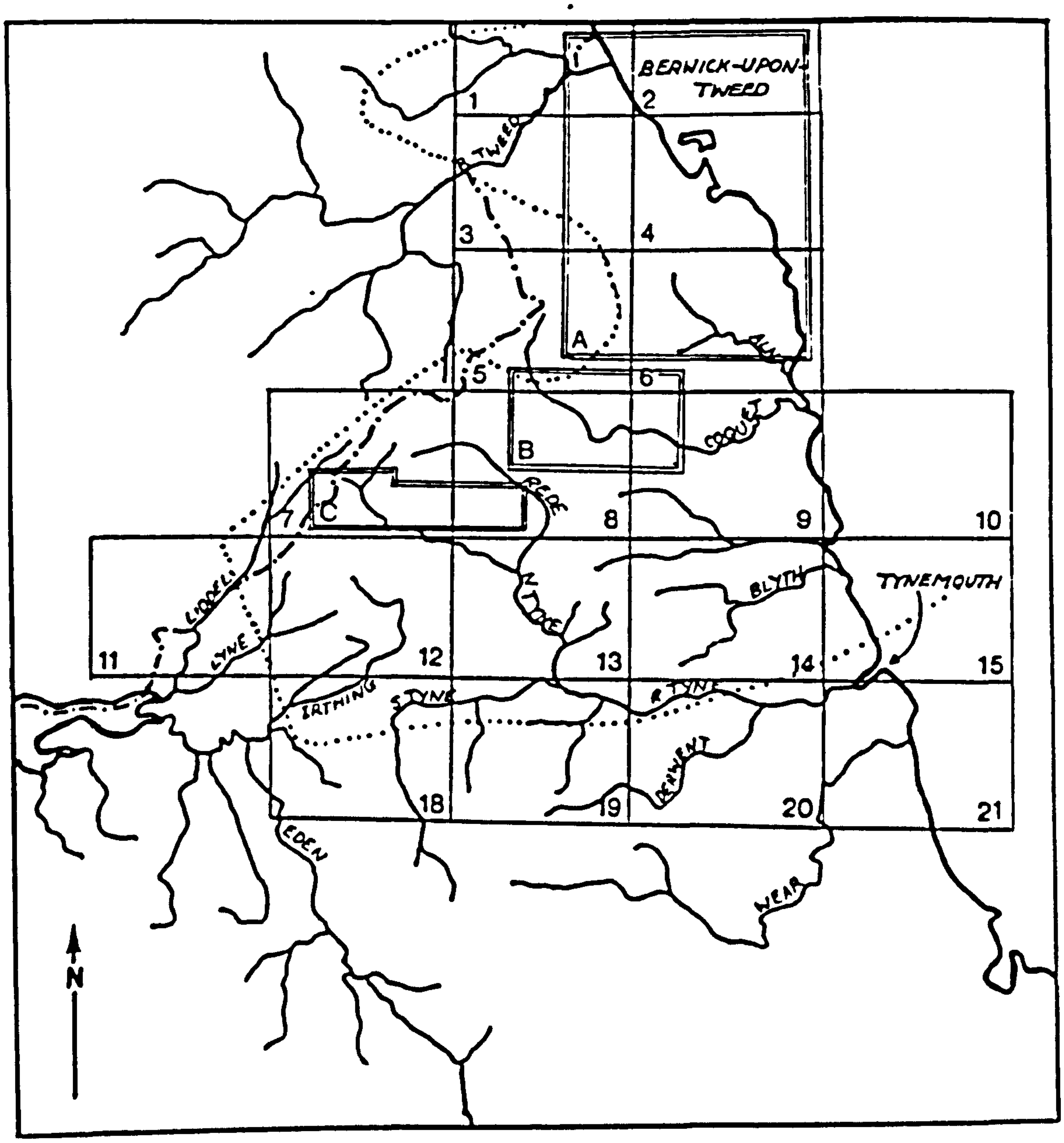


Fig. 33 Map to show locations of BGS sheet memoirs and principal published data sets for Northumberland. Sheets 1-21 available in map-form and memoir except 14 (map only), 19 (map only), 20 (map out of print and no memoir), 21 (map only).

3:2:1 Structure: Distribution and geometry.

For the purposes of this section it is proposed to take the earliest works for each of the BGS sheet memoir areas and then up-date regions where data exists. The areas covered by the discussion are sheets 12, 11, 18, 13, 15, 9 & 10, 6, 3 & 5, and 4 (map 20 is out of print and there is no sheet memoir) and are illustrated in fig. 33.

The Langholm District (sheet 11)

The authors of sheet memoir 11 (Lumsden, Tulloch, Howells & Davies 1972) describe structures for a "downwarping" meaning the extreme north-west of the Northumberland basin. They identify three periods of "earth-movements" since the Silurian (fig. 34).

a) A phase of early "Armorican" events which are intra-Carboniferous, producing an unconformity in the Canonbie area. This unconformity is at the local base of the Coal Measures and produces a notable angular discordance between the Namurian and the Westphalian.The authors describe a secondary reddening of the Coal Measures below a late Carboniferous/Permian surface and also reddening for about 75m beneath the Namurian/Westphalian unconformity.

b) A late Carboniferous phase that occured prior to the deposition of the "New Red Sandstone". This produced widespread folding and faulting. The folding is described as trending N to NNE and occasionally E/W which is an observation at odds with Anderson's (1951) interpretation of N/S compression over the area at this time. The faults are generally normal faults with a strong "wrench" component oblique ENE-SW to the fold axes. No detail was given concerning the size or geometries of the structures recorded.

c) A post-Carboniferous phase of minor folding and faulting believed to have occured in the Tertiary giving rise to the Carlisle syncline. Again no clue as to the extents or geometries of these structures is given.

It is not clear from this memoir what the "Armorican" event is but it is assumed that this is the Variscan orogeny.

The Bewcastle District (sheet 12)

In the west of the basin, the Bewcastle district is dominated by a regional scale (fig. 35) 20km+ anticline trending NNE-SSW to NE-SW over the area (Land & Mills 1927; Day 1970). It is an asymmetric structure facing north-west with a steep or overturned westerly limb. Land and Mills discerned three deformational episodes within the Carboniferous; two in the post-Carboniferous/pre-Triassic phase of what they call the Hercynian orogeny and the third in the Tertiary.

a) The earlier of the two deformation phases was suggested to be one of N/S

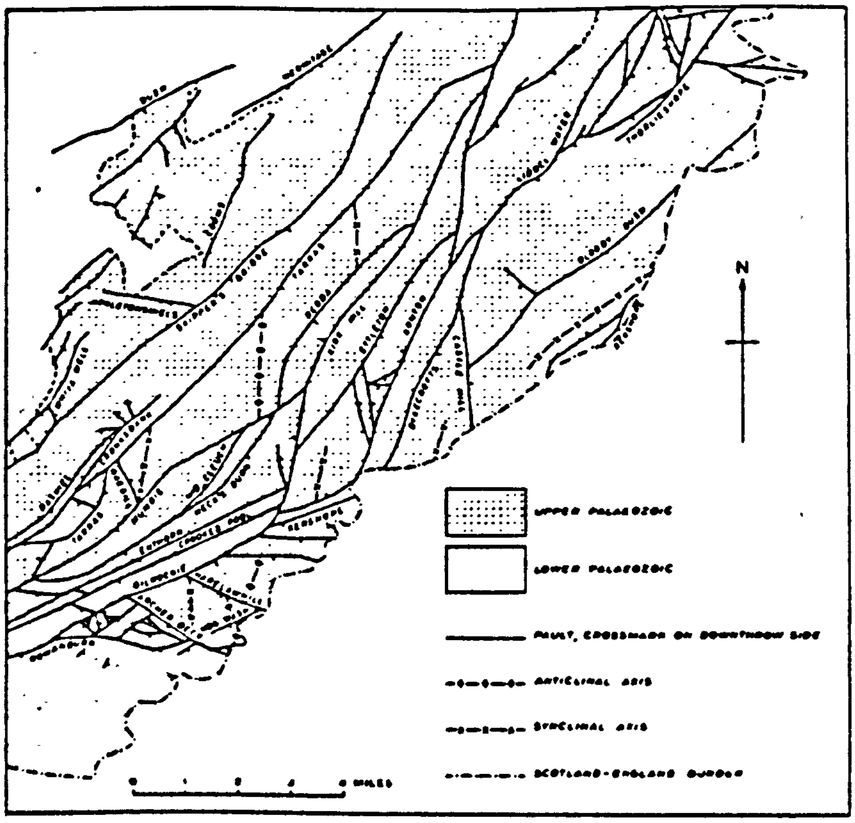


Fig. 35 Sketch-map showing the main structural elememts of the Bewcastle area (after Day 1970).

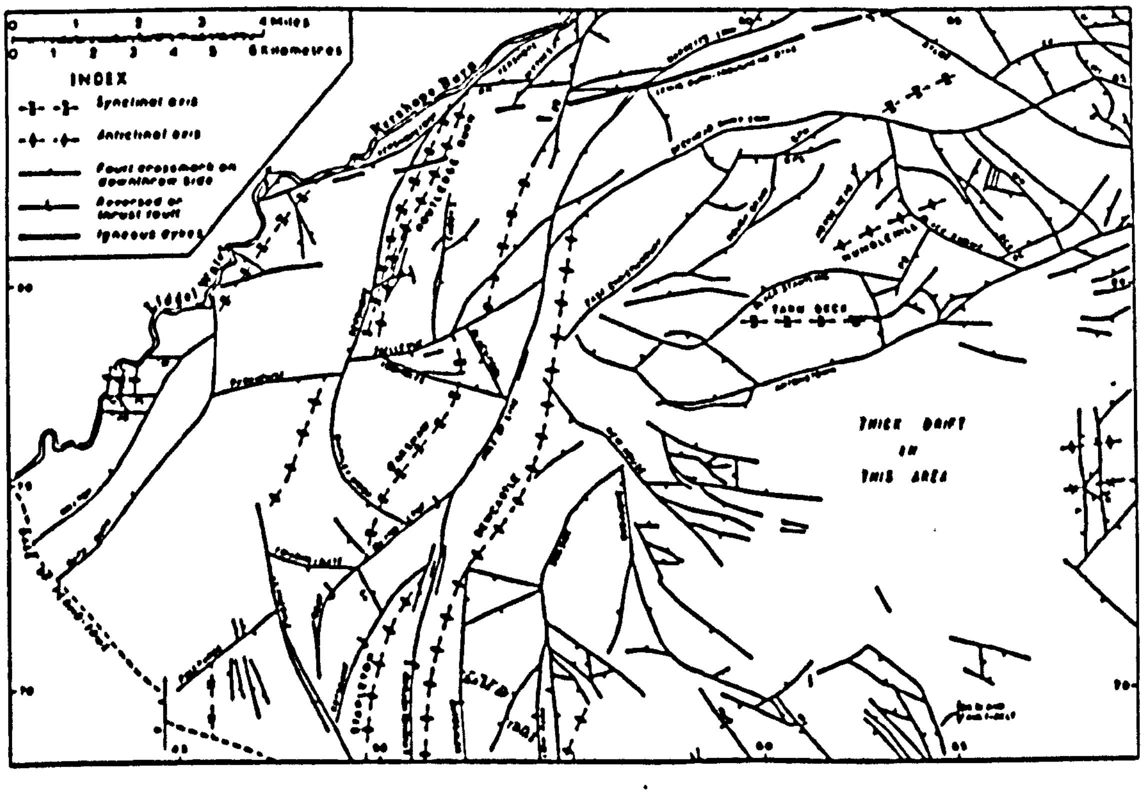


Fig. 34 Sketch-map of principal faults and folds affecting Upper Palaeozoic strata in the Langholm area (after Lumsden et al 19**).

compression producing an east-west axis. The Bewcastle anticline was thought to have been initiated at this time as a broad E/W dome. This early compression was followed by a period of tension producing movement along ENE faults (though it is not clear if these are early deformation faults or original basin faults).

b) The second deformational phase was a period of renewed compression that produced "intense folding". This is believed to have been E/W directed producing numerous NNE folds. The oblique trend of the folds was attributed to "deflection by the Caledonoid Southern Uplands Massif". The Bewcastle anticline developed as a NE trending arcuate structure during this phase with over thrusting to the west. The anticline is bounded to the NW by a NE-trending reverse fault, the Hole of Lyne and Goat Island thrust. The area is complex, not only containing the curvilinear Bewcastle anticline but 2 miles to the NW, in the Routledge Burn area another antiform axis occurs bounded to its NW by a tight synform and the NE trending Dappley Moor fault (see fig.35). The Bewcastle anticline is truncated on its northerly edge against the Beckhead-Binky Linn fault. The southern edge of the structure is complicated around the Stapleton area where the Hole of Lyne thrust breaks into several strands, the Kaysbank thrust and the Lyneholmeford thrust,which bound the Stapleton anticline also facing NW. The area contains numerous NE and NNE faults and several major E-W faults including the Antonstown fault. There are several NW faults and the thrusting was believed to accompany slip on the E-W faults (Day 1970).

c) The deformation phase affecting the Permo-Trias produced gentle tilting to the south-west and renewed movement along previous faults e.g. ENE and E/W trends.

The Brampton District (sheet 12)

Trotter and Hollingworth described the Brampton district (1932) and identified folding and faulting they believed to be Late-Carboniferous in age, caused by Hercynian "earth movements". Despite poor exposure, much small scale folding (2m amplitude and 5-20m wavelength) is present in the area especially adjacent to the Alston block around the main strand of the Stublick fault. Apart from folding which generally trends NNE-NE over the area, there also a number of tear faults. These are orientated NW-SE in the district and include the Upper Denton fault and the Blenkinsop Boundary fault. Similar faults are found on the Alston block and trend more N-S. Folding is described as being repeated on the NE sides of the NW-SE faults.

Trotter and Hollingworth concluded the folds and faults were of similar origins and acknowledged that the Alston block responded to deformation in a different way to the basin.

Folding on the block is very limited, concentrated on the western side along the area adjacent to the Pennine fault. There is a major east facing, reverse faulted monocline the Burtresford disturbance, running centrally across the block from north to south trending NNE.

The authors identify a late Carboniferous event which produced the small folds aand also broad open antiforms and synforms trending NE-SW e.g. Farlam antiform and the Denton Fell antiform (both of which are over 1km along strike and $^1/_4$km in wavelength). The late Carboniferous event is cited as the cause of the strike-slip faults. Trotter and Hollingworth (1932) suggest that the Whin Sill was intruded during the same deformation event,though they offered little detailed discussion of this timing. A later episode of faulting is proposed, which affects the Permo-Trias as well as the Carboniferous, and displacements are observed on both the Pennine and Stublick faults.

The Bellingham District (sheet 13)

Frost and Holliday (1980) outlined the general structure of the region by dividing it into two areas separated by the ENE-WSW trending Sweethope fault. South of the fault strata dips gently with only minor displacements. North of the fault the strata are commonly faulted and folded.

A graben feature is outlined between the above Sweethope fault and the similarly ENE-ESE trending Antonstown fault (see fig. 36). They (the authors of sheet 13) describe three deformation events;

a) Hercynian N/S compression produced numerous E/W orientated folds e.g. Bellingham and Ridsdale anticlines (though there are several NW folds and arcuate fold traces).

b) The relaxation of N/S compression resulted in tension producing shear faults trending N and SE.

c) A late episode of Whin Sill intrusion, and a later still period of Tertiary dyking e.g. the Bingfield dyke.

Frost and Holliday (1980) describe the folding as increasing (in intensity and frequency) to the south-east as the southern margin of the basin is approached. Folding is up to 3m amplitude and 10m wavelength and traceable over several 10's of metres. The fold axes are NE orientated in this area (between the Sweethope and Antonstown faults and the southern margin). Some of the folds, antiforms in particular are described as "dying-out vertically" and are interpreted as pene-contemporaneous with sedimentation; although no supporting evidence is offered.

The Tynemouth District (sheet 15)

The author (Land 1974) describes faulting and folding of late Carboniferous age. Several broad N-S to NE-SW folds were mapped as open structures up to 10m in wavelength and traceable over several metres along axis. However the area appears to be less "disturbed" than other districts. Land suggested that folding and faultingare simultaneous. He describes some of the faults as dying-out rapidly and splitting into smaller fault strands e.g. the Crimea fault.

Land (1974) recognises post-Carboniferous movements on the 90 Fathom and

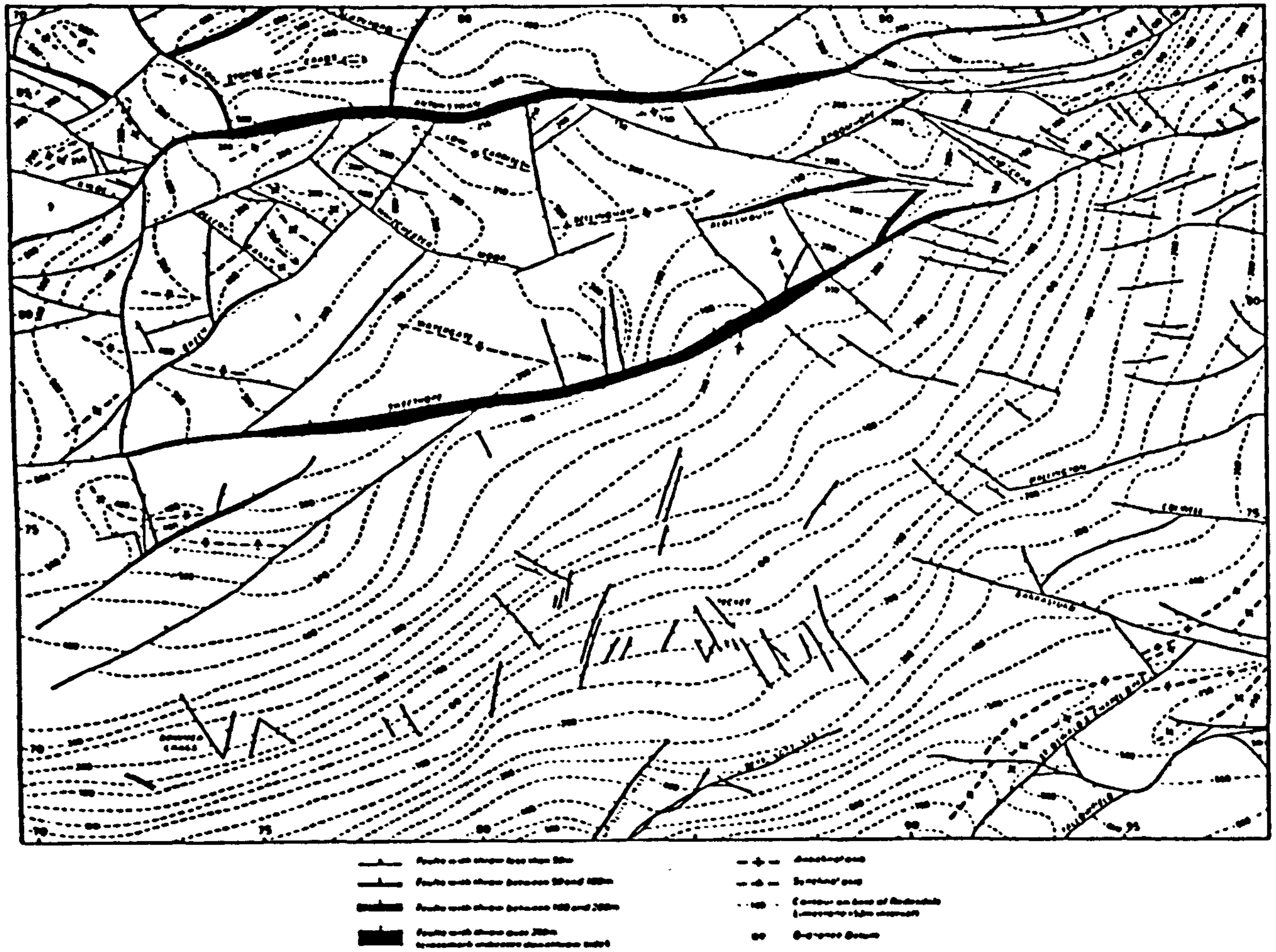


Fig. 36 Structure of the Bellingham area, shown by contours on the base of the Redesdale limestone (Frost & Holliday 1980).

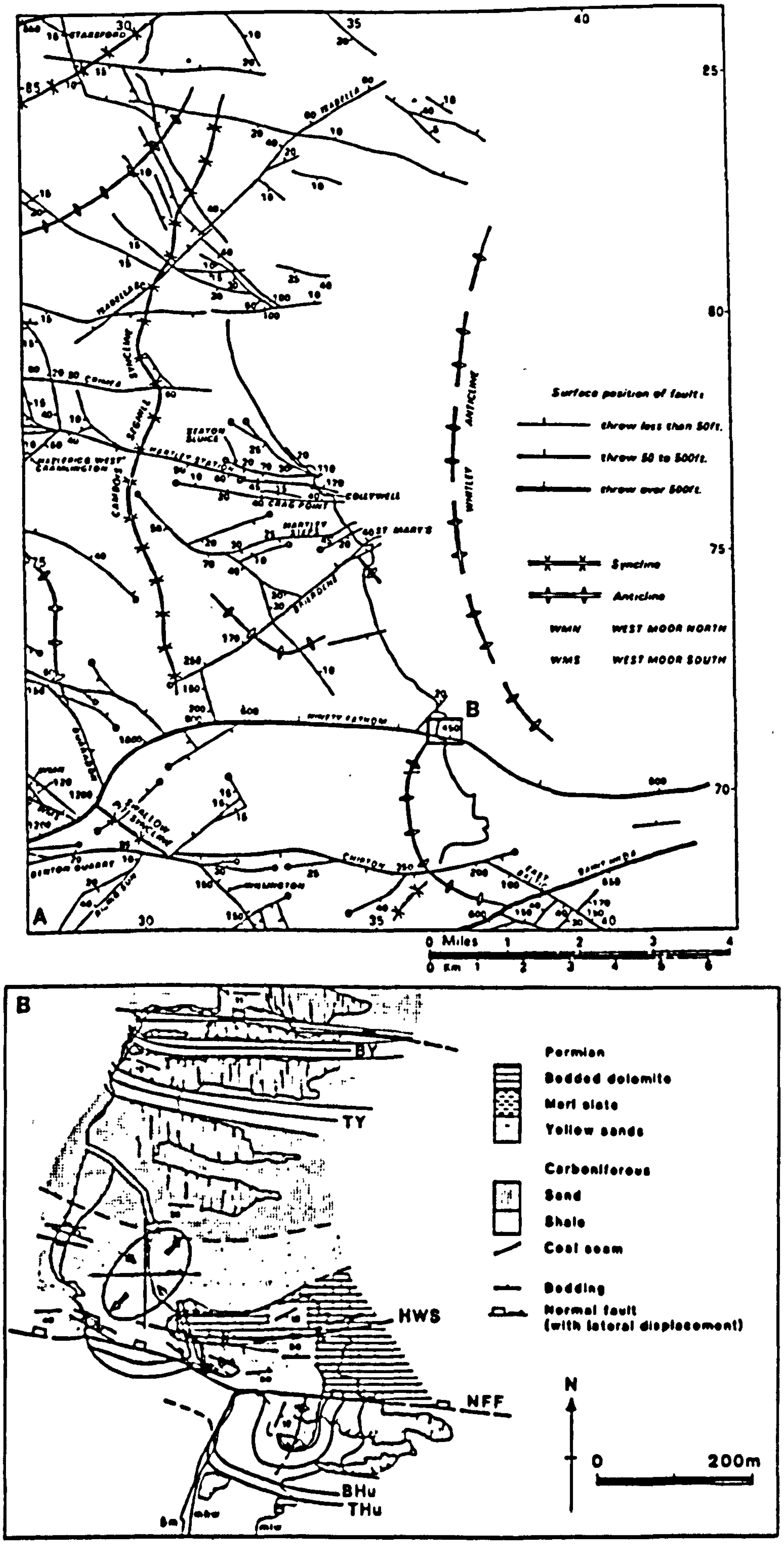


Fig. 37 a) structure of the Tynemouth area (after Land 1974). b) structure of area around A in a) compiled from field data. The inferred stress elipse, of Permo-Mesozoic extension is compatible with right-lateral motion on the Ninety-Fathom fault. NFF= Ninety FAthom fault. HWS= hanging-wall syncline, BHu Bottom Hutton coal seam, THu= Top Hutton seam, By= Bottom Yard seam and TY= Top Yard seam (taken from Collier 1989).

Colywell fault as they both displace Permian strata. A slight E-W south facing anticline is recorded in the hanging-wall of the 90 Fathom fault and this is attributed to post-Carboniferous movement on the fault. This structure has been described as a roll-over by subsequent workers (Collier 1989; Leeder et al 1989). Little detail of structure is offered beyond the above except individual descriptions for some faults.

The Tynemouth district was partially re-appraised by Collier (1989). Collier interpreted the roll-over on the 90 Fathom fault to be indicative of a listric normal geometry and by reconstruction techniques suggested that the decollment to the fault was well within the Carboniferous sedimentary pile. The roll-over (although it affects Permian strata) is described as "having been subject to some Variscan compression". If the roll-over is indeed a post Permian structure, it is difficult to see how it could have been subject to late Carboniferous deformation.

Collier (1989) re-iterates the observations of Land (1974) in describing N-S folds, though there is variation in the strike of the folds giving NNW to NNE trends. Collier adds fold orientation data and a section over the 90 Fathom fault from immediately offshore (c/o British Coal) at Tynemouth (fig. 37a & b).

The North-Tyne District

The North-Tyne region was described in Fowler's 1965 publication (not a sheet memoir). He notes several interesting structures for the area .

1) Soft sedimentary deformation structures: These are interpreted as early Carboniferous occuring whilst the sediments were unlithified. Around March Head in particular the Fell Sandstones show large scale contorted bedding, the result of what Fowler calls "contemporary slip". However the dimensions and the density of distribution of these features are not given.

2) Late Carboniferous structures: These are described in some detail and in block diagram form. The most notable structure is the Akenshaw Burn anticline which is described as a tight asymmetric, NE fold possibly reverse fault related (the faults at the surface today on the NW and SE sides are steep to vertical). The anticline is an inlier of Cementstone lithofacies (LBG) in surrounding Fell Sandstone and is traceable over a mile in the north Kielder area. The Akenshaw Burn anticline is immediately SSW of but separated by E-W faults from a large open antiformal structure that extends over the Kielder area, trending NE-SW.

This structure is very similar to that of the Bewcastle anticline. The Akenshaw and North Keilder anticlines are both cut by E-W trending normal and/or wrench faults; another point of similarity with the Bewcastle district.

The Rothbury, Amble and Ashington Districts (sheet 9 & 10)

The author of this memoir (Fowler 1966) describes faults and fault "crushes" in some detail but neither indicates age relationships or mentions any folding. Two major

fault systems were identified in the district;
1) The Bolton-Swindon fault system
2) The Cragend-Chartners fault system.

Both of the above were mapped by Robson (1955) in his sedimentological study of the former Fell Sandstone group of the Coquet river valley. The fault systems trend roughly ENE to NE though the Bolton-Swindon fault curves southwards 2$^1/_2$ miles west of Rothbury producing a minor repetition of the Fell Sandstone and Cementstones contact.

The fault (Bolton-Swindon) is associated with gentle SE dips,though these steepen to dip NW adjacent to the fault curve where it trends NE-SW and NNE-SSW, possibly associated with minor folding.

The Cragend-Chartners fault extends towards the Alnwick district across the southerly tip of a major asymmetric anticline in that district, the Lemmington anticline.

The Alnwick District (sheet 6)

This region covers a large area from Holburn south to Alnwick and east to the coast. Carruthers (Carruthers, Burnett & Anderson 1930) describe two major anticlines in this district.
1) The Holburn anticline.

This extends NNW to N-S from Holburn to north of Lemmington over-lapping with the second (Lemmington) anticline. The Holburn anticline is traceable over 15miles and forms a prominent topographic feature, repeating the Lower Border Group. The anticline is asymmetric, facing NW with a steep >70^o limb bounded by the Hetton fault. It more gently dipping (20-40^o) limb extends eastwards towards the coast interrupted by occasional open folds trending NE-SW to N-S.
2) The Lemmington anticline.

This trends more noticeably NE-SW and extends over 22 miles through Lemmington village to the north-west of Alnwick. The Bolton fault bounds the steep (up to 80^o) westerly limb of the anticline and has been interpreted as a steep reverse fault at the surface (Robson 1955) trending SSW.

Between the anticlines and the Cheviot mass numerous SW-NE trending faults occur. The anticlines are cut by a number of E-W trending faults, though it is thought that most of these do not link with the previous SW-NE trending faults (Carruthers et al 1930; Shiells 1964).

The Bolton fault is traceable over 35km from near Otterburn (where it is called the Swindon fault) northwards to Middlemoor. It has a maximum throw of 930m and the Hetton fault has a throw up to 1020m.

Of the E-W and SSE faults in the area some are described as being post-folding, strike-slip faults and are associated with minor scale folding (though geometries and sizes were not indicated by Carruthers et al 1930) e.g. the Longhoughton fault.

The deformation in this region is assigned to late Carboniferous events but no orientation of stress systems was indicated.

The Alnwick area was described in more detail in 1955 (Westoll, Robson & Green) when the Holburn and Lemmington anticlines were compared to the Bewcastle anticline. The E-W and NE-SW faults were described again but the dominant set was recorded as trending ENE-WSW over the area. Taking data from the survey maps, Westoll concluded that on analysis of the fault patterns compared between the two anticlines the dominant ENE faults intersected the anticlines at 65°. A minor set intersected at 115° which with the former set were interpreted to be cognate shear faults. The shear faults were suggested to be related to the compression that produced the anticlines but were rotated 25° relative to each-other.

Dextral lateral movement was involved on several faults trending ENE-SWS e.g. the Longhoughton fault and a component of oblique dextral motion invoked for others e.g. the Howick fault.

The Whin Sill in the area cuts over the folding of the Holburn structure and so the "great periclines" (Holburn and Lemmington) are interpreted as pre-Whin Sill intrusion or late Carboniferous in age.

The Cheviot District

The authors of the previous memoir also collaborated to produce the first memoir for the Cheviot area (Carruthers et al 1932). No particular section of their publication was dedicated to structure but faults and "crushes" were described.

There are many E-W faults with southerly down-throws and for the NE trending Skinsfield fault "sharp" N-S trending folds are described as associated with it. Some of the folds are described as asymmetric but no details of geometry, size or orientations are given.

The authors suggest that E-W trending faults are pre E-W dyke intrusion (Whin Sill suite) but no age is given for the NE-SW faulting except to suggest they were reactivated Lower Palaeozoic features.

North East Northumberland

This region includes the area around Belford, Holy Island and the Farne Islands described in the 1927 memoir (Gunn 2nd ed. Carruthers, Dinham, Burnett & Maden). Several large faults are described as running through the area, including;

1) The Berrington fault; a NE-SW orientated fault with both a northerly or southerly downthrow up to 155m.

2) Dryburn Colliery fault; a NNE-SSW orientated fault with a 150m southerly downthrow.

3) The Hetton fault; bounding the Holburn anticline to the west and orientated N-S. It was described as having the same age as the anticline (Carruthers et al 1932) and a throw

in excess of 800m.
4) Cockenheugh fault; a NE-SW trending structure with a southerly downthrow of >70m.

Several NE-SW faults are described in detail (see sheet memoir 4) and cut into the Holburn anticline. No mention of folding is made in this work although later works describe over 200 small folds in north east Northumberland.

In an excellent piece of detailed work, Shiells (1964) describes the area from Berwick-Upon-Tweed to Cullernose Point (for full details see Shiells 1964). Shiells concluded that the deformation in the region was due to the "Armorican orogeny" (though this presumably is the Hercynian orogeny rather than the Armorican phase within it). The deformation was attributed to east-west compression which produced:

1) Early major folding generating the Holburn and Lemmington anticlines. These were interpreted (Shiells 1964) as having formed by deformation around the rigid mass of the Cheviot. Similarly the Southern Uplands was invoked as a barrier to produce the Berwick monocline. The monocline is a N-S orientated, east facing, reverse faulted structure. The reverse fault in the Berwick monocline breaches the Lower Palaeozoic north of Berwick-Upon-Tweed.The asymmetry of the folds was interpreted as due to; a) a rotational (shear) couple caused by differential movement between upper and lower layers of Carboniferous sediment, b) rejuvenation of basement structures, c) compression of a thinning sedimentary series on an inclined pre-Carboniferous surface.
2) Contemporaneous lateral shear development. This system produced dextral shear in the south of the area e.g. Swindon and Cragend Chartners faults and sinistral shearing to the north e.g. Felkington-Ford disturbance zone.In between these areas, between the major anticlines, intense buckling and faulting accomodated deformation e.g. Rock and Annstead faults.
3) Later minor folding sub-parallel to the main anticlines.
4) A system of NE-SW faults considered to be part of the conjugate shear pattern described in 2).

These were Shiells' conclusions implying deformation due to E-W directed compression. The place of the Whin Sill intrusives in this scenario is not clear and the asymmetry of the anticlines takes no account of the reverse fault interpretations for the Hetton and Bolton faults.

The tectonic evolution of the Northumberland basin has been much neglected in terms of the late Carboniferous (Asturian) deformation. Recent work (Leeder et al 1989; Collier 1989) has addressed this problem and directly associates the deformation in the basin with shortening deformation in the Westphalian C/D to Lower Permian interval;. Leeder (1989) draws attention to NNE-SSW and NNW-SSE orientated structures which he classifies as typical of the late Carboniferous basin inversion.

The deformation in this region is assigned to late Carboniferous events but no orientation of stress systems was indicated.

The Alnwick area was described in more detail in 1955 (Westoll, Robson & Green) when the Holburn and Lemmington anticlines were compared to the Bewcastle anticline. The E-W and NE-SW faults were described again but the dominant set was recorded as trending ENE-WSW over the area. Taking data from the survey maps, Westoll concluded that on analysis of the fault patterns compared between the two anticlines the dominant ENE faults intersected the anticlines at 65°. A minor set intersected at 115° which with the former set were interpreted to be cognate shear faults. The shear faults were suggested to be related to the compression that produced the anticlines but were rotated 25° relative to each-other.

Dextral lateral movement was involved on several faults trending ENE-SWS e.g. the Longhoughton fault and a component of oblique dextral motion invoked for others e.g. the Howick fault.

The Whin Sill in the area cuts over the folding of the Holburn structure and so the "great periclines" (Holburn and Lemmington) are interpreted as pre-Whin Sill intrusion or late Carboniferous in age.

The Cheviot District

The authors of the previous memoir also collaborated to produce the first memoir for the Cheviot area (Carruthers et al 1932). No particular section of their publication was dedicated to structure but faults and "crushes" were described.

There are many E-W faults with southerly down-throws and for the NE trending Skinsfield fault "sharp" N-S trending folds are described as associated with it. Some of the folds are described as asymmetric but no details of geometry, size or orientations are given.

The authors suggest that E-W trending faults are pre E-W dyke intrusion (Whin Sill suite) but no age is given for the NE-SW faulting except to suggest they were reactivated Lower Palaeozoic features.

North East Northumberland

This region includes the area around Belford, Holy Island and the Farne Islands described in the 1927 memoir (Gunn 2nd ed. Carruthers, Dinham, Burnett & Maden). Several large faults are described as running through the area, including;

1) The Berrington fault; a NE-SW orientated fault with both a northerly or southerly downthrow up to 155m.

2) Dryburn Colliery fault; a NNE-SSW orientated fault with a 150m southerly downthrow.

3) The Hetton fault; bounding the Holburn anticline to the west and orientated N-S. It was described as having the same age as the anticline (Carruthers et al 1932) and a throw

in excess of 800m.
4) Cockenheugh fault; a NE-SW trending structure with a southerly downthrow of >70m.

Several NE-SW faults are described in detail (see sheet memoir 4) and cut into the Holburn anticline. No mention of folding is made in this work although later works describe over 200 small folds in north east Northumberland.

In an excellent piece of detailed work, Shiells (1964) describes the area from Berwick-Upon-Tweed to Cullernose Point (for full details see Shiells 1964). Shiells concluded that the deformation in the region was due to the "Armorican orogeny" (though this presumably is the Hercynian orogeny rather than the Armorican phase within it). The deformation was attributed to east-west compression which produced:

1) Early major folding generating the Holburn and Lemmington anticlines. These were interpreted (Shiells 1964) as having formed by deformation around the rigid mass of the Cheviot. Similarly the Southern Uplands was invoked as a barrier to produce the Berwick monocline. The monocline is a N-S orientated, east facing, reverse faulted structure. The reverse fault in the Berwick monocline breaches the Lower Palaeozoic north of Berwick-Upon-Tweed.The asymmetry of the folds was interpreted as due to; a) a rotational (shear) couple caused by differential movement between upper and lower layers of Carboniferous sediment, b) rejuvenation of basement structures, c) compression of a thinning sedimentary series on an inclined pre-Carboniferous surface.
2) Contemporaneous lateral shear development. This system produced dextral shear in the south of the area e.g. Swindon and Cragend Chartners faults and sinistral shearing to the north e.g. Felkington-Ford disturbance zone.In between these areas, between the major anticlines, intense buckling and faulting accomodated deformation e.g. Rock and Annstead faults.
3) Later minor folding sub-parallel to the main anticlines.
4) A system of NE-SW faults considered to be part of the conjugate shear pattern described in 2).

These were Shiells' conclusions implying deformation due to E-W directed compression. The place of the Whin Sill intrusives in this scenario is not clear and the asymmetry of the anticlines takes no account of the reverse fault interpretations for the Hetton and Bolton faults.

The tectonic evolution of the Northumberland basin has been much neglected in terms of the late Carboniferous (Asturian) deformation. Recent work (Leeder et al 1989; Collier 1989) has addressed this problem and directly associates the deformation in the basin with shortening deformation in the Westphalian C/D to Lower Permian interval;. Leeder (1989) draws attention to NNE-SSW and NNW-SSE orientated structures which he classifies as typical of the late Carboniferous basin inversion.

Summary

Previous works indicate widespread late Carboniferous folding and faulting throughout the Northumberland basin. The folding is particularly intense in low stratigraphic horizons and especially along the southern margin of the basin in the vicinity of the Stublick fault (and to a lesser degree along the 90 Fathom fault). The northern parts of the basin are dominated by major asymmetric anticlines, the Bewcastle, Holburn and Lemmington anticlines with lesser similar structures along the poorly exposed northern margin e.g. Akenshaw Burn anticline and the open Kielder anticline. No large scale anticlines are described for the southern basin margin and deformation is limited over the Alston block compared to the basin. Dominant trends of folds are NNE-SSW to NE-SW though N-S and E-W folds are not uncommon. Fault systems fall into three groups;

1) ENE-WSW normal faults,

2) NNE-SSW to NNW-SSE and NE-SW faults, generally normal to strike-slip with occasional reverse structures,

3) E-W and ENE-SWS faults, which were originally normal, sometimes reactivated as oblique to strike-slip faults.

Of the above at least 2) seem to be related to the folding often post-dating 1) and pre-dating reactivation on 3). The faults identified in 1) are taken to be early Carboniferous normal faults. The structures in 3) tend to be dyke orientations with demonstrably post-Permian movement.

3:2:2 Early Fault Activity

Syn-sedimentary faults were active in the Northumberland basin during rifting. This activity spanned the rifting event from the onset of the basin to the end Dinantian (Leeder 1987; Gawthorpe, Gutteridge & Leeder 1989). The period of rifting has been determined by subsidence analysis of the sedimentary pile (Leeder and McMahon 1988). Leeder and McMahon were the first to produce a back-stripped, de-loaded subsidence curve for the Northumberland basin. They determined the rifting event as the period of the basins subsidence curve that was the steepest and Gawthorpe et al (1989) suggested the rifting to be when sedimentation was associated with active normal faulting. Leeder (1988) determined a post-Brigantian thermal subsidence phase (based on a McKenzie two layer uniform stretching and subsidence model, 1978,1979). Periods of intense fault activity coupled with rapid subsidence and syn-sedimentary "growth" faulting are likely therefore to represent active rifting in the basin.

Syn-sedimentary faults are rarely observed but their positions can be gauged from their effects on facies distributions, soft-sediments (dewatering) and thickness variations in their hanging to footwall thickness ratios (fig. 38). This type of analysis was coined "palaeotectonic" analysis (Leeder 1987) and has been elegantly applied to both the ancient and modern extensional province (Leeder 1987; Collier 1988). Leeder (1987) suggested that the approach would be to;

1) identify the major thickness and facies changes (across a potential syn-sedimentary fault) using geological and geophysical data,

2) define basin margins and adjacent footwall uplands from the data in 1),

3) identify basin margin faults and hinge lines from 1) and 2) and the location of all margin parallel, intra-basinal faults (assuming that all basin faults will be parallel, this will not always be the case),

4) all faults outlined in 3) are analysed for their syn-sedimentary potential using the suggested criteria (Leeder 1987),

5) identify any subsequent reactivation of the faults considered in 4) and assessed for potential "inheritance" from older structures (pre-basin faults).

Once the faults in the basin were identified from 3) above they were analysed for their potential syn-sedimentary character (see fig. 39). Leeder (1987) suggested that the following be considered:

1) Syn-sedimentary faults may retain their listric geometry (assuming that all syn-sedimentary faults are listric normal faults).

2) The fault may show a roll-over associated with contemporaneous movement on the fault and may also show reverse drag features.

3) A syn-sedimentary fault will have a marked influence upon sedimentary thicknesses as the hanging-wall slope is descended (Leeder & Gawthorpe 1987).

4) An active fault is expected to produce earthquakes and subsequently a syn-sedimentary fault will be associated with high concentrations of soft-sediment deformation structures.

5) Predictable facies changes are expected around syn-sedimentary faults and these will be preserved in the sedimentary record.

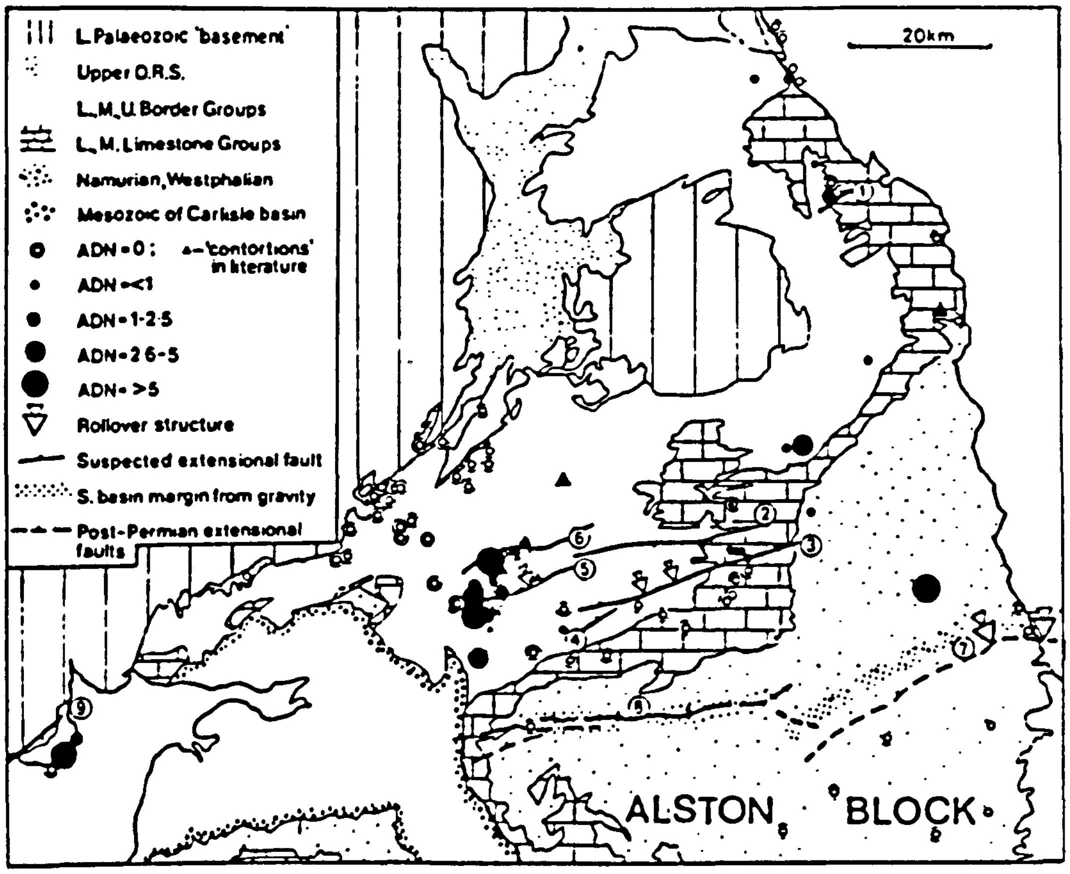
6) Any gravity structures produced in the system will show a marked orientation down the hanging-wall dip-slope of the active fault.

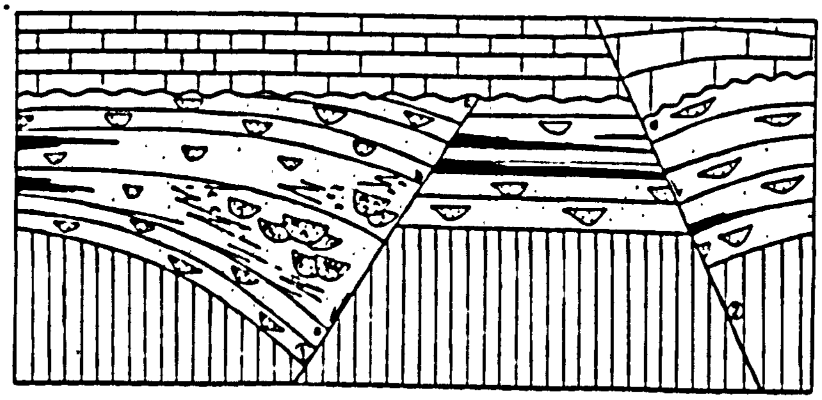
In addition to these active faults can be suspected if facies are channelled by the faults e.g. fluvial systems will exploit the palaeoslopes and topography caused by the faulting (but only in conjunction with the above).

From the previous section (2:1:2) it can be deduced that the basin margin faults were the Stublick fault and a fault system a little to the north of the present day 90 Fathom. These appear to have been active until the Upper Limestone Group and after this may have continued to have influenced topography through differential subsidence across them. This passive influence continued to the Namurian, though may have continued to

Fig. 38 Map to show: (i) the spatial and temporal distribution of ADNs in the Carboniferous of Northumberland; (ii) rollover structures; (iii) suspected extensional faults active during the Carboniferous; (iv) suspected extensional faults active during post-Permain. Numbered faults: 1 Bowden Doors; 2 Antonstown; 3 Sweethope; 4 Sam's; 6 Beckhead/Binky Linn; 7 Ninety Fathom; 8 Stublick; 9 North Solway (after Leeder 1987).

Fig. 39 Diagram to illustrate the kinds of stratigraphical and sedimentological data required to test whether a fault was active during deposition. Fault 1 was inactive until the interval a-b when facies and thickness changes and allokinetic soft sediment deformation structures indicate syndeposition motion. The fault was then inactive during the deposition of units b-c, whose further fault motion occured before the deposition the upper limestone (brick ornament). The central horst block shows facies changes (thick coals = black ornament) in the interval a-b. Fault 2 was initiated after deposition of the clastic units (stippled) but during deposition of the limestone after position d. Note; the presence of a roll-ovr is not evidence of syndeposition without other criteria being present.


L.Palaeozoic 'basement'
Upper O.R.S.
L.,M.,U. Border Groups
L.,M. Limestone Groups
Namurian, Westphalian
Mesozoic of Carlisle basin
ADN=0; ▲–'contortions' in literature
ADN=<1
ADN=1-2·5
ADN=2·6-5
ADN= >5
Rollover structure
Suspected extensional fault
S. basin margin from gravity
Post-Permian extensional faults
20km
ALSTON BLOCK



have a minor effect until the Westphalian.

Elsewhere in the basin the following faults are strongly suspected to have been active syn-sedimentary structures during the Dinantian (see fig. 38). In the west of the basin around Bewcastle and Bellingham, the Beckhead and Binky Linn faults, the Antonstown, Sam's and Sweethope faults (Frost & Holliday 1980; Leeder 1987).

In the north-east and central parts of the basin there may well be other faults that were active during the Lower Carboniferous, though none apart from those already mentioned have been named. Many faults with E-W or ENE-WSW orientations are pre late Carboniferous deformation and may be early Carboniferous faults but their syn-sedimentary character has not been proved. The distribution of soft-sediment deformation is restricted to areas of good exposure and notably sandy facies. Contortions of bedding are noted in memoirs for the north-east in the Fell Sandstones and in the Scremerston Coal group, and are recorded for the north of the basin around Kielder (Carruthers et al 1930, 1932; Fowler 1966). So far in the basin no large scale gravity slides or slumps have been identified though such structures were found in the Bowland Basin (Gawthorpe & Clemmey 1985; Gawthorpe, Gutteridge & Leeder 1987) were they were linked to active fault activity in the basin.

3:2:3 Structural Interpretation

The cause of the late Carboniferous deformation so widely acknowledged in the Northumberland basin has been outlined in section 2:2:1 but although the deformation is attributed to Variscan events it was not proved in any of the previous works.

The general pattern of events in the basin appears to be;initial extension during the early Carboniferous producing normal faults, this was followed in the late Carboniferous by a period of compression which produced numerous folds and caused some oblique reactivation of earlier faults. Following the deformation,the Whin Sill was intruded (see later) and the Carboniferous was eroded to a peneplane prior to the deposition of the Permo-Trias. Sometime in the Tertiary there was renewed normal faulting producing reactivation of Carboniferous faults in E-W orientations.

The stress system that was responsible for the deformation in Northumberland was variously interpreted as E-W compression or N-S compression (Shiells 1962; Frost & Holliday 1980) and in some cases both orientations were invoked (Day 1970). Modifications to the system are suggested as strike-slip motions and a more NW-SE compression orientation was forwarded most recently (Collier 1989, see fig. 40).

It is clear that the basin as a whole must be considered if a meaningful principal stress orientation is to be invoked. The basin is quite complex due to the geometries and distribution of deformation. If any structural interpretation is to be made for the basin, then all the structures discussed and their distributions must be included.

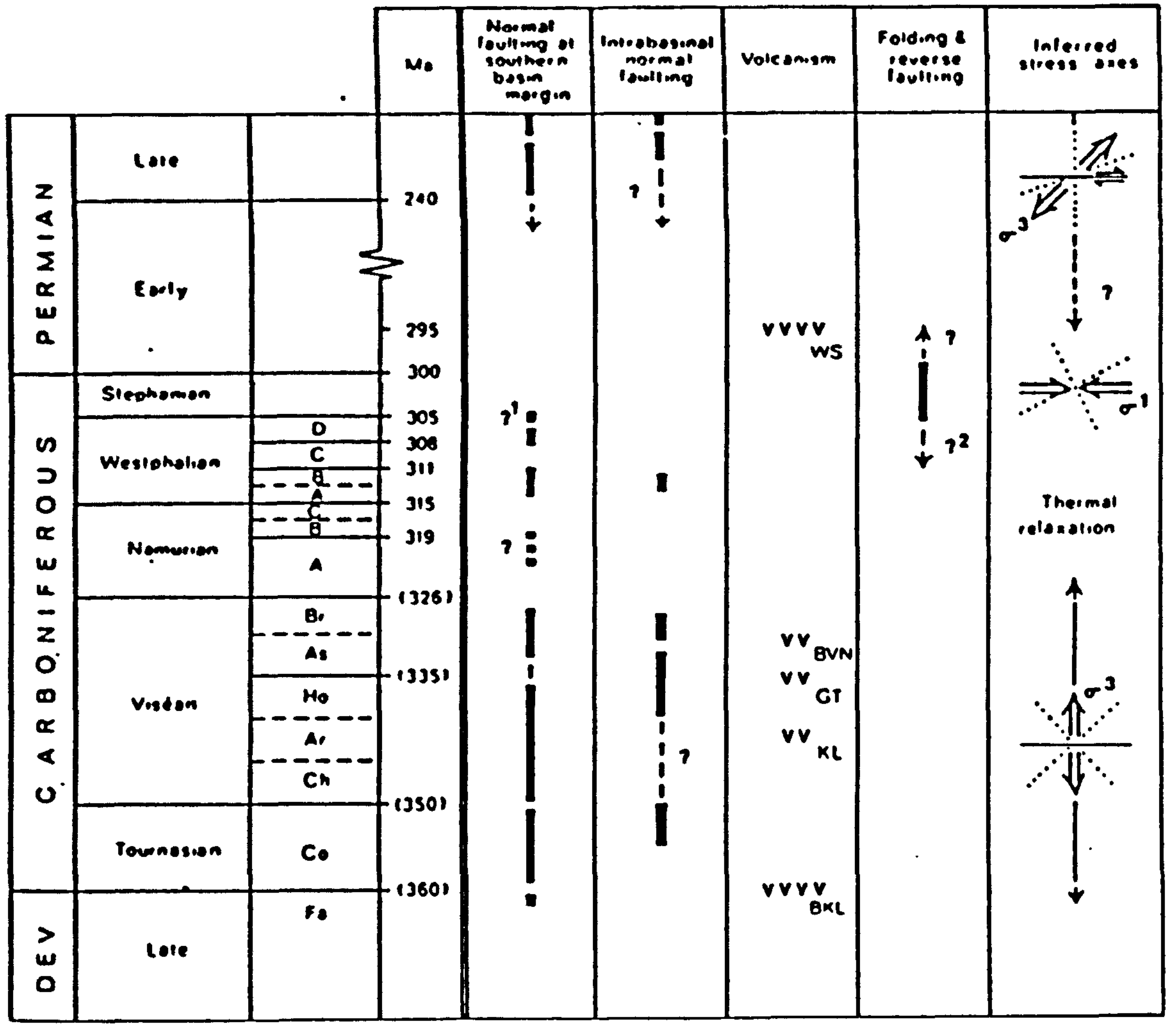


Fig.40 Summary chart of principal tectonic events in Northumberland, according to Collier (1989). Where WS= Whin suite, BVN= Border volcanic necks, GT= Glencartholm tuffs, KL=Kershope lavas, BKL= Birrenswark/Kelso lavas.

A good interpretation should be able to link all the areas in a logical manner and provide explanations for local variations. A structural interpretation should also be capable of predicting the occurrence of structures (their geometries and orientations) in parts of the basin not previously analysed.

PART 3: Post Basin Inversion History

3:3:1 Whin Sill and Whin Suite Intrusions

The Whin sill and the Whin suite comprise a series of dykes and a major sill intrusion in Northumberland and the northern Pennines (Frost & Holliday 1980). The Whin sill was first recognised as intrusive by Tate (1867). The sill crops out in arc across Northumberland and as a linear belt along the western edge of the Alston block (fig. 41). The arc of the sill runs from near Brampton and the foot-hills of Cold Fell to the Farne Islands on the north-east coast (Trotter & Hollingworth 1932; Carruthers et al 1930, 1932). It underlies an area of approx. 5000km^2 and occupies a volume of 215km^3 (Francis 1982). The sill dips south-east and thickens towards the east beneath the north sea. The sill forms an imposing crag running across Northumberland reaching thicknesses in excess of 18m.

The Whin sill outlines the Holburn anticline in NE Northumberland and cuts numerous small folds and faults both in the basin and on the Alston block (Carruthers et al 1932; Dunham 1933; Westoll et al 1955). It forms a series of rhombohedral bodies across central Northumberland, often bounded by E-W to ENE-WSW trending faults (Frost & Holliday 1980). The sill is dated at about 295my (Fitch & Miller 1967), which places it in the early Permian (Leeder & McMahon 1987 after Harland et al 1985).

The Whin sill is a fine grained to medium grained quartz dolerite. Typically its composition is;

48% plagioclase felspar

29% clinopyroxene

7% iron-titanium oxides

11% orthopyroxene, olivine pseudomorphs, amphibolite, chlorite, carbonates, sulphides and apatite.

The dolerite occasionally contains phenocrysts, up to 5% by volume of plagioclase, pyroxene or pseudomorphs after olivine. Late hydrothermal veins cut the dyke which are believed to be related to the intrusion containing quartz, calcite and pyrite (Frost & Holliday 1980). The sill is frequently amygdaloidal, containing quartz, calcite and zeolites. Wherelate hydrothermal alteration is particularly intense "white whin" occurs, a clay and carbonate rock (Frost & Holliday 1980; Francis 1982).

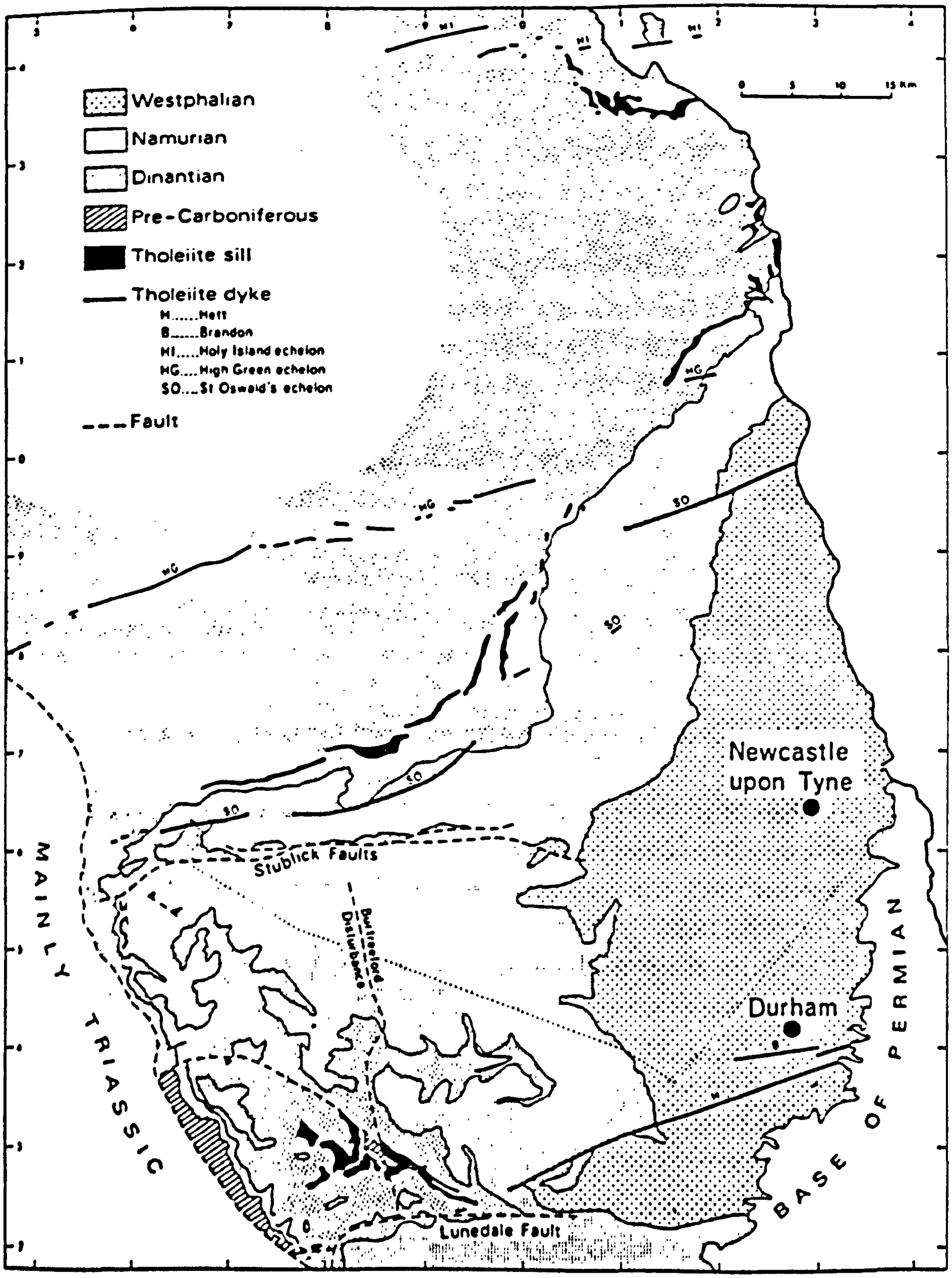


Fig. 41 Geological map of the Whin Sill and contiguous formations (after Francis 1982).

Isopact and palinspastic reconstructions of the sill indictate it was intruded as three shallow "saucers" (Francis 1982) up to 81m thick e.g. at Allenheads (Johnson et al 1980). The sill is often divided into leaves at its edges producing several minor sills and producing en-echelon overlaps (see Francis 1982 for a discussion of the intrusive mechanism).

Associated with the Whin sill are a number of ENE to NE trending dykes (Frost & Holliday 1980). The dykes are dominantly quartz dolerites and very similar in composition to the Whin sill containing; An_{75} to An_{58}, in part devitrified glass and in part a ground mass of quartz-felspar-carbonate $\pm$ olivine (replaced by talc), opaque oxides and pyroxene (augite).

The dykes include (Gunn 1932; Frost & Holliday 1980; Francis 1982);

1) St Oswalds Chapel dyke. A NE trending dyke up to 10m wide associated with a fault (Frost & Holliday 1980).

2) Erring Burn dyke. A ENE trending dyke en-echelon with 1).

3) Bavington dyke. This is up to 1m thick, en-echelon with 4).

4) Causey Park dyke. Trending ENE, is associated in the Rothbury area with a ENE fault.

5) Holy Island dyke. This is up to 12m thick and forms an en-echelon strand in NE Northumberland.

6) Lewisburn-High Green echelon. This is an ENE trending set of en-echelon dykes traceable over 80km across east Northumberland.

7) Numerous small <1m thick dykes trending E-W to ENE throughout the north and north-east of the basin.

The distribution of the dykes bears no obvious relationship to the sill, though they tend to occur outside the outcrop of the sill. The larger dykes may well have acted as feeders to the sill towards the edges of the "saucer-like" intrusion (Francis 1982). The sill transgresses horizons towards its edges so that it is generally at its highest stratigraphic level in these areas. This observation (Dunham 1933; Frost & Holliday 1980) has led to the suggestion that the sill fed by peripheral dykes accumulated in palaeo-lows under its hydrostatic head, having flowed down-hill into the low (Francis 1982).

The intrusion of the whin suite is an anomaly in the pattern of igneous activity in the northern foreland to the Variscan orogeny. It is a single burst of tholeiitic activity in an otherwise basaltic province (Francis 1979). It is of similar composition and emplacement age and style to the Midland Valley sill (Francis 1982). The Whin suite, as described was emplaced along E/W fractures and post-dates the end Carboniferous deformation in the Northumberland basin. Similar intrusions, in age and composition, can be traced over parts of the North Sea and into southern Sweden (Francis 1982). There has been considerable difficulty in relating the intrusions along ENE-E/W fractures to the preceding NE fault patterns in the basin and succeeding NW fault controls

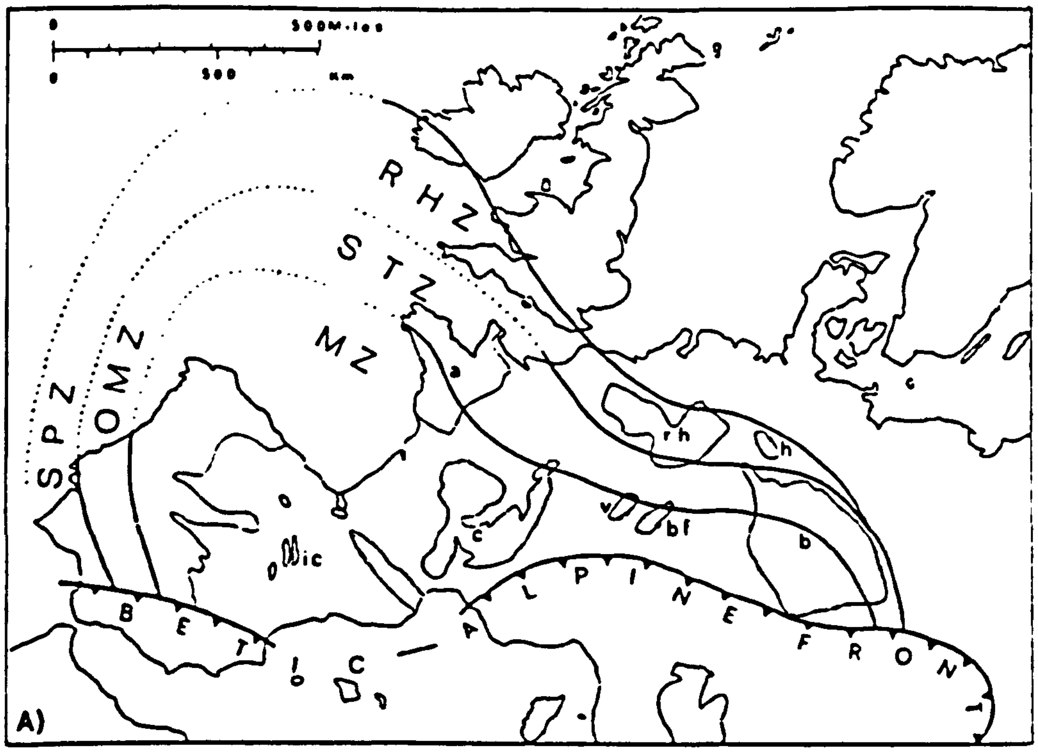
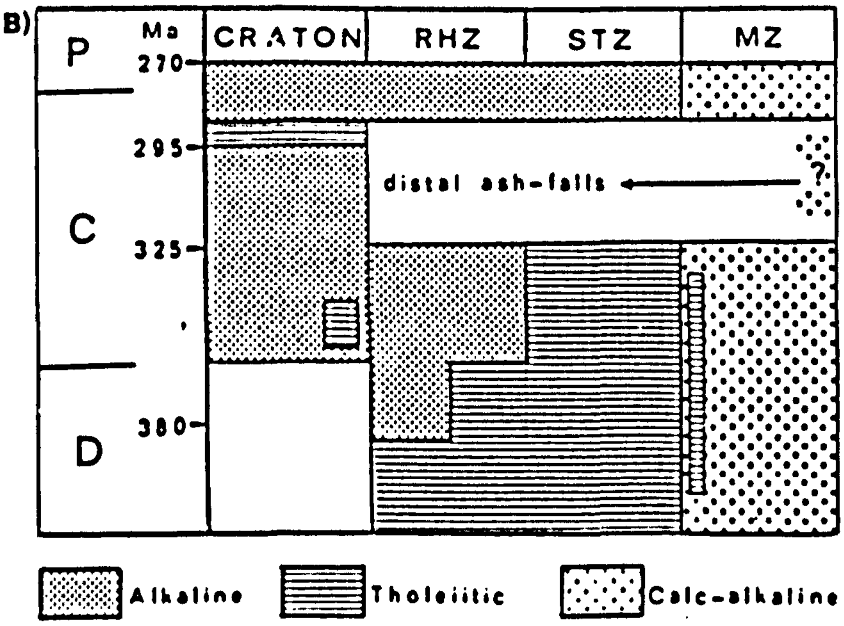


Fig. 42 a) Map of tectonic zones corresponding to tectonic belts in Hercynian Europe. RHZ, Rhenohercynian zone; STZ, Saxothuringinian zone; MZ Moldanubian zone; OMZ, Ossa Morena zone.



b) Time space distribution of magmatic types for a) where D = Devonian, C = Carboniferous, P = Permian (from Francis 1982).

(Francis op.cit.) and the suite can not be directly related to the Hercynian orogeny and plate subduction (fig. 42a & b).

The suite of intrusions is temporally related to the Asturian deformation event in the Variscan foreland and immediately follows the deformation observed in the Northumberland basin. Compositionally the suite has been tapped from melt at higher levels than previous igneous activity (Francis op.cit.). Alternatively a tholeiitic melt could be produced from the same source but it requires a greater volume of melt to be extracted and differentiated to produce such a large volume of quartz dolerite (Dave Latin pers.comm.).

The Whin suite along with post Carboniferous normal fault movements in the Northumberland basin have been interpreted as the result of renewed Permian extension (Collier 1989) but the stretching factors involved are less than those for the Carboniferous basin and could not produce melt at normal mantle temperatures let alone produce a tholeiitic melt. The problem of explaining the Whin suite remains.

The above observations and constraints have to be taken into account for any model for the tectonic evolution of the Northumberland basin. The localised occurrence of the sill and its relatives in the extreme north east of England and the Midland Valley of Scotland are surely no coincidence and there must be a geologically reasonable explanation for them occuring so soon (within 20my of the Westphalian C) after major compressive deformation (the Asturian event).

3:3:2 Tertiary dykes

The Tertiary dykes are a series of basaltic-tholeiite intrusions trending NW-SE over the Northumberland basin and cut all other structures in the basin.

They are part of a much wider dyking episode related to the Brito-Arctic (Thulean) igneous province. Tertiary dykes crop-out over Northumberland and include the Acklington, Greenhaugh, Bingfield and Nark's Burn dykes (Frost & Holliday 1980). Recent geomagnetic image processing (Lee et al 1990) has revealed other dykes of the same orientations, previously unrecognised in the field but believed to be of Tertiary age also.

The tertiary dykes are not in themselves relevant to the Carboniferous inversion of Northumberland, but faults along which they intrude can be dated relative to other basin events.

3:3:3 Pre-Permian Uplift and Erosion

After the Westphalian C and sometime prior to the Permian unconformity seen in Bewcastle and Tynemouth (Day 1970; Land 1974) the Northumberland basin

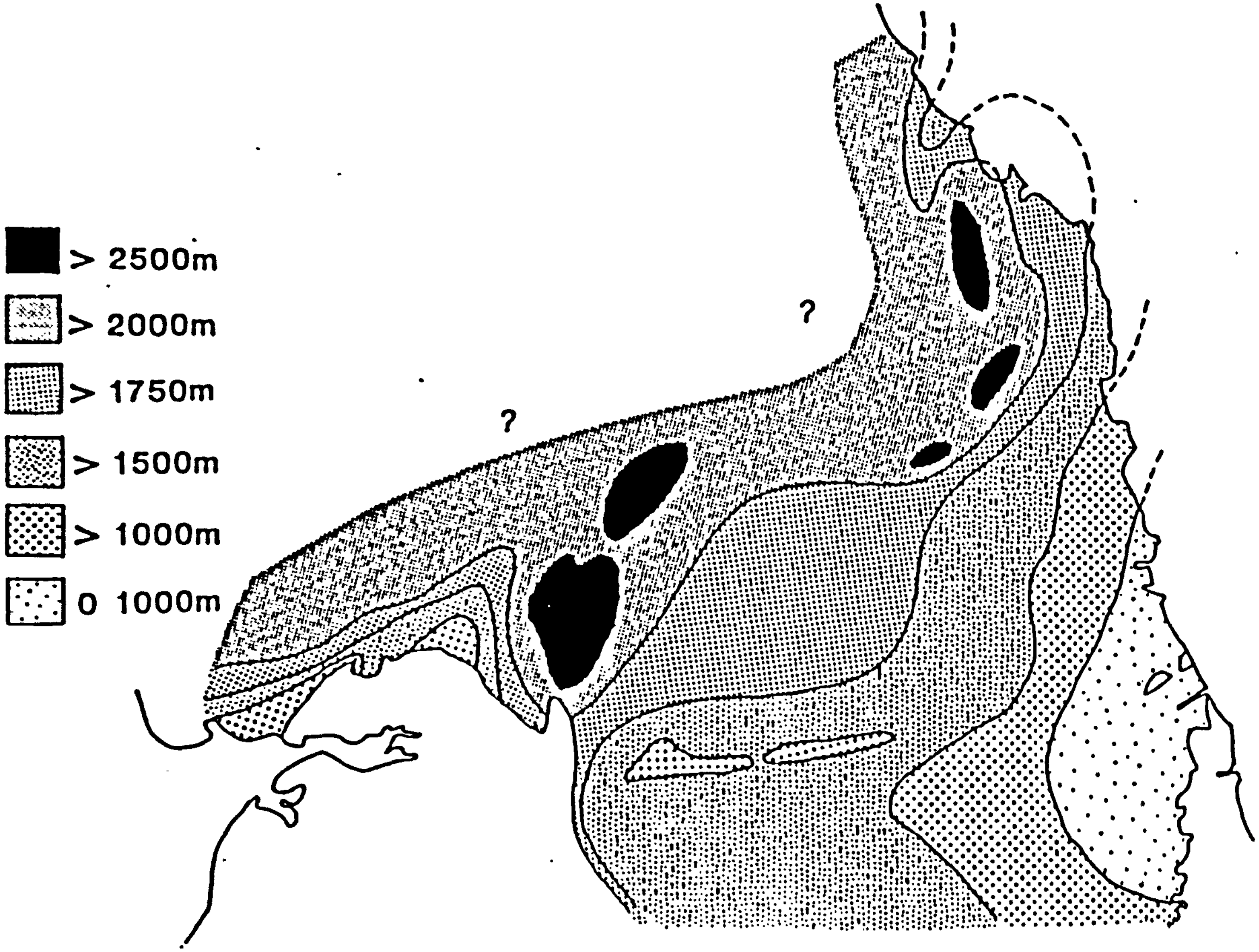


Fig. 43 Estimated uplift and pre-Permian erosion for Northumberland (derived from subcrop against position of the Permian unconformity, relative level of Whin Sill intrusion, estimates of total post Carboniferous uplift from Green 1985, and from Frazer et al 1988).

experienced widespread and variable uplift and erosion to a flat pre-Permian surface.

The uplift affecting the Carboniferous basin fill and the surrounding bocks produced an easterly tilt to the region (Trotter & Hollingworth 1932; Frost & Holliday 1980). The uplift over the basin was variable, and can be estimated based on the position of the Permian unconformity, the Position of the Whin sill and the trend of the pre-Permian surface (see fig.43). As much as 3km of Carboniferous strata is absent over the north of the basin, over the major anticlines e.g. Bewcastle, but only 300m is absent along section of the Stublick fault and 90 Fathom fault systems.

Prior to the deposition of the Permian Westphalian D or Stephanian deposits (Barren Red beds see section 3:1:2) may have also been present and subsequently eroded during late Carboniferous-early Permian uplift. These deposits may have only been local, derived from the newly developed inversion axes in the basin (Besly 1978; Collier 1989; Leeder and Hardman in press). From fig. 43 it is clear that maximum uplift was over the inversion anticlines, resulting in an overall asymmetric uplift pattern for the end Carboniferous (fig. 43 is adapted from Frazer, Nash, Steele & Ebdon 1988). The pre-Permian surface is reddened up to 150m below the unconformity (see section 3:1:2) especially in the north-west, elsewhere the average is 10m in the east. This may be related to the age of the unconformity. In the west the unconformity is Mid-Permian, whereas in the east it is lower Permian (Land 1974; Lumsden et al op. cit.). This reddened surface is a useful time horizon despite its diachronaiety. There is no reported reddening of strata across the basin so it can be concluded that minimum uplift estimates could inaccurate by a minimum of 10-150m. However even allowing for this,the uplift pattern over Northumberland is strongly asymmetric with approx. 10 times as much uplift in the north of the basin compared to the south.

3:3:4 Post Permian Uplift and Erosion

From the Permian to the present day there has been considerable uplift and erosion of northern England. This is therefore a complicatory factor in determining uplift for the Carboniferous. Green (1986) determined ages and amounts of uplift from fission track data derived from the Lake District and Cheviot granitoids. He estimated that sometime in the Tertiary as much as 2-3km of uplift occured over northern England. This pattern of uplift no doubt eroded any Permian (and younger?) rocks that covered Northumberland exposing the Carboniferous basin. The Tertiary uplift could imply an over-estimate for the uplift (end Carboniferous) over NE Northumberland and an under-estimate for the central basin were no other time horizons exist.

Chapter Four
WESTERN NORTHUMBERLAND

Part One
Seismic Coverage

4:1:0 Introduction

Seismic coverage is available for the western end of the Northumberland basin. Two lines have been generously made available for this work by Amoco Exploration Company (UK).

The data was accessed through D. Marsden and permission to reproduce it here was granted by G. Chishlom (Chief Geophysist). The lines are covered by a five year confidentiality agreement (from April 1989) and so exact location of the lines cannot be revealed. The lines are at right angles to each other, intersecting in the vicinity of the Bewcastle anticline. Line AI (see enclosures) is N/S orientated running from the Kershope anticline and fault to the southern margin of the basin. Line A2 runs E/W over the Bewcastle area towards Redesdale, along the line of the Antonstown fault (fig. 44).

The interpretations of the lines are entirely the author's own for which which she takes full responsibility!

4:1:1 Interpretation.

The lines A1 and A2 are migrated stacks and two-way time vibriosis sourced sections with normal move-out. The processing parameters are summarised in appendix II. The lines were hand picked using surface geology and have no well control. The initial interpretation,hand picked major sequence and stratigraphic boundaries which led to a full interpretation of the structure. Interpretation was aided by analogy with published BGS lines for the basin (Kimbell et al 1989) and major seismic events are summarised in diagram 45.

The interpreted lines are presented in enclosure 5 as line drawings alongside reduced photocopies of the original data, and alternative interpretations are discussed in the text.

4:1:2 Discussion

Both the seismic lines are presented in reduced form in enclosure 3. Under each line is a line drawing and interpretation, though it should be emphasised that neither interpretation should be regarded as absolute. In both cases there is considerable room for alternative interpretations but the essentials will remain the same.

Line A1 has a number of individually identified features and major stratigraphic boundaries are marked where they occur at surface. The sub-surface continuations are represented by boundaries with consistent seismic character i.e. crude seismic stratigraphic and dip consistent extrapolations of their surface intersections. The main form of the line is of a strongly asymmetric basin, with a major growth sequence against the southern margin which gradually thins north to approximately half its southern margin thickness. This is approximately from 1.5km-2km to 600m, over a distance of 15-20km. The vast majority of the section is represented by the Lower Border Group, but whilst this is the lowest unit at surface both it does not necessarily imply that all the conformable succession imaged on the line is Carboniferous.

The Kershope fault (see chapter 3 fig. 35 and summary fault map) breaks surface at X (where it has been mapped as a steep normal fault), but is largely seismically invisible . The fault can be interpreted as a low angle thrust, possibly steepening towards the surface; however reflectors are very poor in this area of the line, which may be as much a function of the complexity of structure, as of poor processing. The Goat Island thrust is marked where it cuts surface, and as structure Y. It consists of at least two low angle reverse faults, but their linkage to surface structure is uncertain. The interpreted listric form is not unreasonable here and a slight hanging-wall anticline can be made out in the otherwise poor reflectors. The deep structure at the intersection with basement is complex but it seems that a series of "horses" can be picked on the basis of the repetition and thickness variations of the strong basal reflectors in the area. The thrust appears to flatten into the basin/basement interface but the uniform acoustic signal from the basement cannot disprove that the thrust may cut into basement obliquely. Both the region around the Kershope fault and Goat Island thrust are cut by later normal faults which has "chopped" the section up making true geometries very tricky to interpret.

The southern margin of the basin is quite clear in the region of Z. This is a branch to the Stublick fault system as the line crosses the edge of the Mill Beck/Howard fault, but does not cross over into the Alston block proper. The southern margin can be interpreted as either, a) a step faulted margin, or b) a single faulted margin on the line. The fault itself isn't imaged but its position can be determined from interference from the fault plane itself and the discontinuation of strong reflectors in the hanging-wall sequence. The basement -block interface is not strong here and the suggestion is a sloping block margin in the extreme west of the basin, cut by stepwise normal faults. A single reverse fault is interpreted in the hanging-wall to the Stublick system. This is a steep structure antithetic to the main margin faults, however it is not clear from this line whether the reverse fault can be interpreted as breaching the margin faults or not. Either way the implication is that the basin has suffered some shortening some time after the oldest sediments present (LLG/MLG) causing reverse motion along the fault described. The offset is less than 100m and represents practically the only sign of shortening in the immediate margin area.

'A' represents faint discontinuous picks truncated against the strong basal reflectors. Their age is uncertain, but they may represent pre-rift Carboniferous or Devonian sediments. 'B' is the strong basal reflectors.

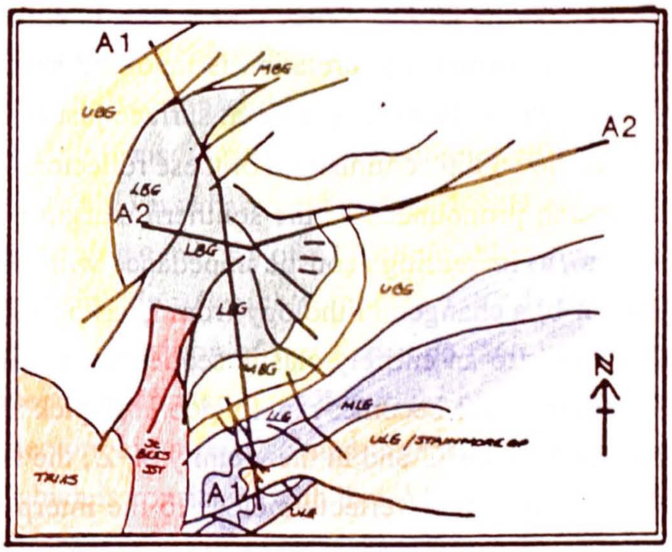


Fig. 44 Sketch map to show approximate locations of Seimsic Reflection lines A1 andA2.

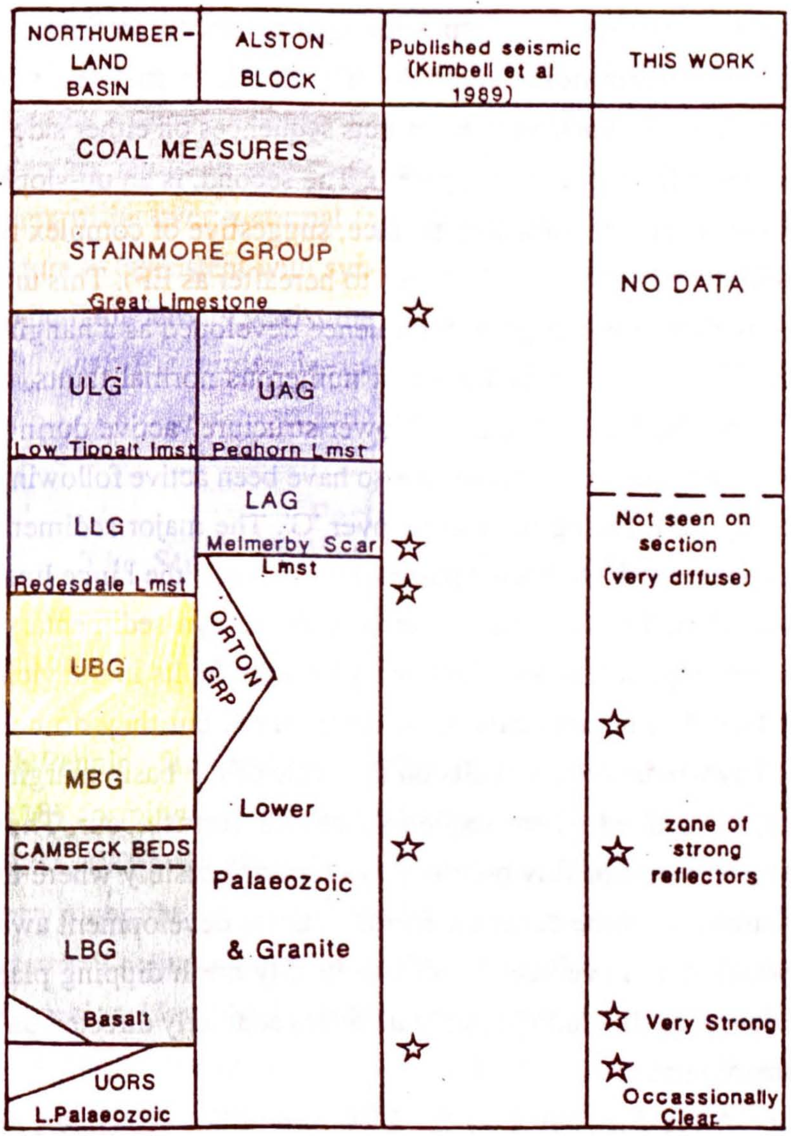


Fig. 45 Table to summarise main seismic events in the Northumberland basin, based on lines A1 and A2 compared to published data.

These are indicative of high energy returns over two-thirds of the section at the base of the "Lower Border Group". They may be due to either a) plateau basaltic lavas, or b) evaporites. The former interpretation is favoured here as there are indeed basal Carboniferous lavas in the Bewcastle area, at surface just off the section line. However 'C' representing the down dip continuation of these reflectors, tends to die out, becoming much less strong and pronounced as the southern margin of the basin is approached. This may be due to, a) increasing acoustic impedance with depth tending to weaken the returning signal, or b) a change in lithology from lavas perhaps into lavas interdigitated with tuffs and clastics to an entirely clastic sequence. It is interesting to note that the sediment/basement interface becomes rapidly poorer to pick after 1.8 secs (TWTT = two way travel time) both along 'C' and in the vicinity of 'Z', the basin margin.

'D' are areas of diffuse reflectors close to the interpreted basin margin, which may be interpreted as regions of fault interference or lithology change linked to buried alluvial systems, which presumably fed off the emerging fault foot-wall, and may explain the inclined reflectors in this region. D" are areas of oblique low angle cross-cutting, rather diffuse reflectors which may be due to fundamental facies changes or to low angle out-of-section faults.

Although there are no basin wide regional unconformities in the line A1, there are two local unconformities marked by 'E'. One is associated with a near horizontal structure similar to a horst as it down-cuts sequences on either side of a central area over which the unconformity is not apparent. The second, is an up-slope onlapping sequence developed over the unconformity surface, suggestive of complex rotation about a hinge zone to achieve this geometry (referred to hereafter as EF). This unconformity is closely associated with 'F' a minor growth sequence developed as a hanging-wall to 'G' a major hinge line. The hinge line is a zone of numerous normal faults, but limited basement offset. This can be interpreted as a "flower structure" active during the formation of EF and the growth sequence F, but must also have been active following these as the basin is dominated by a SE facing monocline over 'G'. The major sedimentary accumulation in the basin appears to have been a palaeo-low between the hinge line 'G' and the southern margin with 'Z' active as a pene-contemporaneous syn-sedimentary fault. Unfortunately reflectors are so poor that any thickening into the faults in the vicinity of the Kershope and Goat Island structures cannot be determined, but they do not appear to be major reactivated syn-sedimentary faults on the scale of the basin margin 'Z' or the hinge line 'G'. Lastly, 'H' is sited where sequences of clinoforms occur. These are interpreted as pro-grading fore-sets of fluvio-deltaic systems or possibly where the forms are isolated as large slumps. In some cases the forms indicate development away from the southern margin, which may have been be due to locally north dipping plaeoslope and in other cases the down dip direction possibly indicates southerly directed palaeocurrents (relative to the plane of section).

Line A2 is dominated by the LBG and unlike A1 shows no major asymmetry, with comparable thickness of sediment across the entire section. A' and A represent where the Antonstown fault cuts the seismic section. This near parallelism has caused oblique interference of the section and rather odd fault trace geometries. 'B' is the position of the Goat Island thrust at surface and rather more clearly than in A1 can be linked via a listric form to a reverse basement offset. The offset is quite minor compared with the interpreted shortening geometry of A1, presumably a function of the section line relative to maximum shortening (which is unclear). 'C' is the uninterpreted region between 'B' and the surface position of the Kershope fault in the extreme west of the line. This region has been left uninterpreted due to the poor processing in the area. 'D' is an area of diffuse reflectors but a few isolated high dipping reflectors pick out a faint antiformal structure, which is consistent with line A1 and a hanging-wall anticline. 'F is a region of increased dips into a basal shallow antiform, This is directly below a minor sedimentary growth sequence linked to 'G", a low angle (seemingly listric) normal fault. G" is a series of low angle interference signals in the basal sequence, possibly caused by faulting. The basal sequence is very similar to that of line A1 showing strong high amplitude reflectors. These are again taken to be basal lavas and these do not appear to greatly change character eastwards over the basin. E denotes regions of dipping clinoforms possibly indicating pro-delta sequences, and E* is a sequence of dipping reflectors truncated by a minor unconformity. The unconformity is on the opposite side of the syn-sedimentary fault and growth sequence 'G', and may represent simultaneous erosion during deposition over a normal fault bounded rotated block. The presence of this type of structure is consistent with syn-rift sedimentation and fault activity but like A1 hints at episodic fault activity whilst the major basin margin controls subsidence and sedimentation.

Part Two
The Stublick and North Pennine faults.

4:2:0 Introduction

The North Pennine fault and the Stublick fault intersect in the Brampton district (Sheet memoir 18) forming the north-west corner of the Alston block (Trotter & Hollingworth 1928a, 1928b; Dunham 1933). The area is moderately to poorly exposed, in high fell country along the east side of the Vale of Eden. It was selected for study, for the following reasons: The junction of two such major fault systems at right angles offers good control on a regional late Carboniferous event since the different fault systems can be expected to respond in unique ways to deformation processes and hence a regional stress regime for any observed events could be determined.

Previous work in the area had mentioned folding of late Carboniferous age along the western margin of the Alston block (Totter et al op. cit; Dunham op. cit.). The Carboniferous forms the foot-wall to a large normal fault bringing the Permian down to the west against the Eden escarpment. This fault is the Pennine fault and includes a region around the Cross Fell inlier (Burgess & Wadge 1967). The Eden escarpment is close to the fault escarpment, and in the Cross Fell region cuts over Lower Palaeozoic structures. Burgess and Wadge interpreted the Pennine fault as a post-Permian normal fault that cuts over folded and reverse faulted Carboniferous strata.

The North Pennine fault is that part of the Pennine fault that extends north of Cross Fell to its junction with the Stublick fault system of the Northumberland basin. The region selected is illustrated in Fig. 46 showing the locations of the main enclosures and A3 pull-out maps referred to in the text.

No published large scale mapping had been conducted in the area for over 50 years prior to this study and so areas were selected for study from existing 1:50 000 solid geology and drift maps, with specific sights chosen from original hand-coloured Geological Survey maps (courtesy of BGS Newcastle).

The area has been divided into two sections for the purposes of this chapter (fig. 46). The first is the region along the North Pennine fault (NPF) from Haresceugh 5km north of Melmerby, to Castle Carrock where the NPF intersects with the Stublick fault system. The second is the region around the Stublick fault in the Brampton district from Castle Carrock to the Westphalian outlier at Midgeholme. The Stublick fault divides in the region mapped into two branches; the northerly of which is made up by the westerly Mill Beck fault and the easterly Howard fault; and the southerly branch, which will be referred to as the Southern Stublick fault (SSF). Each of the sections sequentially describes localities. Where required specific localities are identified by number (marked on the maps) and an eight figure grid reference.

4:2:1 Structural summary

In analysing the North Pennine fault and Stublick fault area, a number of general observations become apparent:

1) The NPF is a normal fault down-throwing the Permian St. Bees Sandstone against the Lower Carboniferous. The throw is generally within the Alston group but faulting sub-parallel to and at high angles to the NPF has brought Basement Beds and the Namurian into contact with the Permian.

2) Folding along the North Pennine fault (NPF) is exclusively concentrated in the Carboniferous, from the lowest stratigraphic levels in the Basement Beds to the Middle limestone group.

3) The folds occur in a narrow zone immediately east of the NPF up to 2km wide.

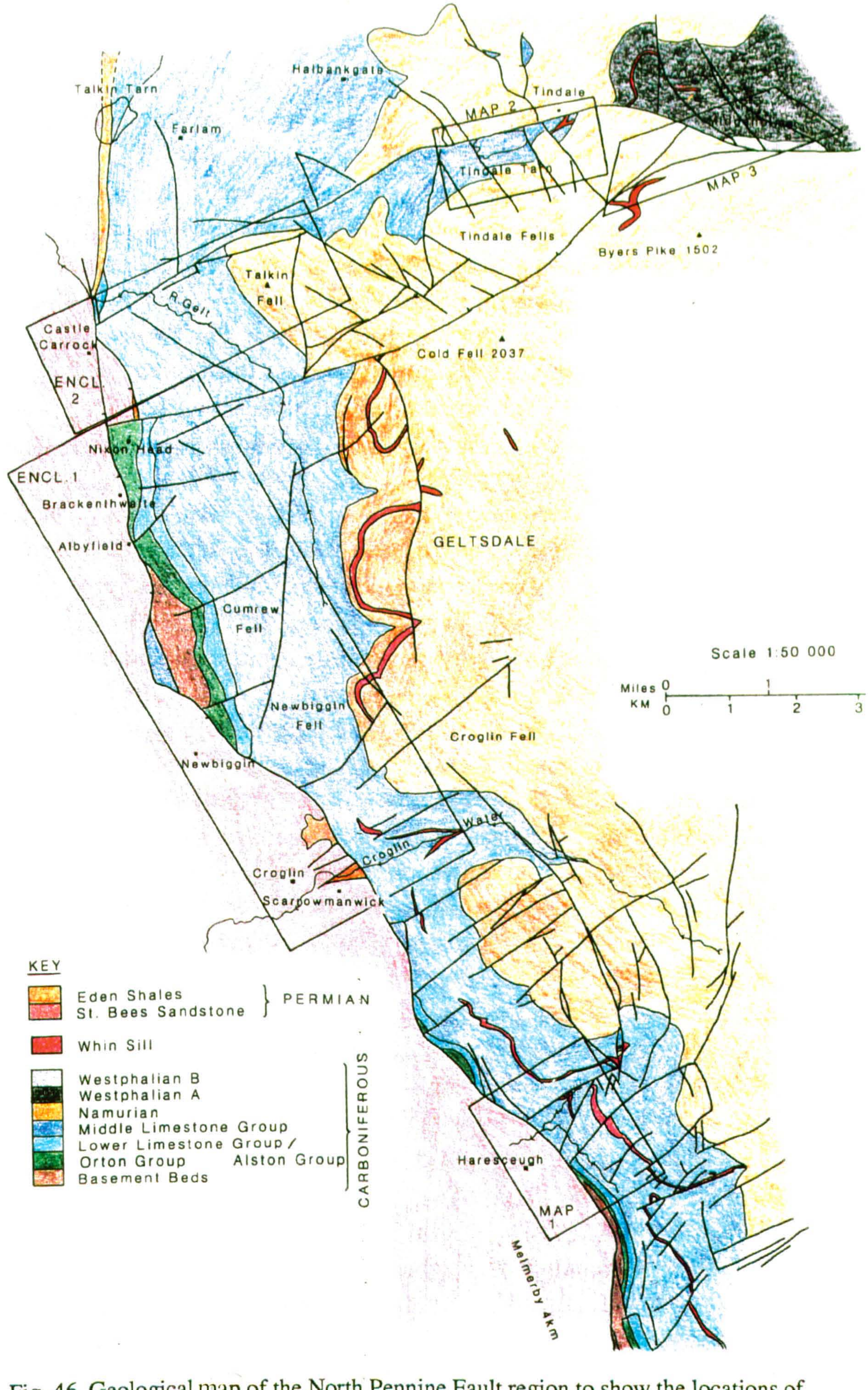


Fig. 46 Geological map of the North Pennine Fault region to show the locations of enclosures and maps for NPF and Stublick fault region.

4) Folding adjacent to the NPF has locally overturned strata, and only where folding is very intense.

5) Fold intensity, distribution, wavelength and amplitude gradually die out away from the NPF.

6) Folding is typically upright, asymmetric facing E and W, type 1B to rare 1C types and uniformly orientated NE/SW to NNE/SSW.

7) The lowest and widest zone of folding occurs in the south of the area (Raven Beck and Loo Gill) where folds are persistent along strike and plunge north up to 10-15°.

8) Folding is associated with high angle rotated features including early easterly or westerly directed thrusts with displacements < 5m.

9) Folding is cut by low angle strike-slip faults orientated NW/SE and N/S and very rarely by high angle reverse faults trending in a similar orientation and associated with syn-folding accommodation minor thrusting.

10) Normal faults trending NE/SW cut the folding and at least some of the previous strike-slip faults. The normal faults also displace the Whin Sill.

11) The Sill intrudes the MLG from the level of the Scar limestone to the Great limestone, rising generally from the south of the area to the north around Stublick reaching its highest level above the Lower Little Limestone coal south of Midgeholme.

12) The Sill changes horizon in places e.g. between Croglin and Raven Beck it "jumps" horizon over an area where it appears as a series of apparently discontinuous outcrops.

13) Apophyses of the Sill cut folding and thrusting.

14) The NPF is dextrally offset by the Stublick South fault by 350-500m (horizontally).

15) The NPF at High Gelt Bridge is a complex zone of N/S normal faults and strike-slip faults that cut folding in the Carboniferous. The NPF down-throws stained Carboniferous against unstained Carboniferous indicating it is post Permian.

16) The Carboniferous forms an angular unconformity with the Permian at High Gelt Bridge, implying the folding to be Pre-early Permian.

17) Folding orientation swings through 90° over the Stublick fault. Only at high Gelt Bridge are N/S folds recorded, though these give way over 500m to NW/SE folds.

18) Thrusting is commonly associated with folds in the Stublick area. Some of which can be proved to be pre-folding and most is consistent with syn-folding formation.

19) Thrusting transports NW/SE and where it is unassociated with folding displacements exceed 2m and transport uniformly towards the basin.

20) Folding is confined to the basin margin and commonly associated with limestone containing sequences. The highest level for which folding is recorded in the Stublick area is the Lowermost Namurian around the Great Limestone.

21) Strike-slip faults occur in the Stublick area with up to 50m displacements, orientated NW/SE. Both sinistral and dextral motions were recorded, but the dextral set is dominant.

22) The Stublick fault has a normal displacement of 350m and nowhere in the area are

reverse geometries observed.

23) There is 210m of Westphalian preserved in the Midgeholme area, implying the throw of the fault must vary considerably along its length.

24) Extrapolation to adjacent areas (Sheets 18,19 & 20) indicatesthat the Stublick fault is a series of overlapping strands. In the Plenmellar district near Hexham, the fault is two main dextrally overlapping (en èchelon) faults.

In discussion with the British Coal Open Cast Executive (Mansfield) it was confirmed that many of the NW/SE faults were of limited extent but reaching high throws over a short distance. Some of the larger NW/SE breach the Stublick e.g in the Plenmellar district (east of Midgeholme). Cross sections over the Plenmellar district derived from shallow bore holes (British Coal) are similar to sections over the Midgeholme area, where no significant deformation of the area is recorded beyond much normal faulting, however a gentle NE/SW syncline was interpreted in the immediate hanging-wall of the fault where the fault trends more ENE to NE (Les Knight BC pers. comm). British Coal bored the Plenmellar area on a 30m scale but if folding was present it is likely that it would have missed by the bore holes in any case. No reverse displacement faulting was int ·preted by the BGS for the Stublick area.

4:2:2 The North Pennine Fault

a) Raven Beck and Loo Gill.

Raven Beck and Loo Gill are streams dissecting the Pennine escarpment near Haresceugh village (map 1). Despite relatively good exposure the NPF is nowhere exposed. Its trace was mapped by features and distribution of red soils derive from the Triassic and Permian. West of the trace of the NPF, Triassic St. Bees Sandstone crop out, dipping gently SW (localities 118, 6112 4348). Folding dies out rapidly over this section from the vicinity of the NPF where folds are 5-10m apart with amplitudes of > 4m, to gentle open folds >50m apart with reduced 2m wavelengths.

Immediately after the line of the fault is crossed,two near vertical beds of the Smiddy limestone occur in the stream bed. The latter is easily accessible from the river bank and has a steep 80° NE dip in the eastern limb of a tight anticline with a locally overturned westerly limb. The fold (loc.. 6110 4341) is cut axially by a sub-parallel vertical NW/SE fault plane, marked by horizontal slickensides indicating strike-slip motion. Upstream high dips persist(up to 80°)until the confluence of Scales Cleugh and Raven Beck. Here approximately 10m above the Smiddy limestone interbedded fine sandstones and black shales of the Alston group occur. Small scale reverse faultsdipping 40° were observed in the shales, with up to 10cm displacements. Slickensides on their surfaces indicated transport in a SW direction.

Upstream from the confluence, markedly gentler dips occur (15°-20°) in a >2m thick sandstone interbedded with fine sandstones and dark shales. These units are separated from the previous locality by a NW/SE fault(inferred dip 60° NE). 40m upstream above poorly exposed shales, sandstones and a thick limestone (identified as the Lower Little limestone), a thick >2m highly fossiliferous 58°W limestone occurs at a waterfall (6130 4355). This unit was identified by the BGS as the Jew limestone. However the opposing dips of the named limestones implies a tight synform between them. This geometry is not consistent with the stratigraphy, as the Jew limestone ought to occur dipping east below the waterfall also. This inconsistently implies that;

1) either the Lower Little limestone has been incorrectly identified and is in fact the Jew, or

2) there is a steep reverse or strike-slip fault between the two limestones dipping west in an "out-of-syncline" position.

The former interpretation is favoured here since the two limestones are quite dissimilar in appearance and thickness. The latter interpretation would have important consequences for the structural history of this area, whereby folding shortening develops thrusting or oblique wrenching.

The Jew limestone forms a broad asymmetric antiformal anticline over the waterfall, cored by second anticline axis in the Lower Little limestone (see map 1). The fold is upright with no plunge detectable over the width of the stream. 25m of interbedded shales and buff-coloured sandstones occur dipping gently eastwards above the Jew limestone. Two fold axes were picked in this sequence, 50-100m apart (approximately 0.5km from the NPF) with a persistent SW facing asymmetry. No further evidence of folding was encountered beyond 1km east of the NPF in a succession including the Tynebottom and Single Post limestones.

Over 0.5km upstream of the waterfall the Whin Sill crosses the stream as a gently dipping (10° E) concordant unit, 2.5m thick. The intrusion is a fine grained basic-intermediate quartz dolerite. It contains 0.5cm felspar phenocrysts, quartz (or zeolite) filled vesicles up to 0.5cm, 2mm glomerocrysts of mafic minerals with ferrugenous weathering.

The north side of the Raven Beck valley is marked by features corresponding to the units mapped in the stream bed, however folding is not discernible on a <10-20m wavelength scale. A fault is interpreted as running NE/SW along the valley side where dips become 5° E (see map fig. 49). This fault cuts the Whin Sill, making it the youngest structure observed in this section.

Loo Gill runs approximately at right angles to Raven Beck meeting at a confluence below the Waterfall (loc. 120). The Lower Little limestone (LLi.Lmst) is easily picked out in Loo Gill where it contains large crinoids and is dolomitic in character. It is succeeded by 10m of shales and a 1m thick massive sandstone not seen in Raven beck at the same level. Another 1m or so of shales occurs before a 8.5m thick westerly dipping limestone occurs.

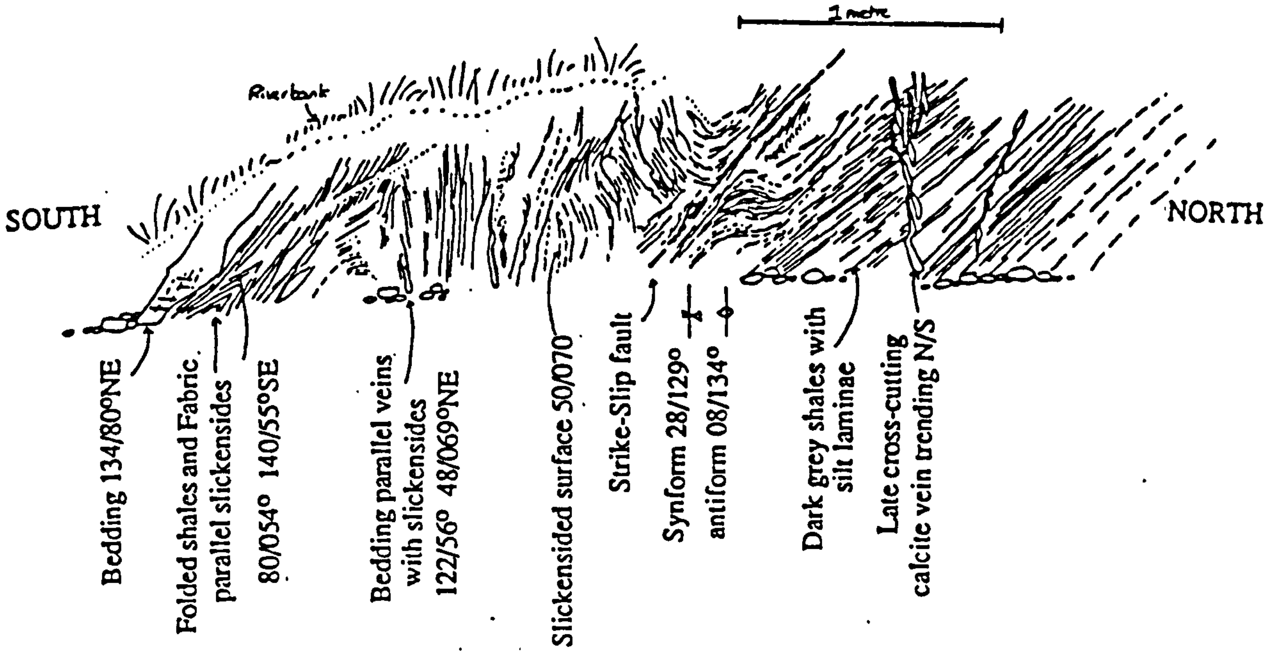


Fig. 47 Field sketch of strike-slip zone around locality 121a in Loo Gill.

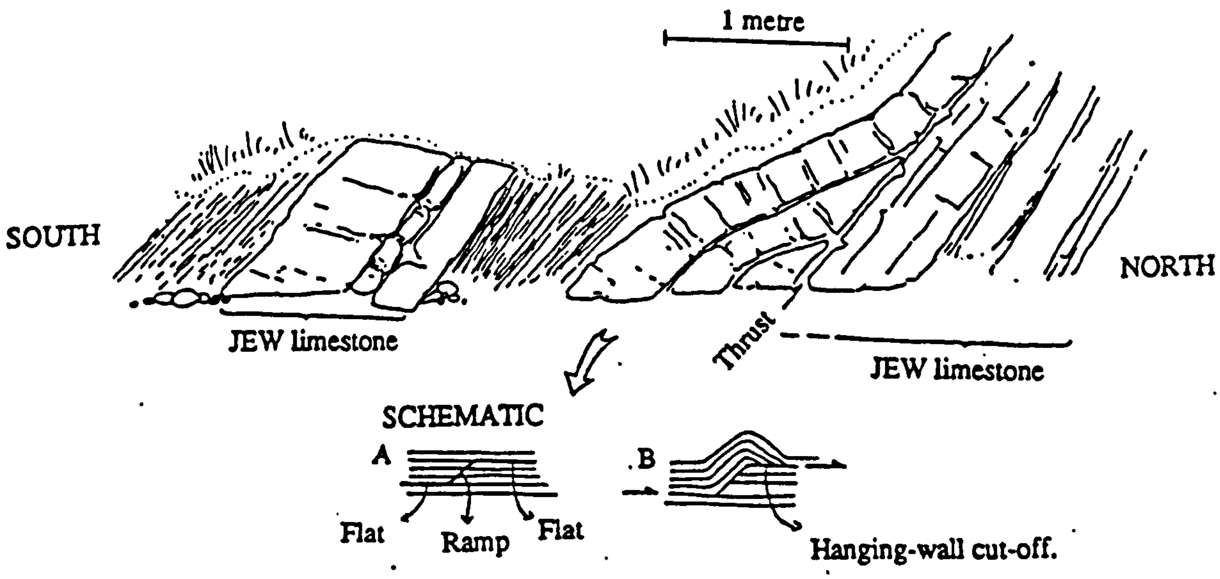


Fig. 48 Field sketch of locality 121b), Loo Gill showing early thrust related structure and schematic cartoon to show development of hanging-wall cut-off.

This is the full thickness of the Jew limestone, and is identified by the large abundant oysters and productids in its upper surface.

The shales below the Jew limestone contain a narrow zone of small scale folds (< 50cm wavelength). The fold axes plunge 10-20° NW trending 130° (see fig.47). Calcite veining parallel to the shale laminae (135/52°W) is frequently slickensided (50/070° NE) indicating oblique dip-slip motion. The folding and bedding parallel slip is consistent with an oblique-slip cutting regional dip (and therefore post-folding).

The Jew limestone (see fig. 48) above the shales is divided into two units, divided by a 1m shale horizon. The upper unit (dipping west) is thickened by a partially exposed thrust structure. This feature (locality 121). is interpreted as a hanging-wall anticline. Caused by the easterly transport of limestone beds over a flat-ramp-flat geometry. The thrust is at a steep angle trending 135°SW and although it is consistent with formation during folding, i.e. transports up structure, it was probably formed in near horizontal strata and may be an example of pre-folding shortening.

The Tyne Bottom limestone is seen above the stream in an NNE/SSW asymmetric synform with a steeper NE limb. This outcrop confirms the presence of an oblique fault between the Tyne Bottom and Jew limestones, but itself is cut out against a younger NE/SW fault (see map 1, fig. 49). The trace of the anticline in the Jew limestone can be traced southwards to locality 120 where silts and shales below it are tightly folded into a double antiform axis. This structure is cut by a low angle fault associated with drag fold structures. These are illustrated in fig.50 and are the result of oblique motion on the fault but the lack of slickensided surfaces and the general disaggregated nature of the minor folds indicates early deformation, affecting only semi-lithified sediments.

A series of tight parallel folds can be traced along the entire length of Loo Gill. Folding is slightly asymmetric facing west, and affecting all lithologies. Westerly limbs are 60°-80° whereas the easterly fold limbs are 15°-40°. The folds are 5-10m apart with amplitudes of at least 4m and periodically cut by NE/SW trending normal faults. The latest structure in the area is a 1.3m wide vertical dyke identified as a member of the Cleveland Armathwaite dyke. The dyke is a very fined grained basic body containing occasional < 3mm white felspar phenocrysts. The dyke cuts folding and the NE/SW faults.

Fault data plotted on stereonets (fig. 51) for Loo Gill show two groups of NW/SE and N/S strike-slip faults, and a single set of NE/SW normal faults. The intersection of the strike-slip fault sets indicate the approximate position of the principal stress axes, assuming the strike-slip sets are conjugate and contemporaneous. The direction σ_2 is near vertical with σ_1 in a NNW/SSE direction. The normal faults are later than the folding and at least some of the strike-slip faults. The normal faults also cut the Whin Sill displacing it vertically by up to 50m.

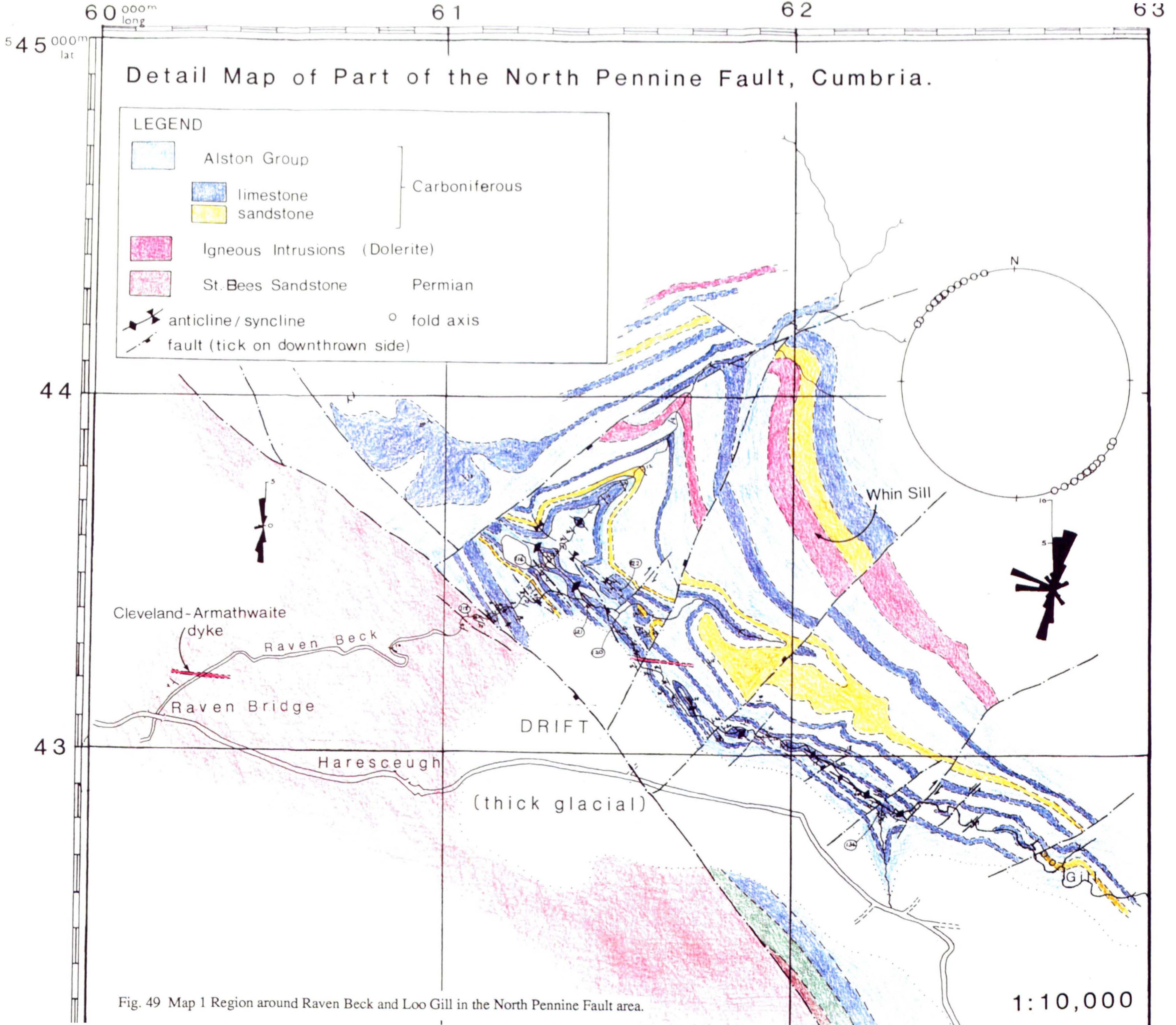


Fig. 49 Map 1 Region around Raven Beck and Loo Gill in the North Pennine Fault area.

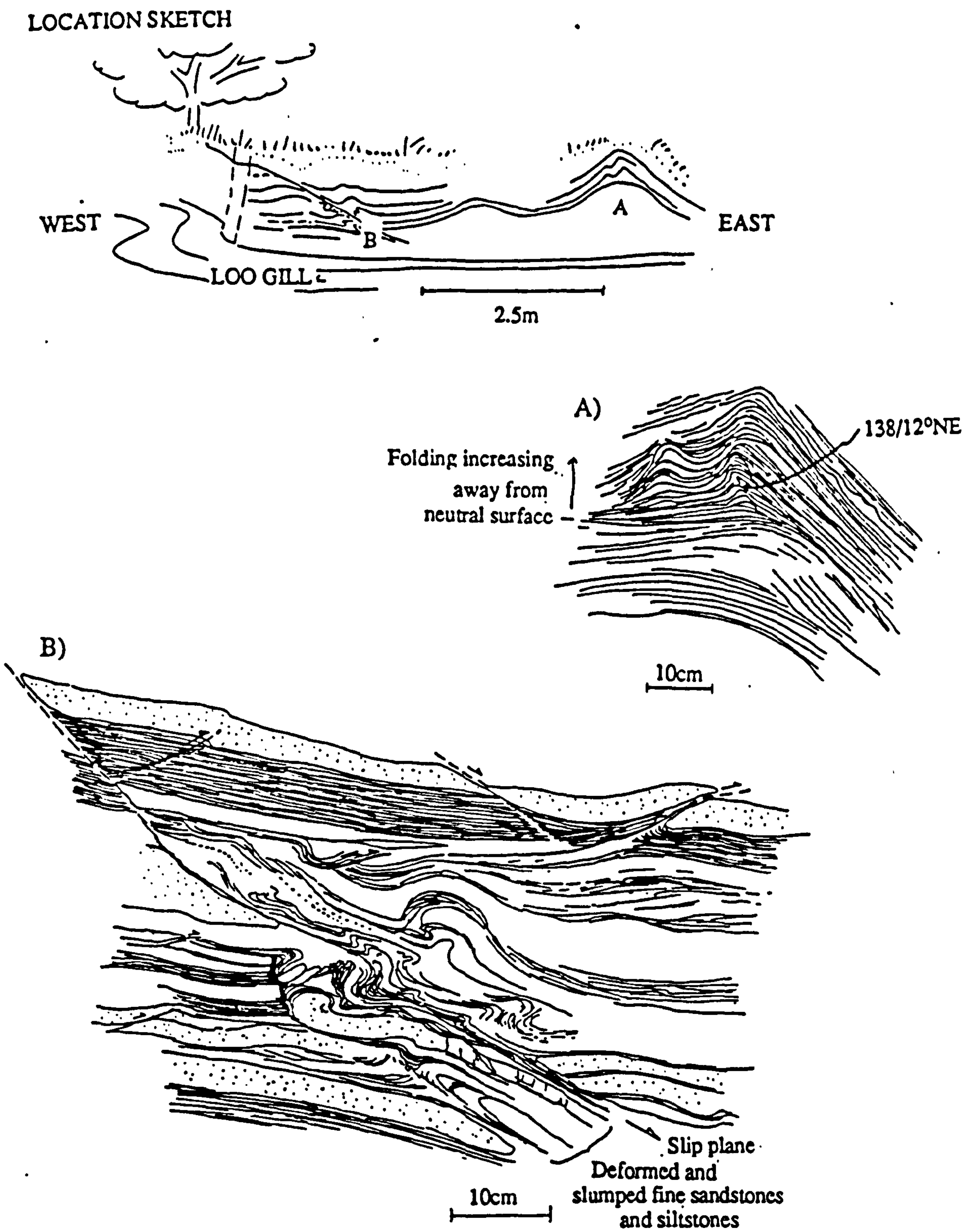


Fig. 50 Diagram of locality 120, with detailed field sketches of a) and b). Showing early faulting in semi-lithified sediments.

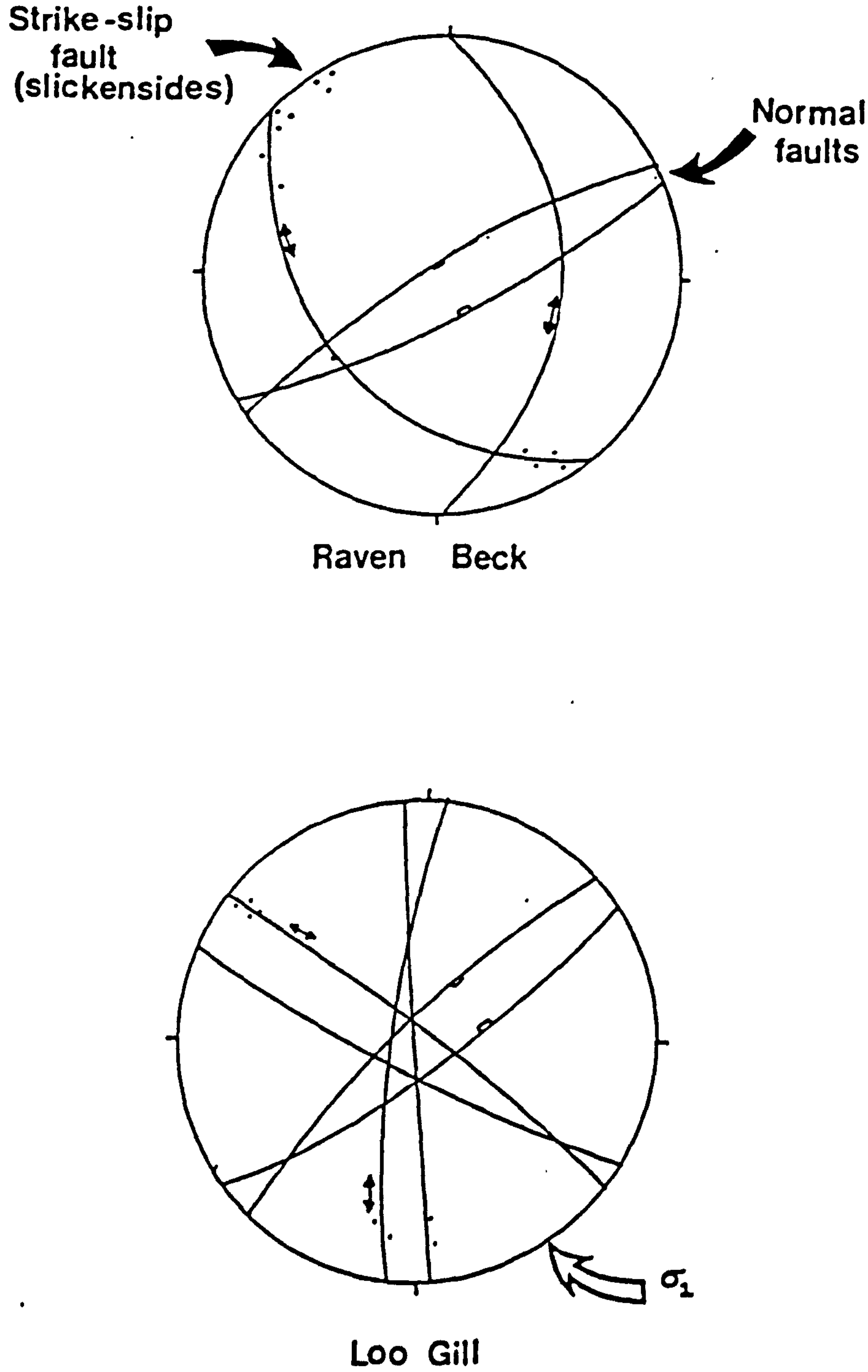


Fig. 51 Stereonet data for Loo Gill and Raven Beck.

A similar pattern of structures is seen in plotted data from Raven Beck. The same NE/SW set of normal faults occurs and the N/S trending set of strike-slip faults. The NW/SE strike-slip set is less obvious and occasional normal faults occur in this direction.

b) <u>Croglin Water</u>

In Croglin Water and Croglin Beck, exposures of St. Bees Sandstone occur adjacent to the trace of the NPF. East of the fault the Alston Group is exposed along the Pennine escarpment. Both Croglin Water and Croglin Beck have relatively good exposure, though Croglin Water is better but requires wading to access outcrop.

Folding deformation in the Carboniferous is most intense adjacent to the NPF. Fold style is slightly asymmetric tight upright 1B types, between 5m and 10m apart. Folds here are of large amplitudes up to 5m and occasionally associated with reverse faults of minor displacements (<1m) and small scale minor folds (15cm). Over a kilometre east of the NPF the folding has dissipated to open upright structures, broadly symmetric and of low amplitudes (<2m) and long wavelengths (>50m). A section line drawn along line A/B is presented in fig. 60.

Approximately 0.5km east of Croglin village in Croglin Water, massive lensoid red sandstones of the St. Bees Sandstone group occur dipping gently NW or SE up to 18°. These are down faulted against yellow sandstones interpreted as Millstone Grit (survey NY 54 NE Hollingworth 1927 and Arthurton 1968). The sandstones are fine grained well sorted and are overlain by purple shales and thin reddened sands. This suggests that they were faulted to their present position prior to the deposition of the Permian, hence the reddening of the exposure.

The outlier of Millstone Grit series is downfaulted against the NPF in Groglin Water immediately south of Fieldhead and NE of Scarrowmanwick (see enclosure 1). Immediately east of the NPF trending NNW/SSE, red fine grained sandstones and shales are found in the river bed. Bedding is varies in dip from 70° SW adjacent to NPF to 49° SE 150m from the fault. The age of the these beds is uncertain. Subparallel to the NPF a second N/S fault occurs bringing fine-grained micaeous sandstones and shales to river level. These are interbedded with 60°SW dipping. The succession east of the fault trace is the Alston Group and shows no reddening. The interfaulting of reddened and less reddened beds suggests that the NPF divides into at least two major strands in this area. The more easterly strand is a pre-Permian structure whereas the N/S easterly fault appears to be be post Permian (i.e. displaces reddened units).

Within 200m of the Fieldhead fault (see map), the N/S fault described above, folding is encountered for the first time. Anticlines and synclines in sandy shales occur trending NW/SE with no discernible plunge. Within the shales at loc. 15 a number of small scale flexures occur in the axial region of a gentle parallel fold. These small scale recumbant folds are 20cm in amplitude, trending 130°-160° with horizontal axes (see fig. 52).

Folding in the river section is generally symmetrical, 10-30m apart with occasional gentle 10° N plunges. A number of minor normal (<2m) faults disturb the section up to the first limestone at loc. 19 (see enclosure 1) trending sub-parallel to the Fieldhead fault. In one case (loc. 17) beds swing into parallelism with an unexposed N/S fault. This suggests an earlier structure is cut by the later fault and may represent a rotated thrust feature (similar to the hanging wall anticline at locality 121 in Loo Gill).

A low reverse angle fault with a 5cm gouge of sheared rock (170/32°NE), causes thickening of shales in the limb of an anticline at loc. 18. The shear directions in the fault indicate a SW transport direction.

The Lower Little limestone (L.Li. Lmst) encountered at loc. 19 is 1m thick and overlain by grey shales and mudstones, above which the Jew limestone (3-4m) occurs in a series of open anticlines and synclines over a distance of 250m. These NW/SE symmetrical are upright with 2-3m amplitudes. Above the Jew limestone gentle dips persist in laminated shales and silts of the Alston group until a thin limestone (20cm) occurs above a seatearth (12cm) and coal (4cm) at locality 29 (5923 4781). The coal was identified as the Tyne Bottom limestone coal. The limestone is gently folded into an open asymmetric NE facing NNW/SSE anticline. Above the limestone a local landslip has produced unusual dips in a sandstone, obscured by river terrace deposits (loc. 28 5935 4789).

Very open folding >50m apart occurs upstream of the Tyne Bottom limestone, gradually dying out altogether by the Scar limestone, although a fold was recorded by the Survey (BGS) immediately below the Whin Sill at locality 26 (5990 4802). The Whin Sill dips 15°-20° NE immediately below the Scar limestone. The succession below the sill includes the Single Post limestone and a series of well bedded cross stratified sandstones.

The Scar limestone can be traced from the Croglin Water valley to disused quarries 0.5km NE of Fieldhead (5830 4810). Here the limestone is approximately 10m thick forming a series of dark grey beds up to 1m thick interbedded with shale partings up to 5cm thick. The top of the Scar limestone occurs in the upper quarry under the Whin Sill, implying the sill has changed its intrusion horizon relative the limestone from its outcrop in Croglin Water.

In the upper quarry a series of open upright 1B folds are visible. These trend 150°-130° between 5 and 10m apart. At locality 7 (5838 4811) a small thrust repeats the top two beds of the limestone by 25cm. The thrust strikes 160° dipping west by 23° and slickensides on its surface indicate NE transport (approximately at right angles to the thrust strike). The thrust tips out into a series of calcite vein splays showing distributed displacement over the thrust tip. The thrust displacement of 25cm is taken up in shears oblique to the main movement (this is illustrated in detail in fig. 53). At locality 7 (5832 4818) a small lens of Whin Sill has intruded into the top 3m of the limestone. The lens has a level base and a convex-up upper surface reaching a thickness of 2m over a width

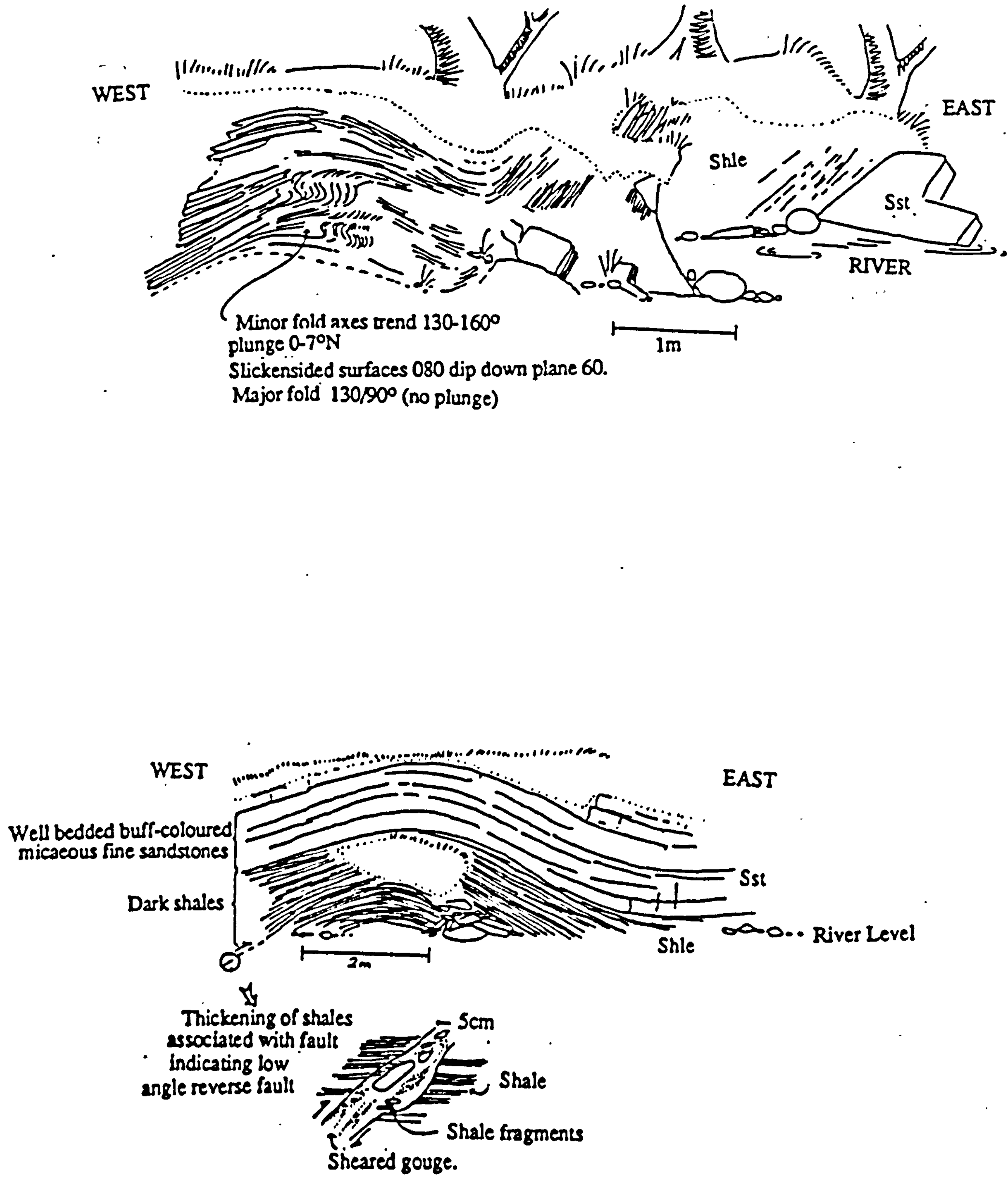


Fig. 52 Field sketch of folding at locality 15, Croglin Water.

of 10m. The base of the Whin Sill apophysis truncates an E/W striking thrust which transports SE with a displacement of 2.8m (see fig. 54).

The Scar limestone crops out from the lower quarries (loc. 8 5839 4803) to Croglin Beck over a minor NE normal fault. In Croglin Beck no folding is apparent. At locality 12 (5804 4833) red stained shales and medium grained sandstones crop out at a waterfall. These are probably Alston group beds stained red due to proximity to the Permo-Trias. The staining probably indicates the position of the post Permian NPF surface or an eroded Permian escarpment, to within about 50m.

The NPF occurs 200m below locality 12 bringing poorly exposed red sandstones (St, Bees Sandstones) to the surface. These sandstones are overlain locally by red-purple siltstones and shales of the Eden Shales formation.

c) Newbiggin Beck.

Newbiggin Beck runs NE of Newbiggin village into the Pennine escarpment exposing St. Bees Sandstones in a series of patchy, red fine to medium grained sandstones interbedded with silts up to 7cm thick. The units fine upwards and dip uniformly 10° W but increase to 36° W adjacent to the trace of the NPF.

Within 50m of the NPF fault at locality 31 (5647 4925) the sandstones are cut by steeply west dipping NNW/SSE normal faults. Calcite veining is present in the faults but no slickencrysting is apparent. Some conglomerate boulders of Carboniferous Basement Beds were found in the stream at locality 31, either derived from further north on the escarpment near Cumrew or from a local, unexposed outcrop.

At locality 32 (5649 4927) two beds of easterly dipping (43°) Melmerby Scar limestone occur and over the next 80m the limestone forms in a series of steeply dipping beds and 150° trending folds. Dips are up to 70° adjacent to the NPF and decrease over 200m to 20° by locality 33 (5648 4932). Upstream of locality 33 a second limestone occurs dipping 30° E, but folding is not encountered until a well bedded thick sandstone (3-4m thick) at localites 34 & 35 (5666 4940) which is folded into a symmetrical syncline and asymmetric NE facing NW/SE anticline. The fold axes are 20m apart, upright with no discernible plunge. Beyond this locality beds are features and so no further folding was visible until a disused quarry at locality 36 & 39 (5718 5010). The quarry exposes the light grey and fossiliferous Scar limestone in a large upright, asymmetric, 168° directed anticline.The fold faces SW with a 20m wavelength. Slickensides on the bedding surfaces in the fold are consistent with formation through down-dip flexural slip dying-out over the axial region. The same limestone occurs at locality 40 (5695 5027) downthrown to the NW by an unexposed NE/SW normal fault.

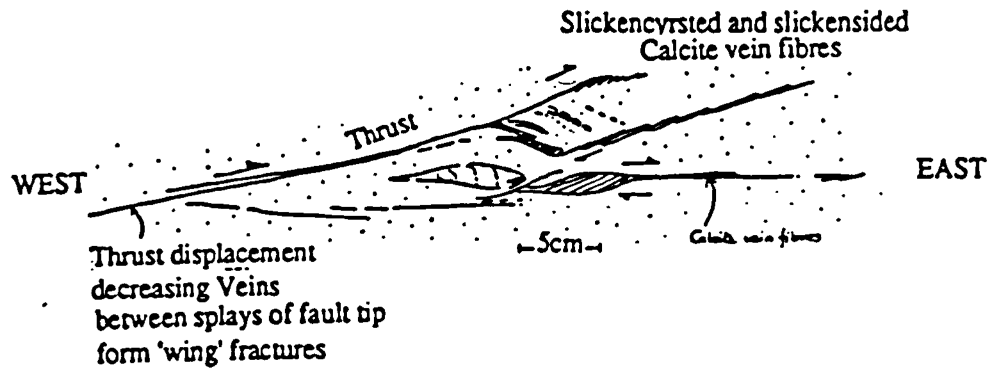


Fig. 53 Diagram of thrust tip at locality 7, Scar limestone, Croglin Quarries.

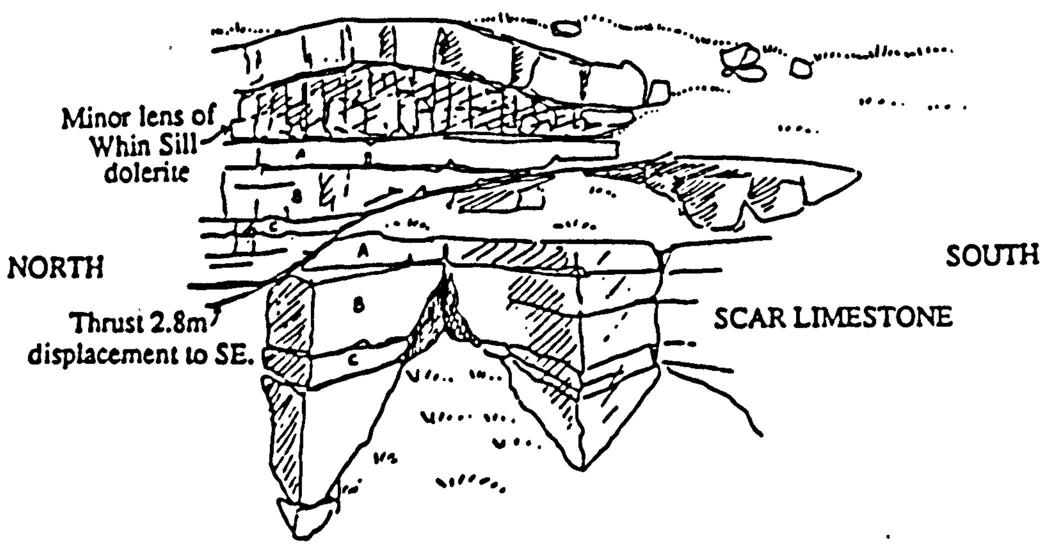


Fig. 54 Field sketch of thrust truncated against Whin sill (loc.7) in the Scar limestone, Croglin quarries.

Between Newbiggin Beck and Trowslinn Gill above Cumrew farm (see enclosure 1) no folding was observed in the escarpment east of the NPF. This may be due to a) total absence of folding in the area which seems unlikely, or b) the strike of the structures coinciding with the strike of the hill side.

d) Trowslinn Gill (Cumrew).

One kilometre north of Newbiggin, Trowslinn Gill cuts into the escarpment NE of Cumrew farm (see enclosure 1). A section drawn along the section line A'/B' is presented in fig.60 to show the structure of the Alston group outlier.

The NPF is not exposed along this section but swings more N/S around the foot of the escarpment forming the western limit of the outlier. The Alston Group sediments are poorly exposed at locality 103 (5518 5095) where 4m of grey micritic limestone is interbedded with fissile black shales. 20m east of locality 104 (5525 5098) patchy exposures of dark red micaeous sandstones occur and a well rounded pebble conglomerate dipping 38° SW. These units rest on steeply SW dipping black shales of uncertain age but may represent Lower Palaeozoic units beneath the red beds. The red units could be Permian but its likely that the conglomerate represents the Basement Beds of the Lowermost Carboniferous in this area.

The outlier sparsely exposes high dips (80° SW and E) in highly fractured limestone and shales found in Trowslinn Gill 200m south of locality 104 (5530 5084). The limestone was not identified, and no evidence was found for a massive limestone in the centre of the outlier mapped by the Survey (sheet 18).

Along Cumrew Beck (see enclosure 1) at locality 105 (5520 5121) Permo-Trias, red micaceous fine sandstones crop out covered by a drift of pebbles derived from the Basement Beds, indicating the northerly limit of the Alston group outlier. In Trowslinn Gill the Basement beds are exposed high up on the escarpment with steep easterly dips and across the hillside where dips vary from gently west near the boundary with the outlier to the high dips seen in the Gill. The Basement beds vary in character from thick imbricated crudely bedded red/brown conglomerates to coarse yellow sands with lag conglomerates at their bases. The crude bed forms indicate high E and W dips persist until the Melmerby Scar limestone at locality 108 (5606 5102) above a 50m section of non-exposure. The non-exposure represents the Orton group in this area. Variable and opposing dips in the limestone indicate folding trending approximately 160°. The folds are spaced 10-20m apart with a tendency to steep westerly limbs (70°) and more gentle easterly limbs (18°-40°). It is difficult to determine fold geometries but they appear to be upright, moderately tight, parallel folds.

The sheet memoir for the Brampton district (sheet 18) describes acute, small folds in the Basement Beds in Trowslinn Gill at the 900-700ft contours (290m) but regrettably these exposures are no longer apparent and no details of the folds were given in the

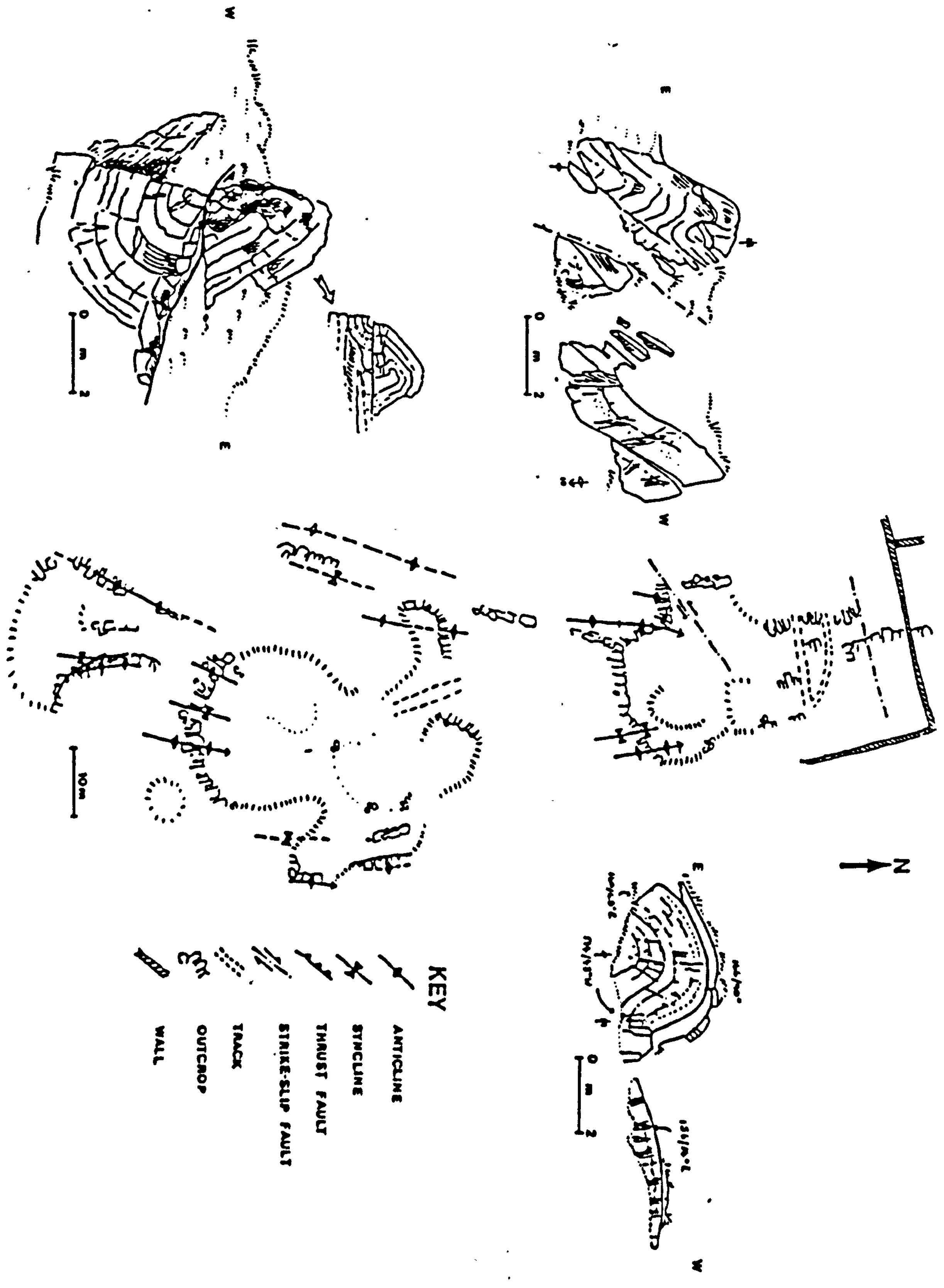


Fig. 55 Plan map of Garth Head Quarries with sketches to illustrate typical structures.

Survey's memoir except to indicate these structures trended NNE/SSW. This direction is consistent with directions recorded for the folding in the Melmerby Scar limestone.

e) Albyfield.

250m NE of Albyfield, 0.5km N of Trowslinn Gill, the Melmerby Scar limestone (MS lmst) occurs 150m E of the trace of the unexposed NPF. A disused quarry (5465 5272) north of Albyfield exposes fine grained red St. Bees Sandstones with extensive jointing (see enclosure 1), cross bedding and gentle 15° SE dips. The MS limestone forms a series of isolated outcrops along the escarpment with variable and opposing dips (from 15°-60° W to 25°-60° E). These are interpreted as open synclines and anticlines trending 160° NE. A minor NNW/SSE fault strike-slip was interpreted as cutting the outcrop (5502 5272).

No folding was observed in the escarpment north of Albyfield until the quarries at Garth Head. This is partly due to poor exposure and partly due the strike of the escarpment coinciding with the strike of the folding.

f) High Gelt Bridge.

High Gelt Bridge is included in the section on the North Pennine Fault because, although it lies north of the intersection of the NPF with the Stublick fault system, it is the sole locality in the area where the NPF is exposed.

At High Gelt Bridge (loc. 76a 5417 5617) 0.5km NE of Castle Carrock village, the River Gelt flows through a narrow gorge of St. Bees Sandstones. The sandstones are a sequence of cross bedded, massive, dark red medium to fine grained sands interbedded with red silt/mud partings and have a uniform 5-10° SW dip.The cross bedding is on a large scale with dune fore-sets 2-3m high.

10m west of locality 76 (5431 5617) the red sandstones end abruptly against red silts/shales and finely laminated sands. These give way with much minor faulting to westerly dipping (up to 45°) sandstone and interbedded fines. This complexly faulted junction is illustrated in fig. 58. Between here and locality 76b the westerly dipping beds are identified as those of the Carboniferous though their stratigraphic horizon is not known.

At locality 76b westerly dipping (40°) reddened sandstone and interbedded silt, shale and fine sands end suddenly against a vertical fault zone. Immediately east of this are dark grey-black laminated shales and fine sands. This is the position of the NPF, downthrowing reddened strata to the west (see fig. 58 for details).

The shales are near horizontal east of the NPF but increase in dip upstream over 30m to dip moderately 40° SW. A massive sandstone above a thick limestone form the west limb of an asymmetric steeply inclined antiform, trending N/S. The antiform has a wavelength of 50m and an amplitude of >5m. The core of the antiform is cut obliquely by intersecting strands of two strike-slip faults. A limestone in the core of the fold has

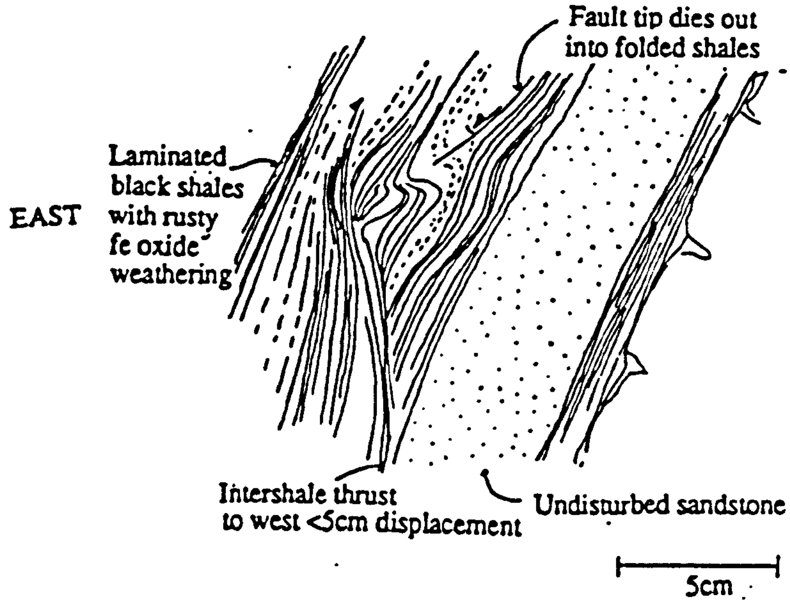


Fig. 56 Diagram of early thrust structure 100m west of locality 79, Gelt River.

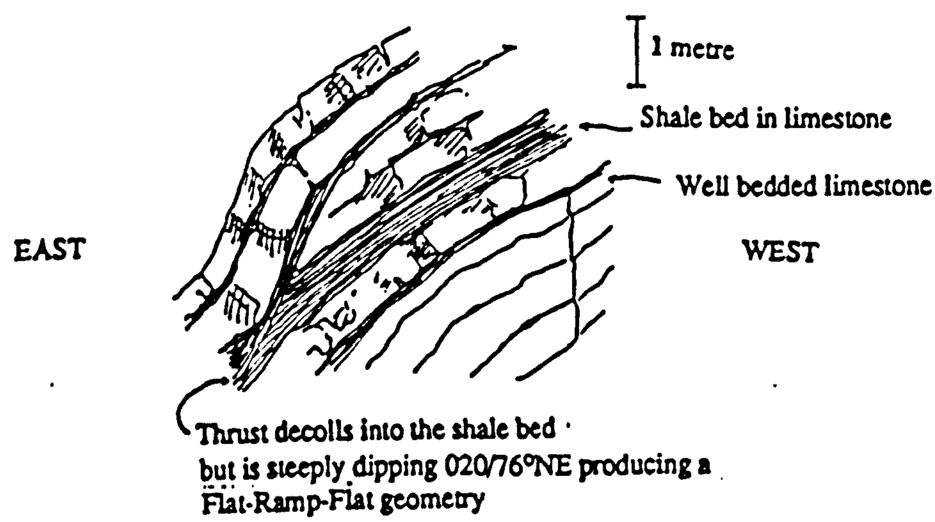


Fig. 57 Diagram of thrust in limestone in the vicinity of locality 76b), Gelt River.

minor westerly directed thrusting in its axial region, where the uppermost bed is displaced by >1.5m. The easterly limb of the antiform is more gentle (30°-40° SE) but dips remain generally high (up to 70-80° SE) until locality 77 (5471 5624) where an unnamed limestone is folded into a tight almost isoclinal inclined NE/SW anticline, with a slightly overturned easterly limb.

At locality 77 (5494 5619) the high dips of the silts/sands and limestones of the previous section are truncated against laminated ferrugenous shales and thin sandstones dipping 10-20° east, containing two thin coals (up to 3cm thick). This junction is the position of the northern branch of the Stublick fault system; the Mill Beck fault. Unfortunately the fault itself is inaccessible.

The High Gelt Bridge section shows a number of interesting features reminiscent of other sections on the NPF. 100m downstream of locality 77 (5402 5020) vertical black shales with fine sandstone laminae above an unidentified limestone contain a small reverse fault. The fault illustrated in fig.57 has a displacement of less than half a metre and has been rotated into an overturned position. 150m east of locality 76b in a thick limestone there is a flat-ramp-flat thrust geometry, in a near vertical position, very like a structure seen in Loo Gill (loc. 121).

The area around the NPF is very complex and so is illustrated in detail in fig. 58. The section can be summarised as two normal faults, where the more easterly (X) brings St. Bees Sandstones down east against a limited exposure of Eden Shales which appear to over-lie or are faulted against red stained steeper dipping Carboniferous strata. The second fault (Y) here named the NPF is the larger in throw of the two, bringing red-stained Carboniferous against unstained Lower Limestone Group (LLG) beds. The limestone in the core of the antiformal anticline (i.e. younging upwards) east of the NPF is interpreted as the Smiddy limestone at the junction of the LLG and Middle Limestone Group (MLG). This interpretation makes the section from locality 76b) to the Mill Beck fault, part of the MLG but does not account for the numerous limestones over this section unless there is more folding than interpreted. Alternatively the stratigraphic placement is incorrect.

The NPF of indeterminate throw, must be post-Permian as it brings reddened strata against unstained rocks. If the red stained section (between X and Y) is MLG or LLG then the throw is <500m. The fault described as 'X' is at least post Lower Permian but its exact age is poorly constrained. Both faults (X & Y) affect strata that was folded prior to faulting, and as no significant folding occurs in the Permian, the deformation must be post - Lower Carboniferous in age.

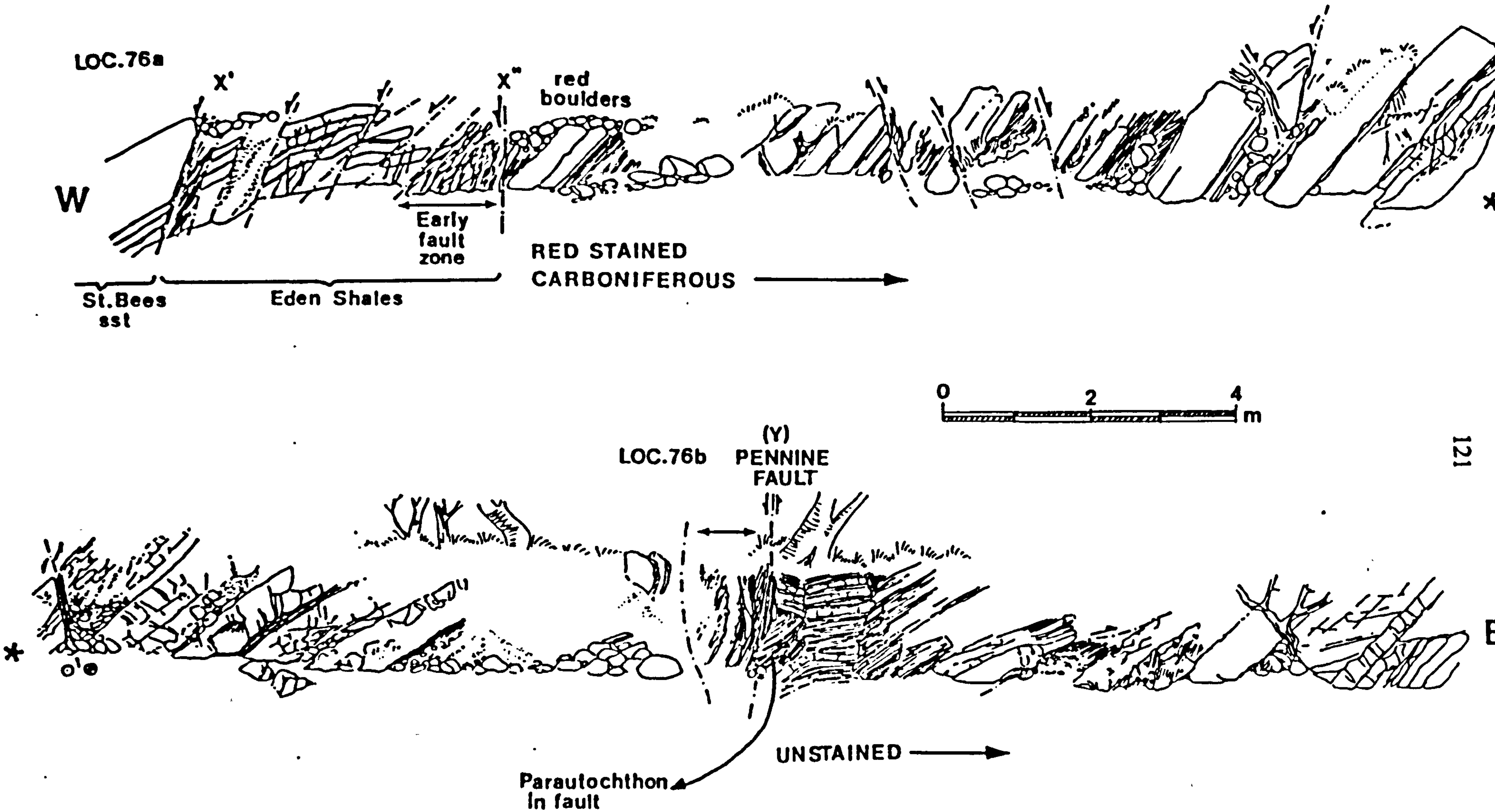


Fig. 58 Detailed sketch of the High Gelt Bridge area around the North Pennine Fault.

4:2:3 The Stublick Fault System.

The Stublick fault branches in the Brampton area from a single strand east of Midgeholme in a Westphalian outlier to two strands that pass either side of the Tindale and Talkin Fells (see fig. 46 & 69). The northern branch is composed of two faults, the easterly Howard fault running along Tindale valley and the westerly Mill Beck fault, following Mill Beck valley. The Mill Beck faults intersects with the NPF system 0.5km south of High Gelt Bridge, north of Castle Carrock village. The southern branch, here called Stublick South fault, runs over the Tindale Fells to cross the Gelt River at Castle Carrock Fell and intersect the NPF 0.5km north of Nixon Head (see fig. 46 and enclosure 1).

a) Garth Head. (5536 5470)

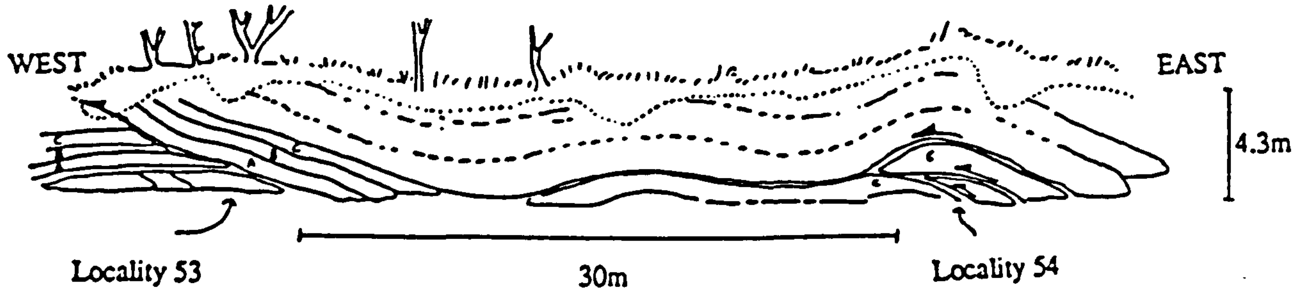
One kilometre E of the reservoir at Nixon Head, in the escarpment above Tottergill, are the disused quarries at Garth Head where the massive micritic Scar limestone crops out above a highly lensoid sandstone.

The limestone can be traced a few metres south of the quarries where it ends against an unexposed fault. The Melmerby Scar limestone seen at Albyfield can be traced as a feature towards Tottergill where it too ends against a second unexposed northerly dipping fault. This is interpreted as the Stublick South fault and immediately west of here (5505 5420) red shales and mudstones of the Eden Shales are sparsely exposed at the head of Tottergill (5509 5440). The Stublick South fault displaces the NPF main strand, laterally east (dextrally) by 300-400m.

Garth Head quarries display a series of spectacular folds and thrusts in the Scar limestone. The quarries are illustrated in plan form and with details of structure in fig.55. Folding in the quarries is characteristically asymmetric 1B anticlines and synclines, facing east with occasional tight 1C folds. Fold axes trend from 160° N to 170° S (or 190-200° N) with slickensided bedding surfaces plunging 90° to bedding strike i.e. E and W. This is consistent with down-dip flexural slip. Folding is irregularly spaced from 1m to 5m apart with amplitudes up to 4-5m. Two thrusts were observed in the quarries (see fig. 55) and in each case displacement was at least 1m. The thrusts are near horizontal structures and cut across folding. Plotted data indicates the thrusts strike 098° to 040° with oblique transport indicated by slickensides to the SW or NE.

b) River Gelt.

The River Gelt flows between the northern and southern branches of the Stublick fault, through the Middle Limestone Group (= Alston Group). The following section continues the exposures described under 4:1:2 f) at High Gelt Bridge.



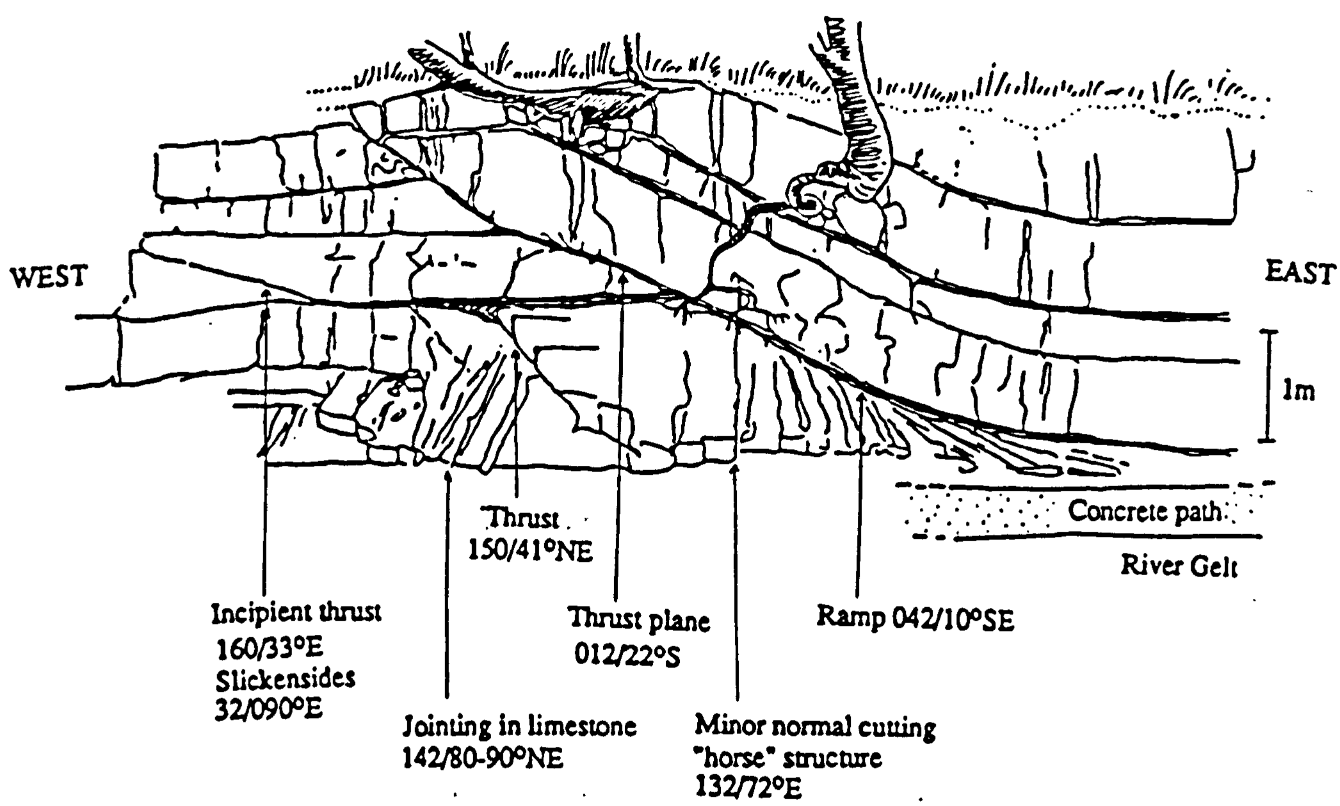


Fig. 59 Diagramatic section along river Gelt, a) from loc. 53 to 54 and b) detail field sketch of limestone at loc. 53.

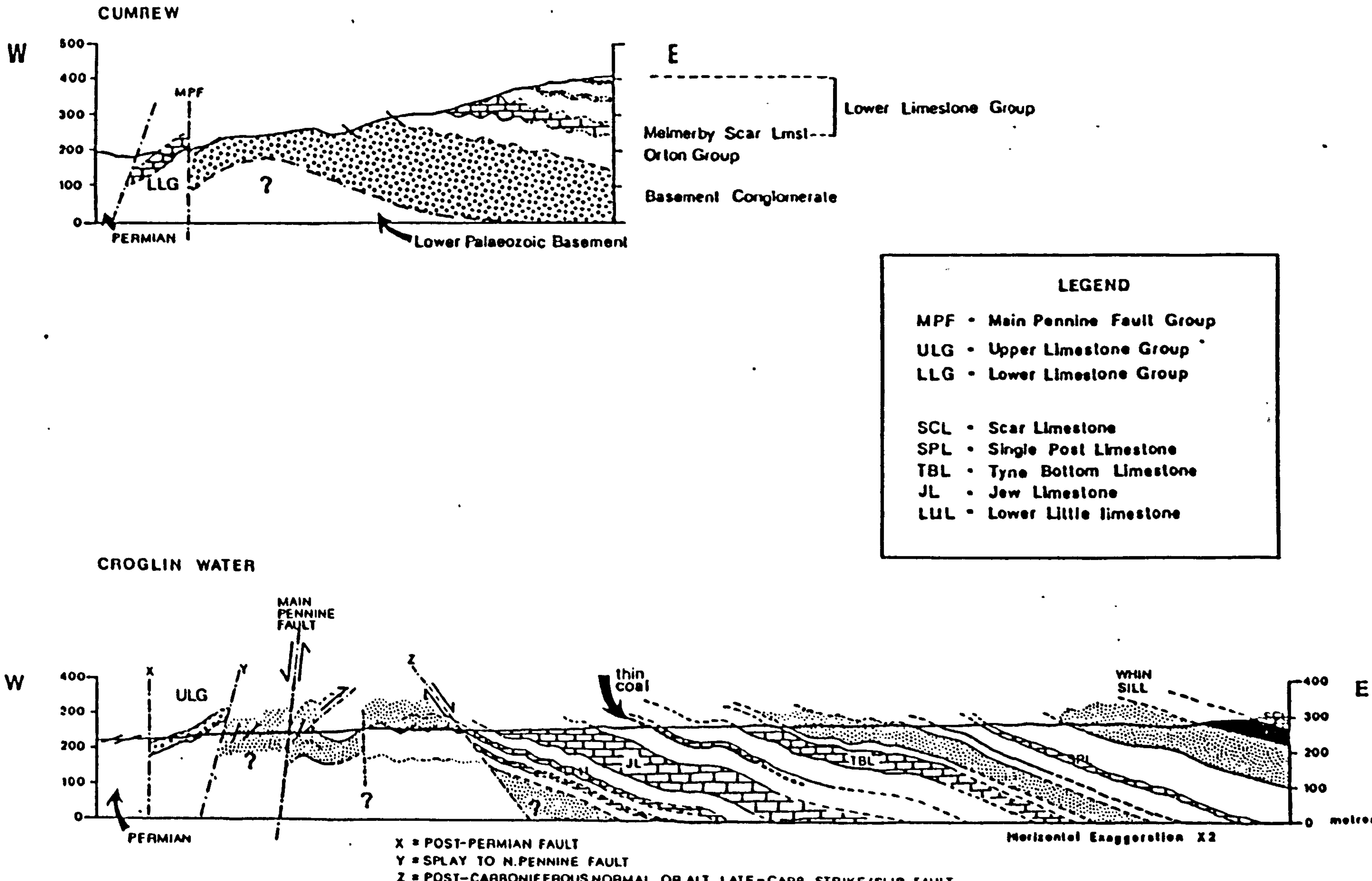


Fig. 60 Cross sections through the North Pennine Fault zone. A-B = Cross section through the Alston group outlier at Cumrew. A'-B' = Cross section through the Croglin Water section.

The succession exposed is from the Scar limestone to the Great limestone at the base of the Upper Limestone Group (see enclosure 2) and contains several 5m+ thick sandstones interbedded with unexposed silt/shale sequences and thick limestones.

The lowermost sandstone exposed below the Scar limestone (loc. 74 and 75; 5560 5600) is displaced close to the Mill Beck fault 100m N of locality 72 (5511 5624) where underlying lensoid sandstones and laminated silty shales crop out. Displacement over the Mill Beck fault is between the Jew limestone and the Scar limestone (assuming the limestone at High Gelt Bridge to be the Low Tipalt or Bankhouse limestone) a vertical displacement of 100m.

Folding is almost completely absent along the Gelt River section. At locality 52 the thick bedded sandstone immediately below the Scar limestone, is cut by a near vertical NNW/SSE fault plane. There is limited vertical displacement over this fault, >4m but it is associated with locally steepened bedding (see enclosure 2). At locality 53 (5676 5520) the Scar limestone deformed into two gentle NNW upright anticlines and NE striking thrusts. These are illustrated in detail in fig. 59 and are interpreted as ramp structures transporting in a NW direction, with a minimum displacement of 2.3m. Below the ramp feature shales have been dragged around a low angle limestone break, indicating a possible earlier thrust structure with a NW trend. The transport direction is not clear for this earlier structure due to the absence of slickensides.

In the same horizon as the limestone at locality 54 (5683 5521) the tip of a hanging wall anticline formed by a flat-ramp cut-off occurs. This structure has a minimum displacement of 1.8m, and the antiform it has produced trends 150^{o} N. The south side of the river at the last two localities shows little sign of the thrust structures but dips are up to 40^{o} SW which may indicate further localised thrusting. Similarly at locality 56 (5673 5510) opposing dips in the limestone indicate the presence of an unexposed low angle reverse fault.

No further thrusting or folding was encountered in this section and the position of the Stublick South fault is not exposed. However the fault can be inferred to run ENE over the river valley towards Castle Carrock Fell. Its position is marked by changes in dip east of locality 63 (see enclosure 2) and where the 5 Yard limestone appears for the first time in the river bed where it is associated with a local swing in strike. South of the Stublick South fault the 5 Yard limestone shows no folding over its exposure on the Alston block.

c) Mill Beck.

Mill Beck is a poorly exposed section (see enclosure 2) in the upper Middle Limestone Group. Folding along this section is only apparent by dip and strike changes but extensive faulting has disturbed the section e.g. locality 48 (5564 5655) where a thin coal occurs above ferrugenous silts/shales and is truncated against a steep (normal?) fault

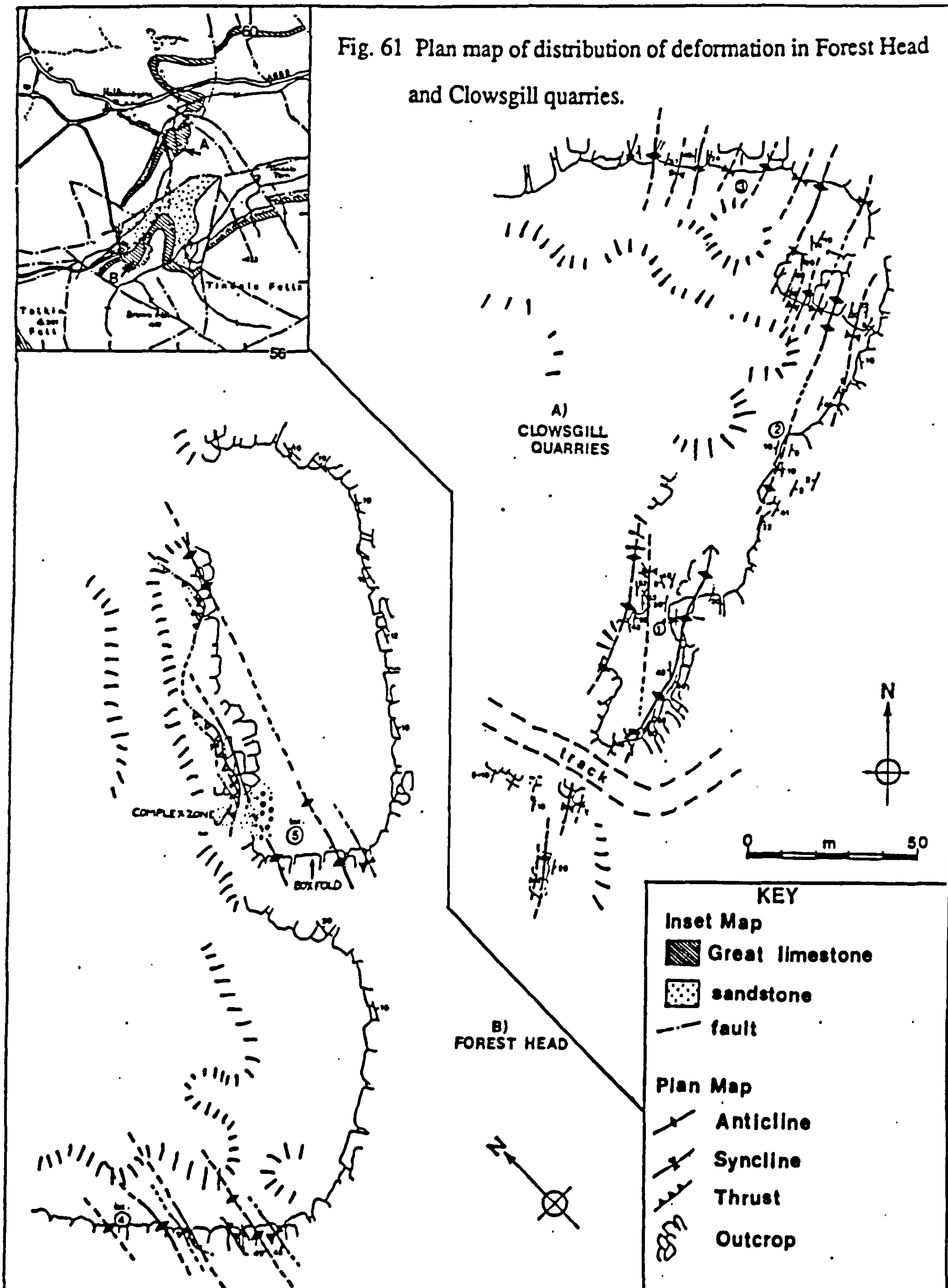


Fig. 61 Plan map of distribution of deformation in Forest Head and Clowsgill quarries.

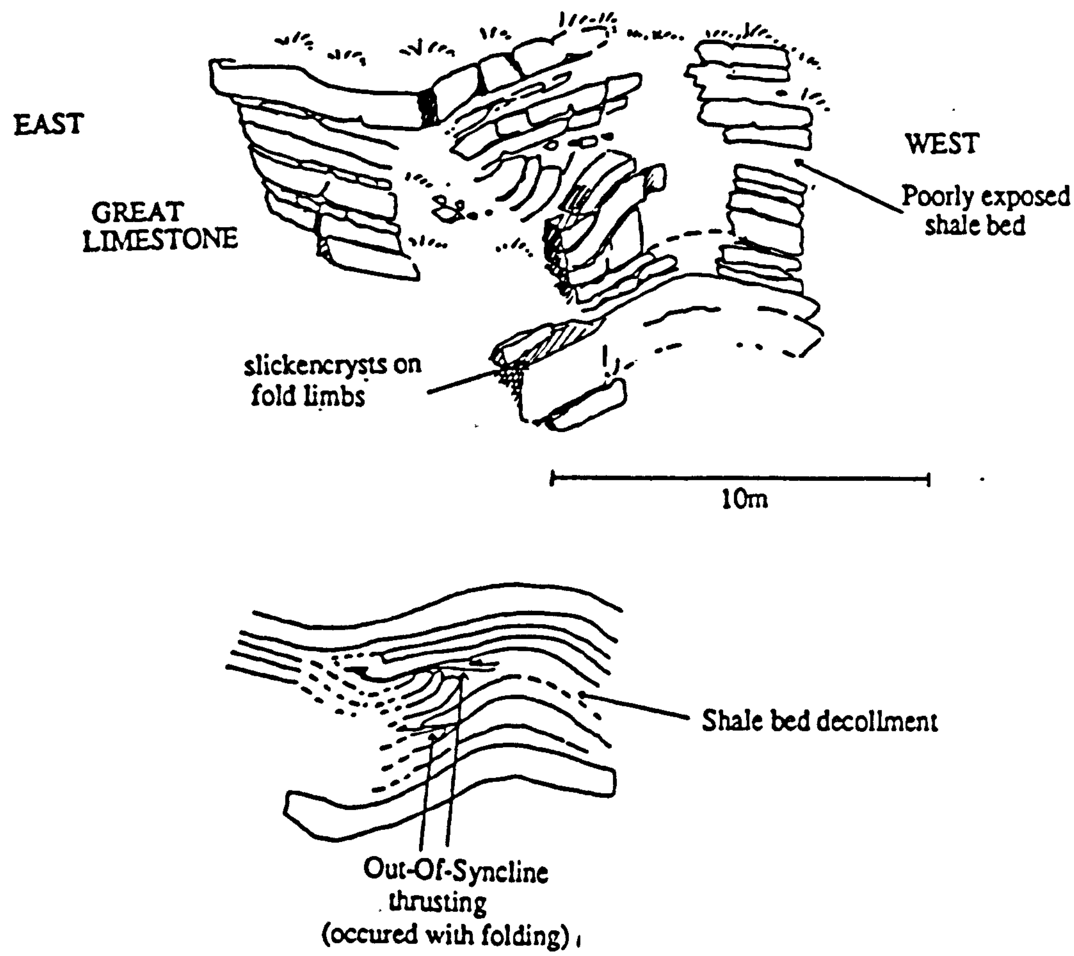


Fig. 62 Field sketch of fold styles and thrusting at locality 4 with schematic explainations in the Great limestone, Forest Head, Halbankgate.

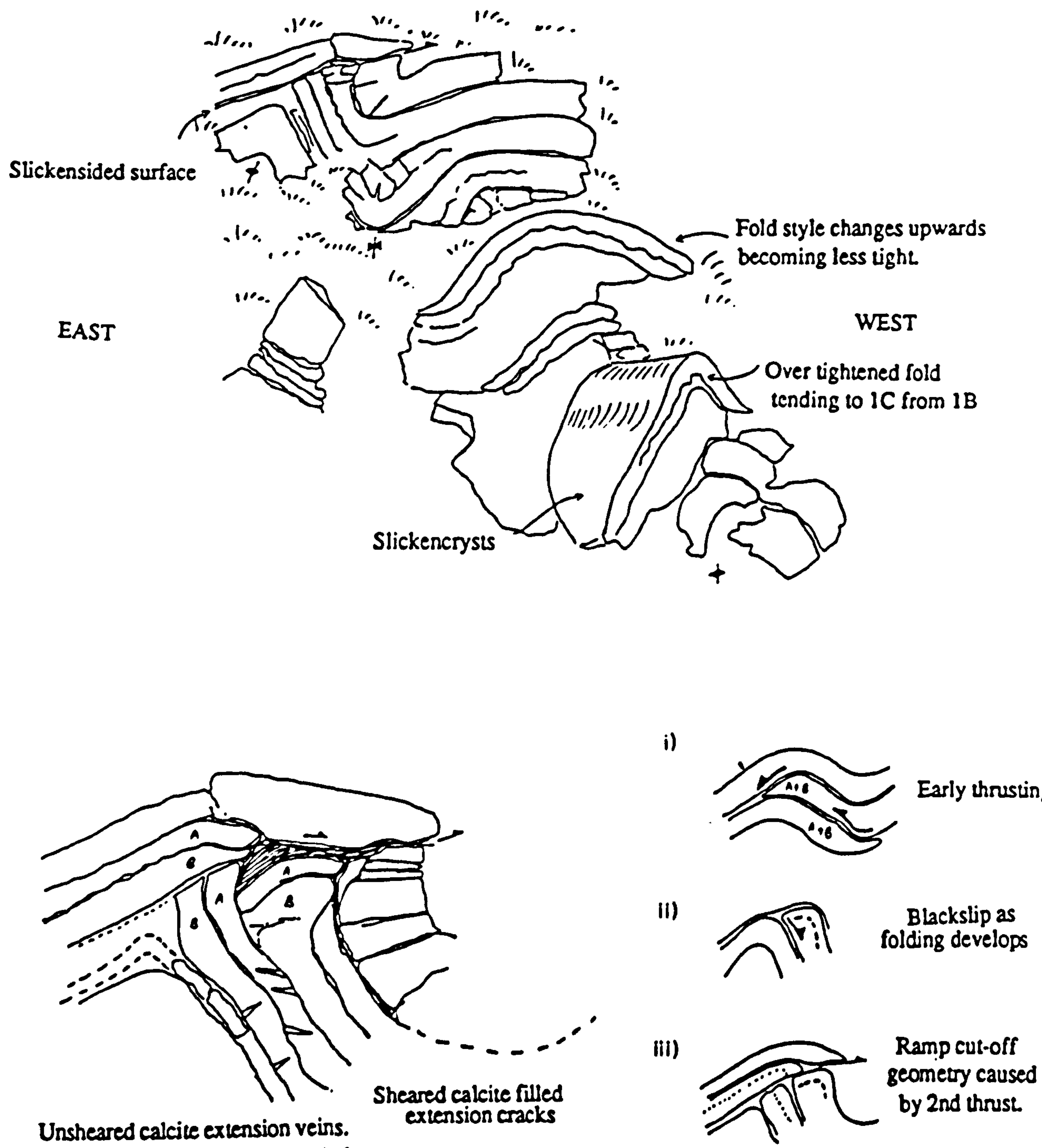


Fig. 63 Detail sketch of folding immediately east of locality 4 showing schematic thrust development, Great limestone, Forest Head quarry (south).

trending 180/60° W.

A fault zone at locality 59 (see map enclosure 2) trending 116/21° NE, displaces a massive buff coloured sandstone to the E, associated with numerous fine fractures and quartz filled breccia NW/SE zones. Two directions of movement are indicated by slickensides in these zones, one set (08/032) is near horizontal indicating strike-slip motion and the other (70-75/132) indicating dip-slip motion. Net fault displacement however is within 2-3m as there is no apparent vertical stratigraphic offset and therefore must be less than the thickness of the sandstone. At locality 61 (5570 5659) a massive sandstone occurs above a section of highly disturbed fines and carbonaceous shales. No folding is apparent but the confused state of the outcrop indicates the proximity of the Mill Beck fault which runs NE along the north side of the beck.

d) Forest Head and Clowsgill quarries.

The quarries are complex and are illustrated in plan form in fig.61.These quarries are situated 1km E and 2km S of Hallbankgate village respectively. They are both in the Great limestone, the highest stratigraphic level encountered thus far. The quarries are situated either side of the Stublick fault's northern branch (around the point of overlap between the Mill Beck and the Howard fault) approximately 0.8km apart. The position of the Howard fault is a feature running NE/SW across the area between the two quarries from Green Lea Cross (5780 5803 spot height 305m) to Tindale Tarn.

i) Forest Head quarry.

Folding occurs throughout the quarry but is best developed in the south face of the more southerly quarry. Here at locality 4a) (5823 5724 fig. 62) a type 1B similar fold occurs with an inclined axis trending 187/75-85° E. Accommodation of stress during folding has produced a minor out of anticline thrust directed east towards the top of the structure. Bedding plane calcite and slickencrysts are abundant. Two directions of motion are recorded, one 038 across the limbs and another 086 down-dip. In the second case slickencrysts were absent over the fold hinge and are therefore flexural slip indicators. These are plotted on stereonets in fig.68.

Immediately east of the fold at 4a) a second fold (4b) was observed (fig. 63). This is a tighter, chevron 1C type anticline with a slightly overtightened core region. An out of syncline thrust breaches the eastern limb transporting westwards. Slickensides on the thrust are near horizontal. Displacement on both of these minor thrusts is less than 1m. Detailed field sketches of the localities 4a) and 4b) are given in figs.62 and 63 illustrating the development of the minor thrusts. The interpretation of the geometries of the structures described indicate pre-folding intra-bed thrust development and possibly later modification of these structures during folding. Slickensides plotted for the thrusts at 4a) and 4b) indicate transport to the SE/NW and the two slickenside directions for 4b) show that the first direction coincides with slickensides plotting flexural slip during folding,and that the axial fold slickensides are consistent with the thrusts slickensides directions. Two slickenside directions on the thrust at locality 4a) show that the first set is consistent with other thrusts in the quarry and that the second set is consistent with slickenside directions recorded for minor normal faults in the quarry (fig. 68). This might indicate initial thrusting and then back-slip on the surface during folding.

25m E of locality 4 in the SE corner of the quarry, an inclined anticline occurs (see fig.64). In its steeper easterly limb there are rotated thrusts and in the westerly limb there is a structural "pop-up" formed by the intersection of opposed thrusts. The fold is an asymmetric parallel fold with downward facing thrusts and overturned thrust surfaces in the east limb repeating a single limestone bed. Slickensides on the thrust surface indicate orthogonal transport to the east. Fig.64 shows the schematic development of the structure implying the thrusts could have formed during or before folding. Slickensides plotted for the thrusts and "pop-up" in the western fold limb are spread over 40° from SE to ESE with a concentration of values in the SE direction.

In the north quarry, at locality 5 the top 15m of the Great limestone is exposed below the Great shale. The uppermost 5m are interbedded limestones 50-120cm thick, with shales 10-30cm thick. Two major features dominate the north quarry.

The first structure in the north facing wall is a "box-fold". This feature is illustrated in fig.65 . The fold is a double axis N/S structure. The axial planes are inclined towards one another between 60° E and 75° W. Sub localities i) and ii) are thrusts in the limbs of the box-fold.

i) An inaccessible sequence of two minor thrusts, thickening and repeating two beds. These appear to transport westwards up the inflection point of the anticline apparently consistent with the fold geometry, however their high dips suggest they could have been rotated into position by the folding.

ii) In the axial zone of the westerly facing box-fold axis a series of small oblique thrusts repeat a single limestone bed. Slickenside plots for these indicate NW/SE transport. The thrusts décoll in the shelly shale horizons and are rotated into an over turned position. Back rotation of bedding-restored slickensides on the thrusts gives transport to the SE.

The second important structure in the north quarry covers the whole of the east facing wall. This will be referred to as the "complex zone". The easterly axis of the box-fold can be traced into the "complex zone" immediately above the level of the shale used as a decollment in the box-fold. The central zone is a series of disharmonically deformed limestone beds above a basal décollment in a thickened shale. The shale contains a thin limestone bed which is deformed in a series of minor thrusts that were subsequently folded over the basal décollment. Slickensides in the décollment zone give a NW/SE transport direction, diverging between 160° to 090° N.

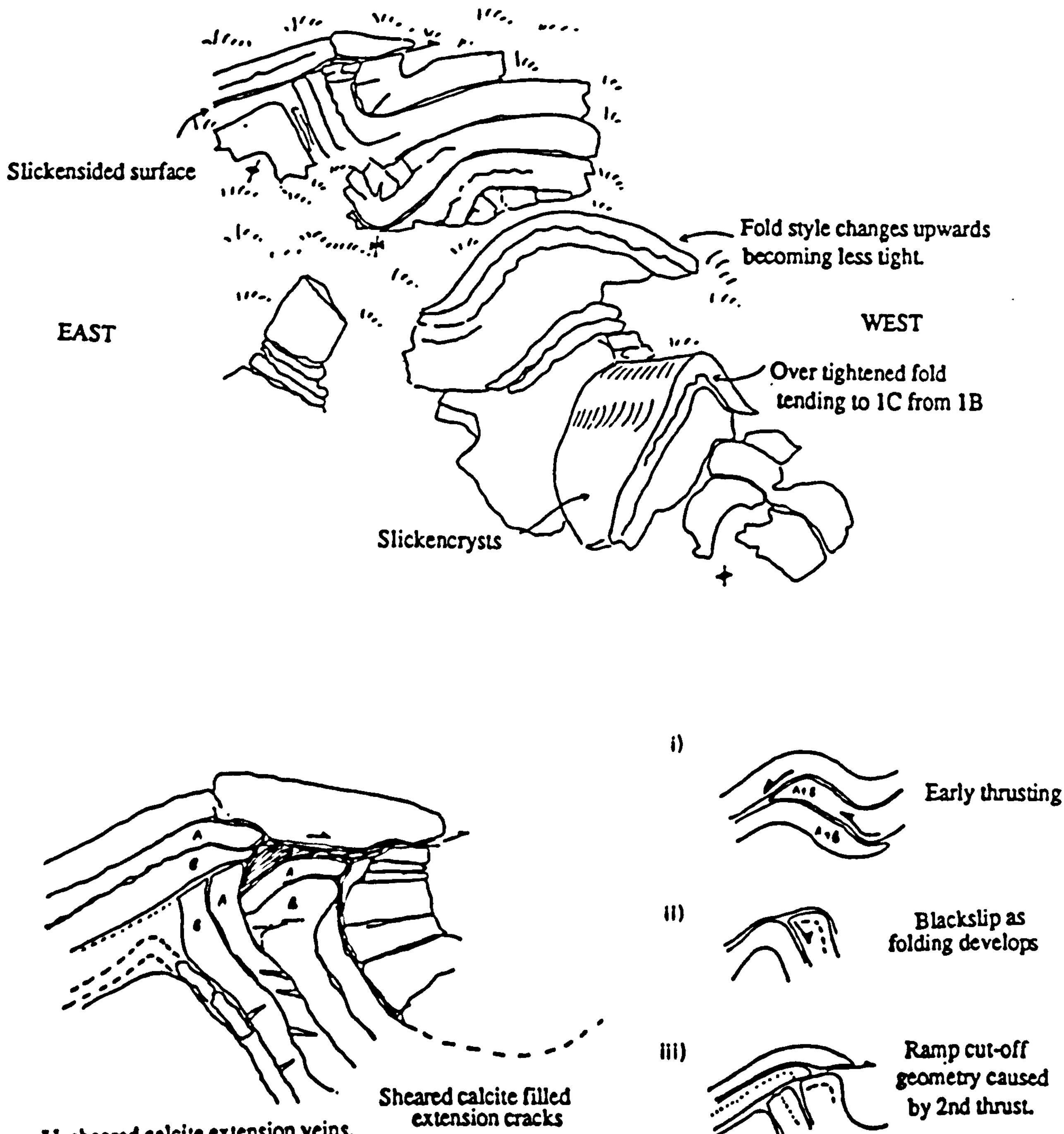


Fig. 63 Detail sketch of folding immediately east of locality 4 showing schematic thrust development, Great limestone, Forest Head quarry (south).

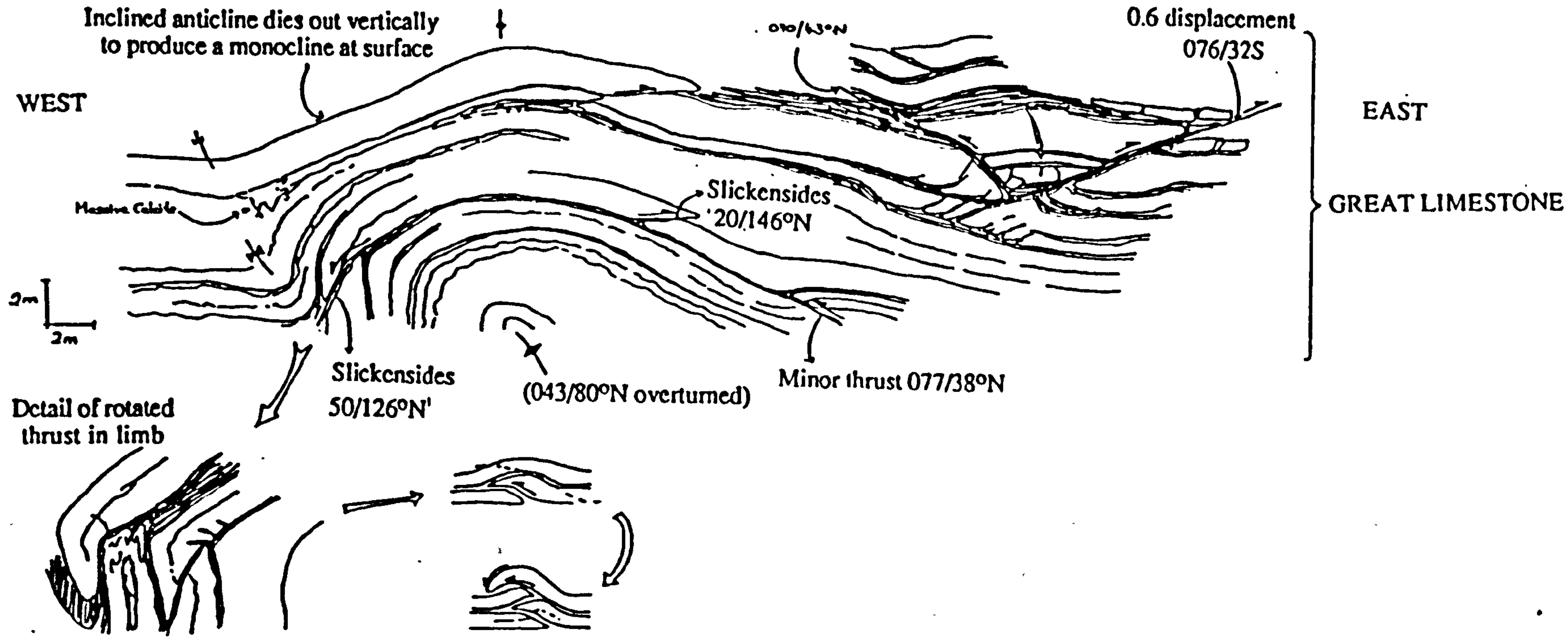
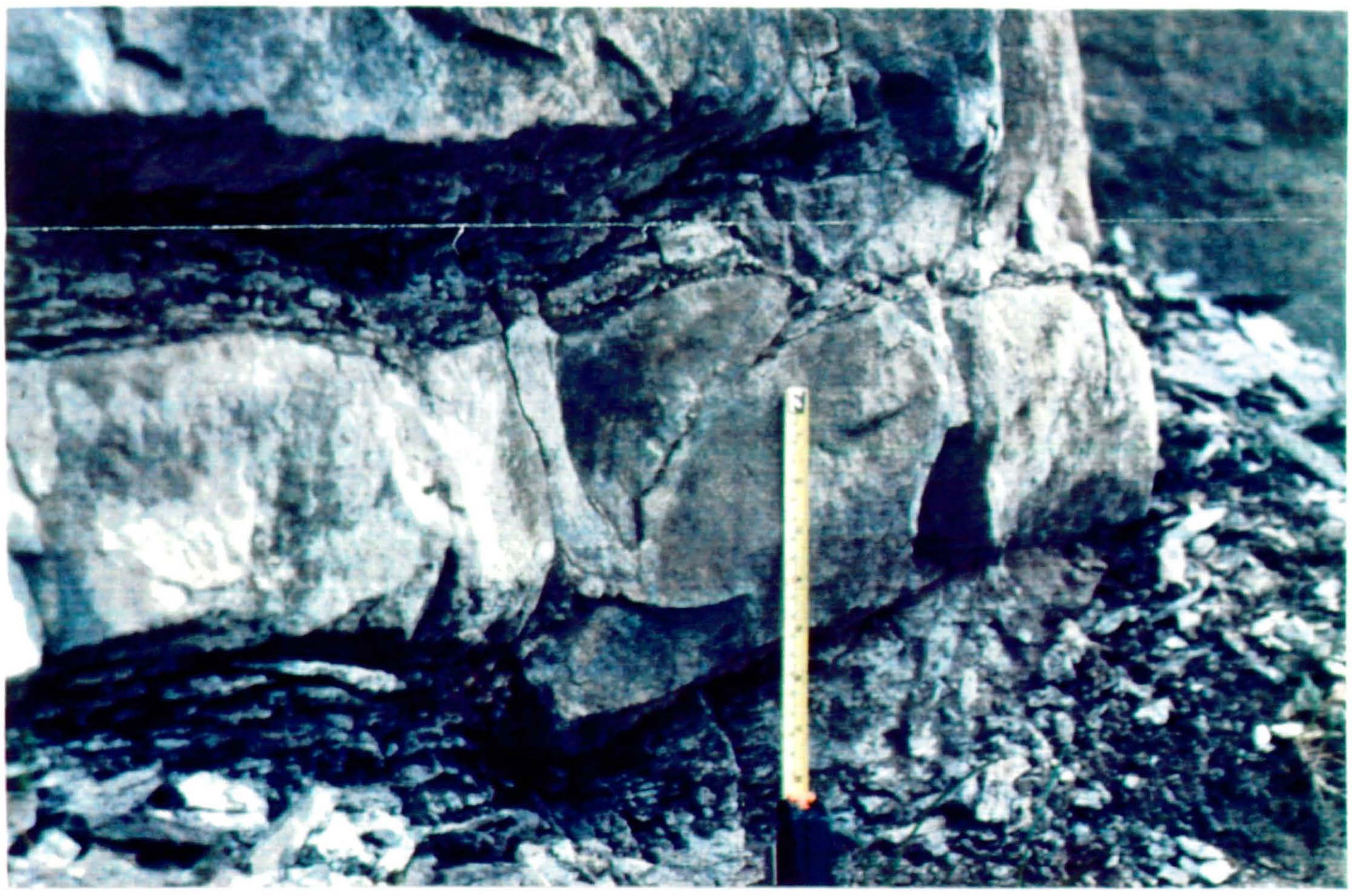


Fig. 64 Field sketch of folding and "pop-up" structure (east of loc. 4), Great limestone, with schematic explainations, Forest Head quarry (south).

Fig. 66 Photograph of the "complex zone" in Forest Head, showing the whole zone

Fig. 67 Photograph showing intra-bed limestone thrust in Forest Head, north quarries.



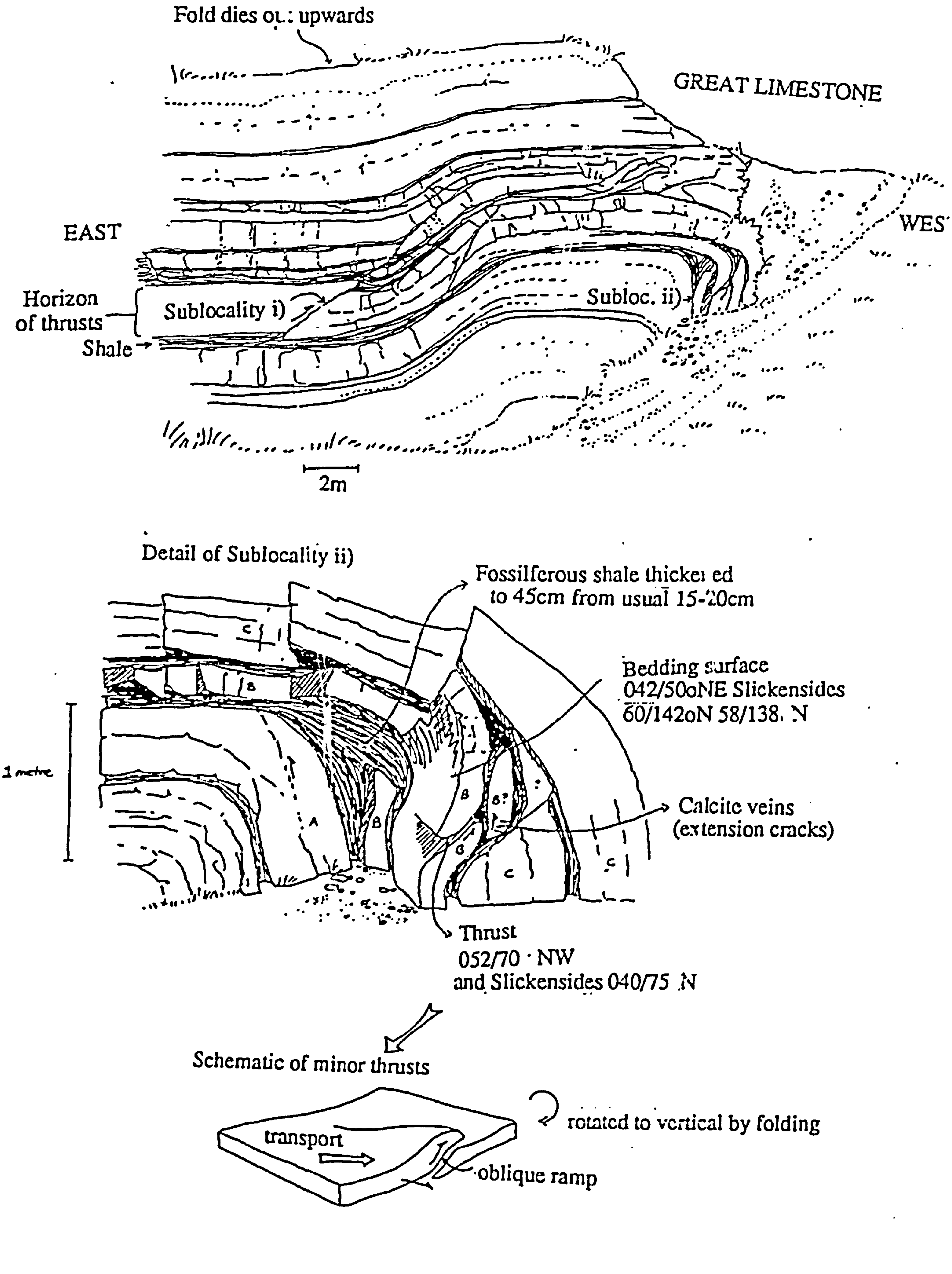


Fig. 65 Field sketch of locality 5 around the "box-fold" in the north quarry of Forest Head quarry, Halbankgate.

Slickensides observed on bedding surfaces in this complex zone also give a similar range of movement though trending more WNW\ESE.

Figure 66 illustrates the structure of central complex zone. This structure records a history of early thrust-like duplexing of minor limestone beds decolling from a thick basal shale. Later this was folded and re-thrust during the major folding in the area.

Throughout the rest of the quarry the Great limestone is relatively undisturbed except for isolated intrabed bed thrusts. These are generally inaccessible but a 20-50cm order of displacement and often unslickensided (fig. 67).

ii) Clowsgill Quarries

Folding occurs throughout the Clowsgill quarries and is shown in map form in figure 61. The folds are generally parallel 1B types varying from 5m to 2m amplitudes with wavelengths between 2.5m and 5m. In the tighter folds where folding is closely spaced, the axial zones are almost chevron in style. Fold axes trend 010-020° N and are without exception upright structures plunging 5-10° N, with rare non-parallel axes. The folds are asymmetric facing both E and W and there is an absence of the type of thrusting seen in Forest Head. All slickensides found on bedding planes indicate NNW\SSE slip perpendicular to folding (flexural slip slickensides).

At locality 1 (5904 5914) in the west facing limb of a tight anticline a pre-folding slump structure was observed. The structure affects a small area of limestone less than 50cm in extent and confined to 35cm thick zone, repeating limestone layers in a duplex fashion and extending the same bed through boudinage. A similar feature was found 5m west of the first confined to a 60cm area. These slumps indicate a slope to the south existed some time prior to the folding.

e) Tindale

The Tindale quarries are in the lower part of the Great limestone, where it crops out on the northern side of the Tindale Fells 250m south of Tindale Tarn. This region (see fig.69) is a section through the Upper Limestone Group and the Lower Millstone Grits in the foot-wall of the Howard fault. The region is shown in figure 69.

The area is dissected by a series of NW/SE to NWN faults. These displace the Great limestone by up to 100m but appear not to breach the Howard fault. There is little exposure in the hanging-wall of the Howard fault, but feature mapping of a thick sandstone indicates a shallow synform trending NE/SW around Tarnhouse Rigg (0.5km NW of Tindale, see map 2).

Two disused quarries occur in the Howard fault's foot-wall, in the Four Fathom limestone and the Great limestone respectively. The Four Fathom quarry is at locality 86 (6140 5889), and the second in the Great limestone is from localities 88 to 92 (6080 5835).

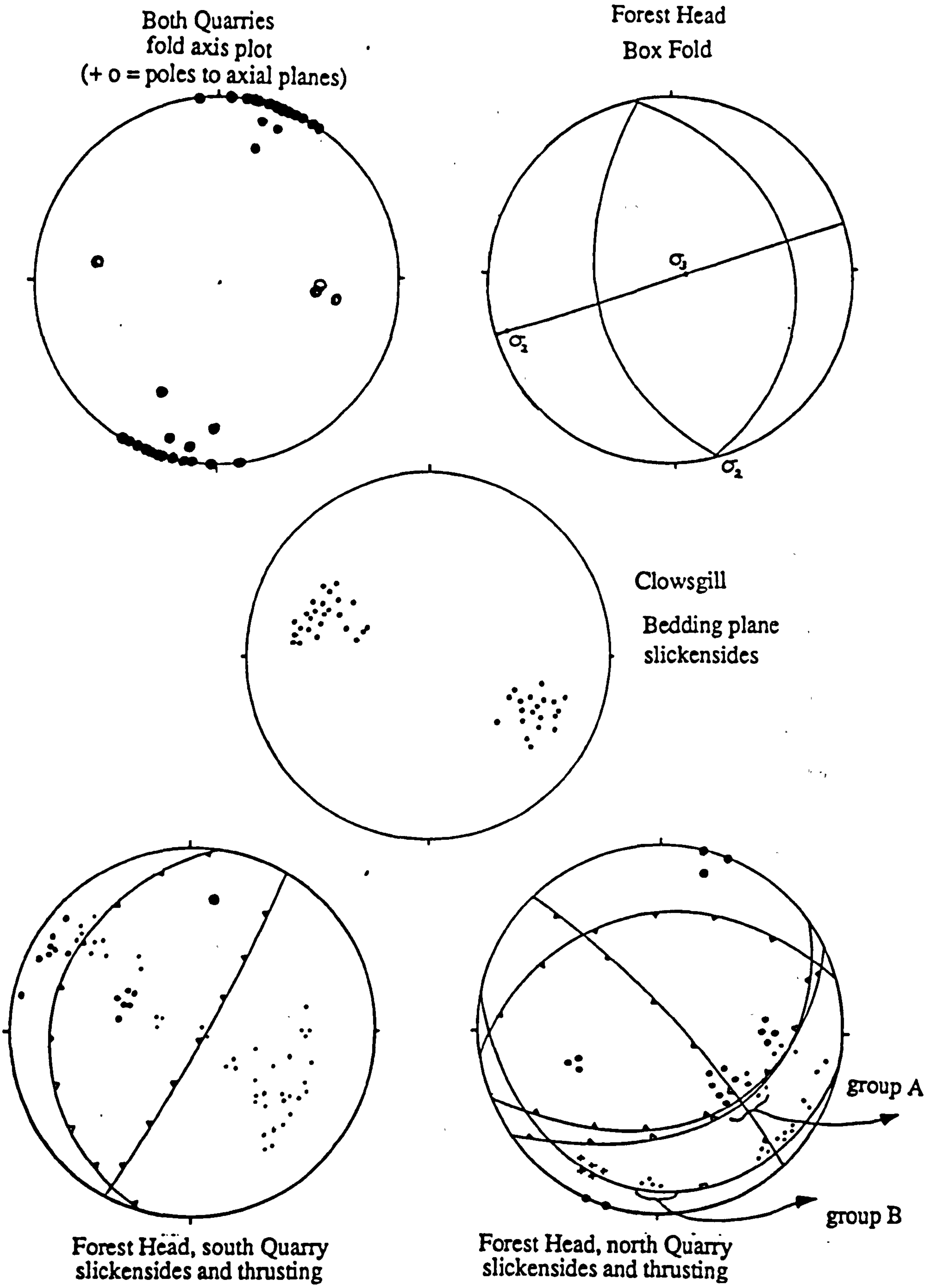


Fig. 68 Stereonet-plots for the deformation in Forest Head and Clowsgill quarries.

Fig. 71 Photographs of vertical strike-slip faults in the vicinity of the Black Burn fault, Stublick system, Midgeholme. A) shows the Black Burn fault as it crosses the burn and B) shows the curved fault surface with horizontal slickensides.

In the Four Fathom quarry the limestone lies immediately above a flaggy, medium to coarse grained sandstone. At locality 87 (6130 5983) the Whin Sill is intruded below the sandstone and a sub-vertical dyke of Whin occurs in the north of the quarry at locality 86. The dyke is cut by a minor fault trending NW/SE and also by a number of mineralised veins 115/86° S. The veins are exposed as surfaces of calcite, minor quartz and limonite (pseudomorphing an unknown mineral). There is no folding evident in this quarry, though this may be due to the main face running parallel with strike.

The Great limestone quarries are situated immediately south of Tarn House and will be referred to as the Tarn House quarries. Folding is common in the quarries, being of moderately tight to open upright 1B types. Fold distribution is highly irregular, from 5m apart in the east quarries to over 150m further west.

Folding is associated in one location i) with a minor thrust (for sub-localites see map 2 inset plan). The structure is interpreted as a hanging wall anticline approximately 1m high, above a slickensided surface in an out-of-syncline position. Estimated displacement on the thrust is at least 2m. The slickensides indicate transport ENE, but this may be misleading as the structure may be folded in the syncline from which it is directed. Unfortunately exposure is such that this cannot be proved.

At sub-locality ii) a asymmetric (to the east) syncline-anticline pair occurs trending NE at 030° N, however the inflexion dies out upwards over 10m to become an east facing monocline at the top of the Limestone. A similar structure was observed at iii) where a monocline faces west (see fig.69).

The distribution of the folding has no obvious association, although for the eastern quarry the section is 170m W of a large normal fault. No folding was found on the other side of this fault, in the Lower Little limestone or in the Great limestone (down thrown by 50m).

f) <u>Midgeholme</u>

The Stublick fault bisects this area (see fig.70) as a single fault strand south of Midgeholme village and branches into the Stublick South and Howard faults immediately SW of here. None of the major faults are exposed but their positions are relatively well constrained by a history of coal mining in the area. An outlier of Westphalian A-B occurs in the hanging-wall of the Stublick fault down-thrown against Namurian strata at the Lower Little limestone level, a vertical throw of approx. 450m.

The area covered by map 3 (fig.70) covers at least two southerly splays of the Stublick fault trending NE/SW to ENE/WSW. No folding was observed in the area, either in the foot-wall or the hanging-wall of the fault.

In the hanging-wall along Hartley Burn, east of Low Midgeholme, a series of strike-slip faults break up a thick (3m) cross-bedded sandstone in Westphalian A shales. The faults have dextral displacements from a few cms to 15m, trending 160°-170°

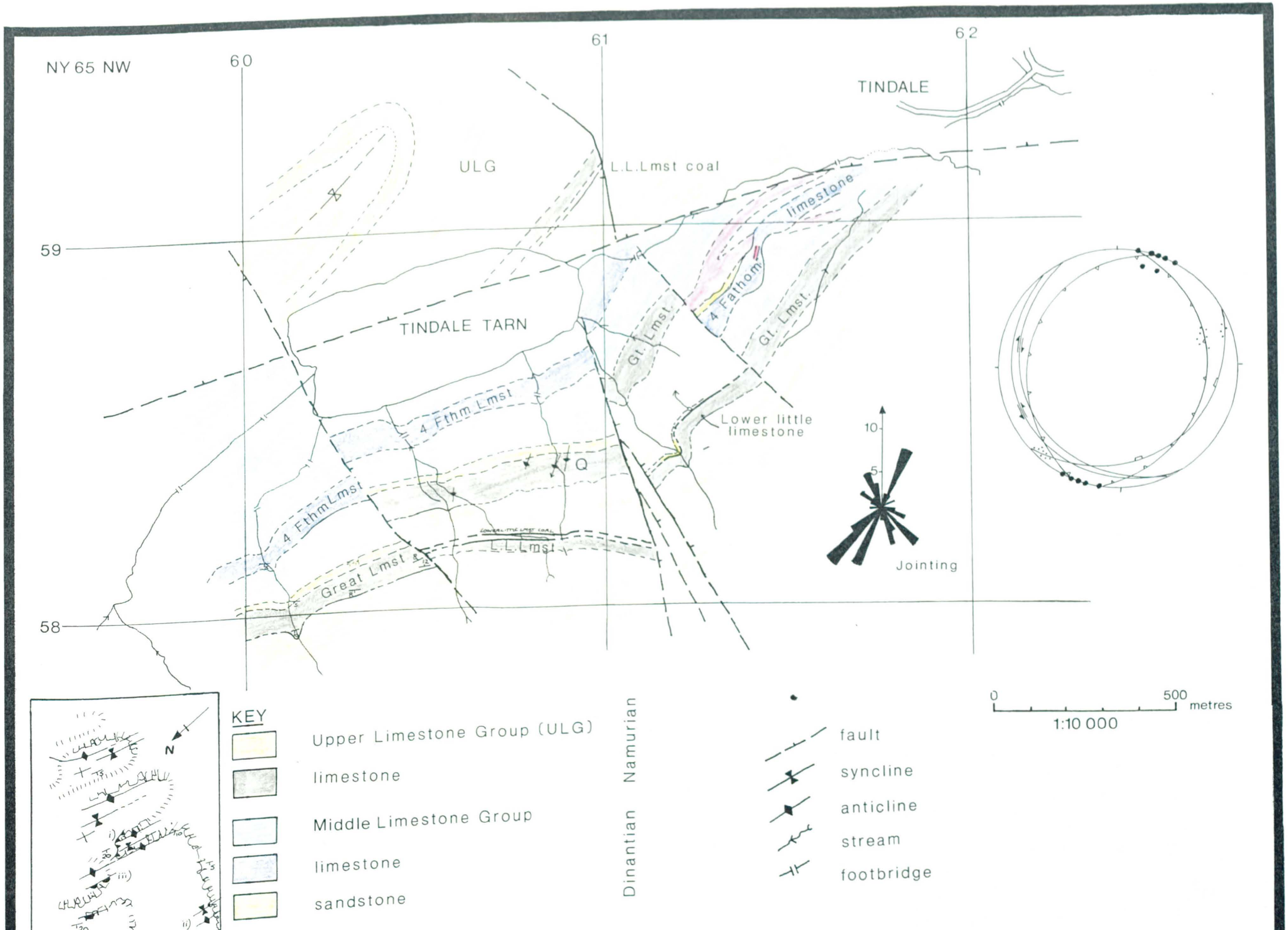


Fig. 69 Map 2, to show region around Tindale Tarn. Inset is a plan of the Tarn House quarries, Great limestone, Tindale.

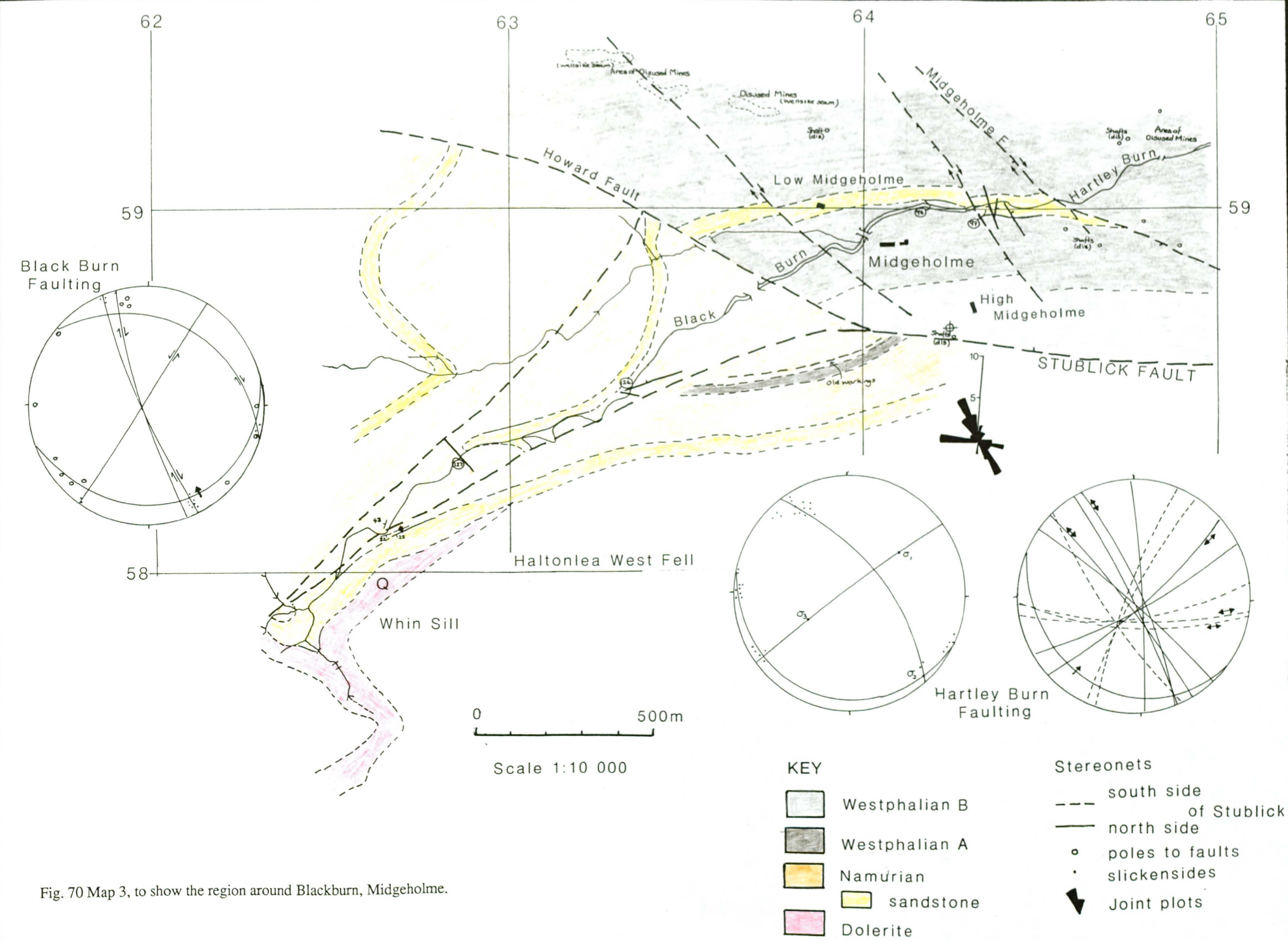


Fig. 70 Map 3, to show the region around Blackburn, Midgeholme.

steeply dipping 65-85° E, with near horizontal slickensides.

South of Stublick fault along Black Burn a succession of well bedded-lensoid sandstones, bioturbated silts and shales are present. The sequences often contain thin carbonaceous shales and plant fragments, including trunks of *Lepidodendron sp.*. Many small faults and fractures dissect the section and the larger faults e.g locality 124 (6323 5852) are sub-parallel to the trace of the Stublick South fault (locally named as the Black Burn fault) with horizontal slickensides indicating strike-slip movement (fig. 71).

South of Black Burn, a thick 3-5m thick crystalline sandstone crosses the river below waterfalls immediately below >4m of Whin Sill. The Whin sill is exposed in disused quarries above the river (6230 5775) and ends abruptly against the unexposed Black Burn fault (see map 3). This implies the fault is later than the intrusion of the sill, but the sill must have changed level from between the Great limestone and the Four Fathom limestone at Tindale i.e. well below the Lower Little limestone and coal to Midgeholme where it is now above the Lower Little limestone and coal (marked by a line of old workings in the map in fig.70). This can be interpreted as follows;

a) the Whin Sill was intruded across the area with no change in horizon, implying the areas between Tindale and Midgeholme were already separated by faulting, so only minor subsequent faulting has truncated the Sill; or

b) the Sill changes horizon by utilising a pre-existing fault. This would mean the sill changed down in horizon towards Tindale, but it could have originally been an upward transgression subsequently displaced by dip-slip movements on later normal faults.

In both possibilities some normal faulting is inferred prior to the intrusion of the Sill and normal faulting must have occurred sometime after the sill intrusion.

Chapter Five
EASTERN NORTHUMBERLAND

Part One
Seismic Record

5:1:0 Introduction and database

Eastern Northumberland has been partially covered by a series of seismic reflection investigations by Hurricane International and by Fina Exploration (UK) Ltd. This study is concerned with the Fina dataset as it covers a section adjacent to the southern margin of the basin in the vicinity of the 90 Fathom fault. Seven lines have generously been made available by Fina (UK) identified as lines F1 to F7 and their approximate positions are illustrated in fig.72. Permission has been granted by J. Staffurth (chief geophysist) to reproduce interpretations of the original data. Unfortunately due to confidentiality agreements the original data cannot be reproduced here.

The lines are migrated stacks forming a rough N/S, E/W grid. They were processed by the company (see appendix II) from vibriosis dynamite sourced data and are normal move-out lines.

The lines were difficult to pick as surface geology maps for the area are currently out of print. However a BGS shallow borehole exists at Throckley, which falls within the NE of the grid close to F3 and F5, permitting correlation down to 600m approximately the level of the Great Limestone.

5:1:1 Interpretations

The lines are presented in a 3D fence diagram in enclosure 4. The lines take the form of line drawings with the Whin sill and Great limestone identified as a tie between each line. The overall interpretation is not scale accurate as this was sacrificed in favour of the three dimensional picture. A plan map on enclosure 4 shows the approximate positions of the sub-surface structure and its relationship to the basin margin.

The original basin margin exists as a buried normal fault WSW-ENE across the area. This margin has occasionally acted as the site for post-rift normal faulting (less than 50m displacements), either as laterally discontinuous fault strands above the original fault but more frequently as listric normals decolling northwards into the Carboniferous sediment - Alston block interface. The Alston block dominates sections F1, F2, F3 and F4 occuring throughout section F4 and as a clear footwall to the buried basin margin in lines F1 - F3. The

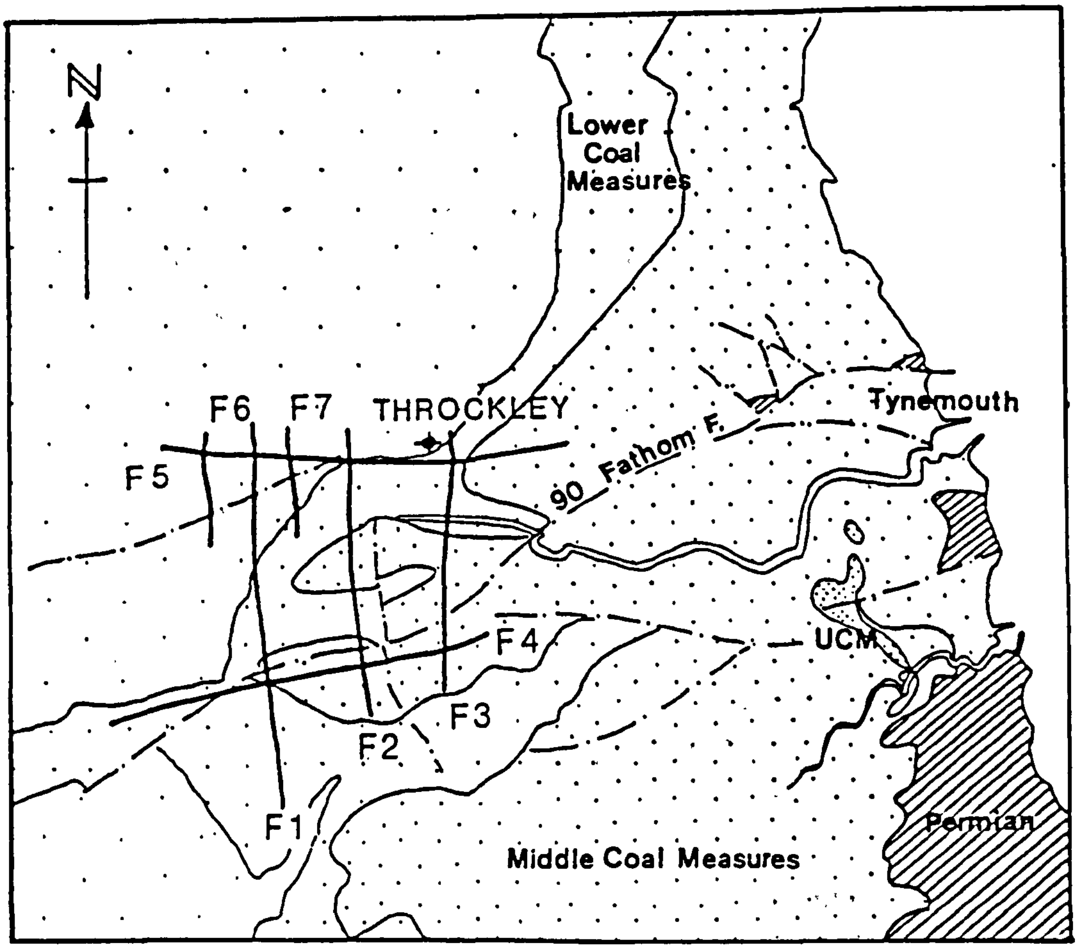


Fig. 72 Location map for Seismic reflection lines F1 to F7 in Eastern Northumberland.

block occurs briefly in the east of line F5 between normal faults marking the basin margin. Line F6 intersects with the basin margin at depth and F7 is entirely within the basin fill. The Throckley borehole identified the Whin sill above the Great limestone in lines F3 and F5, though the Whin sill does change level from below the Great limestone on the Alston block on line F2.

The lines in the lower half of the Namurian and in the ULG, with Westphalian occuring in the SE. The 90 Fathom fault is marked and it can be seen that it is a separate structure to the original basin margin, developed in the foot-wall post-rift cover. The original margin is poorly imaged but its general impression is of a thick Lower Carboniferous sequence (at least 2km) stacked against a fault buried by ?MLG to ULG sediments. Presumably the lateral equivalent of the Melmerby Scar limestone transgression evidenced in the west of the basin/block.

The basin margin is clearly a long lived normal fault showing little evidence for reverse reactivation except where comparison of the plan and the fence diagram reveals that where the basin margin trends more NE/SW the basin fill forms a zone of uplift unassociated with major reverse faulting but forming a SE facing monoclinal structure. This structure trends approximately NE/SW across the section forming a syncline in the east where the basin margin swings back to a more E/W direction. In the west of the area there is no such monocline where the faults trends more E/W but there is a very broad gentle syncline in the hanging-wall (basin fill). There is some evidence for uplift associated with low-angle reverse faulting in line F2 on the Alston block forming a gentle anticline at surface.

Lines F5. F6 and F7 extend to >1.5 sec TWTT (two way travel time) but there is little imaging of basement below the basin fill. At surface there is the topmost Namurian and lowermost Westphalian indicating >2km of sediment in the basin (down to Dinantian).

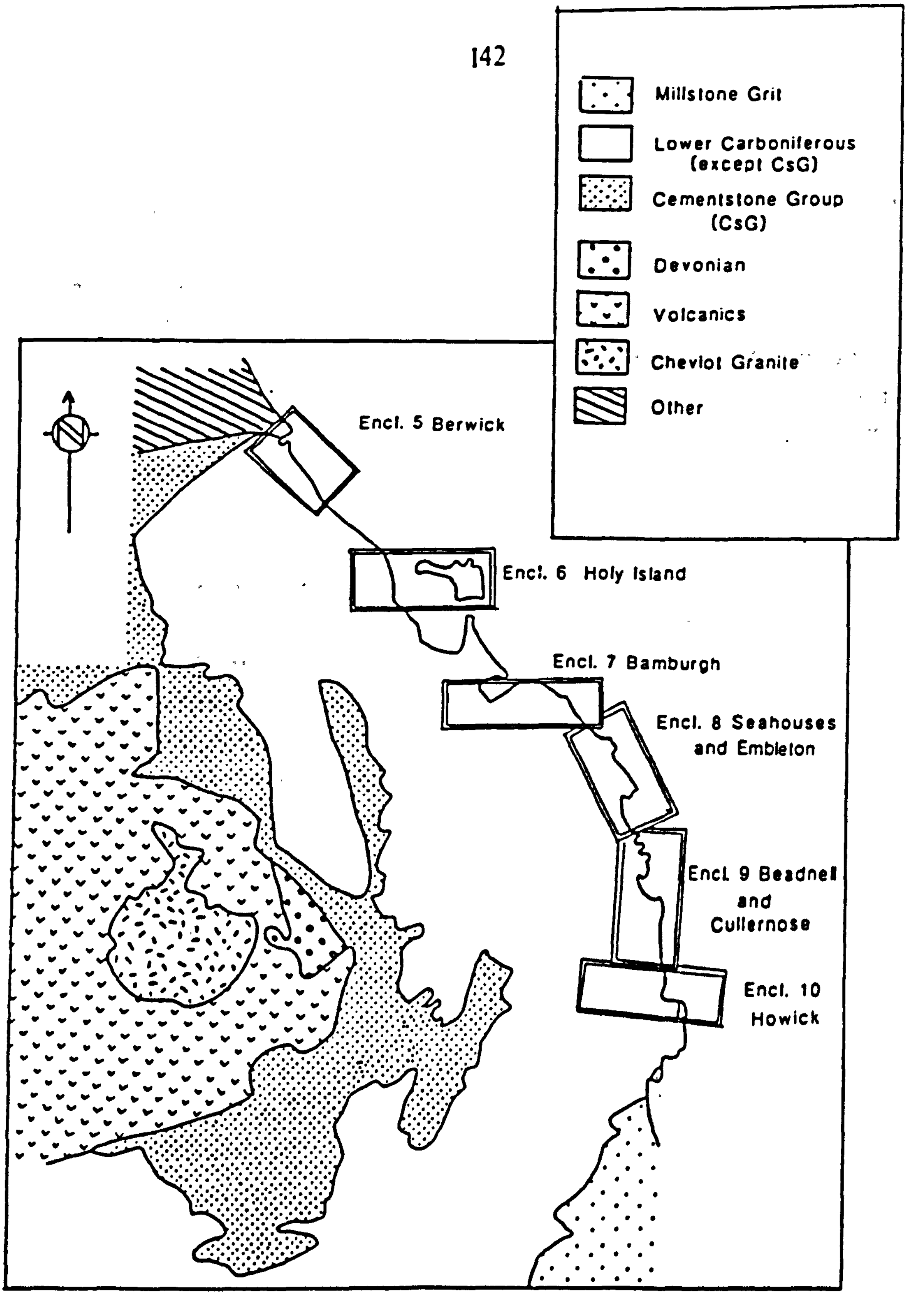


Fig. 74 Map to show locations of map enclosures 5-10 for North-East Northumberland.

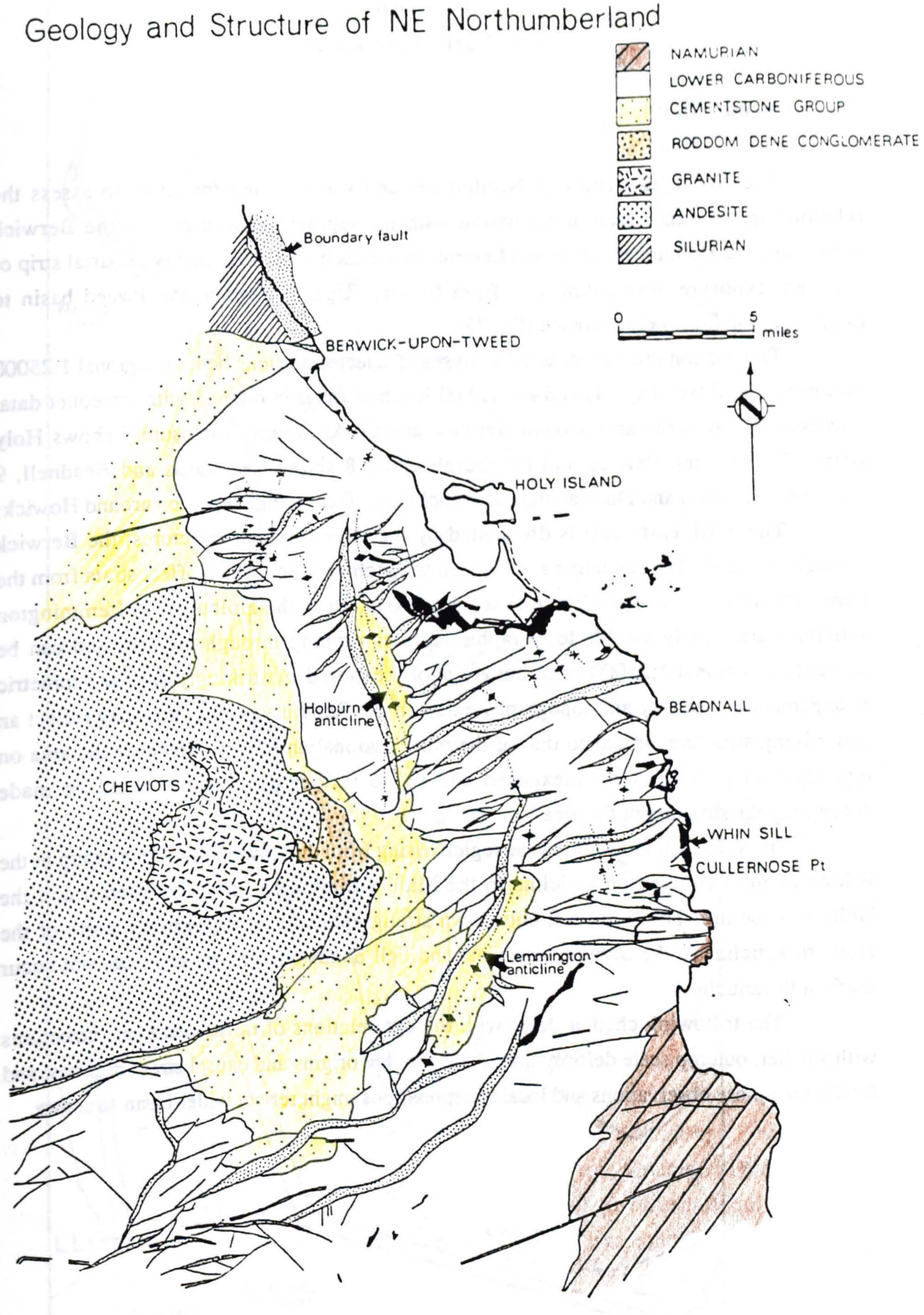


Fig. 73 Geological map of North-East Northumberland to show structure of the Northumberland basin and the Tweed sub-basin.

Part two
The North-East Coast

5:2:0 Introduction

The North East coast of Northumberland was selected for study to assess the relationships of small scale deformation with the regional pattern around the Berwick monocline, the Holburn anticline and Lemmington anticline. The section is a coastal strip of excellent exposure over 55km long from Berwick-Upon-Tweed in the Tweed basin to Longhoughton Steel near Alnwick (fig. 73).

This section presents detailed analyses of selected sections both on regional 1:25000 enclosures 5-10 (see fig. 74) and individual location maps combined with stereonet data. Enclosure 5 shows the area around Berwick and Cocklawburn. Enclosure 6 shows Holy Island, 7 shows the Belford and Bamburgh areas, 8 shows Seahouses and Beadnell, 9 illustrates Embleton and Dunstaburgh with enclosure 10 covering the region around Howick.

The north east coast is dominated by the three regional structures, the Berwick monocline, the Holburn anticline and the Lemmington anticline which affect strata from the Cementstone group to the Middle limestone group. Both the Holburn and Lemmington anticlines are clearly visable topographic features running through the area and can be mapped on regional 1;25000 scale but are poorly exposed. A strikingly similar geometric arrangement of geology and topography exists in the Rothbury region, this may reflect an under lying structure similar to that of the other regional anticlines. However the area on investigation proved to be unexposed and so no further conclusions could be made concerning the structure of the area.

The Whin Sill crops out in the region, rising from the Lower Limestone group in the E limb of the Lemmington anticline to the Middle Limestone group between it and the Holburn structure. The Whin Sill cuts down stratigraphically in the extreme north of the Holburn anticline to the Scremerston Coal and Fell Sandstone groups and does not occur north of the anticline.

The following chapter deals with the age relations of north east coast structures with smaller, outcrop scale deformation, their possible origins and causal stress regimes; and finally how these observations and local interpretations might reflect wider basin structure.

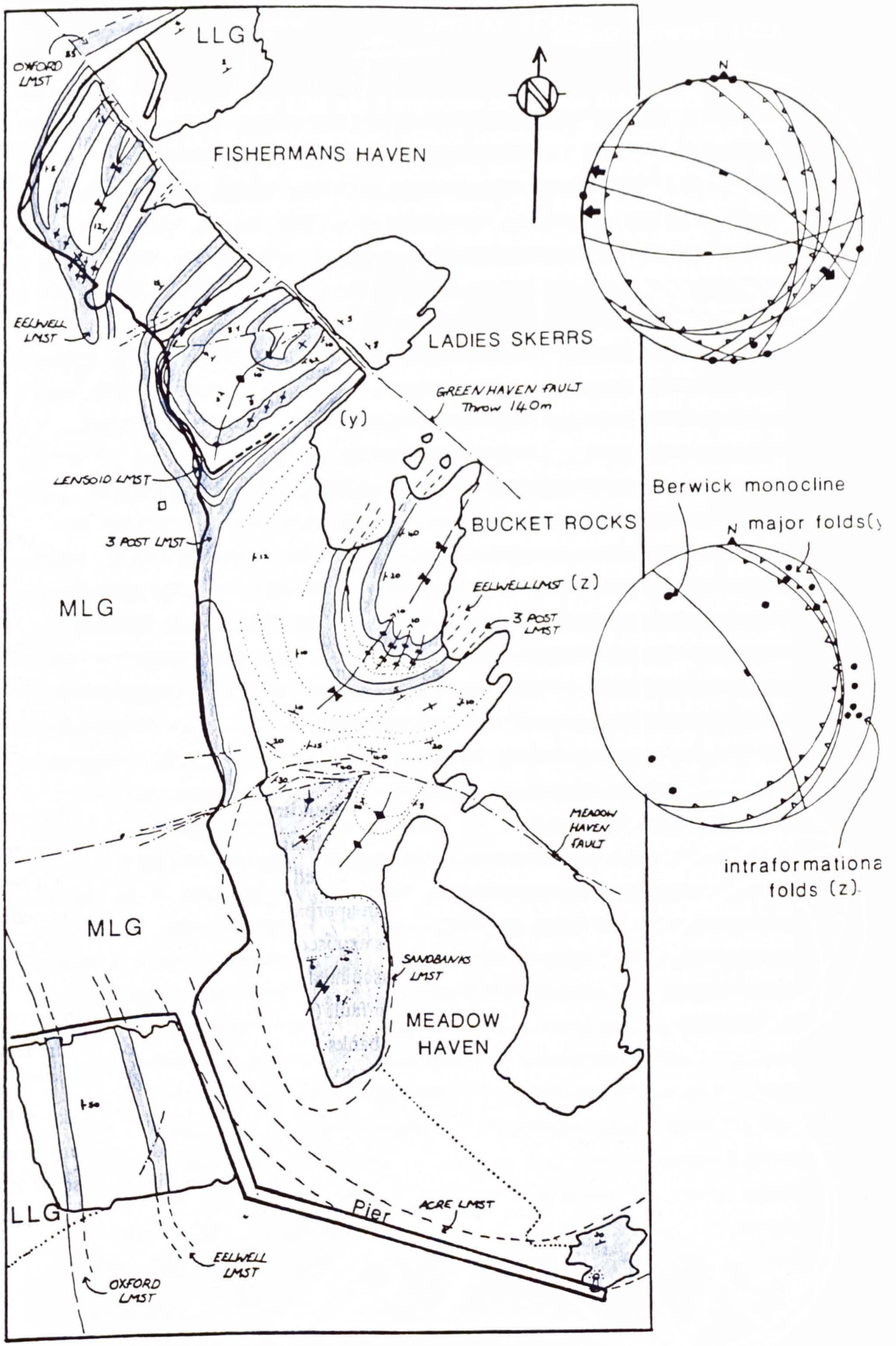


Fig. 75 Detail map of Berwick area as referred to in 5:2:2 i), to show combined geology and stereonet data.

5:2:1 Berwick Region

This area is covered in enclosure 5 and BGS solid geology 1:50000 sheets 1&2. The region exposes the Lower and Middle limestone groups (LLG & MLG) at the coast and the top of the Scremerston Coal group(SCG). The top of the SCG is the Dun limestone, a single (1.3m) bed of dark grey, coralliferous, micritic limestone. The top of the LLG is the Oxford limestone, a distinctive multi-bedded limestone containing numerous irregular red stained algal nodules up to 3cm long.

I) Berwick Foreshore

The foreshore at Berwick exposes strata from the base of the MLG to the Sandbanks limestone approximately 200m above it in the upper MLG. The section is a series of open NE/SW trending folds (see detail map enclosure 5 and fig. 75) cut by the Meadow Haven and Green's Haven (Fisherman's Haven) faults.

The Eelwell limestone occurs in the core of the Bucket rocks syncline, is absent in the Ladies Skerrs anticline and occurs again around the Green's Haven syncline. Where it occurs in the Bucket rocks it is exposed 8m above a thin continuous limestone, a discontinuous calcreted horizon and purple sandy siltstones and shales. The continuous limestone contains no small scale folding in marked contrast to the calcretes and the Eelwell limestone. These are thrown into a series of 3-4 anticline-syncline pairs on the southern limb of the Bucket rocks syncline. The fold are open 1B types dying out vertically over 2-3m, following the main trend of the major syncline, plunging gently 15° NE. The folds are cut obliquely by low-angle ESE directed minor thrusts (<1m displacements). The discontinuous calcrete is cut out by sandy shales below the Eelwell limestone; this contact appears to be planar and may represent a local disconformity (indicating progressive cut-out towards the north). The head of the foreshore at Berwick is marked by a variably exposed 2m limestone of 3 beds. This limestone is gently folded in an approximately NE-E direction immediately north of the Meadow Haven fault. This fault is exposed in the wave-cut platform (WCP) as a series of anastomising strands. The fault is associated with a low angle E-W reverse fault in the WCP where it is truncated against the main fault (see fig.75) as it cuts through the core of an anticline in sands and silts above the Sandbanks (SBL) limestone. The structure forms a fold pair with a syncline in the SBL trending NE/SW and plunging 10°SW.

The 3 bed limestone previously mentioned is unfolded over Ladies Skerrs but is deformed into asymmetric open 1B folds in the SW limb of the major structure. The minor folds in the limestones are up to 1m amplitudes, up to 5m apart trending EW, some 20-40° from the NE/SW direction of the major folds. Both these directions are divergent from that of

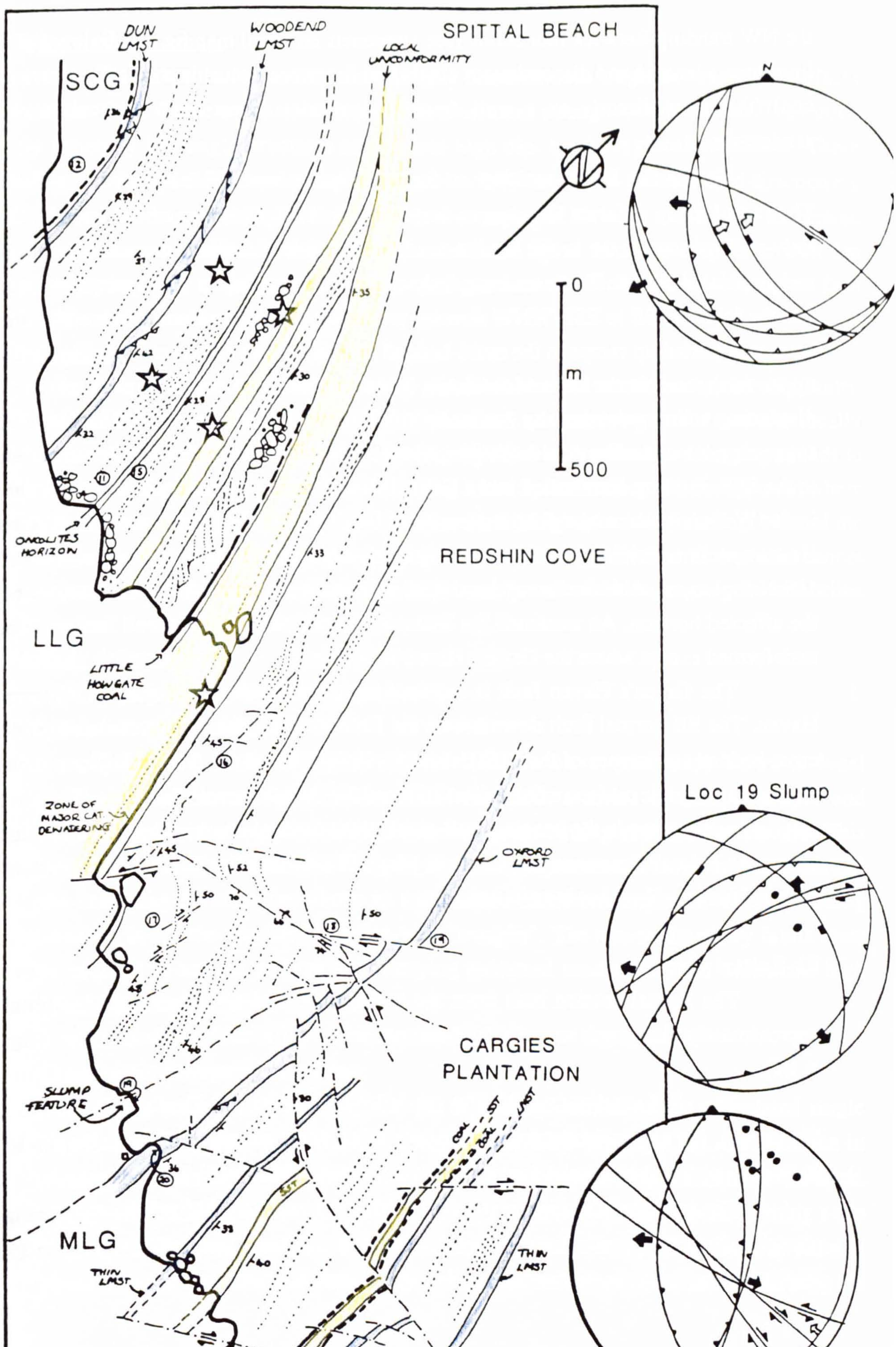


Fig. 76 Detail map and combined data for Spittal 5:2:2 ii).

the NW trending Berwick monocline (see stereonets on detail map fig.75). Below the 3 bed limestone a lensoid and discontinuous single bed limestone occurs immediately above a thin coal (this rests directly on a well developed, rootleted seat earth and calcreted fine sandstones.

The Ladies Skerrs anticline is dissected by a minor NE tear fault in its NE limb. The fault locally deforms limestones, increasing to a displacement of 3m over 10m. The Eelwell limestone at the beach head around Green's Haven displays numerous minor folds and associated thrusts. These are irregularly spaced structures up to 10m apart. The thrusting and the folds are SE to ESE/WNW directed producing hanging-wall anticlines where thrusts have transported up ramps in the multi-bedded limestone. The thrusts transport upwards (i.e up section) towards the axes of the folds, however in at least one example a minor thrust displacing a limestone bed by 1m is directed away from a minor anticline hinge zone; suggesting it was earlier than the folding here. Slickensides on the thrust indicate movement to the ESE. Folding distribution in the Eelwell limestone is irregular, appearing to be absent in the W limb of the major fold and concentrated about the SW hinge zone of the Green's Haven syncline. Folding in the limestone is generally tight, 1B types N/S orientated with 5-10° N-S plunges, with one exceptional ESE axis and does not affect strata above or below the affected horizon. An unnamed 2m limestone occurs above the Eelwell limestone but is undeformed except where the Green's Haven fault cuts it.

The Green's Haven fault is exposed in the cliff behind the quay at Fisherman's Haven. The SE normal fault downthrows the Eelwell limestone against massive reddened cross bedded sandstones of the LLG below the Oxford limestone. The fault plane is clearly exposed as a single surface with vertical slickensides. Minor normal faultlets with up to 2cm displacements occur in the hanging-wall antithetic to the main fault which drag the siltstone below the Eelwell limestone into the fault plane. The Oxford limestone occurs north of the fault at Sharpers Head but is undeformed.

ii) Spittal Section

The Spittal section runs from the southern end of the Promenade at Spittal for approximately 2km south towards the Seahouse on the cliffs north of Cocklawburn (figs. 76 & 81).

The cliff section exposes the top of the Scremerston Coal group (at the Dun limestone), the entire thickness of the LLG and the lower section of the MLG up to the Eelwell limestone, a vertical thickness of approximately 380m.

The strata on this section dip up to 35° in the eastern limb of the east facing SE plunging Berwick monocline. Unlike the Berwick section there is no large scale (50m) folding. Deformation in this section can be categorised as follows;-

1) Intrabed shortening:

This takes the form of discrete laterally discontinuous single contractional surfaces or minor folds. These are characteristic of the limestones throughout this section. The thrusts are generally low-angle structures rotated into high dips by the regional monocline. These thrusts have small displacements no more than 1m E/W directed in their restored direction e.g Woodend limestone (0125 5088). The folds are very open flexures exclusively associated with the thrusts previously described. The folds are up to 50cm in amplitude with 5m wavelengths. They are irregularly spaced tending to occur in thicker limestones e.g the Dun and Woodend limestones.

2) Faulting:

The section is much disturbed by normal faults and occasional strike-slip faults. Locality 18 is a complex strike-slip fault dividedinto anastomising strands around locally overturned strata. Beds swing into the fault (see fig.76) which splits into diverging strands to the east with displacements up to 3-4m. Faulting in the Spittal section is most apparent where folding is absent, but appears to be be older than the folding and minor thrusting. Most of the faults cut the regional high dips indicating a post-monocline age however as the faults cannot be traced through the monocline it cannot be proved that all of the faults are post-monocline formation.

3) Early deformation:

This falls into three sub-categories;

a)Syn-sedimentary faulting;

Below the Little Howgate coal at Redshin cove (see map) below a local unconformity (downcutting to the north) in the LLG, a series of dark siltstones and mudstones occur in triangular sections below a down-cutting reddened sandstone. This locality (0164 5022) is illustrated in fig.79 and are interpreted as a series of listric normal faults extending the siltstones above an undisturbed sandstone sequence. The succeeding sandstones in-fill the resulting hanging-wall "troughs". The syn-sedimentary faults must have occured in-section prior to the overlying reddened sandstones, and before the high regional dips characteristic of this section.

b) Catastrophic dewatering structures;

These are numerous throughout the Spittal section, occuring as isolated single disruptions or as disruption horizons throughout the LLG (see figs.79). One horizon in particular above the Little Howgate coal is ubiquitously dewatered in a horizon 2-4m thick. The thick cross bedded sandstone has been foundered into convoluted beds forming a dip slope in the cliff at Redshin Cove. The dewatering occurs at the top of sequence of channel sandstones and is overlain by undisturbed beds that cut the "escape" structures, indicating the

Fig. 77 Photographs of typical soft-sedimentary deformatio structures in the Spittal area.

A) Collapsed "cone" structure north of localtiy 11 (an isolated, intrabed structure).

B) Disrupted bed in same horizon as A), both starred in fig. 76.

C) Major dewatering in the Scremerston Coal Group, where beds are totally foundered over a wide area (>10m and 2m thick), on main road (old A1) near the Miner's Diner.

D) Close-up of dewatering structures in C) with lens cap for scale (centre) showing truncation against following beds.


A)
B)
C)
D)
0 m 1

deformation was pene-contemporaneous. The isolated structures take the form of collapsed cone shaped structures or discrete laterally discontinuous foundered horizons (see fig.77). These structures form a very small percentage of the total outcrop (<5%) but their density of distribution may suggest they caused by contemporary fault activity, and as they occur around a local unconformity this may be significant.

c) Penecomtemporaneous slumping;

Locality 19 is a unique example of a sedimentary slump. The outcrop occurs as a faulted section in the cliff and was identified by its local thickening of the shales and intercollated sandstones that form the outcrop. The slump is overlain by lensoid reddened sandstones and illustrated in fig.80. The slump is divided into several zones of distinct characteristics as follows;

i) lowermost zone of folded siltstones and thin sandstones approximately 0.6m wide. The folding is bedding parallel, isoclinal , cylindrical and steeply east.

Immediately above this is;

ii) a narrow zone 45cm wide in interlaminated silts and shales of purely contractional structures. These are a series of mini-duplexes and thrusts. Shortening in this section is in excess of 200% and is illustrated in fig.80.

iii) An intermediate 25cm zone that partially overlaps with the previous. This zone contains similar duplexed silts but they are cut by later extensional faults.

iv) The uppermost zone is a series of interbedded silts and sandstones resting on the previous. This zone is cut by numerous normal faults, and these tend to decolle into the intermediate zone and the iii)-iv) interface. The extensional structures in the upper zone have produced rotation of the beds, steepening them eastwards down dip.

The uppermost zone is truncated against the aforementioned lensoid red sandstones. Palaeocurrent directions from the red sandstones are directed north-west which is almost 180^{o} away from directions found in sandstones below the "slump" structure. The zones are interpreted as a basal shear produced in the contractional head of the slump, which become overprinted by extensional structures characteristic of the slump tail as the slump proceeds down-slope (palaeoslope). Data plotted for the slump in fig.76 indicates the direction of the slump was to the SE, though the folds are slightly oblique to this probably indicative of a lateral position in the slump. A full interpretation of this locality is illustrated in fig.101 as part of the structural summary (part 5:2:3).

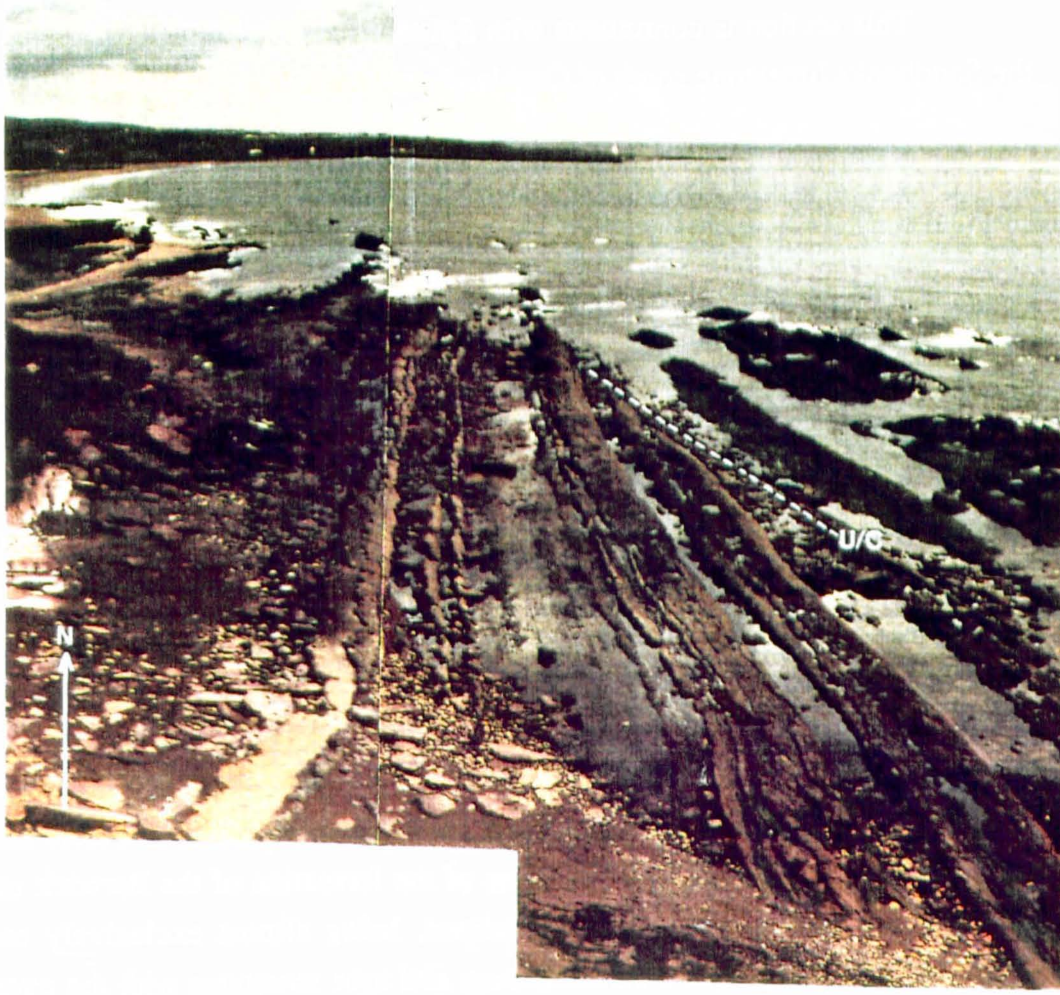


Fig. 78 Local unconformity at Redshin Cove, Spittal in Lower Limestone group.

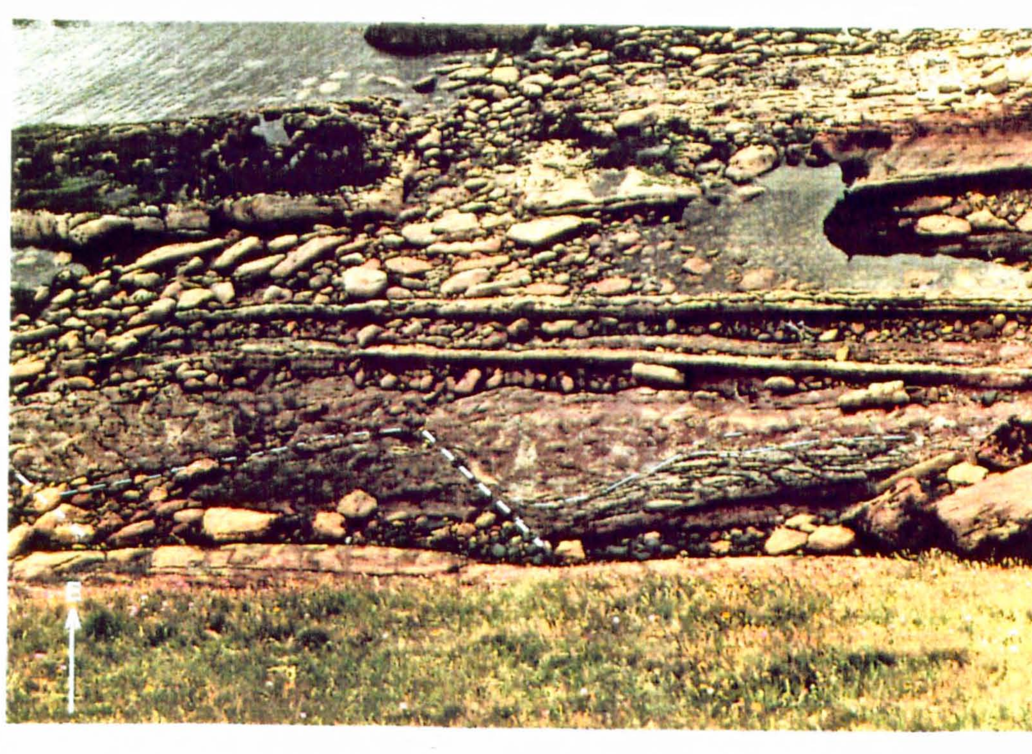


Fig. 79 Syn-sedimentary normal faulting below Little Howgate Coal at Redshin Cove. Note; the offset of the laminated shales by a normal fault (in centre of picture) with hanging-wall "space" filled by subsequent red sandstone, with erosive base.

iii) Cocklawburn section

This section is continuous with Spittal, from the Eelwell limestone in the MLG to the Sandbanks limestone south of Cocklawburn beach (fig. 81).

The Eelwell limestone is 5m thick, composed of 15 beds of shelly micrite with a Fe weathered top (possibly slightly dolomitised). The beds are separated by shale horizons up to 5cm thick. The limestone displays a unique style of deformation. Abundant folding much increases the outcrops thickness from 5-6m to 10-15m).

The deformation takes the form of a series of NNE/SSW trending anticlines and synclines. The folding is closely spaced, 5m apart, of 1-3.5m amplitude and plunges uniformly NNE. Folding falls into the 1B and 1C classes, though class 2 types are not uncommon in axial regions. The folds are generally upright but occasionally west facing, inclined with curvilinear axial planes (see photographs in fig.82). Folding is cut by intrabed reverse faulting geometrically related to the folding. Thrust are orientated N/S to NE and NW with transport to the ENE/SWS. At locality 21 (0240 4942) the limestone is thickened by a thrust and hanging wall anticline (see fig.83) where transport is uniformly to the east. The structure is a series of interbed slip planes, some of which are slickensided. Thickening of the limestone occurs in the vicinity of the thrusts, as a result of bulk transfer (or semi-lithified "rucking") prior to faulting. The thrust transports down dip and is therefore inconsistent with formation of the regional dip at the time of the formation of the Berwick monocline. The folding is lithologically compartmentalised, being almost exclusively confined to the limestone. The folds form a series of cusp and lobe structures with the over-lying shales. Folding is strongly disharmonic with over-lying shales forming longer wavelength folds 10-15m apart. A thin limestone 30m above the Eelwell is largely unfolded and only the Acre limestone (see map) is folded into similar but irregularly spaced structures trending NE.

The Eelwell limestone deformation is cut by steep reverse N/S to NE thrusts, cutting up-section to the NE producing hanging-wall anticlines at the thrust tips. These structures are rotated into high angles and axial regions are associated with 2 sets of en-echelon calcite tension fractures. The earlier vein set is dextrally overlapping, oblique to fold axis and cut by a second later set approximately at right angles to the fold axes. These can be interpreted as having developed during folding, initially as curvilinear axes develop and later as the folds became overturned (see fig.100 in section 5:2:7).

Locality 26 (0245 4903) is a thick 15cm coal above a calcreted and Fe stained micaeous, medium-fined grained sandstone, The coal is repeated by a structural "pop-up". This is a 1m displacement SW directed thrust and a partner 20cm displacement N/S thrust. The thrusts are both low angle cutting up section and cause a zone up to 6cm thick of deformed carbonaceous shale and coal. Above this structure in shales are a number of

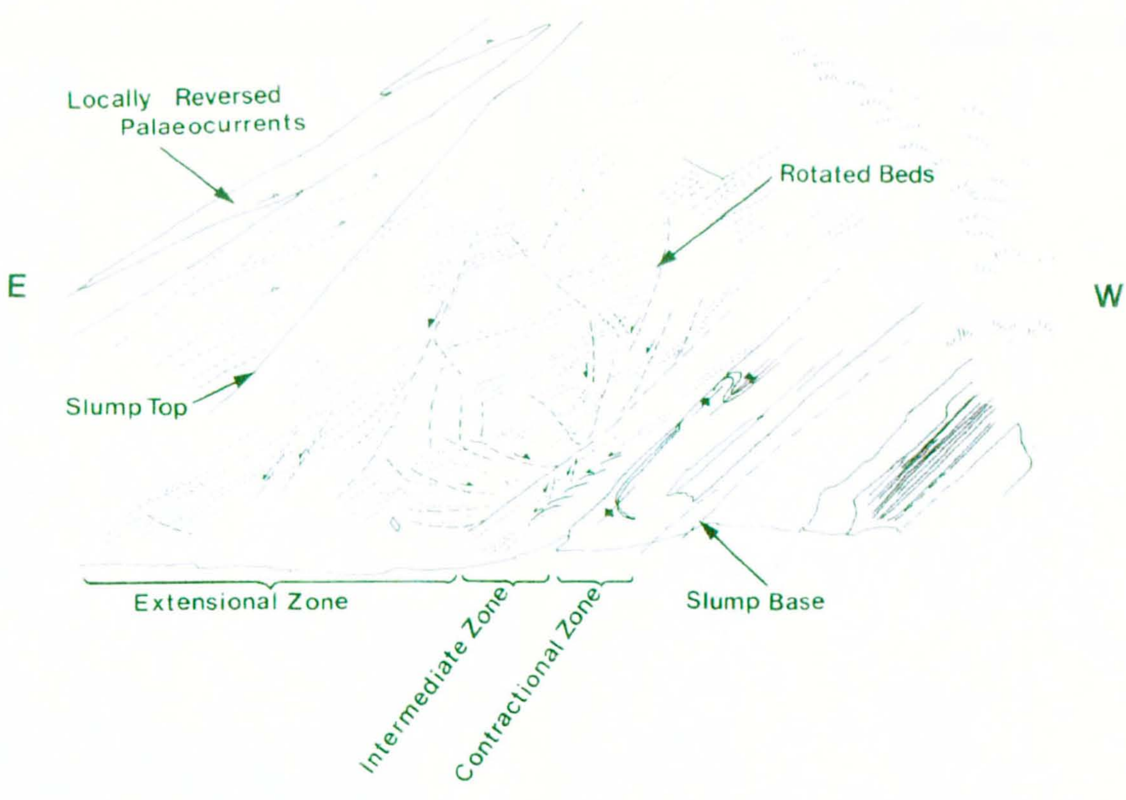


Fig. 80 Photograph and sketch of locality 19 showing penecontemporaneous slump structure.

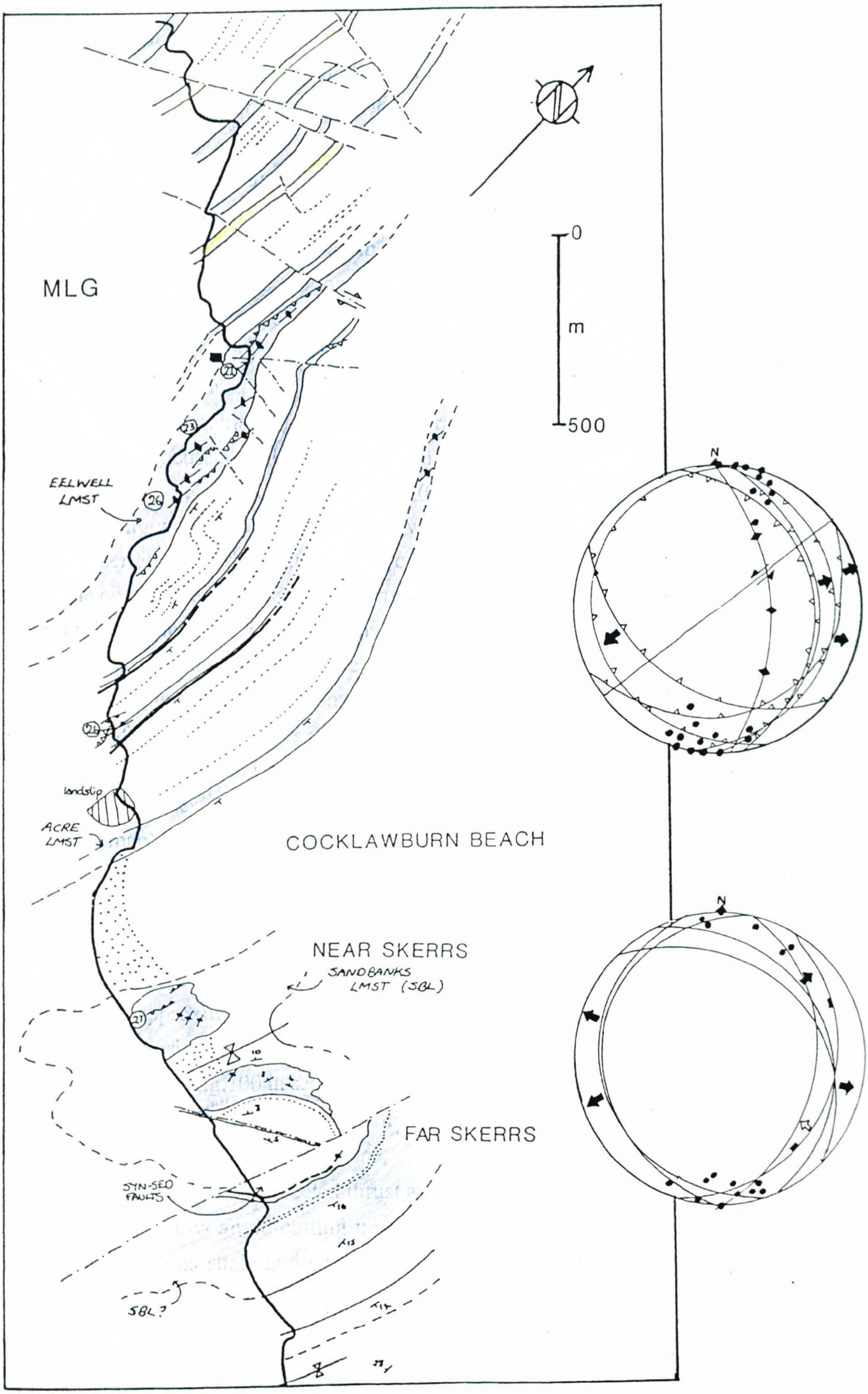
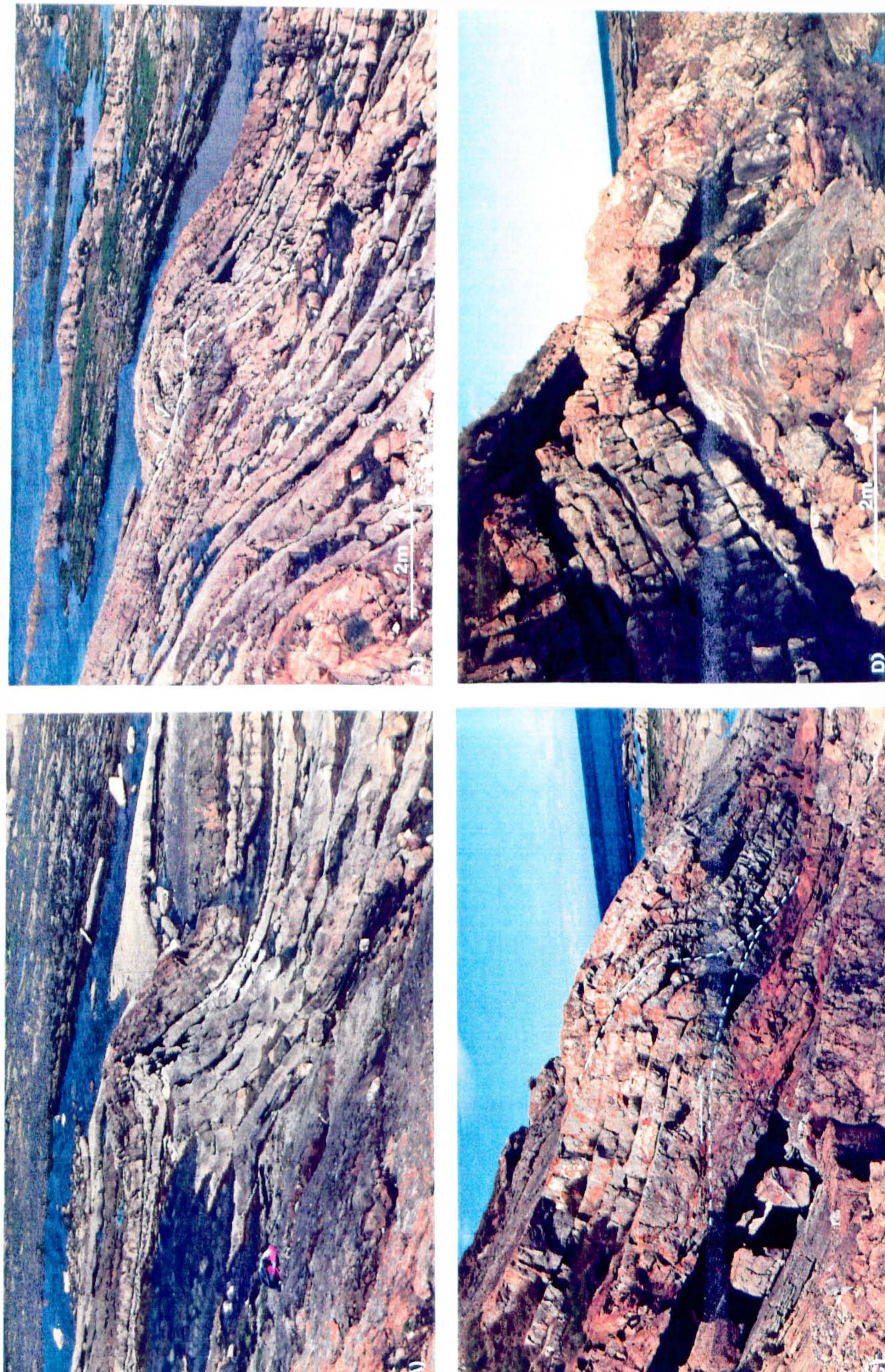


Fig. 81 Detail map and combined structure diagram of the Cocklawburn area (continuous with Spittal section) 5:2:2 iii).


B)
2m
D)
2m
A)
C)

Previous Page

Fig. 83 Photographs showing structure in Eelwell limestone around localities 23 and 26.

A) Upward tightening fold above rucksac, with cuspate fold at limestone - shale interface immediately above.

B) Shows a northwards transporting thrust in the uppermost beds of the limestone. Note the thrust transports laterally with respect to the regional dip and the formation of a hanging-wall anticline above the hanging-wall cut-off.

C) An eastwards transporting thrust in the east limb of the Berwick Monocline. This structure transports down-section, therefore pre-dating regional dip and is associated with pre-thrusting thickening of the limestone around the thrust branch point.

D) Two sets of mutual opposing calcite extension veins in the core of a curvilinear anticline axis.

Facing Page

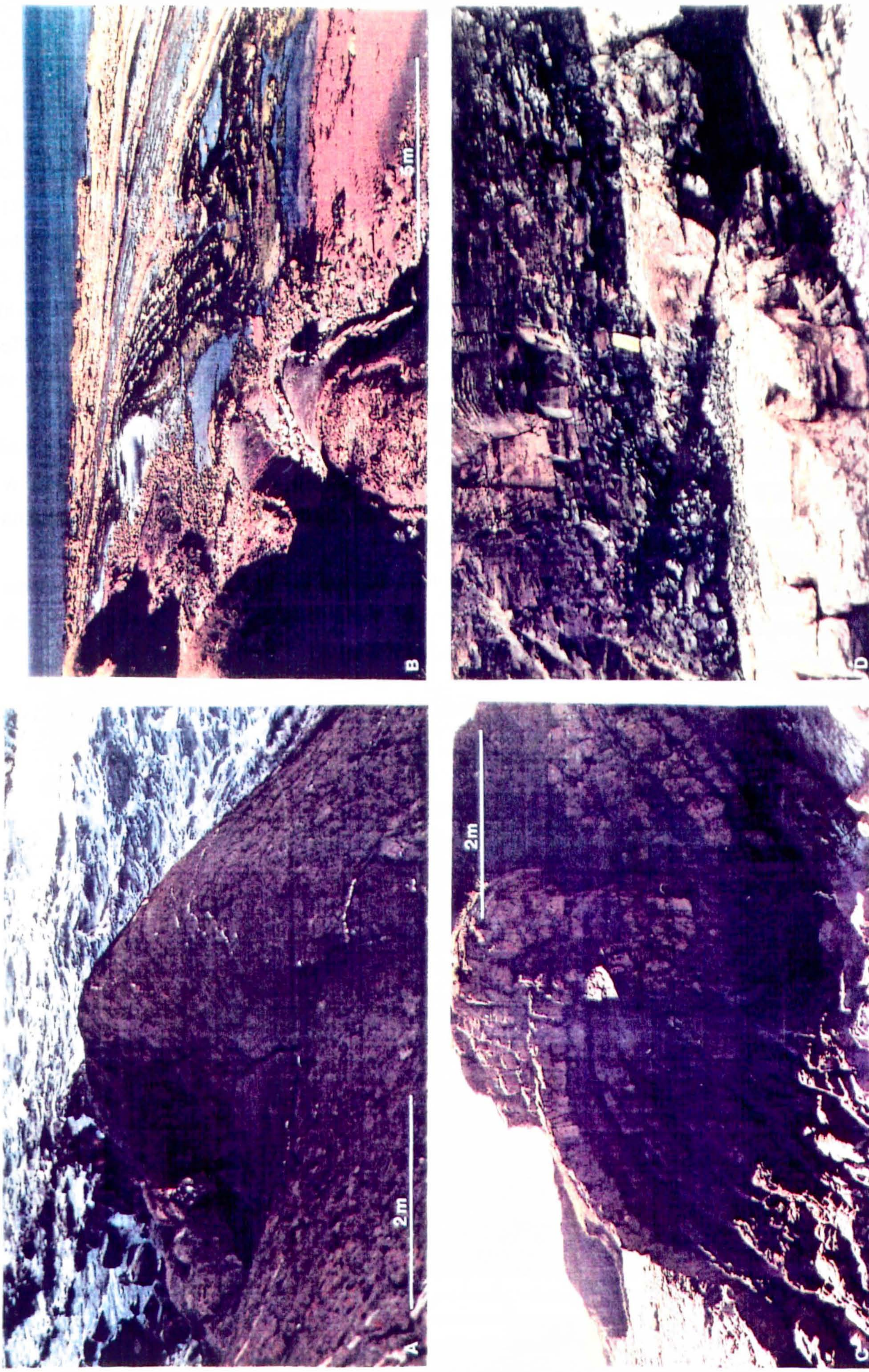
Fig. 82 Photographs of folding at Cocklawburn in the Eelwell limestone.

A) Plunging curvilinear fold axis with oblique calcite veins at locality 21.

B) General view of the Eelwell limestone showing disharmonic folding and cusp and lobes with the overlying shales and silts.

C) Overturned fold pair at locality 24 in the Eelwell limestone (looking south).

D) Reverse faulting in the Acre coal at locality 26. Note back-thrust has formed a "pop-up" type structure.


A
2m
B
5m
C
2m
D

discrete 1-2cm horizons of sheared fabric sub-parallel to bedding. These are interpreted as movement horizons tending N/S to NE/SW.

Folding occurs south of Cocklawburn beach, in the Sandbanks limestone on two scales around the Near and Farr Skerrs (see map). The limestone is deployed into large scale gentle open folds, 150-200m across. These are locally low amplitude <1m open thrust associated hanging-wall anticlines. These folds are not unlike the major and minor fold association characteristic of the Berwick area, but not as well developed. The small scale NNE/SSW folds occur above minor displacement, ENE and SWS directed thrusts (<1m) which can be traced over the limestone, often switching transport direction over local "tear"zones (laterally discontinuous tear faults, up to 20cm long with <5cm offsets e.g. locality 27 (0280 4862). At this locality also are a number of 180° vertical fractures which dextrally displace (up to 5cm) earlier 070° joints and fractures. The gentle folding affects underlying sands in the Far Skerrs but the folding is not associated with thrusts and is very irregular.

At locality 27b (0325 4800) a sequence of fine sandstones and interbedded siltstones shows small scale thickening and early minor normal faulting consistent with formation through synsedimentary fault activity. This is illustrated with a schematic explanation in fig.84.

No further deformation was recorded beyond the Skerrs but isolated outcrops of limestone show such variation in strike and dip that it is likely that folding occurs south of loc. 27. below the Great limestone (see map enclosure 5).

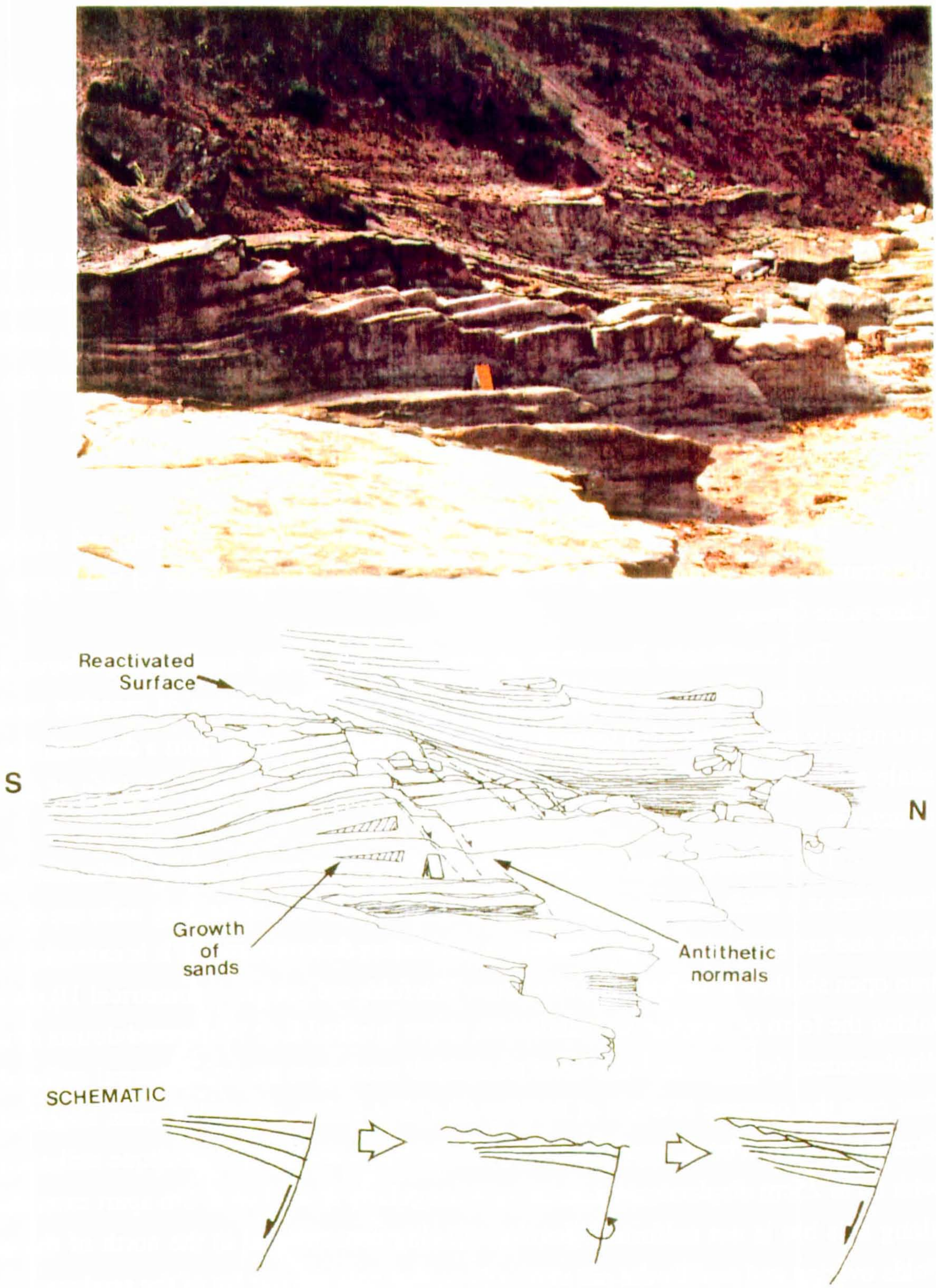


Fig.84 Photograph and explanatory diagram for syn-sedimentary faulting observed at the Far Skerrs (see fig.81) with schematic cartoon illustrating the possible origin of the structures.

5:2:2 Holy Island Region

This is the area covered by enclosure 6 exposing the MLG south of the Berwick monocline in the extreme north-eastern edge of the Holburn anticline.

i) Beal

The Oxford limestone occurs as a feature over the farmland adjacent to Beal Farm (see map encl. 6) but is not exposed. At Beal Point two badly exposed limestones occur (locality 30, 0802 4330) neither of which show deformation typical of previous areas though there is some strike variation. The thicker of the limestones was identified as the Eelwell limestone but was without folding.

ii) North Lindisfarne

This includes the area around Sandham bay, Coves Haven and Snipe Point, illustrated in fig.85 exposing the Sandbanks and Acre limestone of the upper Middle Limestone Group.

The Sandbanks limestone occurs in Sandham bay immediately above a poorly developed coal (up to 8cm thick). The coal rests on a sequence of massive sandstones, extensively cross bedded in lensoid beds. The sands cut laterally into a discontinuous black shale and thin silts. Directly below this 3.5m thick shale is a 50cm horizon of dewatering structures.

The limestone has an unseen top and is a sequence of eight distinctive beds, the basal one is a thick 60cm unit below a calcareous shale. The remaining units are up to 20cm thick and are prone to orange weathering (indicating dolomitisation). It is extensively folded into open shallow anticlines and synclines. The folds are upright symmetrical 1B class, often taking the form of hanging-wall anticlines above intrabed E or W directed thrusts of minimal displacement (<1m). The folds trend NNE/SSW tending to arc into a dextral strike-slip fault that cuts the outcrop NW/SE at locality 32 (1314 4388). As with thrusts observed in the Skerrs at Cocklawburn, opposing transport directions are linked by oblique strike-slip faults with up to 25cm displacements. Folding is irregularly spaced up to 5m apart extending 35m along axis but is not uniformly developed,being concentrated in the north of the outcrop. Folds overlap and rapidly die out vertically so that only the top 1m of the sandstone is gently flexed.

Where the limestone is not folded it has a gentle 20^{o} SE dip. The outcrop is cut by sets of SE/NW en-echelon calcite filled veins. These are often fractured along a mid line and offset dextrally up to 4cm.

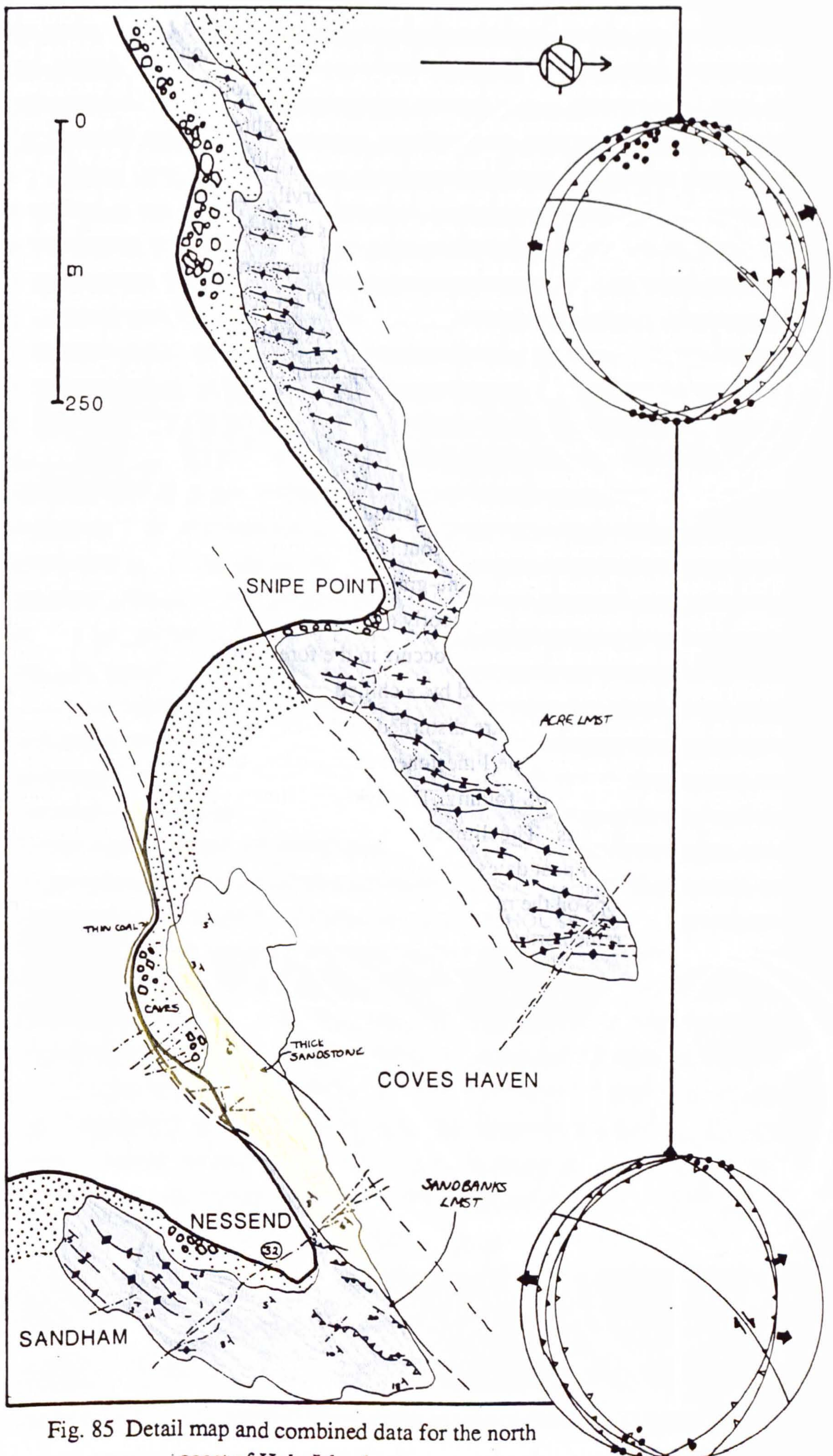


Fig. 85 Detail map and combined data for the north coast of Holy Island.

At Snipe Point, the N side of Coves Haven the Acre limestone crops out, and is deformed in a very similar pattern to the Sandbanks limestone. The folding here is more regularly spaced and uniformly developed over the outcrop. Folding is exclusively 1B class with moderate interlimb angles, >90° though this is tightened to <90° within 3m of a strike-slip fault that cuts the point. The folds are upright, plunging gently SSW up to 10°, 3-5m apart and of 1-2m amplitudes tending to have curvilinear axes passing en-echelon into the next anticline-syncline pair over saddle regions between culmonations. The folds die out vertically as before into neutral surfaces at the limestone/clastic interface. Folding is cut by numerous veins and joints, with a dominant 160° en-echelon vertical calcite vein set. Two sets of joints occur trending 180° and 060°N. As with the Sandbanks limestone, the Acre limestone is disturbed by sporadic thrusts displacing single beds up to 30cm and transporting NE to E/W.

iii) South Lindisfarne

This is the area around Holy Island village foreshore and the Castle foreshore. The Acre limestone occurs immediately south of the remains of the Priory cut by an E/W feature. This is the Holy Island dyke, a fine-grained basic to intermediate vertical dyke up to 60m wide. The Acre limestone is very poorly exposed with no visable folding deformation.

The Sandbanks limestone occurs in the foreshore to the Castle at locality 35 (1356 4166) cut by the dyke and marked by a chilled margin 3m wide in the dyke and a baked 2m zone in the limestone. Both are disturbed by ENE minor dextral strike-slip faulting, with displacements up to 2m. The limestone has a patchy outcrop with variable strike dipping SW-SE which hints at N/S folding. The dyke and limestone are cut by a series NNW/SSE oblique normal faults. The limestones are offset by the dyke by 300m (horizontal displacement) which post dates the regional dip in the area. The dyke belongs to the Whin suite which outcrops on the mainland at Thrumble Hill (0420 4050) in the Scremerston Coal Group, in the extreme northern edge of the Holburn anticline.

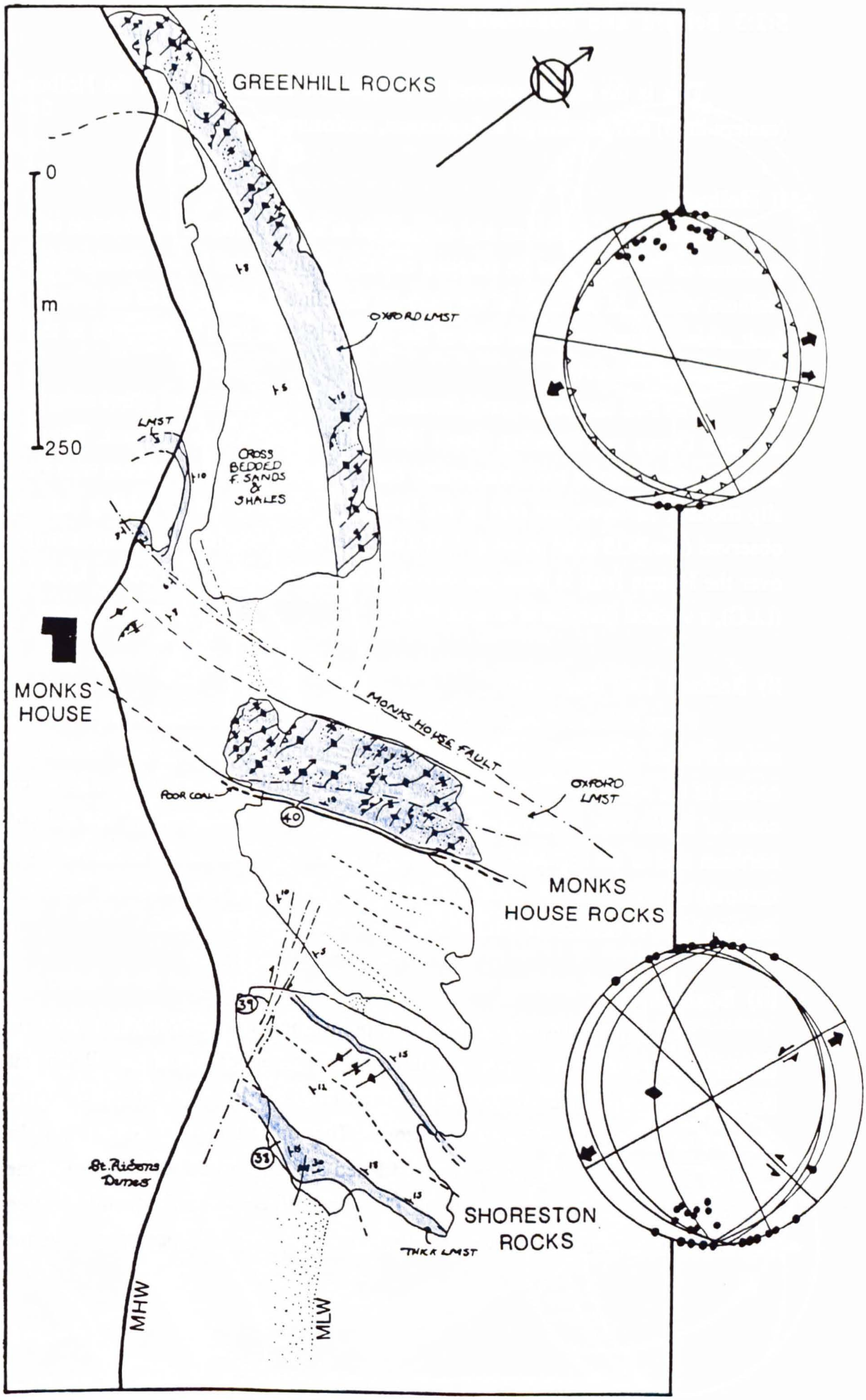


Fig. 86 Detail map and combined data for Greenhill and Shoreston rocks.

5:2:3 Belford and Seahouses

This is the region covered in enclosure 7 from Belford in the Holburn anticline (eastern limb) and Bamburgh to Seahouses, enclosure 8.

i) Holburn

This isn't included on any enclosures as little additional information concerning the structure of this area can be mapped beyond features and broad stratigraphic divisions. Holburn village, in the north of the Holburn anticline is 1/2km east of the trace of the Hetton fault which bounds the west side of the anticline. The fault is a feature at the base of an escarpment running N/S.

The Fell sandstone group forms a series of normal faulted offset units from Lyham, Bowden Doors and Dancing Green Hill to the crags above Holburn. The faults are of southerly downthrows and occasionally the displacements are consistent with dextral strike-slip motion. However not one of the faults was exposed and no folding deformation was observed (see BGS solid geology 1:50 000 sheet 4Holy Island). The maximum displacement over the Hetton fault is from the Scremerston Coal group to the Lower Limestone Group (LLG), a vertical distance of at least 700m.

ii) Belford and Easington

From Belford village to Budle Point (1/2km north of Bamburgh) the Whin sill crops out as a series of irregular oblique sinistral overlapping NW-SE to E/W trending lensoids. It occurs in the top of the LLG at Belford and at the Budle limestone in the MLG on the south coast of Budle bay, approximately 120m higher in the stratigraphy. The sill cuts over the northern end of the anticlinal structure that runs NW/SE from the Bradford Kaims (glacial features) to West Hill (see enclosure 7) clearly post-dating this structure. The anticline is cut through by E/W normal faults with displacements of the 20m order.

iii) Bamburgh

The Whin sill is exposed at Budle point where a series of NNE to E/W faults cut the sill displacing rafts of sandstone and limestone in the upper part of the sill. The sill has a flat base visable below the castle at Bamburgh (1824 3512) where it rests conformably on massive cross bedded reddened sandstones. The top of the sill cuts the Budle limestone at locality 36 (1712 3996), where it is reddened and chloritised and the limestone is locally "baked" (but retains its fossil content). The upper sill contact is frequently faulted by strike-slip faults with displacements up to 10m. The top of the sill appears to have intruded as a

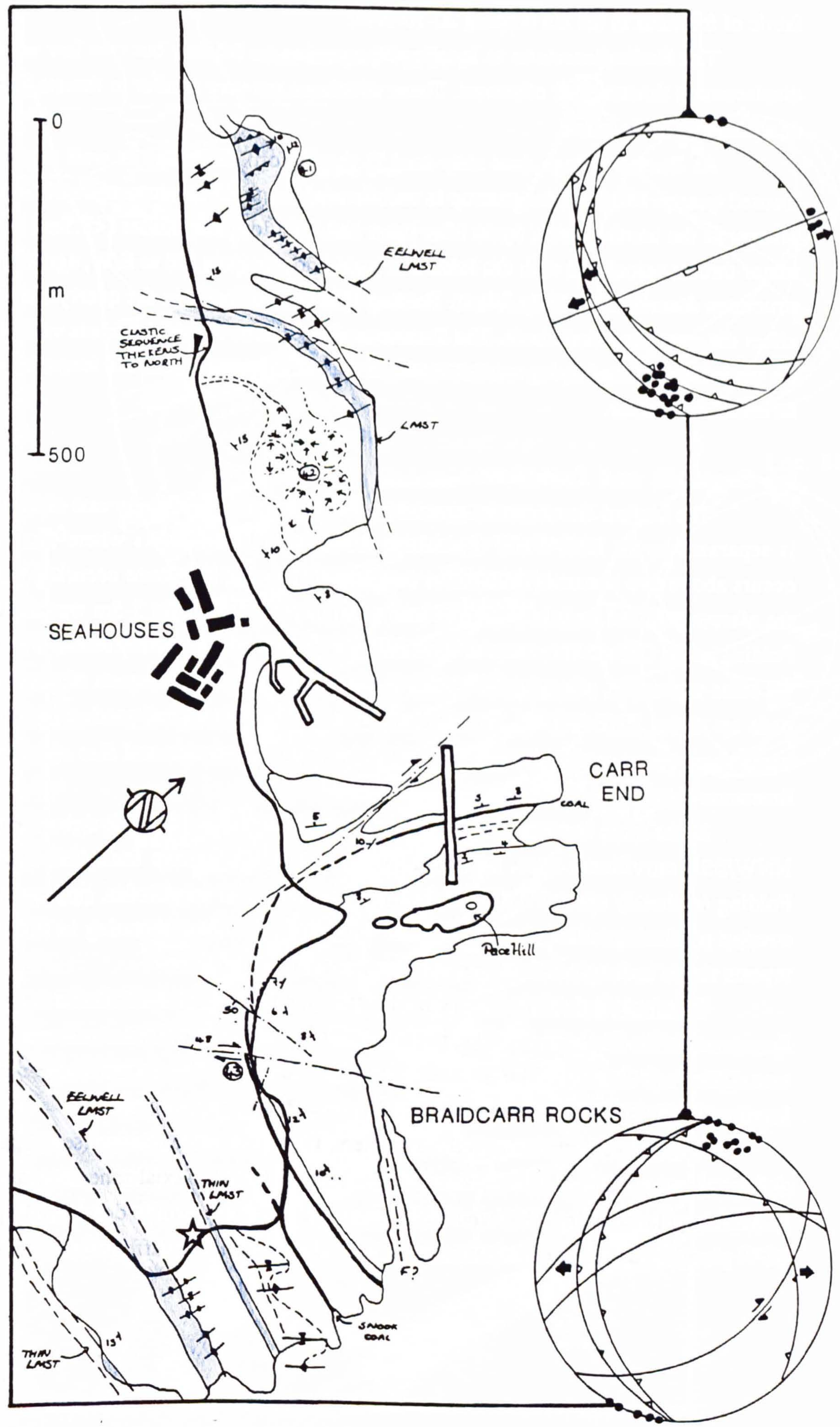


Fig.87 Detail map and combined data for the coast at Seahouses.

series of thin lenses, occasionally trapping slivers of sediment. This has produced a notable fabric of fractures in the sill dipping 20-10°NW.

The Budle limestone at locality 36 contains no folding but two low angle <1m displacement thrusts were observed. These structures are very similar to thrusts previously described for Holy Island.

At Burton village (see map encl.7) the Oxford limestone is well exposed in a disused quarry. Much of the outcrop is undeformed but there are three open 1B class folds present in the south quarry, up to 10m apart and with low amplitudes (<1.5m). There are minor thrusts associated with the folds that appear to transport NE to E/W, again similar to structures described for Holy Island. Folding dies out vertically in the quarry and does not affect the overlying shale beds. The limestone shows some lateral thickness variation with the uppermost 1m bed dying out to the east. It was not apparent if this is a tectonic feature or an erosional surface.

iv) Greenhill and Seahouses

The Oxford limestone is exposed on the foreshore immediately east of Greenhill. It is separated by an ESE/WNW fault from the Monk's House rocks where the limestone occurs above two unnamed limestones (see. fig. 86). A thin limestone occuring adjacent to the aforementioned fault is deformed into a single NW/SE upright 3-5m wavelength fold. Folding in the Oxford limestone at Greenhill is typically upright, gently rounded N to NNW 1B class structures, plunging 20°N and is associated with minor thrusts displacing single beds up to 1m ENE-WSW). The folds tend to be non-cylindrical producing "dome and basin" type structures. Deformation is confined to the limestones and dies out towards the limestone-clastic interfaces.

In the more northerly outcrop of the Oxford limestone folding is tighter with N-S to NNW/SSE curvilinear axes, swinging into a sinistral strike-slip fault (see detail map). Folding is closely spaced as before 3-5m apart with 1.5m amplitudes, and again tends to overlap producing rather elongate "dome" and "basins". Minor thrusting in the limestone repeats single beds up to 30cm, transporting uniformly NE/SW.

Gentle N/S folding occurs in the fine sandstone and dark shales below a thin limestone on the Shoreston Rocks, but the structures are so open that a true axial direction was difficult to measure. The Shoreston Rocks are cut by a N/S dextral strike-slip fault at locality 39 (2068 3340) with an offset of 12m, over 2-3 overlapping strands.

The Eelwell limestone at the Tumblers, 1km north of Seahouses (see detail map) is deformed into parallel, 5-10m wavelength, 2m amplitude folds. Axial zones here are rounded to semi-angular trending SSW and NNE. The north of the outcrop is dominated by a NNE, 10°N plunging anticline of at least a 3m amplitude.This structure affects both the limestone

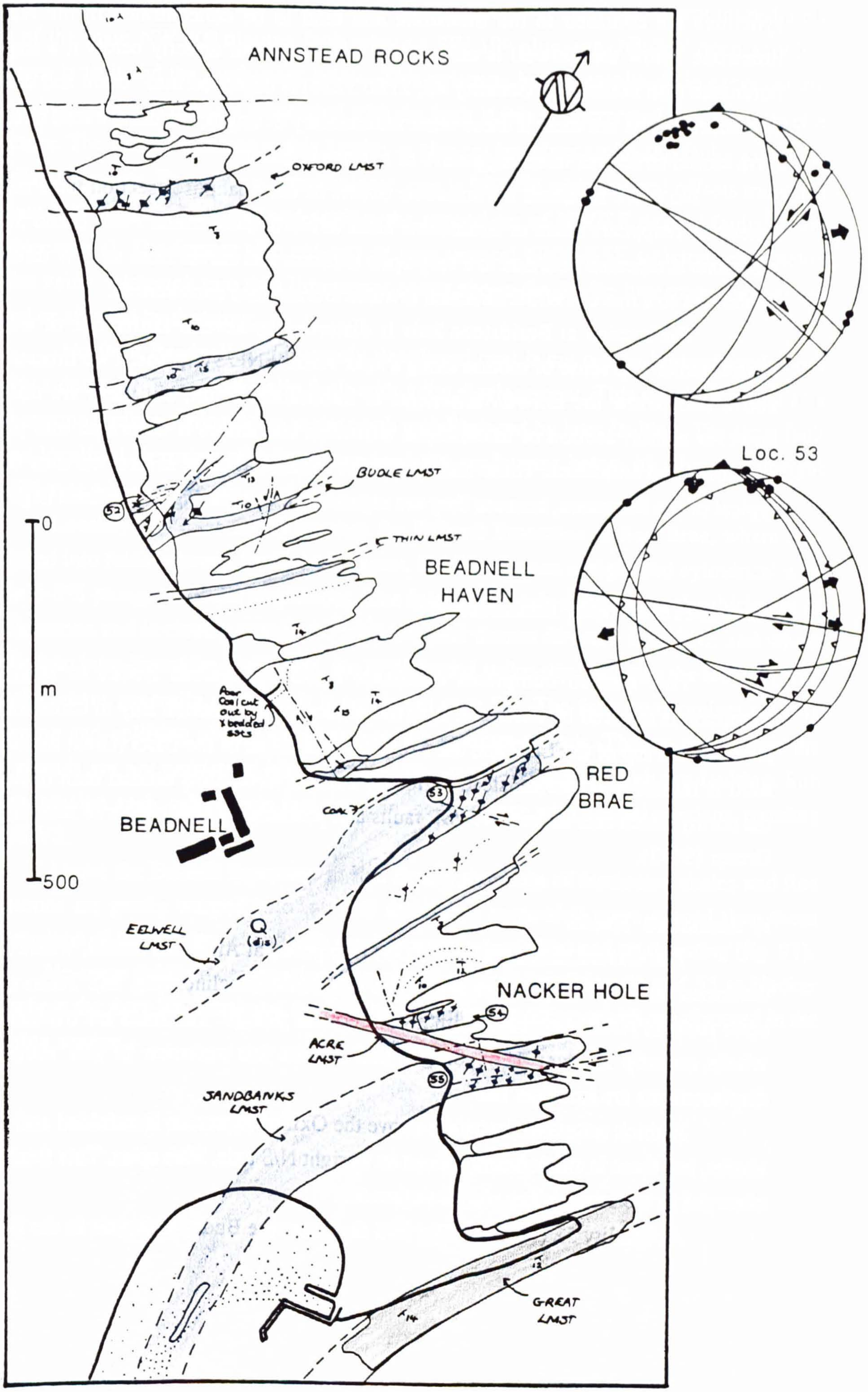


Fig. 88 Detail map and combined data for the region around Annstead rocks and Beadnell

and the surrounding clastics. Smaller scale, regularly spaced (5m) upright anticlines and synclines are confined to the limestone and tend to be concentrated in the NE. A thin limestone below the Eelwell is only gently deformed, but directly below it a sequence of laminated fine sandstones (locality 42; 2180 3236) is deployed into "basin and dome" type structures. It was not clear if these were sedimentary in origin, but units traced over the area form closed structures more suggestive of a tectonic feature.

No more localised deformation occurs in the Seahouses section until the Eelwell limestone reappears south of Braidstone Hole at North Sunderland Point (2280 3148). The limestone is repeated here due to a very open antiform that curves from an E/W direction near Seahouses to a more NW/SE direction towards Burton (see enclosure 8).

The section at Braidstone hole is disturbed by several faults, one of which has a dextral strike-slip sense of motion along a near vertical NE/SW plane. Two limestones occur above and below the Eelwell limestone at Sunderland Point, but these are undeformed; however a short section of interbedded siltstones and shales is deformed into parallel 1B synclines and anticlines. These trend NE/SW, somewhat more E directed than the folding typical of the limestone, because they are asymmetric west facing, W inclined (fig. 87).

5:2:4 Beadnell and Embleton

This section comprises enclosure 8 from Annstead Rocks to Beadnell Bay. Embleton is covered by enclosure 9, in the section from Beadnell Bay to Cullnemose Point. It covers the top of the LLG and the MLG up to the base of the ULG (Great limestone). The LLG is faulted into the Annstead region by a major ENE/SWS normal fault (downthrow to the north) which cuts several NW/SE faults and producing a small inlier of Scremerston Coal Group (SCG).

i) Annstead Rocks

The Oxford limestone (top LLG) is exposed at Annstead Rocks, where it is gently deformed into four irregularly spaced, low amplitude anticlines (fig. 88). These are upright, open parallel NNW structures with no discernible plunge. The folds are traceable over the whole outcrop i.e.over 15m. Single bed thrusts are common in this section but all displacements are less than 1m.

A thick unnamed limestone above the Oxford limestone is unfolded and thrusting is absent, but there is weak flexing about an upright N/S axis, 20m apart. This flexing was not observed in the surrounding clastic sequences.

At locality 52 (2326 2970) a N-S fault cuts the Budle limestone in the MLG, and is associated with several NE/SW subsidiary splay faults, which slice the limestone, interleaving it with the surrounding clastics. The limestone is unfolded except immediately east of the main NW 80° dipping fault where a SW 10° plunging, NE/SW open anticline deforms both it and the sandstones below. This structure has an amplitude in excess of 2m and is interpreted as directly associated with the fault if this is interpreted as a steep reverse structure. The Budle limestone at this locality is also cut by minor strike-slip faults with up to 2m displacements. Two sets predominate, one is NE/SW with sinistral offsets truncated against N/S sinistral fractures and against the second set of NW/SE dextral faults (1-2m displacements). The former also cut sets of near vertical NNW/SSE sinistral en-echelon calcite veins. Although two thin limestones occur above the Budle limestone, neither are folded or affected by thrusting.

North of Beadnell, a thin poorly developed coal is cut out by lensoid sandstones and by a dextral NW/SE strike-slip fault with a 5m displacement. This was interpreted as a local erosion surface cutting down to the north and displaced by later faulting. The same fault causes localised flexuring of a limestone (and the sandstones below it), about an upright NW/SE axis where it tips out.

Locality 53 (2366 2938) exposes the Eelwell limestone at Red Brae, where it is deformed into folds between 5m and 15m apart. Folding is open upright and cylindrical with gentle 6-8°S plunges and 2m amplitudes. The folding is again confined to the thickness of the limestone and is closely associated with intrabed thrusts directed E to ENE and which decolle into intra-limestone shale-beds. An E/W dextral strike-slip fault cuts the locality, with a displacement generally <2m but it is persistent over 5m. The fault anastomises causing tightening and uplifting of fold axes between the separate strands. Thrusts traced over the fault strands are not persistent, implying synchronous development with the faulting. Sub vertical tension gash, calcite vein sets occur in the limestone with dextral overlaps, trending ENE/SWS.

Above the Eelwell limestone at Red Brae a sequence of laminated shales and fine sandstones are gently warped into two N/S anticlines, somewhat more spaced than those characteristic of the limestone, and with smaller amplitudes (<2m) and no thrusting (fig. 91).

No more folding deformation was observed until localities 54 and 55 at Nacker Hole where the Acre limestone and the Sandbanks limestone occur; which are discused in the following section.

Fig. 89 Photographs from locality 55 showing:

A) Low amplitude folding, typical of deformation in the limestones.

B) Typical folding associated intra-bed thrusts. (Thrust plane above left of notebook)

C) Interaction of low angle reverse faulting and calcite veining. Note how the thrust tips out into "wing fractures", and cuts vertical stylolites.

D) Close-up of the vertical stylolites, finger indicating direction of layer-parallel shortening.

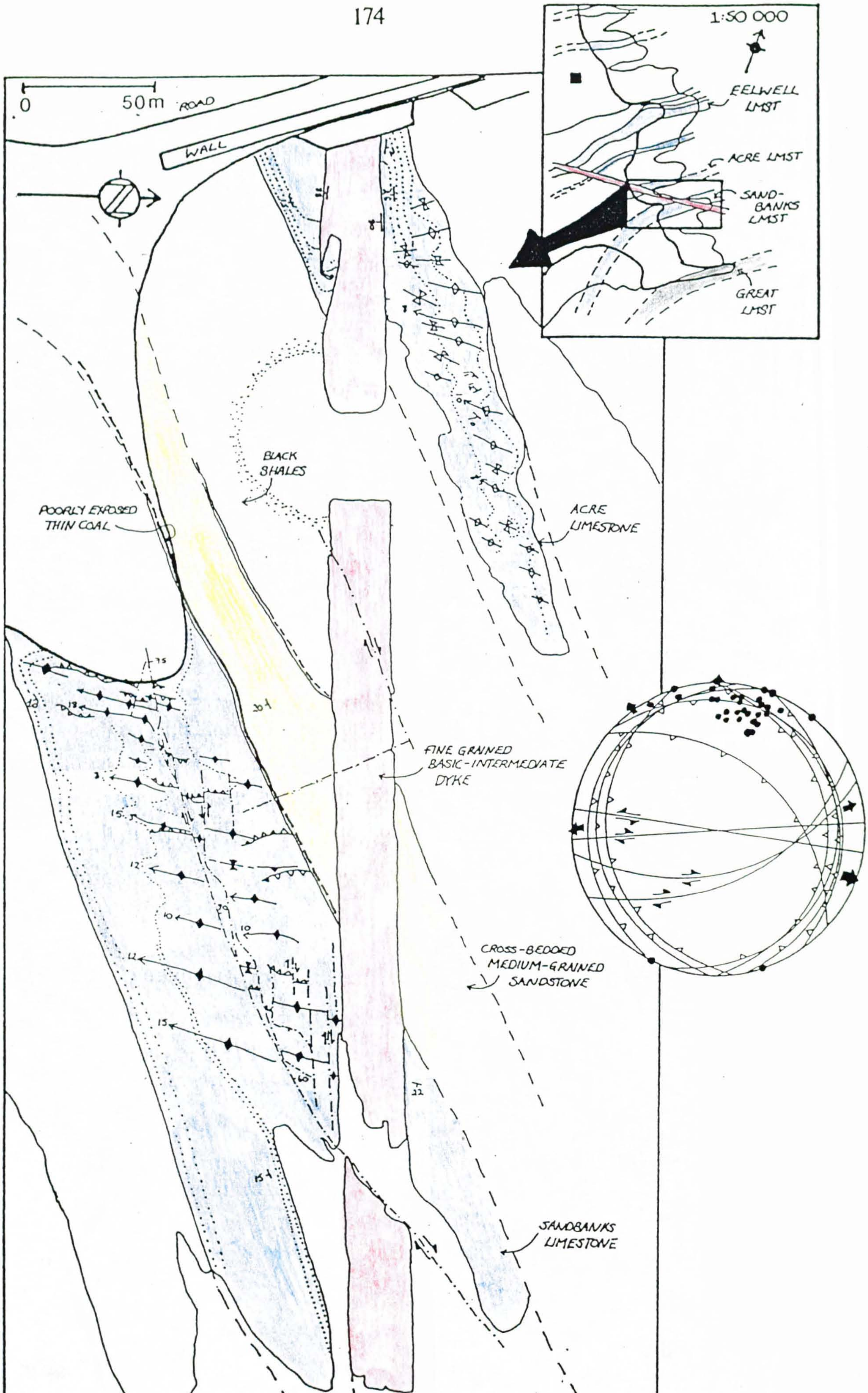


Fig. 90 Detail map of locality 54 and 55 showing the relationship between the folded limestones and a vertical "Whin suite" dyke.

ii) Beadnell

The Acre limestone occuring at locality 54 (2360 2902) is cut by an E/W vertical dolerite dyke. The dyke is a fine grained intermediate to basic intrusion belonging to the Whin sill suite, with minor apophyses intruded into the limestone oblique to the main intrusion trend (loc. 54). The Acre limestone is deformed into numerous closely spaced (2-5m) open parallel south plunging (<10°) folds. The axial trends of the folds are divergent close to the intrusion. Within 15m of the dyke axial traces are NNW but further away become NNE, a swing of 30°. Minor thrusts in the limestone transport ENE/WSW between 50cm and 1m (see fig. 89).

At locality 55 (2360 2900) the Sandbanks limestone occurs and it too is cut by the dyke from locality 54. Both this and the former locality are described in detail in fig.90. The Sandbanks limestone is deformed into closely spaced NNE-NE/SSW-SW symmetrical, parallel folds. The folds have minor plunges to the S, reflecting the dip of the section, and low amplitudes up to 1.5m but are exclusively confined to the limestone.Numerous low angle reverse faults cut the limestone beds, transporting up to 1.2m to the E-W and NW/SE. These structures décolle into inter-limestone bed shales and do not affect the dyke in any way. The outcrop is dissected by an E/W strike-slip fault which cuts the limestone and the dyke. Fold axes are displaced dextrally up to 2m and where the fault divides into anastomising strands, are locally uplifted and tightened relative to the other folds.

This locality contains scattered vertical N/S to NE/SW stylolite surfaces. These are always cut by the thrusts and therefore pre-date most of the deformation, however they do indicate layer parallel shortening has occured in this section (fig. 89).

No further folding was observed in this section; even the Great limestone at Beadnell Harbour is undeformed, although slight variations in the strike of its upper surface might indicate some flexuring.

iii) High Newton-by-the Sea

High Newton is situated between Beadnell and Embleton Bay (see enclosure 9) covering a limited stratigraphical area fromthe top MLG to the lower ULG around the Great limestone.

The Whin sill is intruded into the section immediately below the Great limestone approximately 225m above its intrusion horizon at Bamburgh (around the Budle limestone). Immediately below the sill at locality 57 (2394 2602) a series of antiforms occur in a sequence of micaeous, fine grained cross bedded sandstones. The deformation does not extend however, to the shales immediately below. The antiforms are very open NNE/SSW structures tending to alternate between dome and basin type structures, especially within 10-

15m of the sill trending more NW/SE.

A series of normal faults along the High Newton section repeats the Whin sill-Great limestone association, three times. No folding deformation was observed over the section, however in St. Mary's Haven (Newton Haven) a 10m thick section of interlaminated silts and sandstones below the Whin sill (same horizon as described above) forms a single open 10m wavelength, SE plunging (10^o) anticline/syncline pair. This structure is rather angular for a sedimentary form but it is unlike any folding observed elsewhere and so their origin is unclear, although are tentatively interpretated as tectonic folds as they occupy the same horizon as at locality 57 (below the Sill).

5:2:5 Dunstaburgh

i) Grey Mare Rocks

The Whin sill occurs at Dunstaburgh castle, forming an imposing cliff >10m thick above a clastic sequence and the Sandbanks limestone. This is approximately 35m lower than its intrusion level at Embleton.

The Sandbanks limestone crops out in a disused quarry at locality 61 (2544 2215) and on the foreshore, east of the quarry (illustrated in fig.92). The limestone is folded into a series of tight N-S to NE/SW anticlines, slightly overturned to the east. The folds are irregularly spaced up to 10m apart, are curvilinear with axial zones tending to 1C class structures. The folds are associated with two minor thrusts with transport directions to the NE-SW. One of the thrusts occurs in the axial zone of a syncline and is itself folded around the fold axis, suggesting it was formed at an earlier stage to the folds. The folding is generally upright but steeply inclined axis are not uncommon. The starred localities in fig. 92 are folds with curvilinear axis and in the cores contain multiple tight "foldlets" trending oblique (more N-S) to the main axis.

Several strike-slip folds cut the outcrop displaying minor dextral displacements up to 1m (see stereonet and map in fig. 92). The outcrop is truncated to its northern side by a sub-vertical sheet of Whin sill type dolerite. This intrusion is at least 3m wide, and where it is in contact with the limestone it is extensively veined by calcite and chlorite.

The presence of rather atypical folding at this locality may reflect a different deformation mechanism.

The change in level of the sill from below the Great limestone at Embleton to the Sandbanks limestone at this locality reflects either;

a) a climb or jump of stratigraphy by the sill of 35m over 2km.

b) a pre-existing normal fault offset between the two localities, subsequently truncated by the Whin sill.

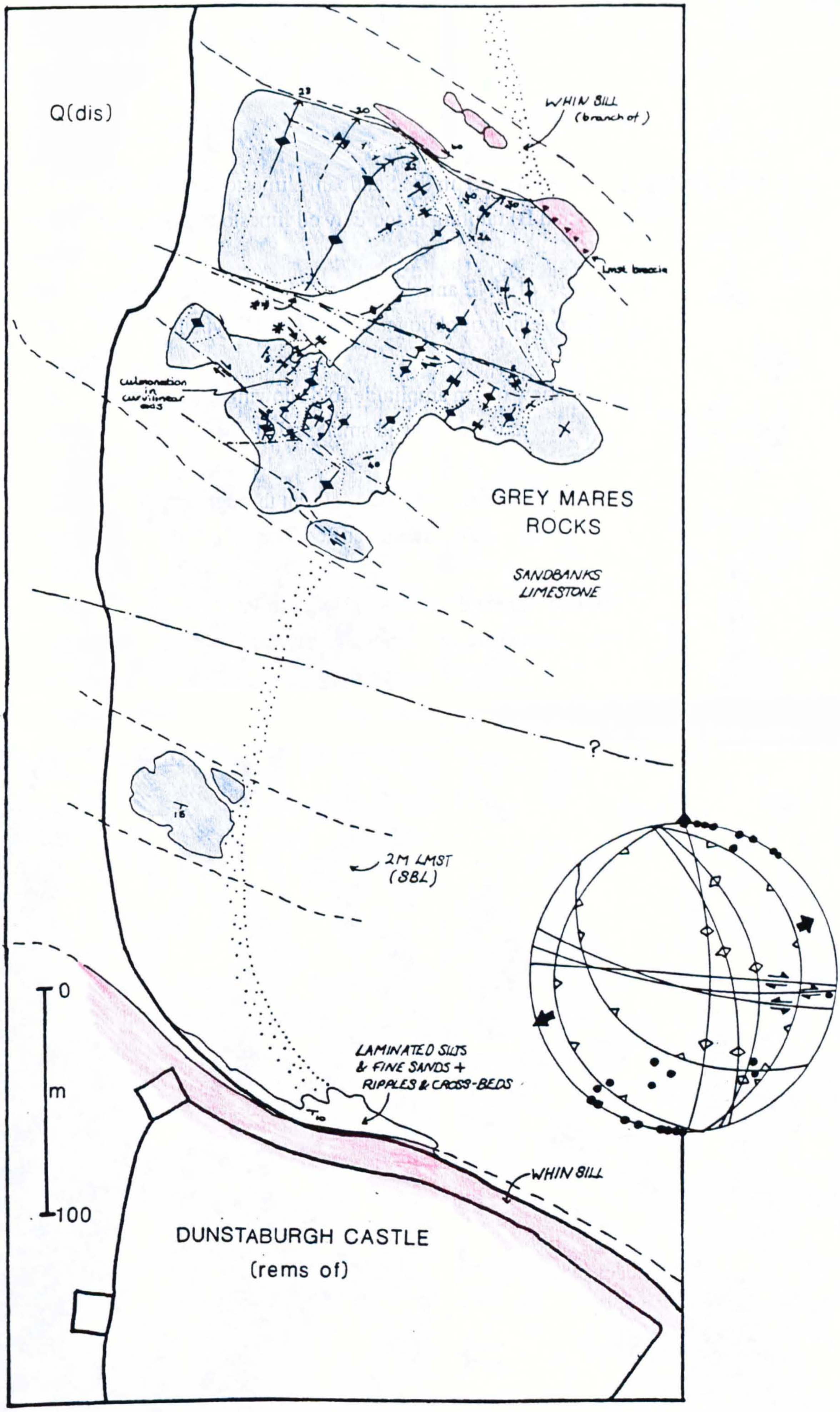


Fig. 92 Detail map and data for the region around Grey Mare rocks, Dunstaburgh.

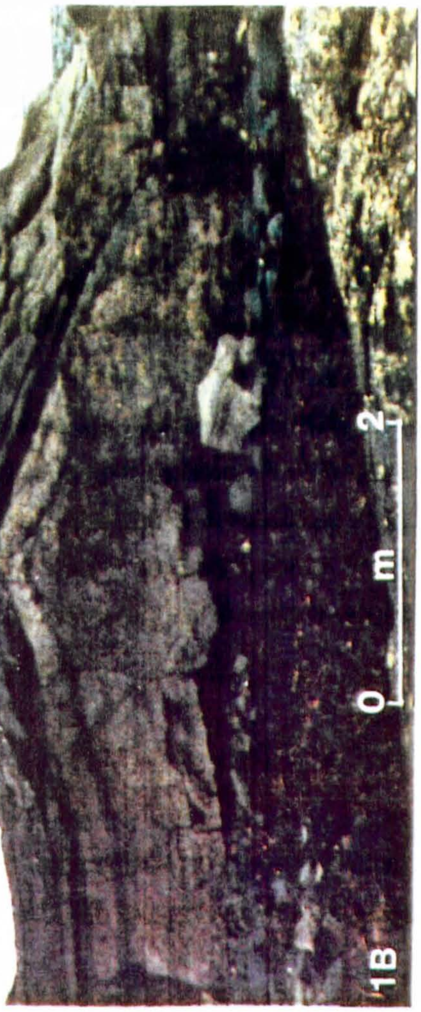
Fig. 91 Photographs of A) folding in the Sandbanls limestone at Grey Mare's Rocks (see Fig. 92) and B) faulting in the Eelwell limestone at Red Brae.

1A) View of NNE anticline (starred in fig. 92) displaying core region of oblique "rucks" in a 1C type fold.

1B) View of 2m amplitude fold showing thickened axial region and small scale folds.

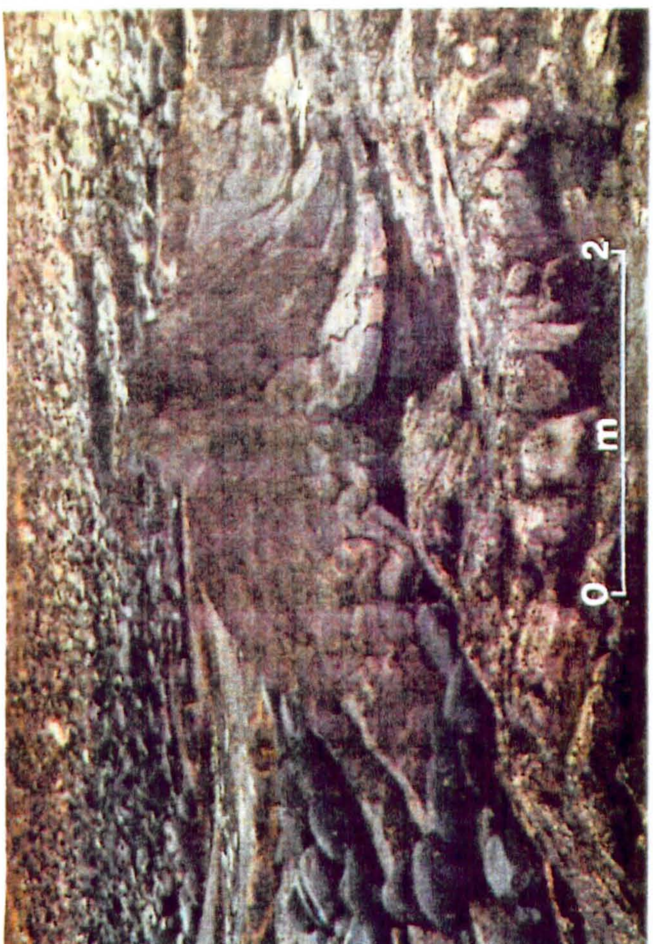
2A) Dextral extensional vein sets cut through by minor E/W faulting at Red Brae.

2B) Curvilinear dextral extensional strike-slip faulting without calcite veining, with a displacement <2m, at Red Brae.



1B


2B



1A


2A

c) a regional structure, raising the level of the Sandbanks limestone in the Dunstaburgh vicinity, e.g.an anticline.

The author favours the first two interpretations with b) as the explanation.

ii) Dunstaburgh to Cullernose Point

The Whin sill occurs above the Sandbanks limestone from Dunstaburgh castle to Cullernose point. It is cut by at least two major faults with unknown normal displacements, one at Cushat Stiel (see enclosure 9) and another at Craster; and several smaller NE sinistral strike-slip faults. The sill is undeformed apart from the faulting. Its upper 5m is composed of sub-horizontal units up to 1m thick. These units tend to have vesicular bases and very fine grained tops with a series of "gutter" structures trending 035°N. This structure possibly indicates a multi-phase intrusion event rather than a single homogeneous pulse.

5:2:6 Howick Region

This coversthe area from Cullernose Point, around Howick and Longhoughton Steel from the MLG to the ULG and Longhoughton Grits (upper ULG) and is cut by a series of major E-W faults.

The Whin sill occurs at Cullernose Point above the Sandbanks limestone on the coast and occurs at progressively lower stratigraphic levels inland to the Acre limestone around Howick village. South of this, the sill changes horizon again to below the Great limestone at Longhoughton village. Further south still of enclosure 10 the sill cuts down into the MLG and then into the LLG in the central region of the Lemmington anticline. The sill finally starts to cut up section as it leaves the anticline (see BGS solid geology 1:50000 Alnwick sheet) and heads across the basin.

i) Cullernose Point

The Whin sill crops out at the cliff in two sub-horizontal sheets. The main sill is >10m thick and intruded into a series of coarse grained cross bedded sandstones. The second sheet overlaps the first and this can be interpreted as the result of intrusion along a pre-existing fault (see fig.93).

The Sandbanks limestone (fig. 94) is extensively folded into irregularly spaced sub-parallel folds (2-8m apart). The folds are gentle 1B type structures associated with minor interbed thrusts transporting ENE/WSW. The limestone is cut by a NE/SW basic igneous dyke which displaces it sinistrally and is associated with sub-parallel and oblique strike-slip

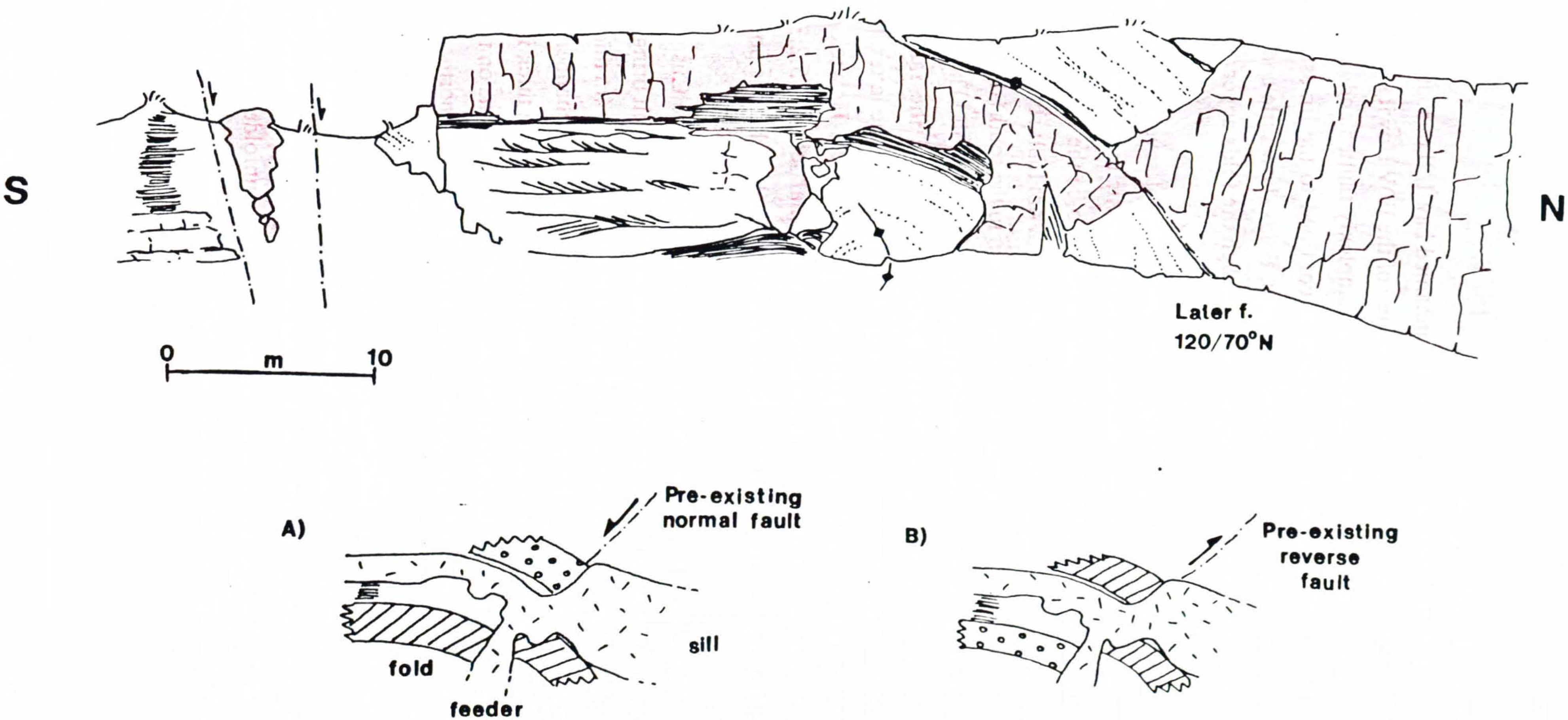


Fig. 93 Sketch of the locality around Cullnernose Point showing the Whin Sill intrusion; and alternative schematic development for the observed structure.

faults. A second NE-SW sinistral strike-slip fault cuts the section south of the Sandbanks limestone. The Acre limestone crops out as an anticline culmonation in the wave cut platform.

ii) Howick Fault region

The Acre limestone occurs in an unnamed bay 1/2km south of Cullnerose point at locality 70 (2590 1806) adjacent to the exposure of the E/W Howick fault. The region around the Howick fault and the Acre limestone is complexly faulted and deformed by a series of E/W faults and NNE/SSW folds. Folding is confined to the limestone but is irregularly spaced as tight, north plunging parallel 1B folds. Folds show little continuity over the faults and so displacement directions are unclear although the folds appear to have been initiated prior to the faulting.

Locality 71 (see fig.95) shows the interaction of several faults. The main Howick fault throws the Acre limestone against a series of clastic units and a thick 15cm coal. The main fault has a throw of 215m, if the coal is taken to be the Parrot coal below the Lickar limestone in the ULG. The Howick fault is series of 2-4m fault strands and minor synthetics. Locality 71 shows a listric normal fault (downthrown to the south) décolling into the coal and cut by a normal (down N) fault, antithetic to the Howick fault. The former (see fig.96) is associated with thickening of carbonaceous shales above the fault plane and can be interpreted as a contemporary fault. This structure is cut by the latter, post dating the syn-sedimentary activity and may be temporally related to the Howick fault. A structural reconstruction of this structure is presented in the final section (5:2:3). Some low angle reverse faulting occurs in this section, illustrated in fig.96, which is post-dated by the E/W faulting.

The Lickar limestone (or alternatively identified as the Cushat limestone) occurs 10m south of the Acre limestone where a down south normal fault brings it to cliff level (fig. 97). The limestone is 8cm thick and occurs in a shale sequence 3-4m thick between two thick cross bedded sandstones. These sandstones represent an E/W channel and thicken slightly towards the aforementioned fault, increasing from 1.5m to 2.5m thick in the faults'hanging-wall. The coarse grained sandstones 5m above the Lickar limestone on the wave cut platform contain minor angular 10^{o} discontinuity which cuts down to the north.

iii) Howick Haven to Longhoughton Steel

In the ULG above the Acre limestone from Howick Haven to Longhoughton Steel, no folding deformation occurs on the same scale as previously described. The limestones above the Cushat coal upwards are largely completely unfolded except for weak flexures about a N/S or NE/SW direction e.g. the Sugar Sands limestone (26061614).

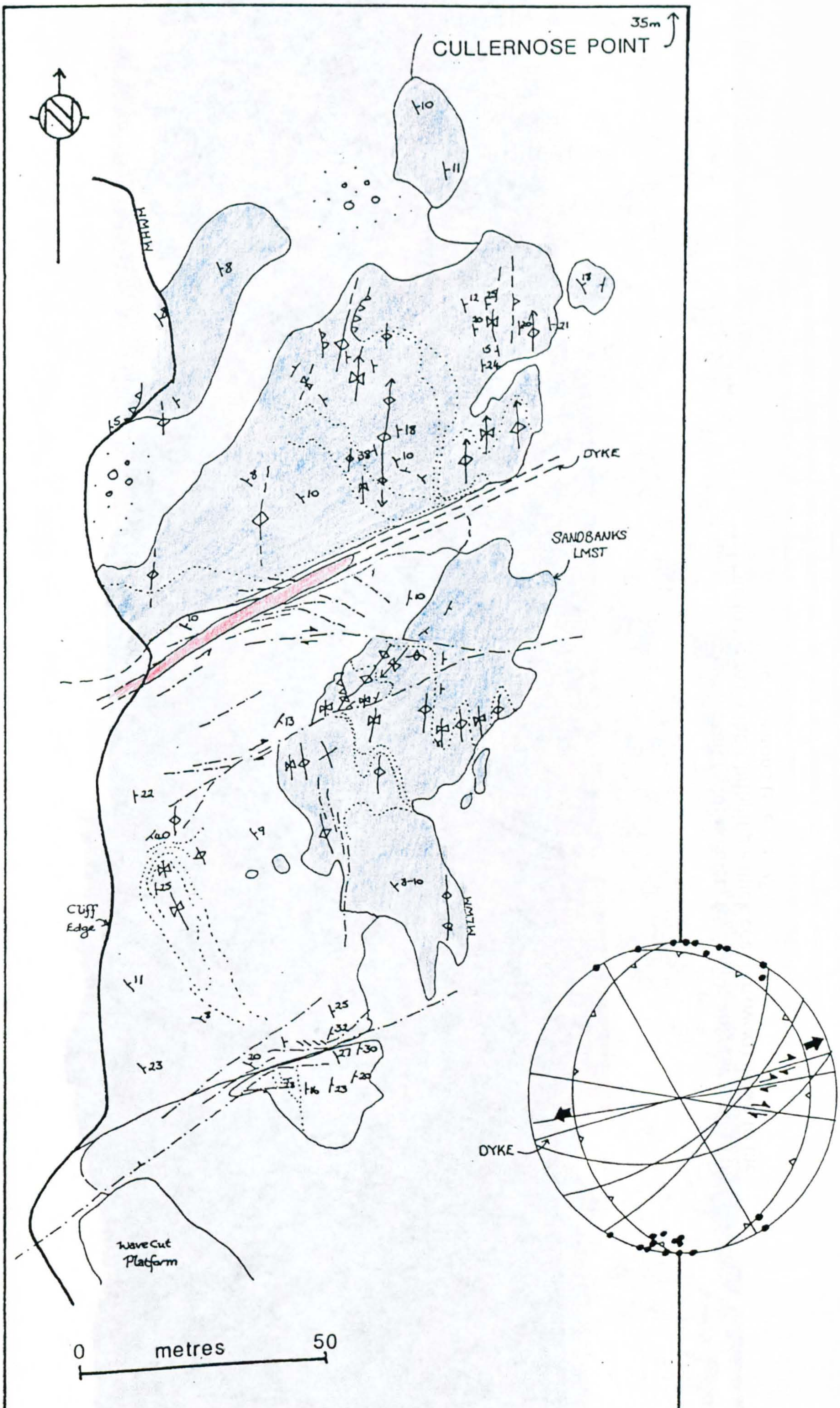


Fig. 94 Detail map of the region around Cullernose point showing the Sandbanks limestone.

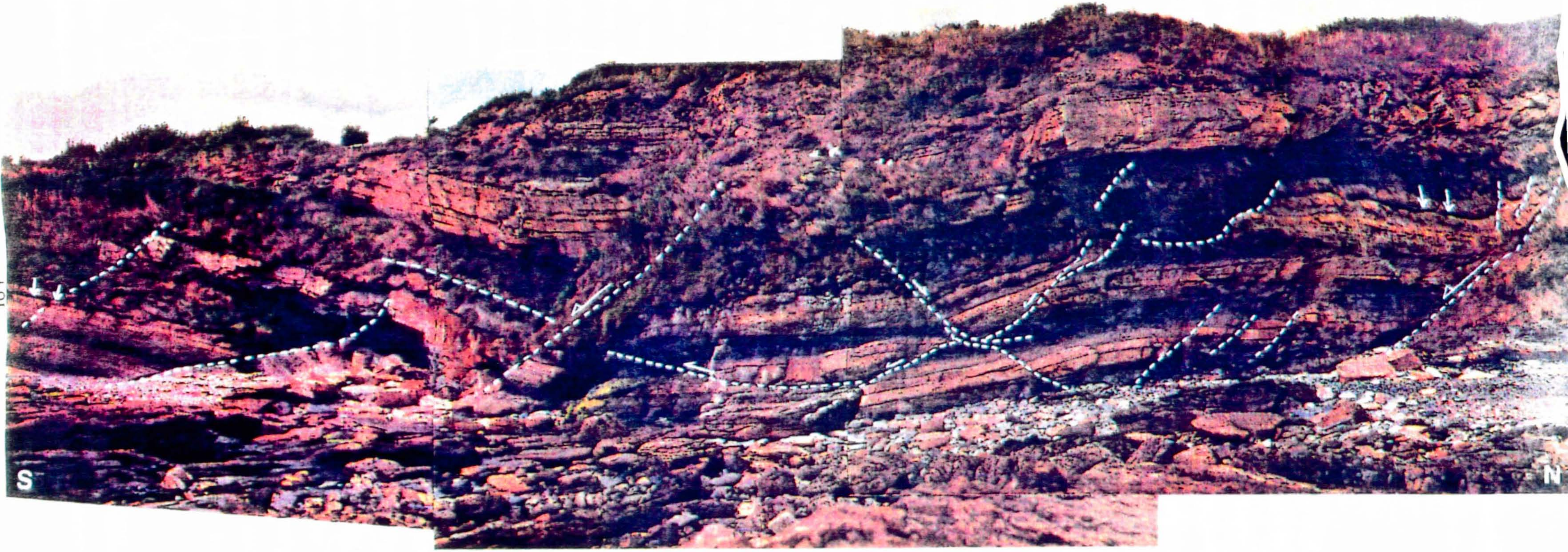


Fig. 96 Photomontage of the Howick fault (with Fulmers for scale); note the fault in the north is a major synthetic to the main fault bringing a thick coal (arrowed) down to the Acre limestone (see fig. 95)

Fig. 97 Photomontage of normal faulting immediately south of the Howick fault; overlapping with fig. 96. Note how the thick sandstones thicken into the hanging-wall of the low-angle normal fault, which truncates the thin limestone.

A thin dyke of basic igneous material cuts E/W immediately south of Rumbling Kern (see map enclosure 10, 2626 1709) into the coarse clastics that are continuous with those described in the previous section. The dyke is intruded along an E/W fault, which may or not be contemporaneous with dyking.

A high level of dewatering disruption occurs in the top 1m of exposed reddened, coarse grained cross-bedded sandstones in Sugar Sands. This probably indicates sedimentary instability due to autocyclic processes rather than active faulting, as the outcrop does not form a significant percentage of the total stratigraphy. The dewatering is confined to a single horizon, producing water escape "pseudo-antiforms" rather than ubiquitous disruption of the whole bed.

The base of the Longhoughton Grits is locally erosive and cuts down into the ULG to above the Upper Foxton limestone. This contact is a local unconformity 4km south of Longhoughton Steel,where the Upper Foxton limestone is cut out completely (see BGS sheet 6 Alnwick; 2590 1160).

The proximity of the unconformity and the dewatering structures is reminiscent of the structures and unconformity around Redshin Cove at Spittal. This coincidence may be due to contemporary (Carboniferous) fault activity in the area. The obvious candidate for such activity is the Howick fault.

iv) Little Mill Quarry

Locality 74 (2260 1718) is situated in the disused quarries at Little Mill Limery in the Acre limestone with the Whin sill directly above it. The quarry is 3km west of the Whin sill at Cullernose point, where it is above the Sandbanks limestone.

The limestone is deformed into tight, irregularly spaced parallel N-S to NE/SW folds. The folds are slightly asymmetric, with steeper westerly limbs and are near upright east facing structures. As with virtually all limestone deformation in the region, the folds are associated with intra-bed thrusts with displacements in excess of 1m. The thrusts are consistent with formation during folding, transporting up section towards fold axes to the NW/SE and E/W. These deformation geometries are very similar to the folding observed in the Sandbanks limestone at Cullernose, but is more regularly spaced between 3m and 10m apart.

The detailed descriptions of the preceding field areas are summarised in the final section, rather than presented as an initial summary of the area as in chapter 4 for the southern basin margin and the North Pennine fault.

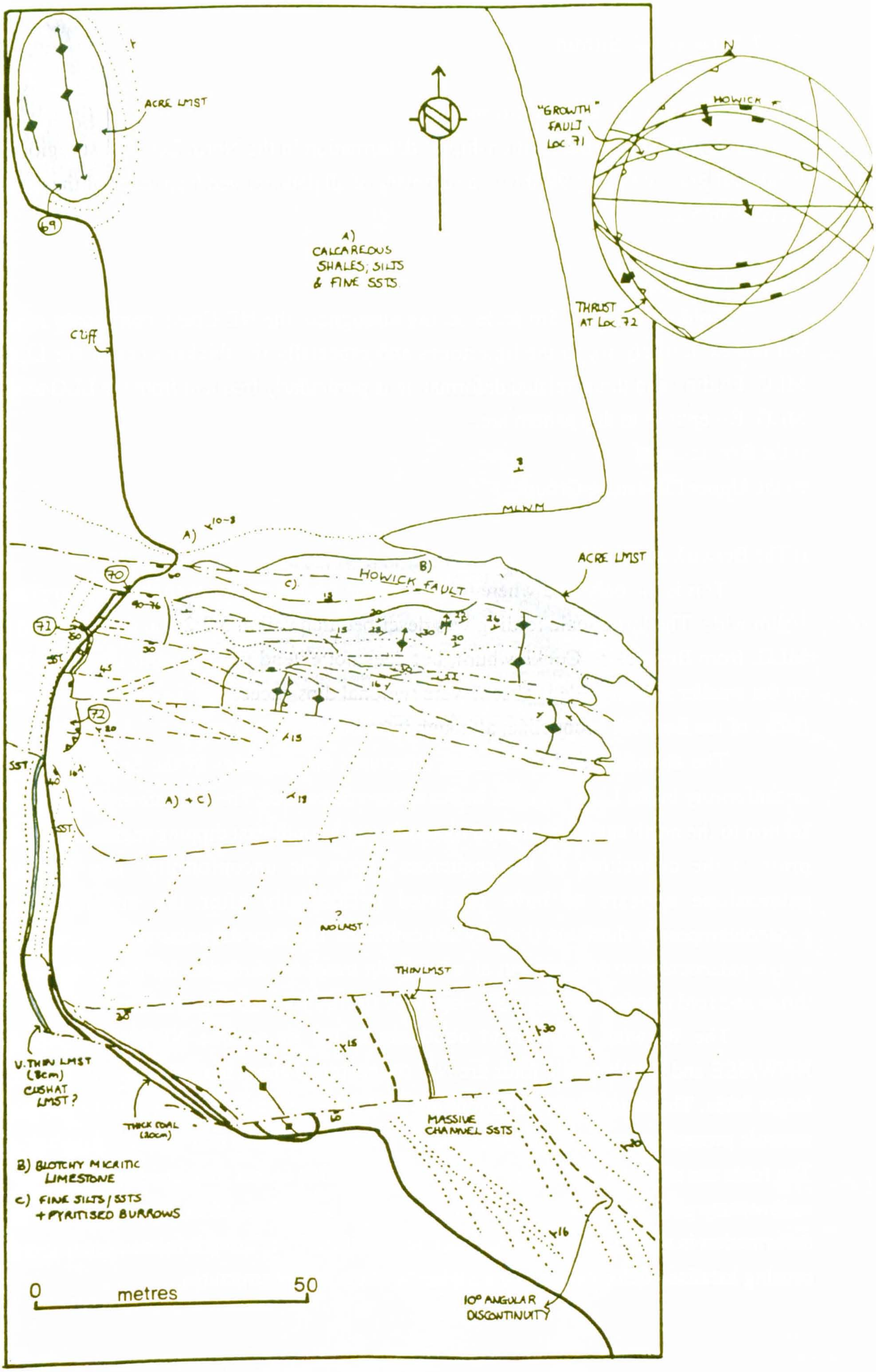


Fig. 95 Detail map of the region around the Howick fault, Howick foreshore (continuous with fig. 94).

5:2:7 Structural Summary

a) Distribution of Deformation

Fig.98 shows the relationship of deformation in the North East Coast region to the local stratigraphy and fig.99 shows a summary of all data derived from each of the described sections in 5:2:2.

Folding Distribution

Folding on the 3-5m scale occurs throughout the NE Coast, commonly restricted but not exclusively so, to the limestones and especially the thicker ones in the LLG and MLG. Folding and thrust related deformation is particularly frequent from the LLG to the top MLG. Exceptions to this pattern are;-

i) the Berwick area

ii) the Upper Limestone Group.

i) The Berwick Area

This is the only area where folds occur on a scale greater than the outcrop extent i.e. $^1/_2$km wide. The large scale folding was described in detail in 5:2:2a) and is confined to the MLG, from Berwick to Cocklawburn, but does not extend further south than this. Folding on the smaller 2-10m scale is absent were regional dips exceed 25^o i.e. around the E and SE flanks of the Berwick Monocline; although intra-bed thrusts do occur.

The abundance of dewatering structures on all scales in the Spittal area and an unconformity in the LLG, together indicate tectonic control. The unconformity cutting down section to the north can be explained by erosion of a south-east dipping regional palaeoslope prior to the deposition of the sequences above the unconformity. The regional SE palaeoslope appears to have persisted periodically after the unconformity, as penecontemporary slumping (locality 19) confirms. The regional palaeoslope tends to be SE as the palaeocurrents suggest but also the main transport direction for the slump based on thrust and fold trends indicates a SE slope (see fig.101 for a detailed reconstruction).

The Berwick folds trend obliquely to the monocline NE/SW as opposed to NNW/SSE and smaller scale folds are N/S concentrated about the cores and SE limbs of the larger folds. Thrust transport directions are NW/SE. The Berwick folds may be the result of tectonic processes but their unique character and distribution is non-typical of the NE Coast. The folds are stratigraphy related and so the suggestion is that they are due to early "within sedimentary pile" deformation, subsequently folded around the Monocline. The smaller scale deformation is spatially confined and can be explained by relating it to maximum shortening causing localised deformation in the SE limbs of the earlier structures.

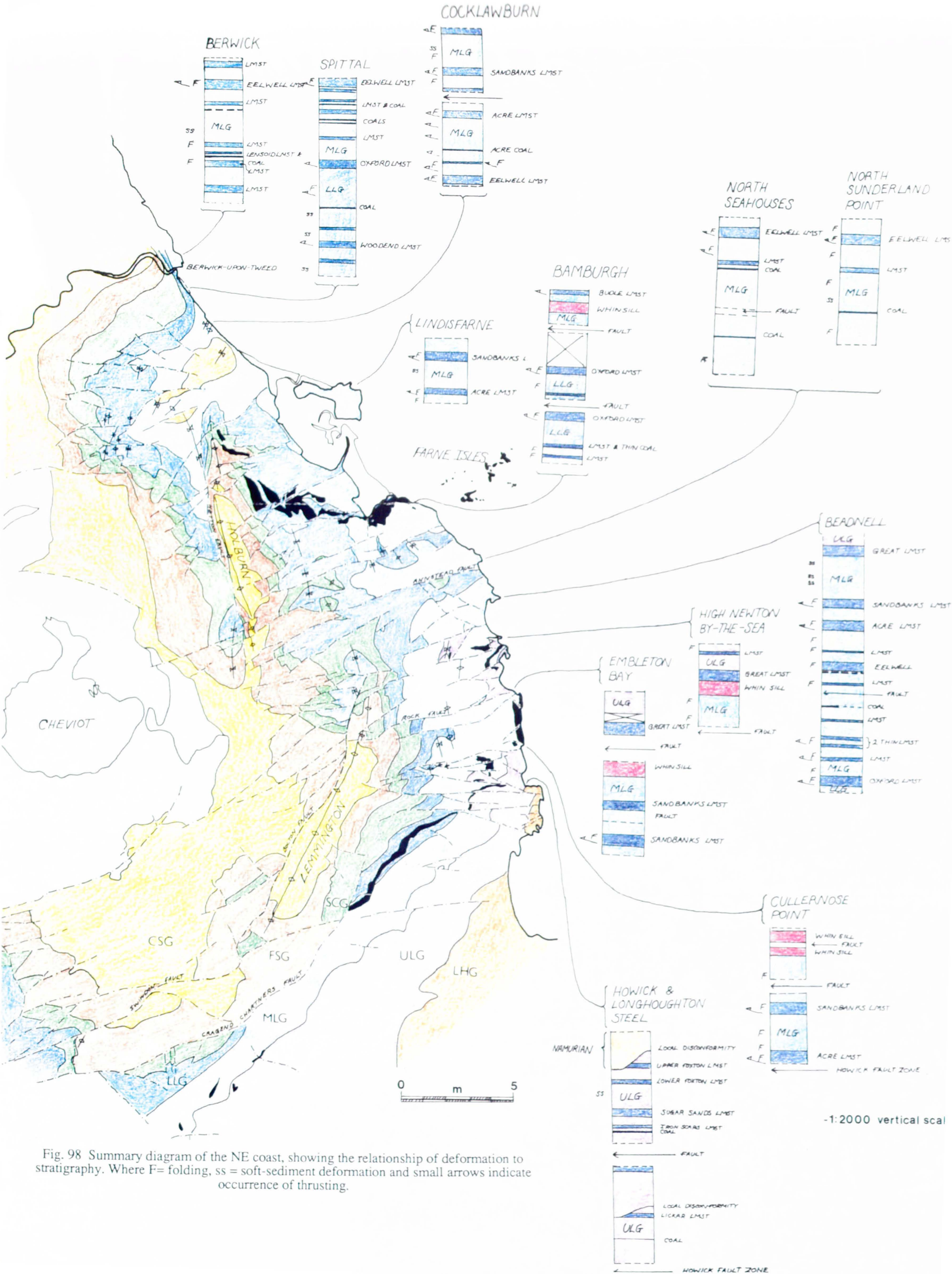


Fig. 98 Summary diagram of the NE coast, showing the relationship of deformation to stratigraphy. Where F= folding, ss = soft-sediment deformation and small arrows indicate occurrence of thrusting.

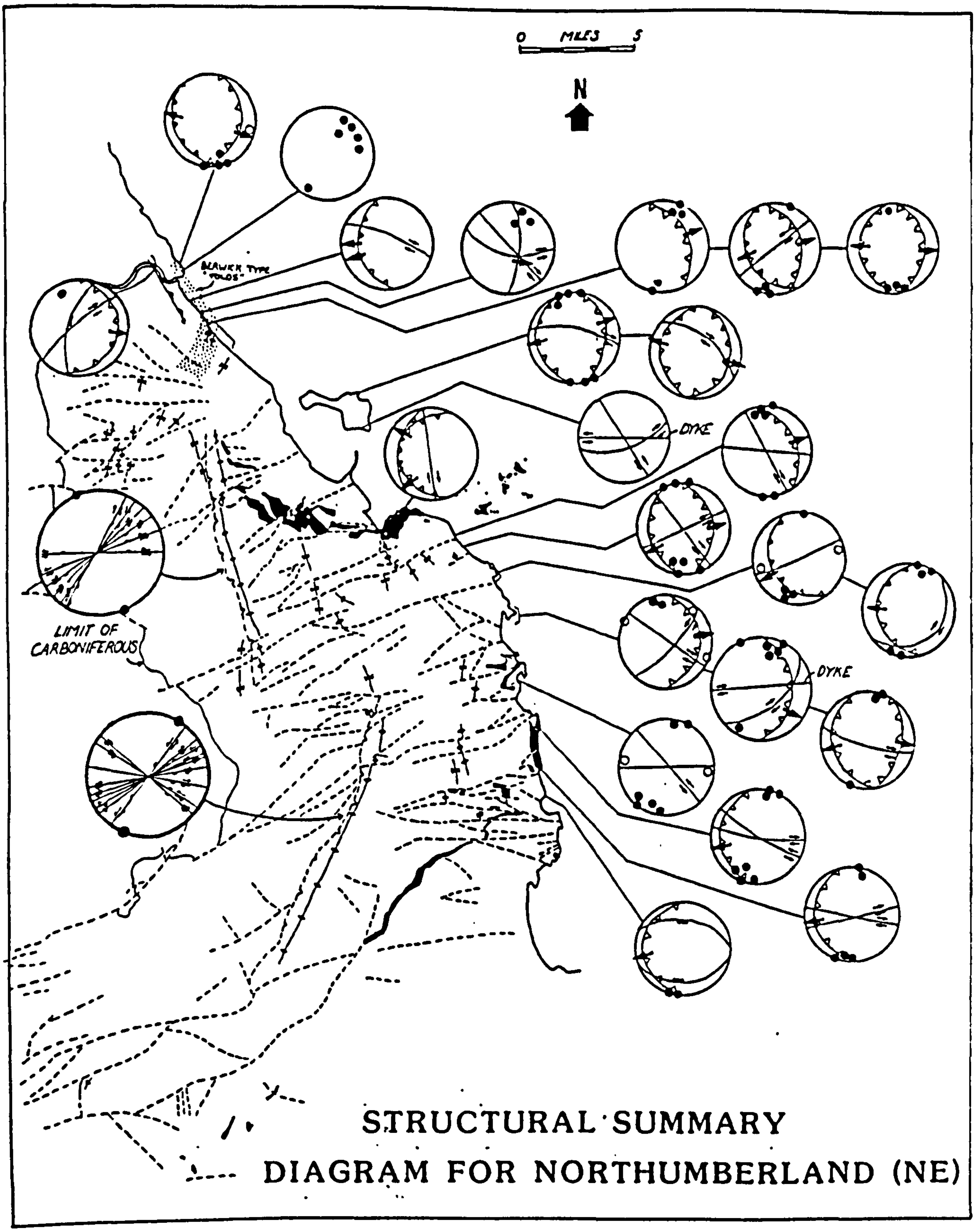


Fig. 99 Structural summary diagram for the North East coast of Northumberland illustrating summarised data for all localities mentioned in text and additional map derived fault data for the Holburn and Lemmington anticlines.

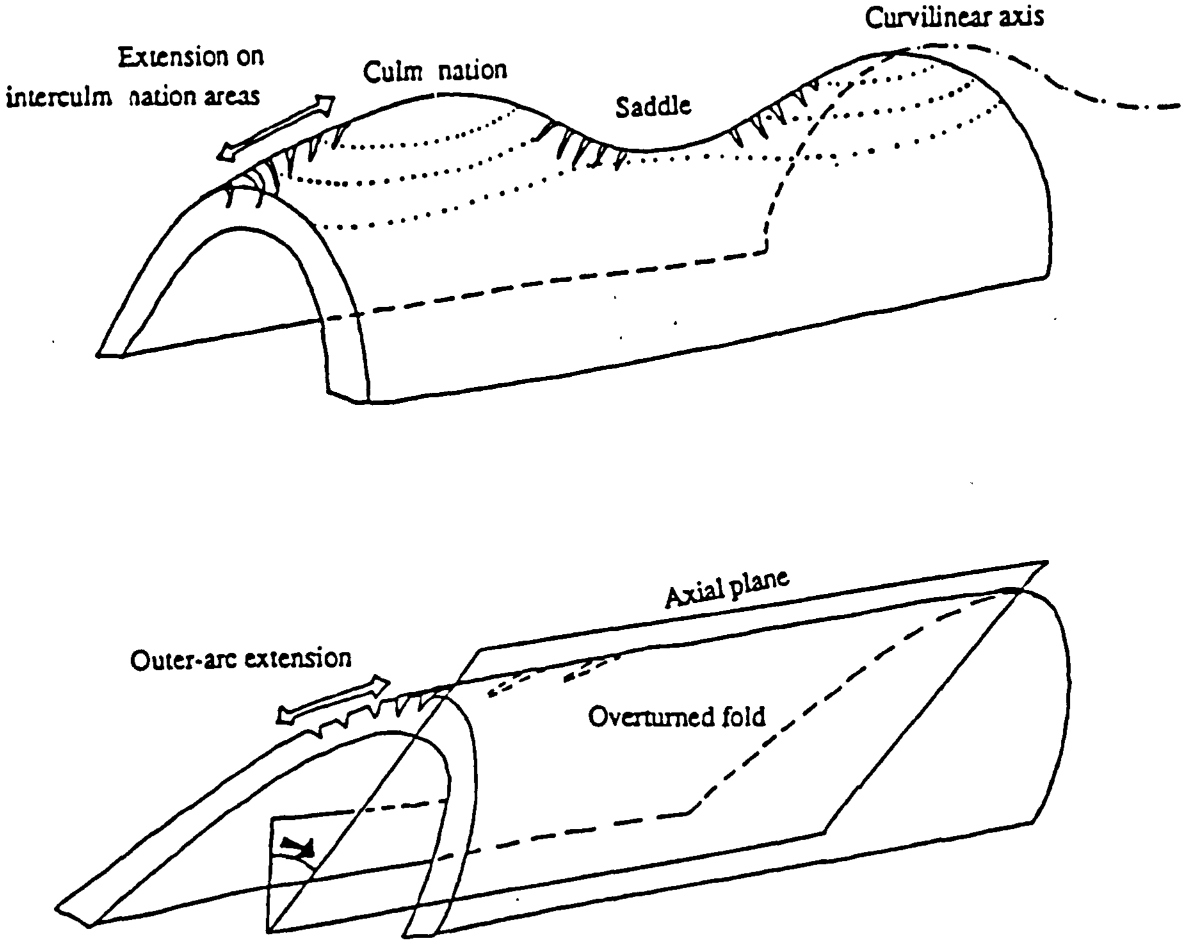
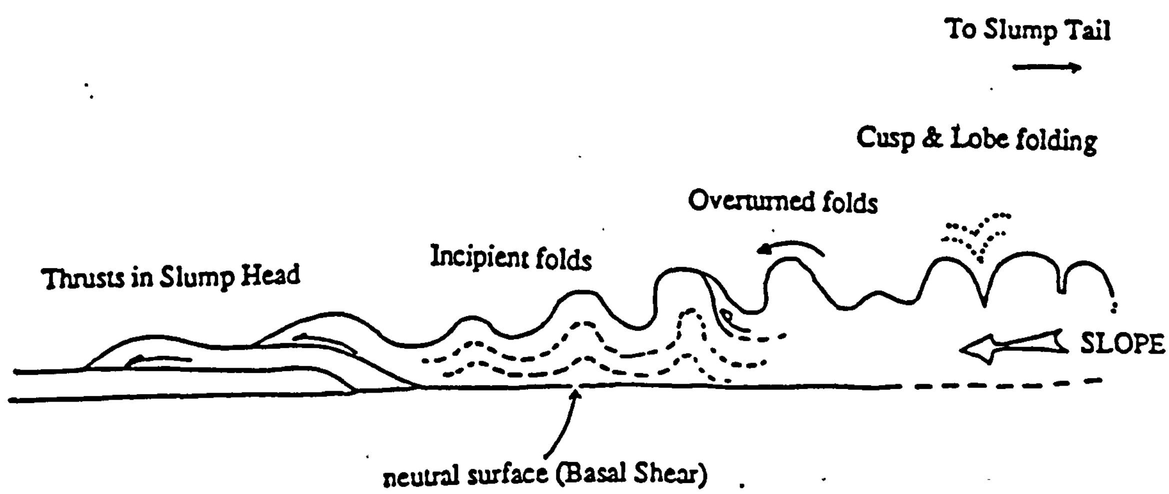


Fig. 100 Schematic development of two sets of calcite filled extension veins in the axial regions of the folds in the Eelwell limestone at Cocklawburn. Lowermost diagram illustrates possible mode of formation.



ii) The Upper Limestone Group

Folding is not developed in this group to the same extent as the LLG and MLG. The Great limestone shows limited warping but even here the regular 1-2m amplitude folds are not apparent. This may be explained in several ways;

a) Folding deformation may pre-date the ULG. In this case an unconformity would be expected at the base of the Great limestone, and no such structure was observed.

b) The ULG occurs in the extreme east of the regional anticlines. If deformation is localised to the major anticlines and marginal basin sequences then the ULG may have less strongly deformed than the other groups.

c) Deformation may be partitioned into certain lithological associations. The competancy contrasts of the limestone containing groups may have acted to nucleate the deformation and produce folds whereas in clastic dominated sequences the deformation is distributed by faulting.

Apart from the following, the general pattern of fold geometry is of parallel to sub-parallel 1B class upright structures with amplitudes in excess of 1.5m.

a) Eelwell limestone at Cocklawburn

b) Sandbanks limestone at Grey Mare's rock.

The general pattern of folding (excepting the previous) occurs in limestones, laminated silt and sandstone sequences and fine sandstone and shale sequences. Folding was never observed beyond very weak flexures in thick sandstones even where it occurs adjacent to a folded limstone, e.g. north Holy Island Sandbanks limestone. Folding is controlled by the most competant single layer in a less competant sequence and very occasionally polyharmonic folding was observed e.g Beadnell Haven where larger 10m wavelength folds occur in siltstones around 3-5m folding in the limestones.

This general pattern is modified when thin <2m limestones occur in a sequence dominated by folding in thicker limestones. This may be a function of the overlap of strain fields around the folds with the thin limestones effectively invisable to the deformation. However where folding is absent intra-bed thrusting still occurs.

a) The Eelwell limestone at Cocklawburn.

Folding here is unique. Folds are upright to inclined often plunging to the NE and forming distinct cusp and dome structures. This deformation is the result of contraction along the limestone shale interface where the lobes are limestone cored therefore the more competant lithology, and the cusps are shale cored; therefore the less competant lithology.

The folds are associated with thrusting of which some can be demonstrated to be transporting out of folds and are therefore likely to pre-date folding. Some of the thrusts show pre-faulting thickening of foot-walls and hanging-walls which are consistent with pre-lithification deformation. The out-of-sequence faults are inconsistent with the regional dip (due to the Monocline) and are interpreted as pre-dating the development of the monocline. The two stage calcite vein set development in the folds formed by extension in the curvilinear axes and during overturning of the folds, can be linked to the previous interpretations and attributed to pre-monocline deformation. The neutral surface base to the limestone adds the final piece of evidence that this deformation was gravitationally driven and slump related (see fig.100 for a schematic interpretation).

b) The Sandbanks limestone at Grey Mare's rocks.

The deformation shows 1C class folding as described in section 5:2:2e). It is more irregular than elsewhere and has a unique example of a folded thrust. This outcrop may be slump related also, as fold axes directions are slightly atypical of other areas with axial regions contain multiple oblique folds.

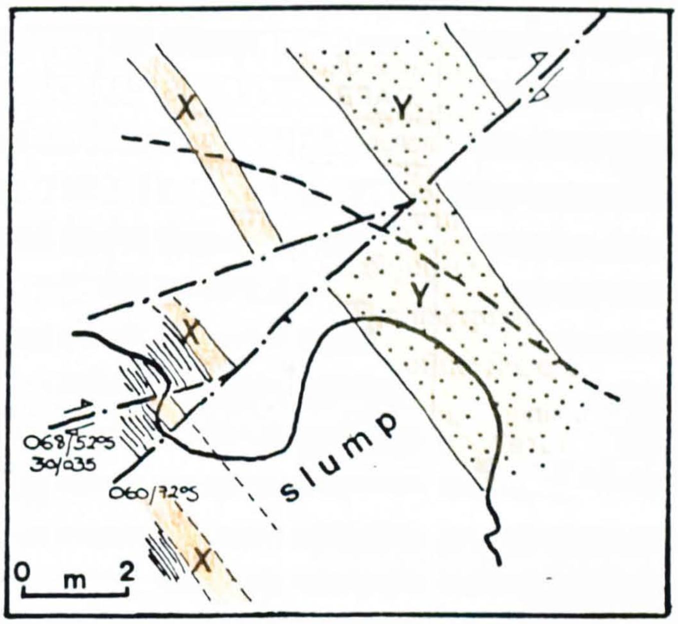
Stylolite distribution

These occur in limestones with deformation typical of the Sandbanks limestone at Beadnell. This is the best locality for observing vertical stylolites orientated NE-SW. These are cut by thrusts and indicate layer parallel shortening. Stylolites were not observed in thin limestones (>2m) which may reflect a higher competancy contrast than in multi-bedded limestones where >2m of limestone is interbedded with thin calcareous shales. Stylolites were not observed in localities where the limestone was not weathered above the high water mark althougth this doesn't preclude their existence elsewhere. Stylolites however were not observed in the limestones in the Berwick area.

Faulting distribution

This does not include the localised thrusts related to folding. Faulting is common in the NE Coast and is generally normal or strike-slip in movement no large scale reverse faults were observed in the entire section (other than the bounding faults to the Holburn and Lemmington anticlines). As figure 99 illustrates motions on strike-slip faults and folding direction are highly variable over the region, but broadly parallel the regional anticlines (except in the Berwick area). Many of the large faults marked on the 1:50 000 BGS solid geology maps are not exposed but their displacements can be estimated.

In the Holburn anticline the dominant faults are dextral, trending NE/SW and in the Lemmington area are sinistral trending NE-SW to NNE/SSW and rarely NW/SE. However when the movement directions are compared with the downthrows it becomes apparent that



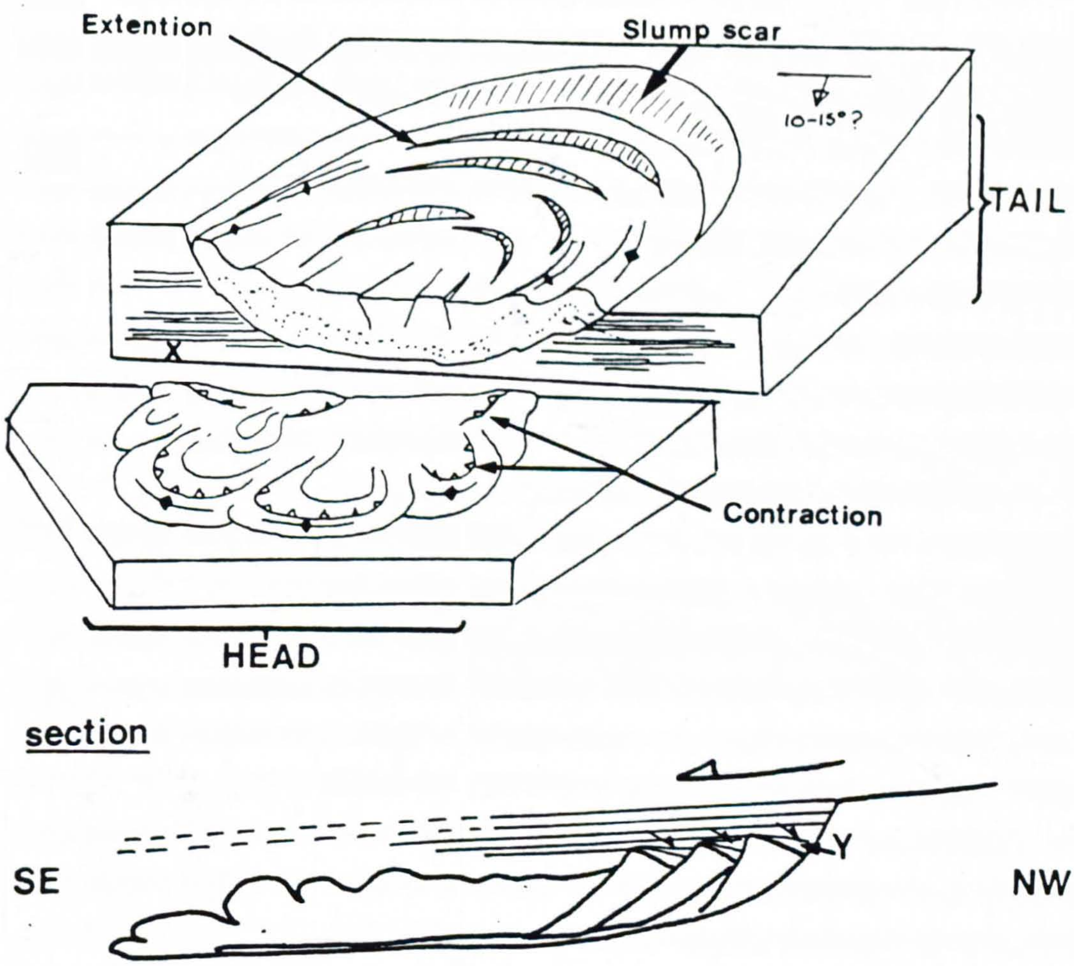


Fig. 101 Detail location map and diagrammatic representation of the formation of Locality 19, a pene-contemporaneous slump.

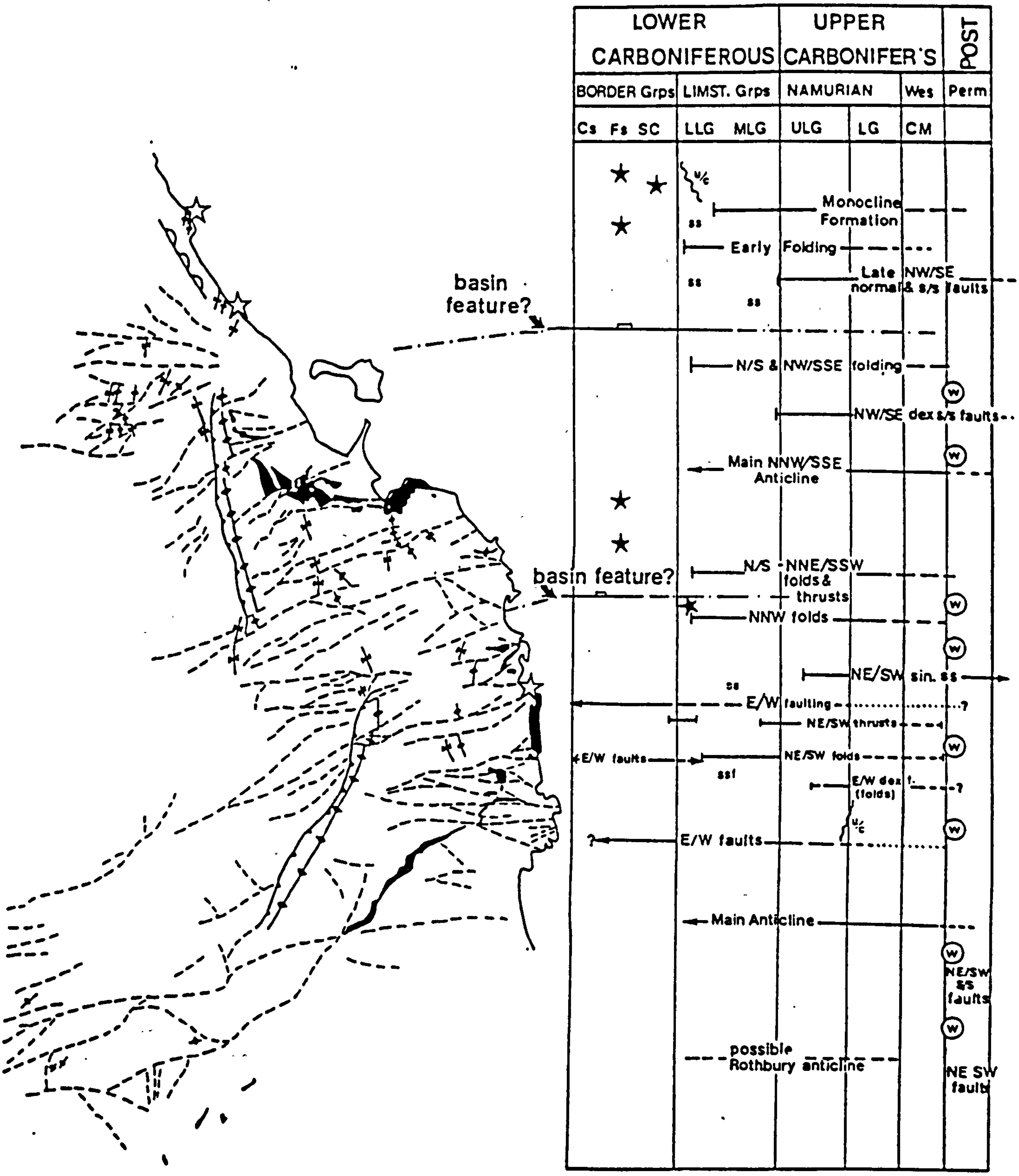


Fig. 102 Structural history diagram for the NE Coast of Northumberland.

the "dextral" faults have southerly down throws and the "sinistral" faults have northerly downthrows. This is a function of normal down-dip displacements superimposed on a regional dip to the east and south-east. Therefore in all cases except where displacements are greater than could be reasonably explained by normal faulting the movement directions of the faults should be regarded as apparent and not actual.

This has important consequences for any regional structural interpretation as the faults cannot be assumed to be conjugate sets or even contemporary if the strike-slip motion can be unequivocally proved. The interpretation is more problematical for some faults as most appear not to dissect the cores of the regional anticlines.

b) Age of Deformation

Deformation along the NE Coast can be divided into three categories:

i) Soft sediment deformation.

ii) Slump or gravitational related deformation.

iii) Compression related deformation.

The ages of deformation can only be determined in relative terms (see 102);

i) Soft sediment deformation:

The earliest type of deformation takes the form of isolated dewatering structures to totally foundered beds. Dewatering horizons are up to 2-3m thick where bedding is almost totally disrupted into overturned and convoluted concave upwards structures truncated against succeeding units. In the spittal section dewatering occurs alongside early LLG normal faulting (below Little Howgate coal at Redshin Cove)& when related to local unconformities e.g. Spittal and Longhoughton Steel, can be regarded as due to early fault activity. Regional palaeoslopes are caused by rotation on normal faults and subsequent erosion.

The Howick fault was an active syn-sedimentary fault during the ULG trending approximately E/W, it is the only exposed structure of its kind in the NE Coast.

ii) Gravitational related deformation:

This occurs as penecontemporaneous slumping e.g. Spittal loc. 19 or as slumps that occured within the sedimentary pile some-time after deposition, e.g. Eelwell limestone at Cocklawburn and the large scale Berwick style folds. The slumps not only prove the existence of regional palaeoslopes but also indicate the direction of the latter. At locality 19 the regional slope at the time of slumping (in the LLG) was to the SE and the remaining slump scar was quickly "back-filled" by the succeeding sandstones. The Eelwell limestone folds at Cocklawburn are overturned to the N perhaps indicating the formation of a NW slope sometime after the deposition of the MLG.

iii) Compression related deformation:

This post dates both the previous,occuring sometime after the deposition and lithification of the MLG and affects most lithologies but is best developed in the limestones. Folding is represented by regional scale overthrust anticlines and small scale folding.

The regional scale deformation was in place by the time of the intrusion of the Whin sill as the sill cuts down stratigraphy into the fold cores and rises away from the cores in the limbs and interlimb areas. The sill is at its lowest level in the north of the Holburn anticline and the south of the Lemmington anticline. This implies that the extreme limits of the structures existed at the time of intrusion but that the central inter-anticline region (Berwick Moor) may have continued to develop after the intrusion. This is upheld by the offshore continuation of the sill which describes a broad antiform around the inter-anticline area and the Farne Islands.

The sill maintains its level fairly consistently across the basin and so therefore where it changes level abruptly around the Howick and Embleton region, the interpretation is that pre-existing E/W normal faults acted as conduits for the dyking and therefore pre-date the sill but appear to post-date the initial deformation during compression as they displace regional anticlines.

Both the sill and the regional anticlines are dissected by a series of NE/SW normal faults. These post-date most of the deformation in the regional anticline limbs and in some cases acted as conduits for Whin sill suite dykes, e.g. Cullernose Point, Greymare's rocks and Boulmer Hall (2700 1420). The NE-SW faults can therfore regarded as at least pre-sill or partially contemporaneous with the sill intrusion (or at least the dyke intrusions). The sill at Holburn is intruded in a pattern of dextral overlapping lensoids which may reflect the ambient stress field at the time of intrusion.

Small scale deformation seems to have developed shortly after the initiation of the regional structures so that some fold plunges reflect regional dips. However in the Berwick area small scale folding developed during the main folding event (which produced the monocline) and may have slightly pre-dated it in cases i.e. some structures are rotated into extreme positions.

The first sign of deformation was layer parallel - shortening, producing stylolites in the limestones and then discrete thrusting, along with folding. This scale of deformation continued to develop during the development of the regional anticlines but had ceased prior to the intrusion of the Whin sill.

Faulting accompanied deformation along NE/SW and ENE/WSW directions which may have reactivated pre-existing E/W faults.

The details of the structures and their relative ages are summarised in fig.102 where the region is divided into areas of similar deformation histories. These regions seem to reflect fundamental basin "divisions" related to persistent structural trends. The full implications of these areas are discussed in the concluding basin synthesis, chapter 7.

Chapter Six
AUXILIARY STUDIES

6:0 Introduction

In a basin study of the present kind, field work alone cannot be expected to give a comprehensive view of the evolution of the basin. In the case of Northumberland, field work gives alternative scenarios for a contemporary stress regime but deciding between these alternatives (see chapter seven) is problematic. It was decided therefore to conduct an exploratory study based on standard palaeomagnetic procedure and techniques. The palaeomagnetic study was designed to constrain the possibility for strike-slip deformation over the whole Northern England Iapetus province. Quantitative modelling was explored to assess the effect of the inversion on the integrity of the basin and explain the distribution of the structures and uplift patterns.This is dealt with in section two.

Part One
Palaeomagnetic pilot study

6:1:0 The project design

During the rifting phase of the Northumberland basin and subsequent inversion, a component of strike-slip movement may have occured. One way of assessing rotations in such a regime is through palaeomagnetism techniques. Large scale crustal block rotations were predicted and proved for areas of active deformation, e.g. strike slip zones and continental deformation regions (McKenzie & Jackson 1983). Such roations were determined using palaeomagnetism (McKensie & Jackson 1983, 1986; Lamb 1988). It was therefore determined that the basin was suitable for a palaeomagnetism pilot study, based on the following reasons;-

1) The basin and its immediate neighbour, the Solway basin contain outcrops of Lower Carboniferous lavas and the early Permian Whin Sill.

2) The lavas and the sill are likely to be more resistant i.e less coercive than the sediments and thus likely to retain stable remnant Carboniferous magnetisation directions.

3) A selection of sites including the basal Carboniferous lavas and lavas from the Middle border group were selected to compare remnance directions relative to the Whin sill.

4) Any rotations about the vertical (declinations) during the Carboniferous would be identified by calculating the relative magnetic poles for each site and comparing them between sites of the same age and against known Polar Wandering curves for the UK. Comparison against the Whin sill, would help to "date" the timings of any observed rotations.

If any rotations were observed, these would represent net rotations and not a detailed or absolute measure of intra-Carboniferous rotation. Two sites were selected from the Whin sill separated by a post-Carboniferous fault, so that a simple tilt test could be conducted to determine the likely age of any remnance. Published examples of Carboniferous remnances were collected to also test the age of the remnance (Addison,Turner & Tarling 1988; Turner, Vaughan & Besly 1985; Briden at al 1989).

Seven sites were initially selected for sampling. These were determined by their easy assess to water (necessary for the drilling process) and by the quality of the exposure. The sites were selected as far apart as possible to eliminate local variations and at least seven cores were drilled for a valid statistical analysis. The sites were;

1) Whin sill

Wall Town Crags, Cumbria. This site is in the extreme west of the Northumberland basin close to the southern margin of the basin, and samples a medium-fine grained quartz dolerite. The samples were selected from near the centre of the sill, and compared to site 2 to assess the effects of secular variations.

2) Whin Sill

Cawfields, Milecastle, Cumbria. This is also in the west of the basin separated from the previous by a NW/SE trending tear fault. The samples were taken from near the top of the sill, within 5m of the sediment/sill contact.

3) Birrenswark lavas

This site at Skippers Bridge, Langholm sampled the Basal Carboniferous lavas. They are olivine basalts containing labradorite, oligoclase, augite, iddingsite and primary magnetite. The olivine is altered to serpentine, iddingsite and secondary magnetite and calcite +/- quartz (Pallister 1952).

4) Kershopefoot basalts

Kershope quarry, Newcastleton. This sampled basic olivine basalts from the Middle Border Group.

5) Birrenswark lavas

Kirkbean, Dumfries. This is in the north of the Solway basin, sampling the basal Carboniferous basalts again. They are broadly similar to the lavas at site 3 being olivine basalts, but this site was very badly fractured and so samples were difficult to extract.

6) Birrenswark lavas

A second site in the Solway basin, at Preston Mill, Dumfries as a back up for site 5.

7) Cockermouth lavas

This was a single site in the basal Carboniferous lavas of the south side of the Solway basin. The lavas include basalts (sampled) and tholeiitic andesites. When fresh the basalts are quartz tholeiites containing olivine, plagioclase and occasionally augite in a ground mass of fe-ti oxides (MacDonald & Walker 1985).

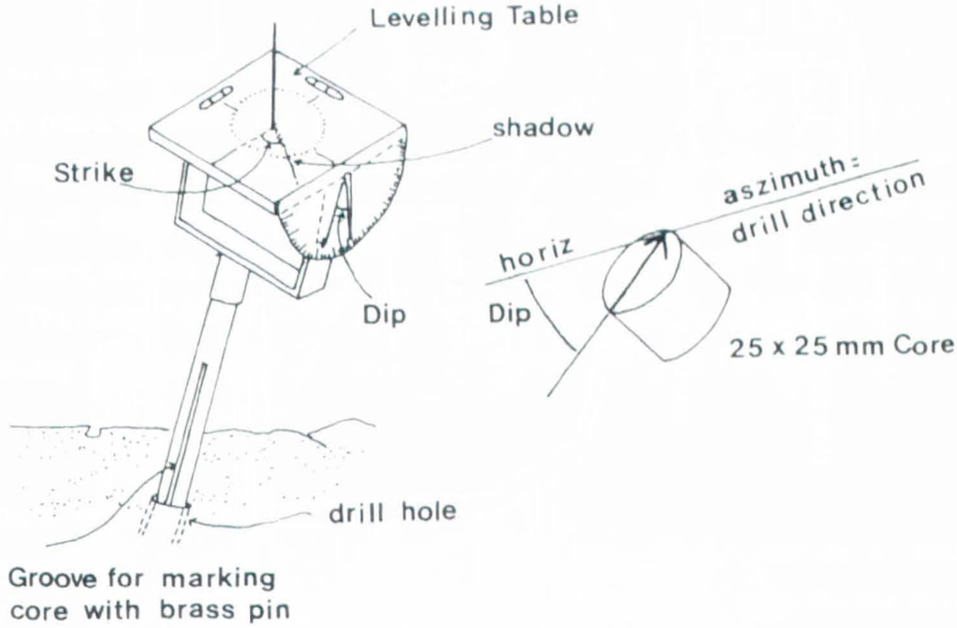


fig.103 Diagram illustrating the orientation convention for palaeomagnetism drilling (in field) and photograph of portable drill in the field.

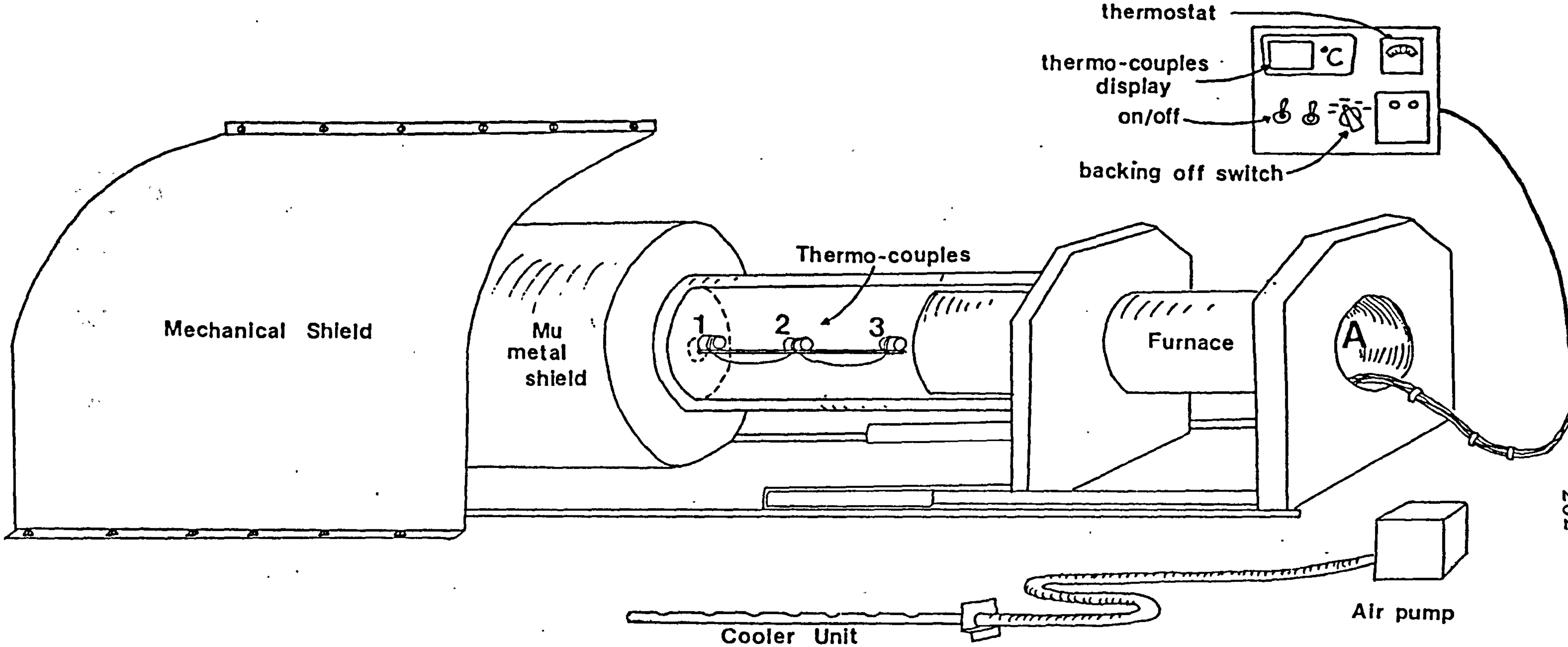


fig.104 Thermal demagnetisation equipment (TDM).

The lavas are ubiquitously altered so that the olivine is pseudomorphed by serpentine and chlorite, augite by serpentine and minor carbonate and the plagioclase is carbonateed and albitised.

Each site was drilled using a portable 1inch drill corer and seven samples up to 10cm long were collected from each site. The cores were drilled at divergent angles to eliminate local angular errors, and each was carefully labelled according to the convention illustrated in fig.103. the samples were bagged and site strike and dip characteristics were recorded. The samples were cut into 1 inch specimens for use in the "Spinner" magnetometer. The holes left by drilling were carefully plugged and disguised to avoid defacing the outcrop, this was especially important in National Park sites 1 & 2.

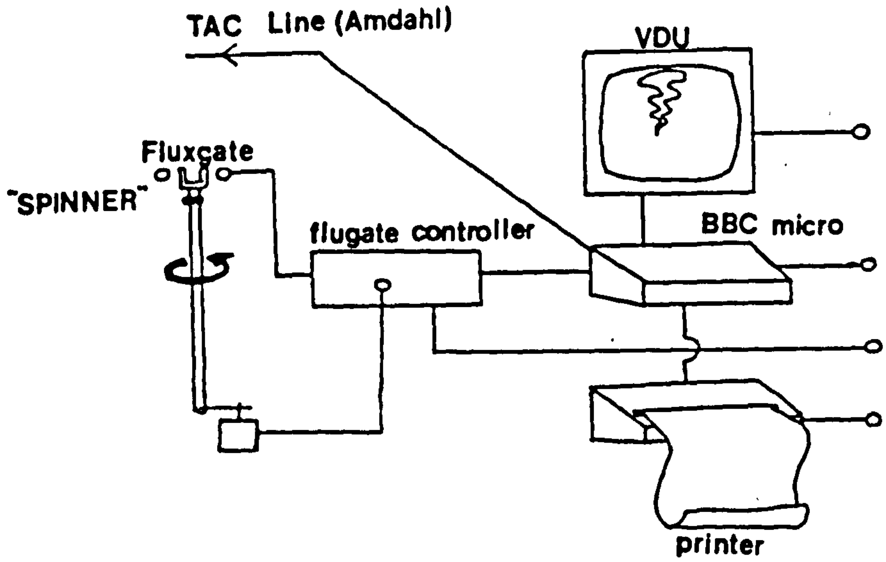
6:1:1 Analytical procedure.

The specimens were measured for their magnetism in a "spinner" magnetometer and then treated stepwise in either by alternating field demagnetisation (AFDM) or by thermal demagnetisation (TDM). A sample from each site was run through both techniques and the results compared. It was decided that for this study the AFDM procedure would be more appropriate (i.e. quicker and just as effective as the TDM process).

Thermal Demagnetisation (TDM)

Three core specimens at a time could be treated and placed in the specimen tray of the furnace illustrated in fig.104. This allowed a good circulation of air about the specimens and so a more accurate estimate of the temperatures each achieved and calculated by constructing a temperature graph (see fig. 106). The furnace is shielded by a series of seven mu metal shields which negate the effects of the Earth's ambient field during the treatment, and the whole equipment is shielded by a metal hood. The range of the furnace was set and the specimens permitted to equilibrated at each new temperature increment for ten minutes, thereafter the furnace was shut off and the specimens cooled to room temperature before testing in the "spinner". A temperature graph was constructed for each thermal step and the results were accumulated on disc in a BBC micro-computer. Results were also recorded on experiment sheets as back-ups in case of equipment failure.

Each treated specimen was stored between stage in a mu metal box and stepwise subjected (in 50°C steps up to 600°C) to the treatment until the natural remnance magnetisation (NRM) was destroyed.



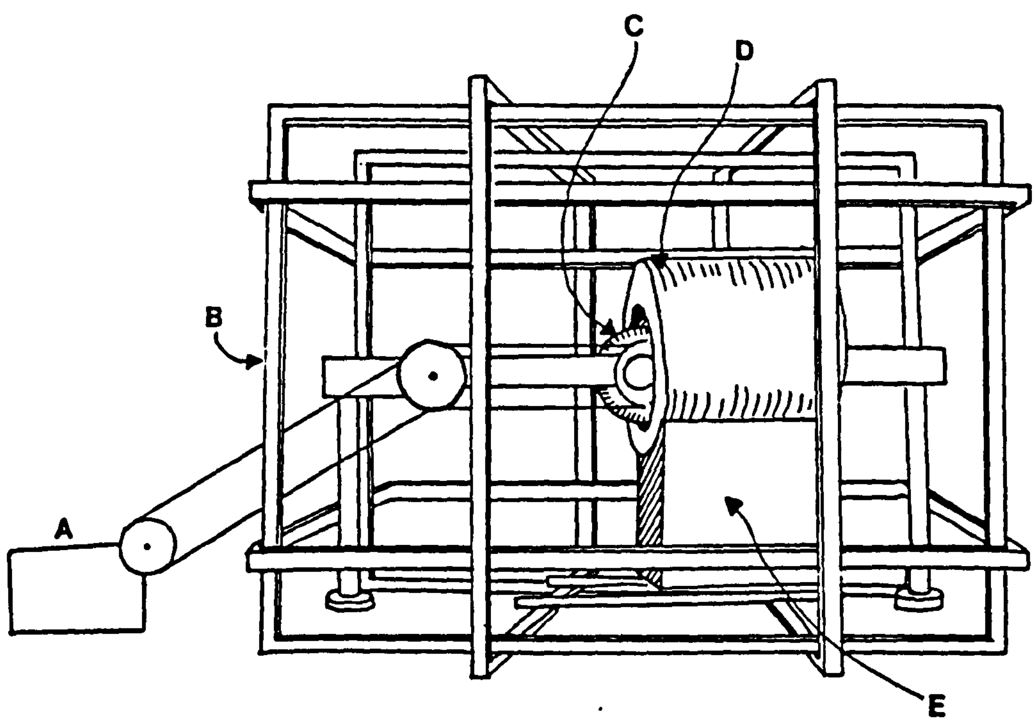
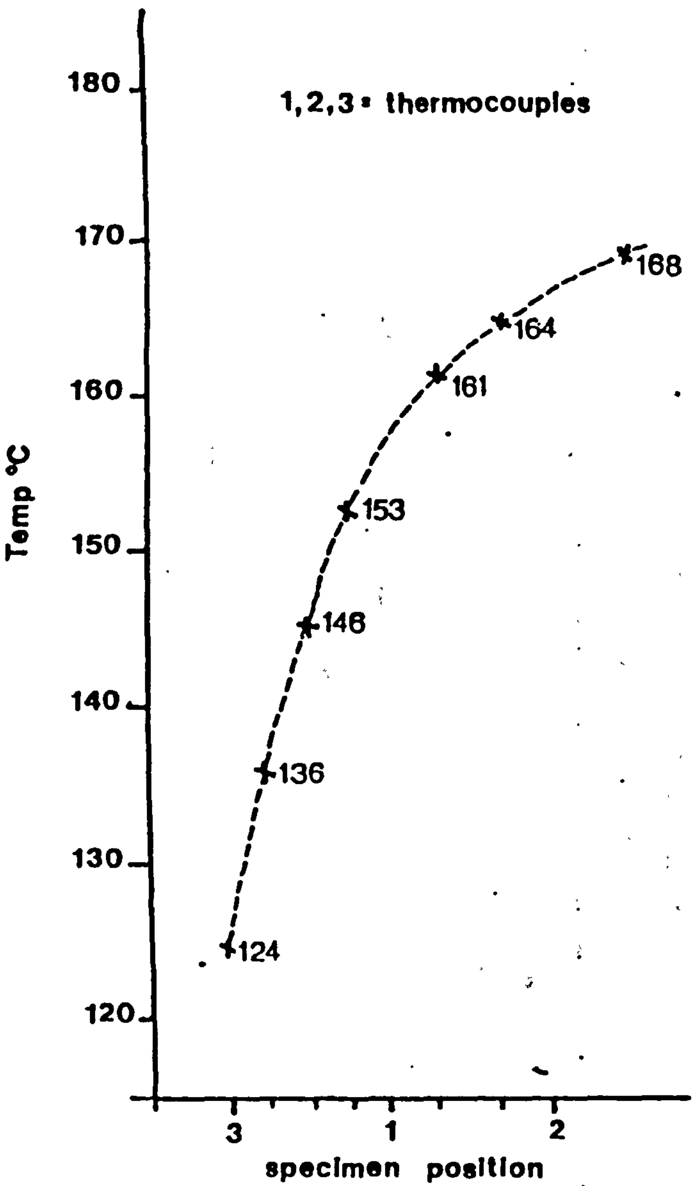


fig.105 a) Computer link to "spinner" and b) diagram of alternating field demagnetometer as used in AFDM.



spec. number		Treatment °C	Intensity $\times 10^{-6}$ cgs	% sd		Rel. to core D	Rel. to core I	Ang. err.	In situ D	In situ I
		(TDM)								
1P2P2		NRM	672.62	1.76		345.6	27.6	1.1	61.5	13.2
		89	605.62	1.81		346.3	7.2	1.2	74.8	-2.8
		136	606.93	2.97		348.5	-3.4	1.9	83.1	-9.8
		185	589.57	1.61		347.7	-6.0	1.0	84.1	-12.4
		224	558.46	2.22		348.0	-7.1	1.4	85.0	-13.1
		272	532.10	2.31		350.6	-7.5	1.6	87.3	-11.7
		304	489.49	2.06		347.8	-5.6	1.3	83.9	-12.0
		353	449.5	1.94		350.5	-4.8	1.2	85.6	-9.7
		408	339.34	1.57		349.4	-1.0	1.1	82.2	-7.4
		477	251.05	5.57		353.7	+0.8	1.0	84.6	-3.3
		490	66.02	4.8		8.0	+10.9	4.0	89.4	13.5
		542	22.58	17.85		347.4	+2.0	11.2	78.9	-6.2

Formation: Whin Sill
Site No. 1 Walltown Cumbria
Age. Early Permian
site coords.
volume: 10.97 cc
096/51.5°E (core)
069/20°SE (Bed)
I Walltown
Whin Sill

fig.106 Temperature graph construction for use with TDM and example experimental record sheet used in both procedures.

Alternating field demagnetisation

Each specimen was placed in a cradle within the coil (see fig. 105) and turned in 2 directions in a stepwise increasing applied alternating field. The coil was erected in a zero magnetic field achieved through a Helmholtz coil arrangement. Before conducting AFDM the coil was zeroed by using a hand held magnetometer and adjusting the coils accordingly. The field was applied through a variac potentiometer in 5 milli tesla increments. The field was increased until the specimen was exhausted.

Spinner magnetometer

After each treatment step the natural remnance magnetisation (NRM) was measured in the spinner magnetometer (SM) linked to a BBC Micro-computer. The "SPIN" program records site data for each sample, its volume and records the NRM through six spin directions. The resulting declinations and inclinations and field intensity were recorded on disc and on experiment sheets (see fig.106). "SPIN" is a development of the "Digico" spinning magnetometer control program (Uni. Leeds) which allows batches of specimens to be run and permits regular measurement of the background magnetisation and recalibration. This helps to eliminate errors due to machine drift to within 1°/o. Recalibration of the equipment was carried out every 4 specimens. The SM measures the dipole moment of each specimen expressed as magnetisation;

$$\text{Magnetisation (A/m)} = \text{Dipole moment (Am}^3\text{)} / \text{volume (m}^3\text{)}$$

An artificial calibration specimen of known dipole moment 1.4×10^{-5} $Am^2 \pm$ 1% was used to fix the calibration and default volume of the specimens to 11.65cc. Therefore the calibration magnetisation is 1200m A/m. For 48 spins the calibration figures and working tolerance levels are;

N = 1200.00 ±10 (magnetisation) E = 000.00 ± (error) Dec = 360.00 (declination)

For each step of the treatment the intensity, declination, inclination and alpha 95 was recorded. An estimation of the precision of the computed magnitude and direction can be made using the statistical theory set out by Briden and Arthur (1981), with the 95% confidence limits for the magnitude M and the circle of confidence (sigma) calculated as follows;

$$\text{sigma (M)} = M + 1.313\ s$$

$$\text{alpha 95} = \tan^{-1} (1.459 (s/M))$$

$$\text{where } s = \Sigma^4{}_{i=1} \frac{(xi - x)^2 + (yi - y)^2 + (zi - z)^2}{36}$$

and $M = (x^2 + y^2 + z^2)^{1/2}$

where x, y, and z are the coordinate axis of the core.

The spin program also enables a tilt (bedding) correction to be made from inputed field orientation data and a virtual geomagnetic pole can be calculated from each specimen using the observers geographic coordinates.

The mainframe computer setup

The data from the analytical procedure was transferred from the BBC Micro to the University of Leeds Amdahl mainframe, via Kermit. The files were then plotted on Zeiderfeld diagrams using the programs ZPLOT FORTRAN, ZPLOT EXEC and ZPLOT TEXT, which were accessed via the Earth Science Geophysics library. The Zplot files were used in conjunction with LINEFIND a series of programs designed to identify straight line sections i.e.vectors on the Z plot graphs and hence determine the directions of the stable magnetisations. The site means for all the vectors (those that were determined as stable) were computed using IKA and the virtual geomagnetic poles for each of the means was determined via KAPAI (a structural transformation program). Both IKA and KAPAI were accessed via D. Robertson (University of Liverpool).

6:1:2 Sources of Error

Sources of error in the procedure may arise from the following;

1) Equipment calibration and drift. This is usually corrected by regular recalibration and background magnetisation measurements.

2) Random power surges to equipment during use. This is usually queried by the "SPIN" program and samples can be re-spun before he next treatment stage.

3) Errors incurred in palaeomagnetism measurement, i.e. acquiring a viscous remnant magnetisation by; a) being left unshielded between steps, b) incorrect orientation during spin procedure, c) being subjected to a non-zero field during AFDM, which induces anhysteric remnant magnetism and rotational RM.

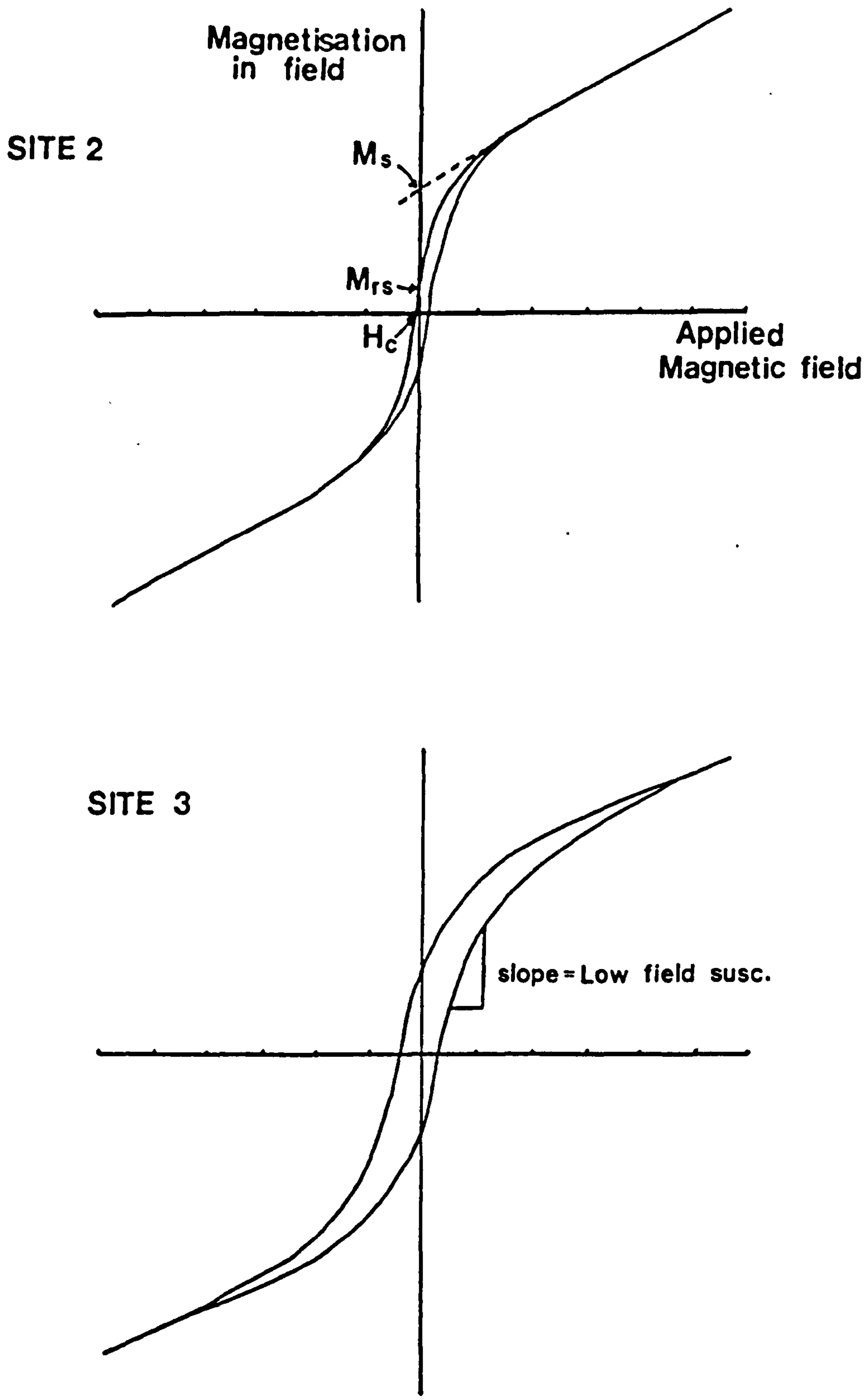


fig.107a Hysteresis loops produced by vibrating sample magnetometer (VSM).

SITE	M_s Am^{-2}/kg	Mrs / Ms Am^{-2}/kg	Mrs Am^{-2}/kg	H_c A/m	Low field Susceptibility m^{-3}/kg	High field Susc. m^{-3}/kg
			$\times 10^{-2}$	$\times 10^{3}$	$\times 10^{-7}$	$\times 10^{-6}$
1	0·640	0·139	8·23	$8{\cdot}23 \times 10^{-2}$	2·25	·110
2	0·147	0·239	3·51	15·8	2·17	2·28
3	0·119	0·454	5·41	50·6	1·28	1·08
4	2·143	0·077	0·165	4·42	3·02	·381
7	0·397	0·059	2·34	3·69	1·77	6·47

Table 8 Results from Vibrating Sample Magnetometry.

4) Restoration procedure error, this may occur during tilt corrections, as the simplest restoration is assumed and this may not be the case.

5) Random error due to; a) samples subjected to exceptional conditions e.g. lightening strikes before sampling. In this case one case (site 2) the samples were collected from the top of the Whin sill in an exposed crag and so may have suffered this fate. b) non-systematic error, i.e. due to equipment failure not noticed or evident at the time of the experimentation.

6) Sampling errors. These are the commonest form of error in palaeomagnetism work and care was taken to label the cores fully and record local bedding strike and dip. In the case of site 6, a sample was extracted for coring in the laboratory and there may be error in transferring the blocks from the outcrop. Throughout the standard right hand rule was used and all dips marked with a direction to be absolutely confident.

7) Real geological processes, such as block rotations and folding.

6:1:3 Remnance carriers

Samples were crushed for analysis in a vibrating sample magnetometer (VSM)conducted at Liverpool University (Palaeomag. Lab.) by D. Robertson.

Samples were calibrated against Copper Sulphate and each was vibtrated in an applied magnetic field and the "in-field" mgnetisation measured. Results were plotted as a series of hysteresis loops where M_S is the saturation magnetisation and M_{rs} is the saturation isothermal remnant magnetisation (see fig. 107). The intersection on the horizontal axis (applied magnetic field) H, is the coercive force H_c and the slope of the loop is the low field susceptiblity. The slope of the loop where it converges in the high field susceptibility. The ratio M_{rs}/M_S indicates a measure of the domain of the remnace carrier (approximately related to size of the grains), where a value of 0.5 corresponds to single domain grains (0.05 to 0.1um) and 0.01 indicates multi-domain grains (i.e. large grains).

An estimate of the quantity of magnetic minerals present can be given by dividing the measured M_S by the mass fraction (saturation magnetisation) of the desired mineral e.g. magnetite. The quotient is multiplied by the low field susceptiblity and this gives a value of the susceptiblity due to magnetite in the low field. Magnetite susceptibilities are saturated in low fields whereas paramagnetics are saturated only at high field strengths, therefore the high field component will be due to varying amounts of illite, biotite, orthopyroxene and ilmenite. Haematite is not saturated at laboratoryfields and so where loops do not converge to an asymtote this is due to the presence of that ferromagnetic mineral. This is found for sample 3, the Birrenswark lavas and confirms the content of Haematite first noted when drilling as the drilling mud was red.

Figure 107 shows hysteresis loops for representative samples to show magnetite and paramagnetic dominated rock (Whin sill) and the effect of Haematite (Birrenswark lavas). Table 8 shows the results for each site.

Magnetite saturates in a field of 300mT, and its saturation magnetisation is 92 Am2/Kg hence the mass fraction of each sample represented by magnetite can be calculated.

Site 1 1.597 x 10-3 = 38% (of total magnetisation due to magnetite)
Site 2 6.95 x 10-3 = 36%
Site 3 1.293 x 10-3 = 68%
Site 4 0.023 = 34%
Site 7 3.989 x 10-3 = 35%

It can be seen that very small quantities of magnetite, produce a significant part of the magnetism the rest being made up by paramagnetic minerals, it is therefore likely that the magnetisation directions of the the samples are due to primary magnetite and paramagnetics. In most cases the Mrs/Ms ratios indicate small grains which are likely to have retained at least some ancient magnetisation directions. In the case of site three, the grains are larger and so more easily coerced than for smaller grain sizes, which may indicate that site three will be unreliable.

6:1:4 Results

The results from the sites are summarised in a series of Wulff (equal angle) stereonets and Z plots, of which representative examples are illustrated in figures 108 to 113. The mean site directions are plotted in figure 114 and these are compared as virtual geomagnetic poles with a known apparent polar wandering path (APWP) illustrated in figure 115 (from Briden et al 1989).

i) The magnetisation characteristics

From the Z plots, the following can be deduced;-

a) <u>The Whin sill at site 1</u>.

Of the five samples finally run from the site, four were treated by AFDM and the fifth by TDM. The four showed very similar patterns of vectors. An early viscous component directed SW inclined -40° was removed in each case over the first treatment stage. Thereafter a consistent reversed component was observed. This was generally SSE inclined shallowly between +15° and -15° (i.e.down) and appears quite stable. This reversed component is strikingly similar to reversed components gained from the Red Beds in the Coal Measures of Central England by Turner and colleagues (Turner, Vaughan & Besly 1985), and is taken to be a stable end Carboniferous / early Permian direction. The fifth specimen (1P2P2) was entirely different showing normal magnetisation directed E (ENE) inclined steeply +70° up. This may reflect a more present day orientation, and obviously reflects the behaviour of the magnetic minerals in the sample to the heating process.

b) The Whin sill at site 2.

These specimens gave stable reversed directions trending S inclined between +10° (up) and -45° (down). The swing towards upwards directed components in the site may reflect the sampling site (in the margin of the sill) and on comparison with site 1 it seems reasonable to suggest that the variation can be attributed to secular variations, although the vector direction is similar and therefore possible the same age. 2P1P2 the thermally treated sample showed a strong stable reversed RM directed W/SW and inclined -45°. This specimen was heated to >560°C and showed no signs of any other components. 2P1P1 was one of the five AFDM treated specimens and showed a great deal of scatter about a reversed direction similar to the others, but with a tendency to "flip" to SSE inclined near horizontal component (up) as if "remembering" a direction between stages. This may reflect lightening strike effects. These directions are not unlike those from site 1.

c) The Birrenswark lavas at site 3.

All the samples including those treated by TDM show a strong stable normal magnetisation direction, directed consistently NW inclined up to -50° (down). These do not appear to be Carboniferous directions but bear a resemblance to Upper Carboniferous (Post Asbian) directions obtained from dolomitised limestones in the Carboniferous around Clitheroe (Addison, Turner & Tarling 1988). The Birrenswark lavas are extensively altered with secondary magnetite occuring as a product of the break-down of olivine, which may suggest the direction represents a magnetisation direction acquired during the post deposition of the lavas, i.e. sometime after the Lower Carboniferous.

d) The Kershopefoot basalts at site 4.

Generally the points from all the samples were very closely spaced, though this is a function of the graph spacing rather than the directions. An early strong normal component directed NE inclined 70 to 50° up gives way to a much weaker and more unstable series of scattered reversed directions with few straight line sections. They are SW inclined ranging between 10 and 50° (down). These indicate a weak direction that from the Z plots alone no further conclusions could be drawn.

e) The Birrenswark lavas at site 5.

These were not analysed as the specimen were extremely friable, and no large enough core sections could be obtained from this site.

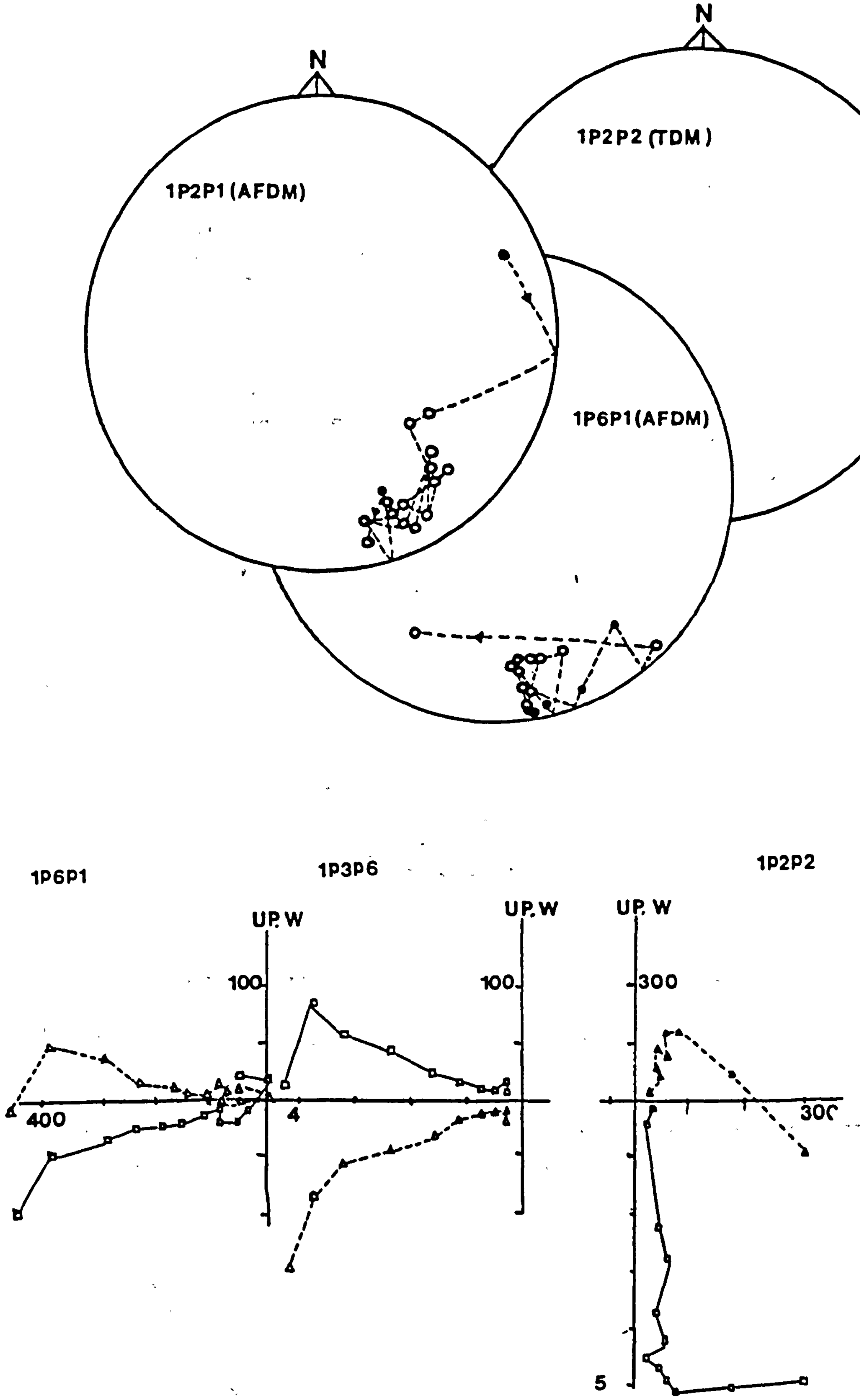


fig.108 Respresentative stereoplots and Ziederfeld diagrams for site 1, the Whin Sill at Wall Town crags, Northumberland.

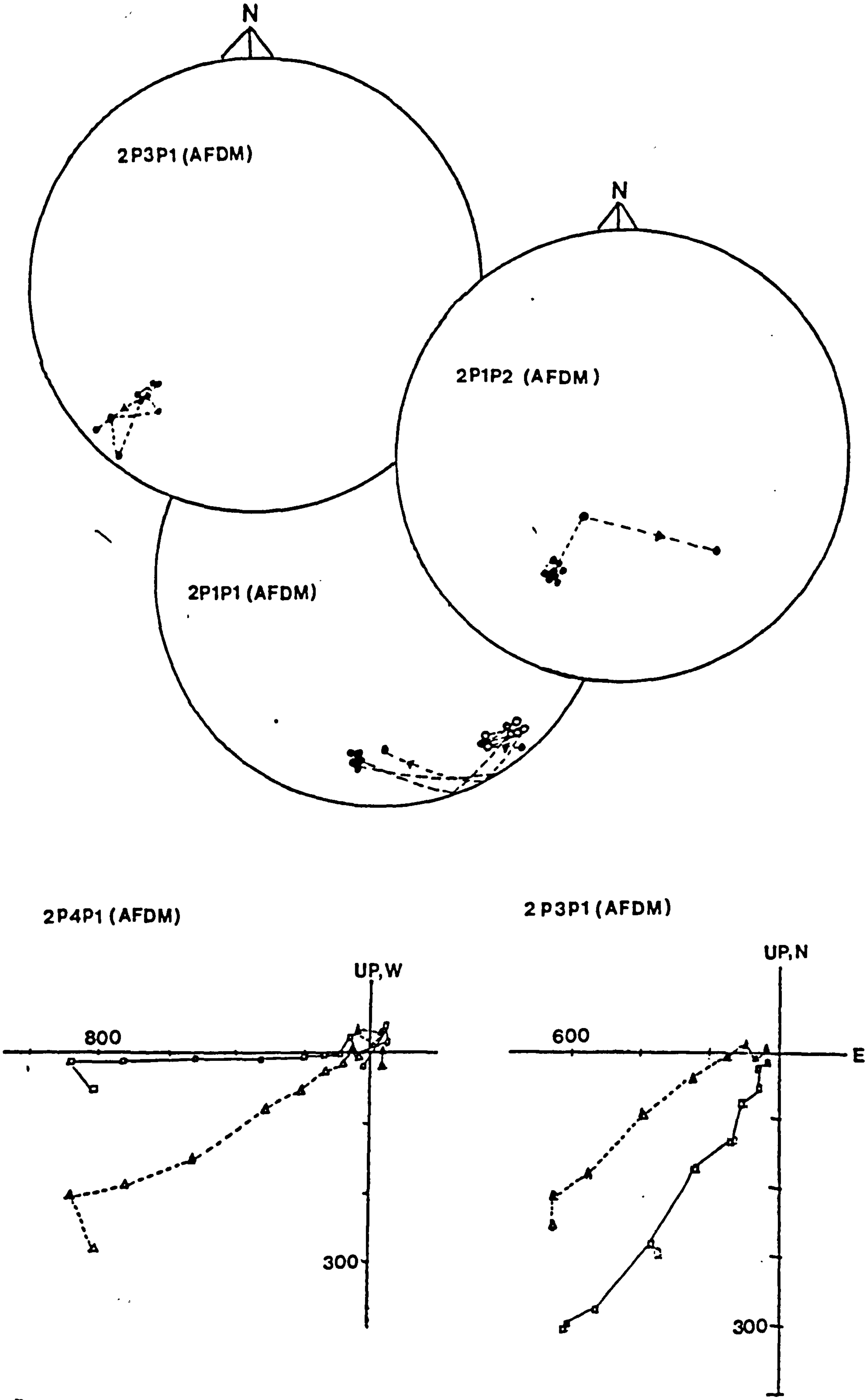
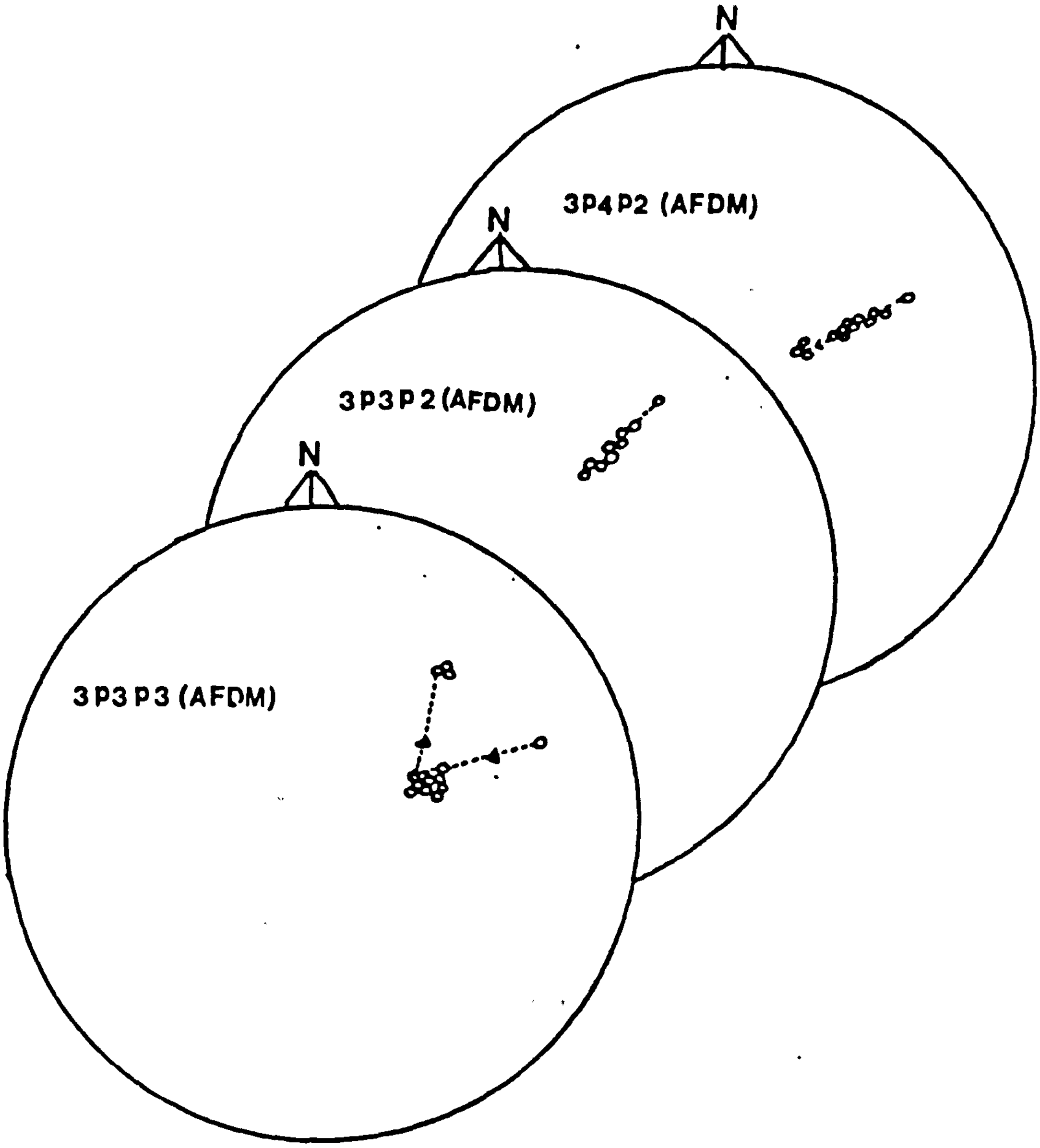


fig.109 Representative stereoplots and 'Z' plot diagrams for site 2, Whin Sill at Cawfields, Northumberland.



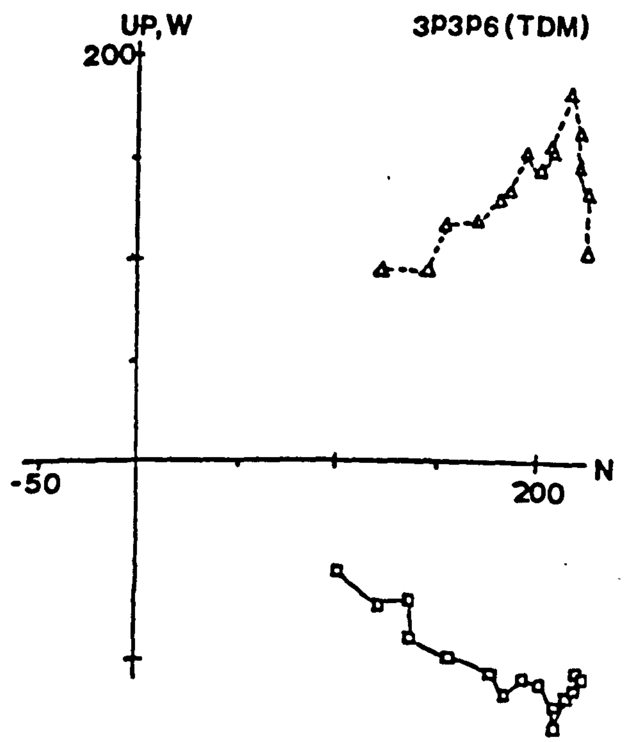


fig.110 Representative stereoplots and 'Z' plot diagrams for site 3, Birrenswark lavas at Skippers Bridge, Langholm.

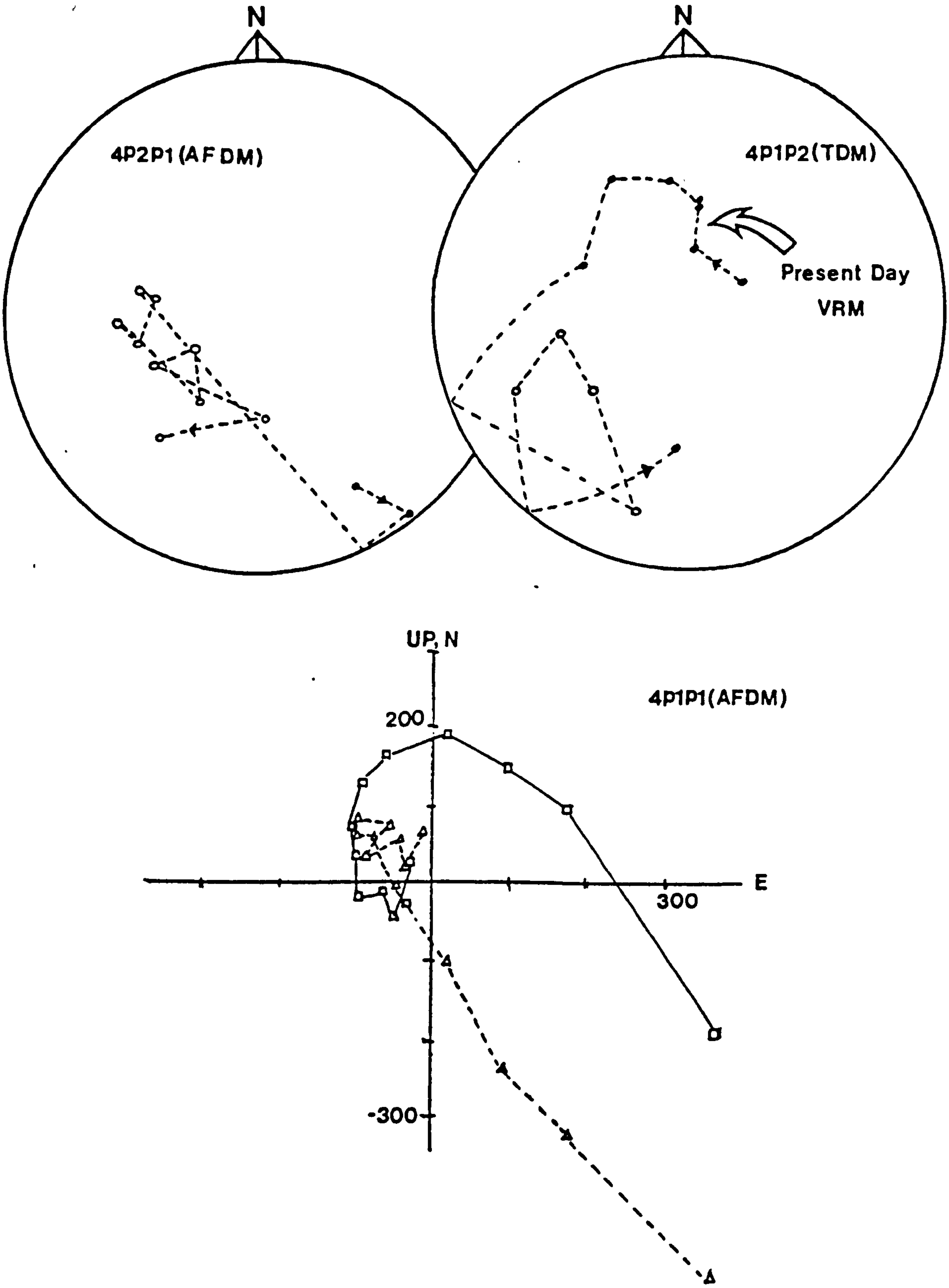


fig.111 Representative stereoplots and 'Z' plot diagrams for site 4, Kershopefoot basalt, Kershope Quarry, Cumbria.

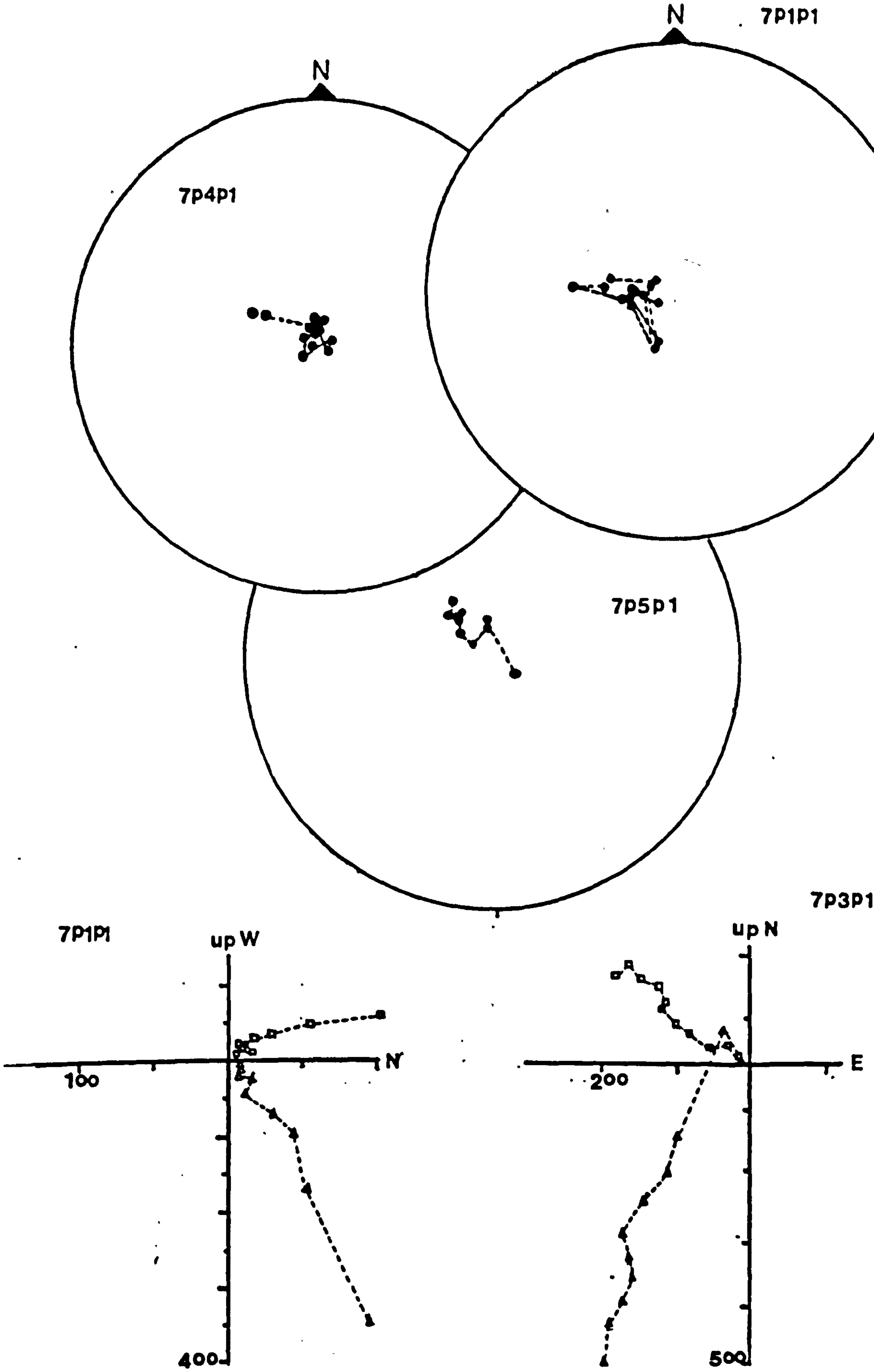
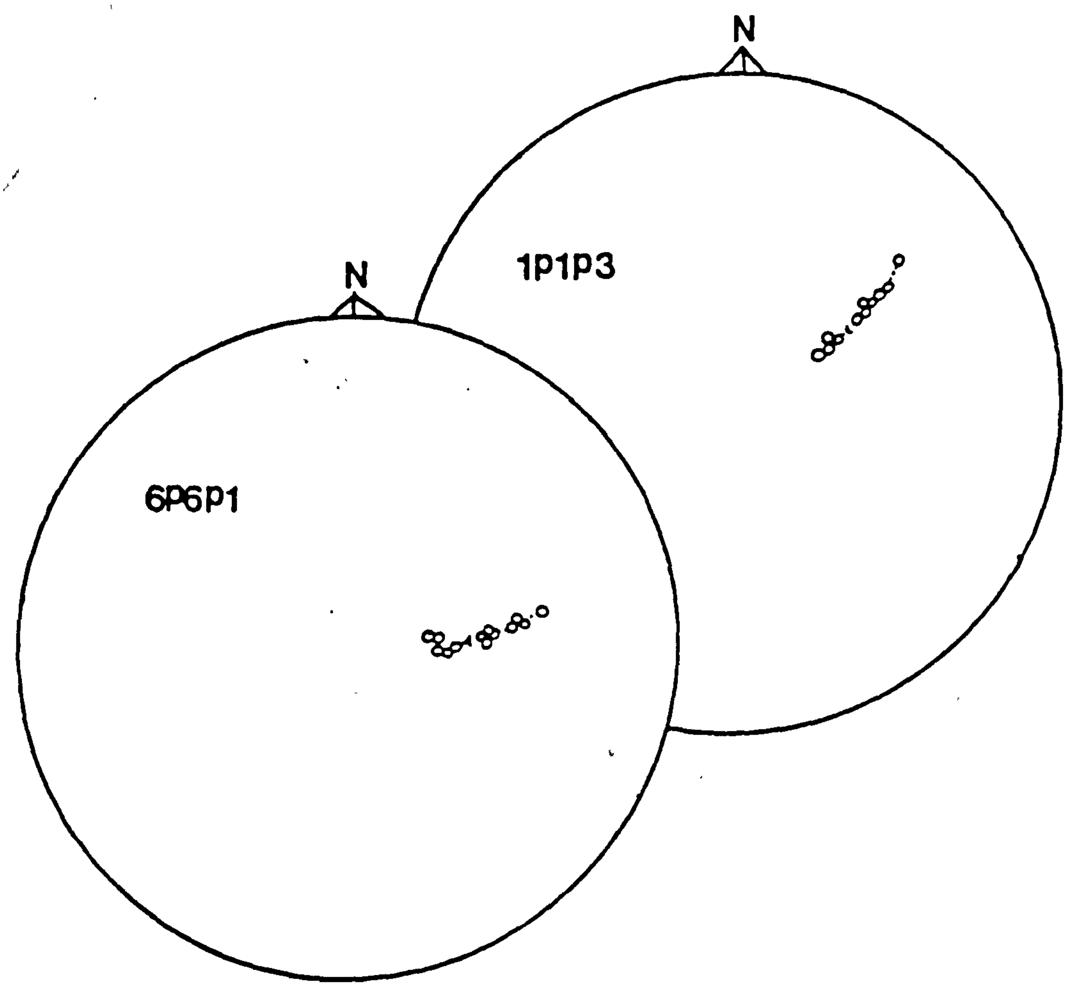


fig.113 Representative stereoplots and 'Z' plot diagrams for site 7, Cockermouth lavas, Wood Hall, Cumbria.



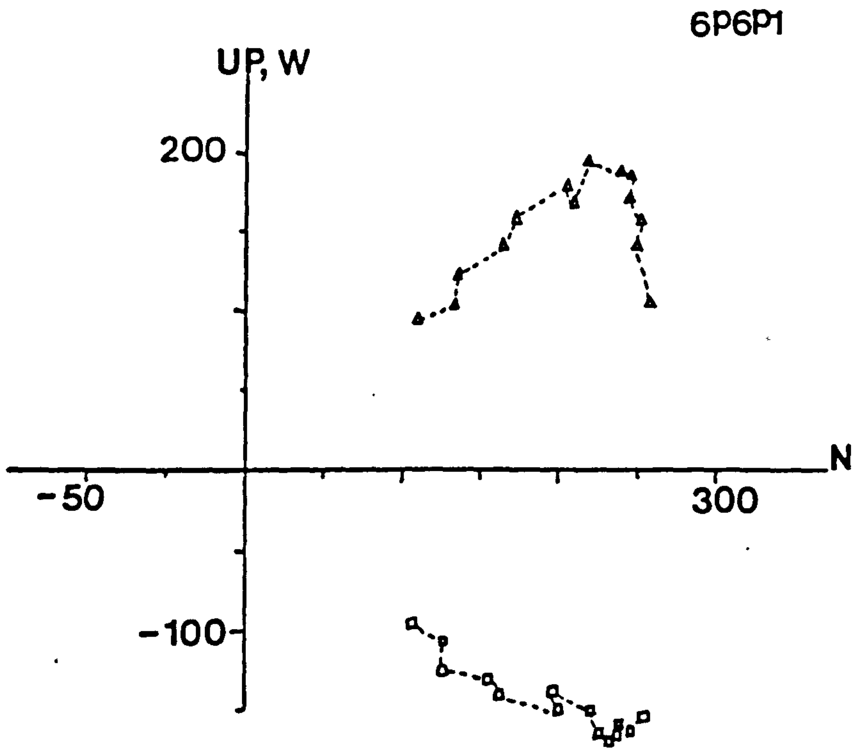


fig.112 Representative stereoplots and 'Z' plot diagrams for site 6, Birrenswark lavas at Preston Mill, Dumfries.

f) The Birrenswark lavas at site 6.

These gave very similar stable directions to those of site 3. The data showed few reliable straight lines sections but those that were identified were west directed vertical down directions. Such directions may reflect some tilting of an originally steep component but as they are so similar to site 3 they were interpreted as not Carboniferous. Unfortunately sampling error seemed to have occured due to imprecise orientation of blocks extracted for drilling in the lab, hence no statistically acceptable number of samples was extracted for calculation of a mean site direction.

g) The Cockermouth lavas at site 7.

The thermally treated sample gave a stable, relatively steady direction NW, inclined steeply -80° (down). The other samples are fairly consistent giving at least two straight vectors directed west and near vertical (down), normal magnetisation. These directions are quite dissimilar to the previous sites and bear no resemblance to published directions from the Carboniferous. The directions, however ar stable and may represent resetting of the lavas in some post Carboniferous magnetic event.

ii) Site means and virtual geomagnetic poles.

The site means for the samples are given in figure 116 as a table and plotted on a Wulff equal angle stereonet, they are circled by estimates of their confidence that the true mean is in that direction (alpha 95) which gives the likely errors in the directions. These can be compared with their respective geomagnetic poles and then compared with the APWP in fig.115.

6:1:5 Conclusions

Site 1 and 2 (Whin sill) represent stable end Carboniferous to Early Permian directions. The sites give one normal and one reversed direction which may reflect secular variations. The poles calculated for the sites are slightly apart, which allowing for error implies a minor rotation anti-clockwise between 1 and 2 of up to 12°. This seems to be due to strike-slip motion on the fault that separates the two outcrops. This fault trends NW/SE and is of the same orientation as the Gilsland and Blenkinsop Boundary faults (BGS Sheet 18, Brampton district). As the supposed rotation is after the sill this implies a post-early Permian age for the movement on the fault.

Site 3 (Birrenswark lavas) has an unknown direction and an unknown age to its pole. The pole direction cannot be explained by rotation about the vertical to achieve a Carboniferous or Devonian direction and is too steep for these in any case. It may be that the

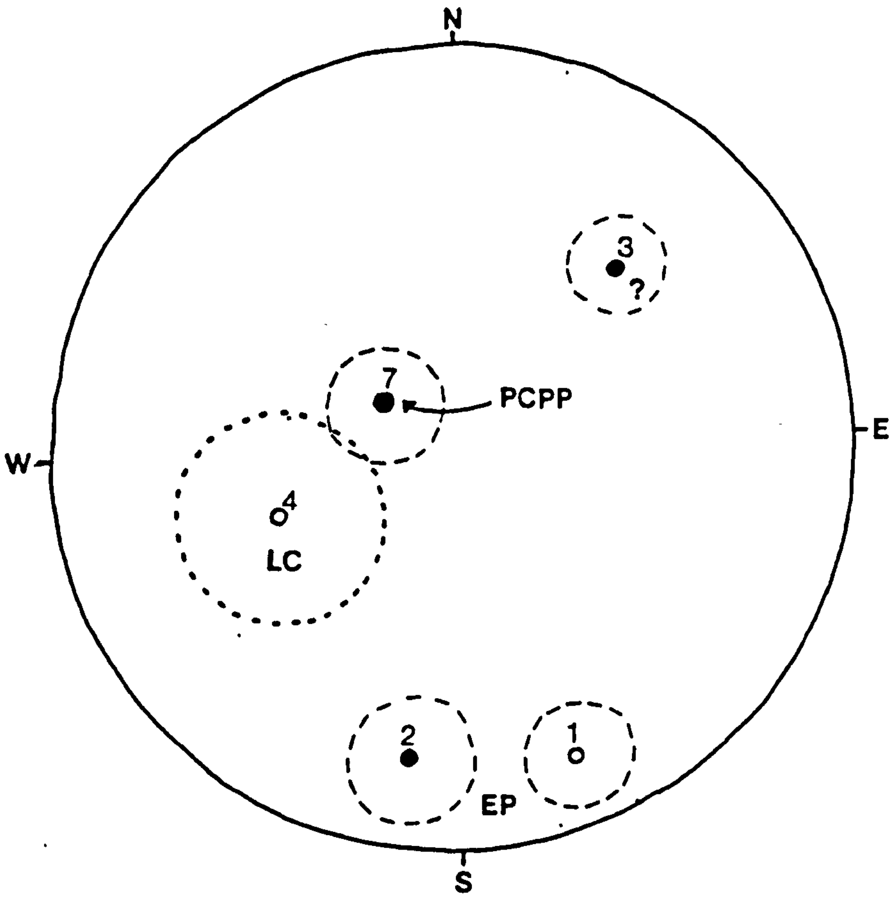
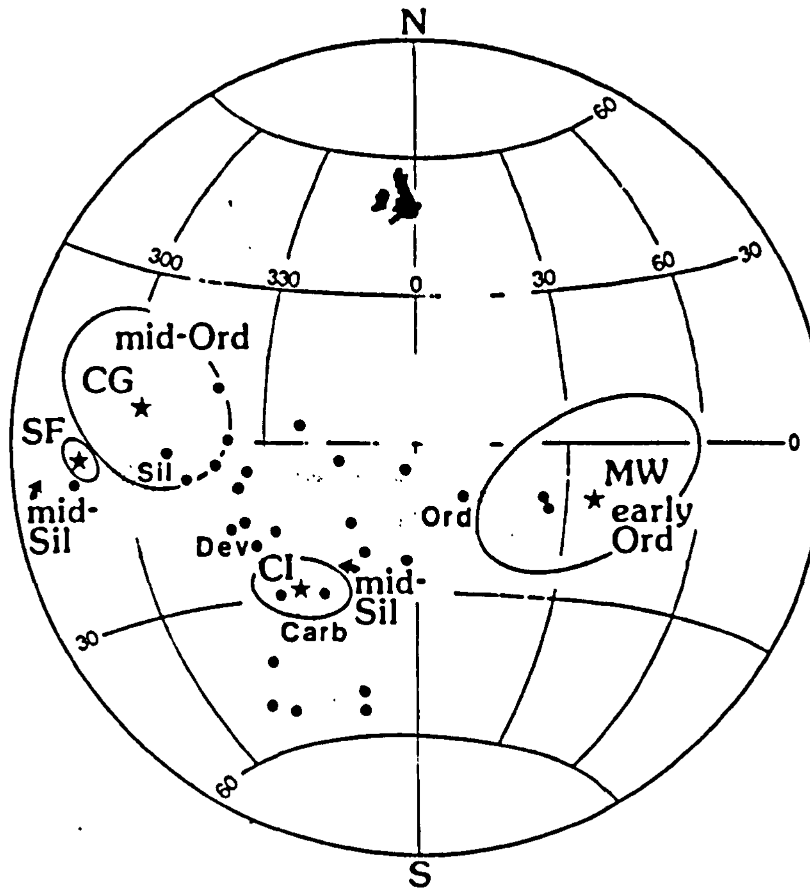


fig.114 Plotted magnetisation directions for calculated site means.

EP = Early Permian, LC = Lower Carboniferous, ? = Unknown, PCPP = Post Carboniferous - Pre-Present day (Tertiary?).



Palaeomagnetic data from possible tectono-stratigraphic terranes in western Ireland compared with Lower Palaeozoic and Devonian data (●) for Scotland, and Carboniferous and Permian data from all of Britain (Briden *et al.* 1984, 1987; Livermore *et al.* 1985). The APW path is a composite of those for northern and southern Scotland (Briden *et al.* 1987). Western Irish data (★) are shown with 95% confidence limits: CI, Clare Island; SF, Salrock Formation; MW, Mweelrea ignimbrites; CG, Connemara Gabbro.

fig.115 Plotted polar wandering path for the British Isles, taken from Briden et al 1989.

site reflects a more modern day direction or a rotated Tertiary pole, but these are unconstrained conjectures.

Site 4 (Kershopefoot basalt) appears to resemble a reversed direction so is likely to be Carboniferous. However by rotation about the vertical the pole can be made to represent either,

a) an Upper Devonian pole (which is unlikely as these lavas are representative of the Middle Border Group), or

b) a rotated Lower Carboniferous pole. The presumed rotation is just in excess of error and can be deduced to represent post MBG, but pre-Whin sill rotation. It is debatable as to the age of this rotation, as it could be due to late rift related extension or due to rotation during inversion compression.

Site 7 (Cockermouth lavas) have a very steep direction likely to be the result of re-setting after the Carboniferous, possibly in the Permo-Trias or younger as the pole direction cannot be explained by rotation.

Table 9 Site means and virtual pole directions (compared with present day) for remnant magnetism directions.

SITE	$\bar{D}$	$\bar{I}$	α_{95}	n	POLE	AGE
Whin sill 1	159·2	-10·8	4·8	5	24·6E -37·7S	Early Permian / Late Carboniferous
" " 2	190·6	14·94	3·8	5	346 2 -26·8S	
Birrenswark Lavas 3	52·2	-35 3	13·8	5	129·7E 3·33N	Unknown
Kershopefoot Q. 4	251·1	41·4	38·4	5	268·9 -30·1	Lower Carboniferous (rotated?)
Birrenswark L. 6		not	statiscally		viable	
Cockermouth Lavas 7	304·2	67·4	15·2		283·4 56·7	Recent to Mesozoic ?

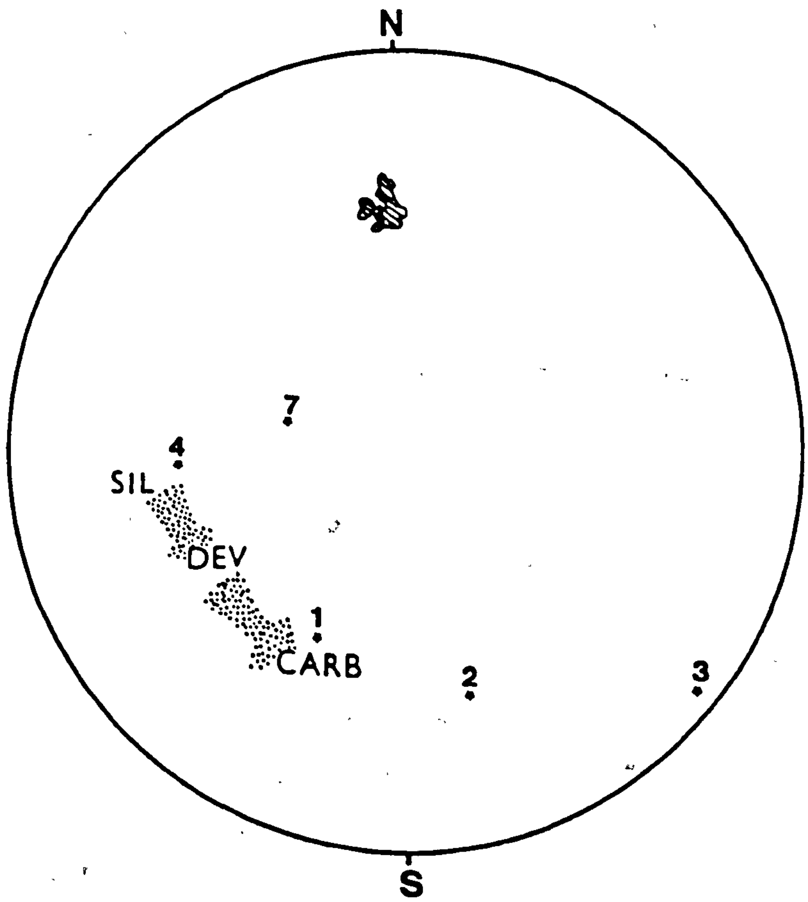


fig.116 Plotted virtual geomagnetic poles, derived from site mean directions.

Part Two
Quantitative Modelling

6:2:0 Introduction

The effect of inversion deformation on basins is little understood. It has been simply regarded in the past as the opposite to the basin stretching and formation process (Chadwick 1985) but this has taken no account of the lithospheric profile of the basin at the time of inversion. It is assumed the basin is no longer subsiding and the effects of uplift are assumed to be homogeneous across the basin (see chapter 3). The inversion event in Northumberland was demonstrably asymmetric and at a time in the basin's evolution that can be reasonably expected to be within the post rift, thermal subsidence phase. Some method of calculating the effects of the inversion is needed that permits consideration of the following;

1) the effect of the loading of the lithosphere by new inversion structures;

2) the effect of shortening (taking the inversion case in this instance to be due to shortening) on the basin lithosphere. This really needs to allow for the changing rigidity of the lithosphere with basin development and hence at the time of the inversion.

3) the effect of different shortening or deformation mechanisms on the basin.

4) the amount of uplift an inversion event produces.

The following section attempts to quantify these parameters starting from first principles, so that basin subsidence can be regarded as a trade off between isostatic compensation and thermal isostasy.

6:2:1 Simple Isostatic Calculations

i) The model

The uplift caused during inversion can be estimated for Northumberland relative to erosion levels against the Permian unconformity and by the level of the intrusion of the Whin sill, which is believed to have been intruded some 200m below surface (Francis 1978). A map showing the broad uplift pattern derived by these methods and from published data is illustrated in chapter three, fig.41, and is reproduced here. This map serves as a check for the order of magnitude of theoretically calculated uplift values (see fig. 122).

To calculate the effect of a new load, a local isostatic balance calculation can be performed on previously balanced comparative sections (see fig. 103). The basic calculation is as follows;

$$\Sigma\, t_s\,(\rho)s + t_c\,(\rho)c + t_m\,(\rho)m = \Sigma\, t_s\,(\rho)s + t_c\,(\rho)c + t_m\,(\rho)m$$

basin = block

where, t = thickness (km) of, s = sediments, c = crustal lithosphere, m = mantle lithosphere, ρ = density.

This enables the calculation of the thickness of the crustal lithosphere at the time of inversion. For Northumberland the inversion was assumed to fall into a time window in the Westphalian as illustrated in fig.112, this of course relies on the assumption that the rifting process was uniform in the upper and lower crust so that over the geological period considered the basin was in isostatic equilibrium. If it can be reasonably proved that the basin underwent two layer extension then even this simple case cannot be applied (see discussion in chapter seven). Fig. 117 also illustrates the average basement (unloaded by sediment) subsidence curve for Northumberland based on published curves (Leeder & McMahon 1988, Kimbell et al 1989) and compared with an idealised subsidence curve for a β value of 1.4, after Cochran's non-instantaneous rifting model (1983). Inversion is believed to have occured some 25myrs after rifting had ceased, and it can be seen that this was well within the thermal "sag" phase of the basin's history. Fig. 118 shows a schematic representation of the variation of lithospheric thickness with time after initial rifting. It can be seen that the inversion must have occured at a time of reduced lithospheric thickness, i.e. thicker than newly rifted lithosphere but thinner than totally equilibrated lithosphere. It is this calculated value of lithospheric crustal thickness that is substituted into the isostatic balance calculation. The same approximate value of crustal lithospheric thickness can be calculated by balancing against a block assumed to be unrifted e.g. the Alston block or estimated from a schematic figure like fig.119.

The parameters listed below were substituted into the first equation, taking the Alston block to be unrifted and where A = thickest basin fill i.e. in south and B = thinner basin fill i.e. in north. This is an oversimplification as the block was involved in thermal subsidence, and formed part of the whole Carboniferous syn-orogenic basin complex. The basin is more complex than the simple half-graben suggested here, but this is a workable model for the purposes of the calculation.

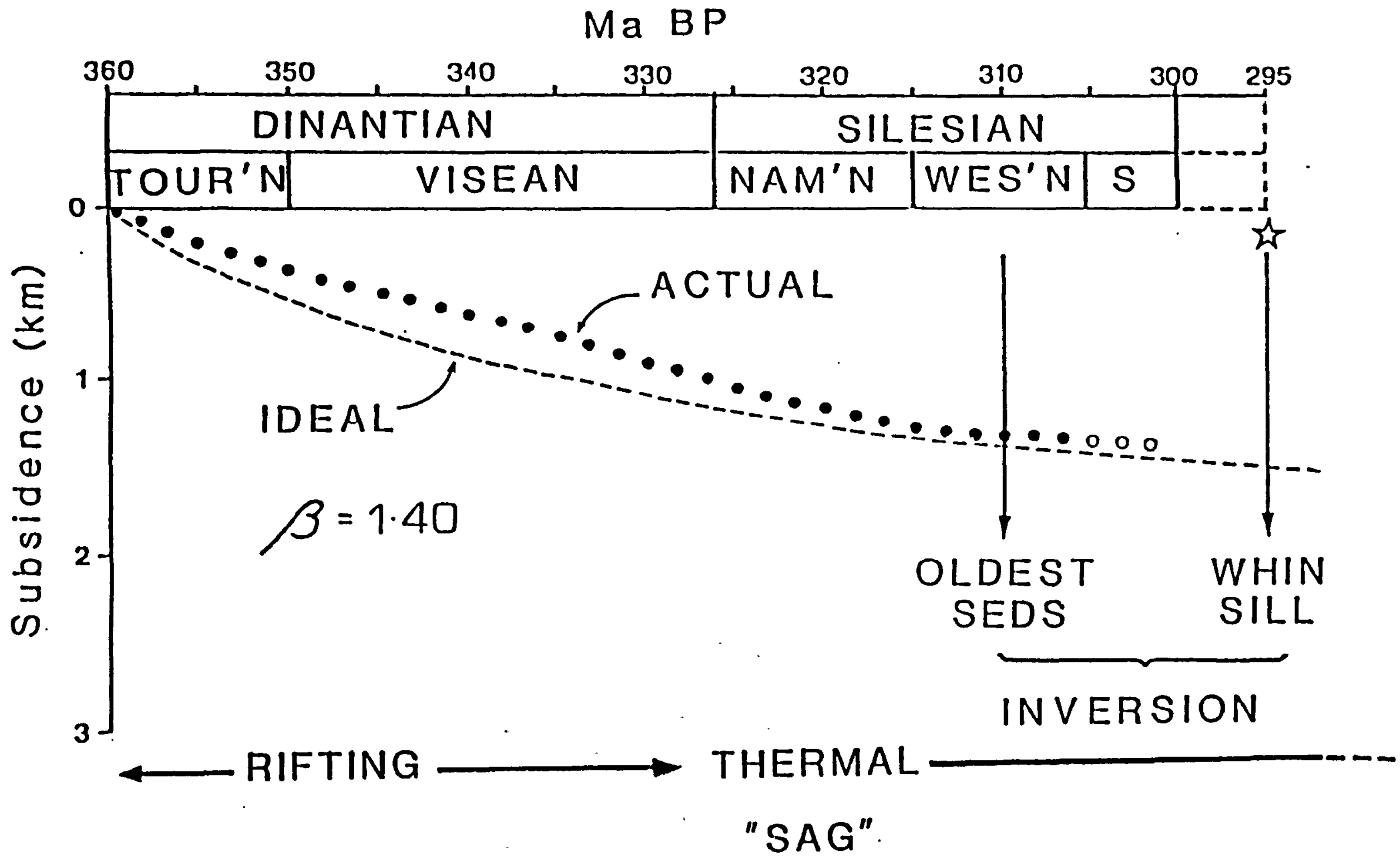


fig.117 Averaged de-loaded basement subsidence curve for Carboniferous Northumberland derived from Leeder & McMahon 1988; Kimbell et al 1989 and shown with an 'ideal' plot based on Cochran 1983 for beta = 1.4.

	basin (A)	basin (B)	block
t_s = sediment thickness	6km	3km	2km
t_c = lith. crustal thickness	xkm	xkm	30km
t_m = lith. mantle thickness			
to compensation depth of 120km	120 - x (+3 or +6)		88km
ρ_s = av. sediments density	$2.5gcm^{-3}$	$2.5gcm^{-3}$	$2.5gcm^{-3}$
(based on Bott 1984)			
ρ_c = av. continental crust density	$2.8gcm^{-3}$	$2.8gcm^{-3}$	$2.8gcm^{-3}$
ρ_m = av. mantle density	$3.4gcm^{-3}$	$3.4gcm^{-3}$	$3.4gcm^{-3}$

The resulting values for x are 24km for A and 28.5km for B, where A and B represent the extremes of the broadly asymmetric basin. In reality these values will be modified by regional compensation (which will tend to decrease the values) and by thermal isostasy which will tend to increase values to the true lithospheric thickness.

Having calculated the starting profile for the undeformed basin prior to inversion, the effects of the additional inversion load can be assessed. The first equation can be rewritten to calculate the local uplift produced by the inversion load.

$$U = \frac{K - k}{(\rho_m - \rho_s) \cdot (\rho_c)}$$

Where U = amount of uplift (km).

K = sum of products of thickness/density products for unrifted block.

k = sum of thickness/density products for shortened basin, where shortening is measured as a percentage.

ii) The Results

The results are plotted as a graph taking percentage shortening against resultant isostatic uplift as in fig. 121. A schematic view of the new basin profile after inversion uplift is given in fig. 120. The alternative labels 1 and 2 represent the variation in uplift related to the shortening mechanism. A represents thin lithospheric crust under the thickest sedimentary accumulation and B represents the thinner lithospheric crust under the thinner sedimentary accumulation e.g. 10% over A = 0.78km whereas B= 3.25km.

Alternative 1 is the scenario where it is assumed the shortening was taken up by thin skinned deformation i.e. entirely contained within the sedimentary cover. As the graph illustrates considerable shortening is required to approximate to the pattern of uplift illustrated in fig. 122. For example the 2-3km of uplift associated with the northern side of the basin.....

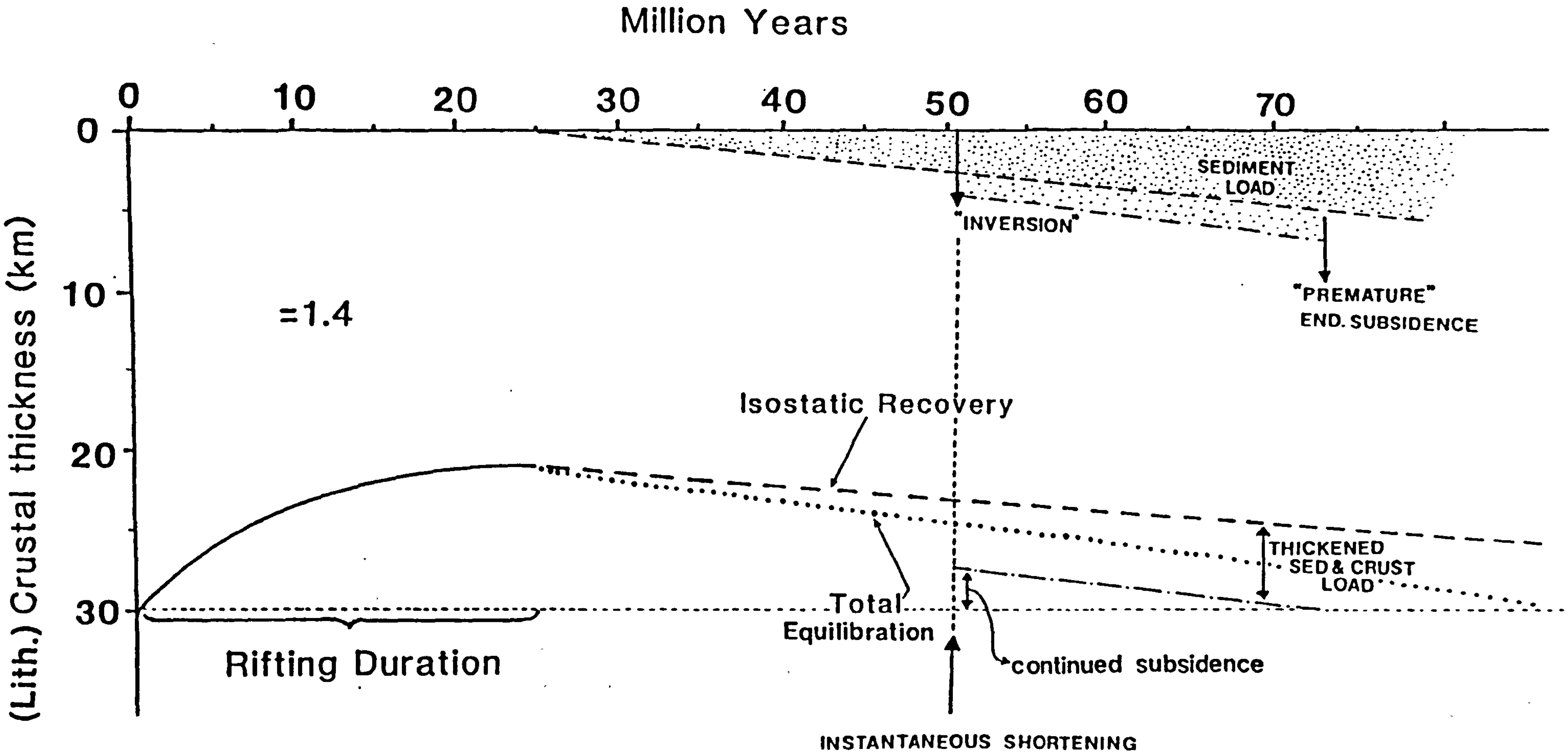


fig.118 Schematic variation of crustal lithospheric thickness with basin evolution, showing the effect of sediment loading after rifting (Airy compensation prior to this) and the hypothetical effect of an inversion event.

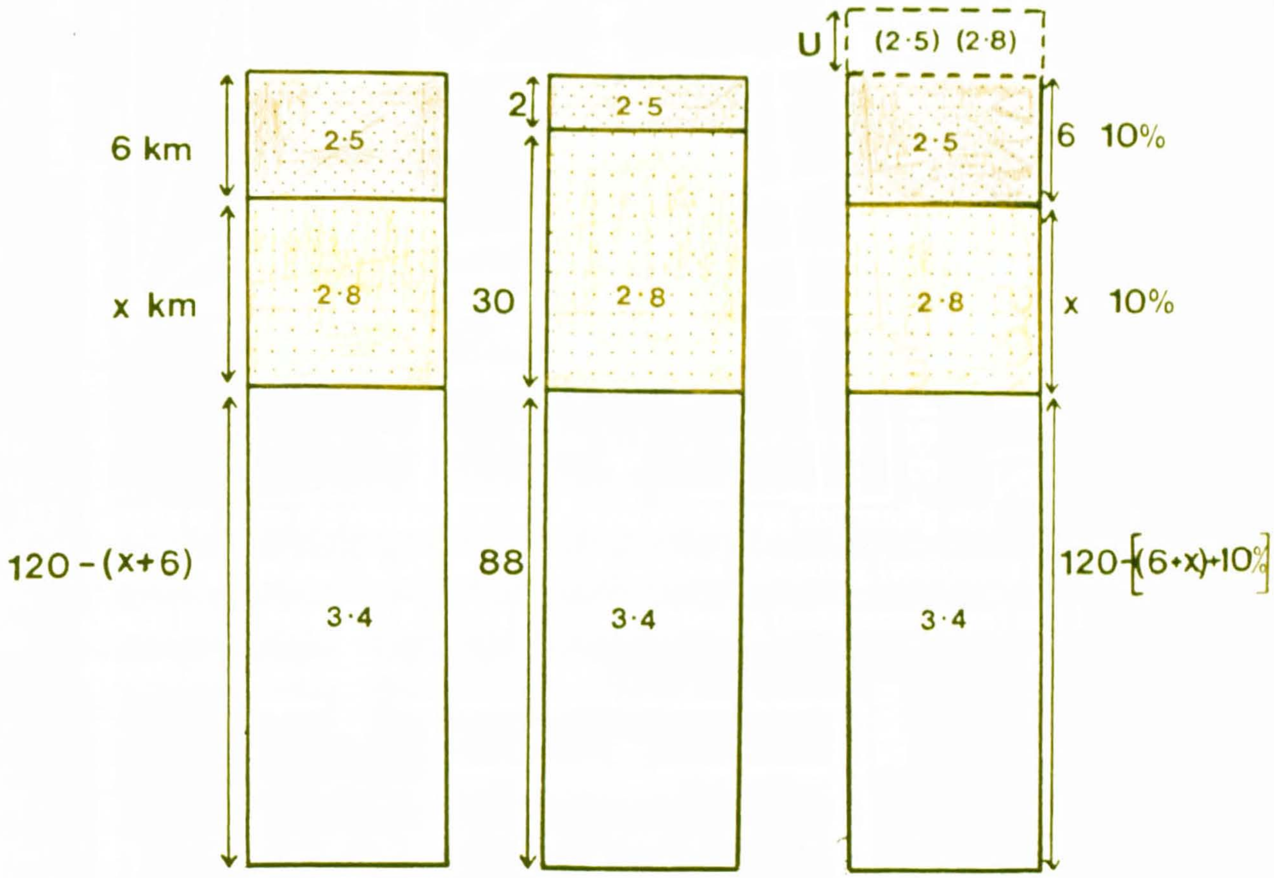


fig.119 Simple isostatic compensation modelling.

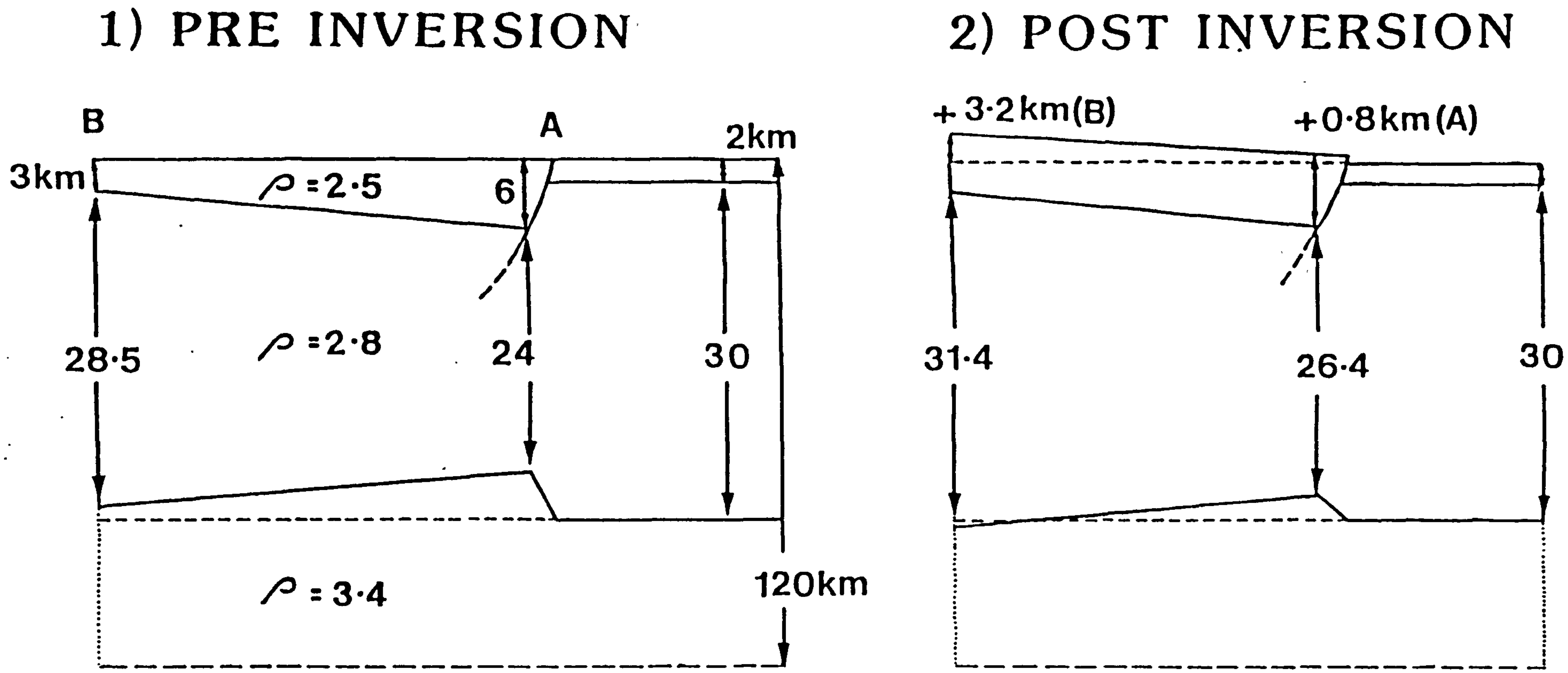


fig. 120 Results of simple isostatic modelling after 10% shortening (sediments and crustal lithosphere).

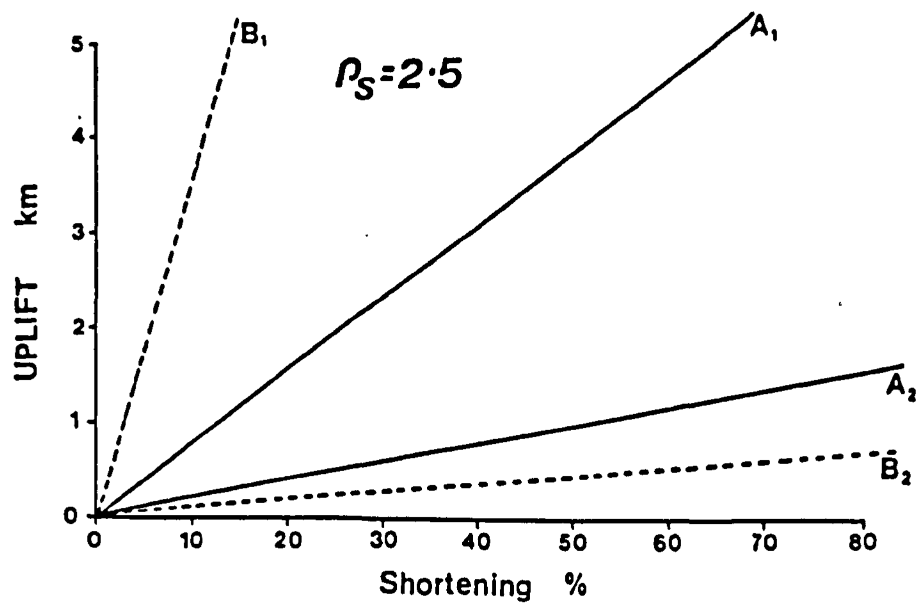
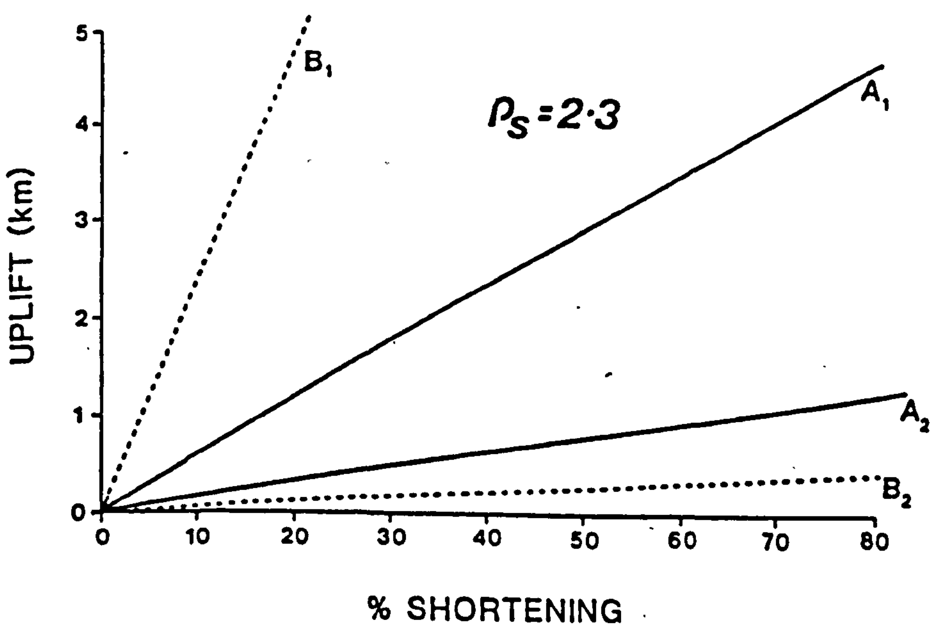


fig. 121 Graphs to show the variation of uplift with percentage shortening and shortening mechanism, where A is thick skinned shortening (sediments and crustal lithosphere) and B is thin skinned shortening (sediments alone) and 1 = north of basin and 2 = south of basin.



requires shortening in excess of 70%, which is geologically improbable for Northumberland.

Alternative 2 is the case where shortening is thick-skinned and involves crustal shortening (this would imply basement involvement in the real geologic example). The 2-3km of uplift required can easily be achieved by this method.

Figure 121 shows the results for sediment densities of $2.3gcm^{-3}$ and $2.5gcm^{-3}$. Another interesting result of this simple approach is that the 3:1 ratio of uplift over the basin between the north and the south seems to be an inherent function of the state of the crustal lithosphere and the thickness of the sedimentary cover. The 3:1 ratio can be explained by;

i) **Thick skinned inversion**, over the whole basin, or a combination of;

ii) **Basement involvement** in the north of the basin and **butressing**, or sedimentary shortening only in the south of the basin in the thickest fill.

6:2:2 Regional Compensation

Local compensation can be assumed for calculations during the rifting phase such that sediment accumulation is compensated in an Airy fashion whilst faulting is active in the basin. After rifting the sediments will exert a load effect during the post-rift or thermal subsidence phase. This is calculated as regional compensation where the best assumption is that loading will produce a flexural response in the lithosphere because it has lateral strength or rigidity. Regional compensation can be expressed as;

$$D \frac{d^4 w}{dx^4} + N \frac{d^2 w}{dx^2} + \rho m g w = P(x)$$

(as derived by Turcotte and Schubert 1982)

Where the first term represents the local isostatic effect and the second term represents the intraplate stress and the final term represents the flexural response of the crustal lithosphere.

x = distance normal to load axis, D = flexural rigidity of the lithosphere, N = intraplate stress and P the vertical load distribution.

The flexural rigidity of the lithosphere will affect the deflection of a given load such that the larger the flexural rigidity the smaller the deflection under a given load distribution. The second term represents the effect of intraplate stress on the deflection. This is usually ignored for extensional basins but will be important in contractional inversion settings.

The difficulties with applying this equation to Northumberland are that;

1) there is no accurate way of measuring or inferring the flexural rigidity of the Carboniferous lithosphere at the time of the inversion event;

2) if it were possible to estimate 1) then the change in this value with time during rifting and subsequent thermal subsidence cannot be estimated;

3) in calculating the flexural rigidity or expressed another way the effective elastic thickness (EET) of the lithosphere, account must be taken of the change in heat flow through the basin's evolution (Watts et al 1982).

Watts and colleagues showed that the EET is independent of the age of the load but depends on the lithosphere's thermal structure, such that when the EET is small the lithosphere is hot and when large the lithosphere is correspondingly cool.

The Carboniferous inversion is followed by the intrusion of the Whin sill, such a large volume of melt no doubt caused a perturbation in the geotherm prior to the intrusion, this may well have overlapped with the inversion and there seems little way of quantifying its effect on the EET and hence on the regional compensation of the inversion event.

The regional anticlines can be thought of as line loads on the lithosphere with a topographic elevation. This can be calculated by;

$$h = h_o \sin 2 \Pi x/\lambda$$

where h, is the height of the topography and λ is the wavelength of the structure.

However, since the amplitude of the topography is small compared to the thickness of the elastic lithosphere, the influence of the topography can be neglected and the corresponding load for the above is (after Springer Verlag, "Geodynamics" 1982);

$$q_a (x) = \rho c\ g\ h_o \mathrm{Sin}\ 2 \Pi x/\lambda$$

where ρc is the density of the crustal rocks associated with the height variation. qa (x) the load can be substituted into the regional compensation equation as P and rewritten as;

$$w_o = \frac{h_o}{\rho m/\rho c - 1 + D/\rho cg\ (2\Pi/\lambda)^4}$$

However if the wavelength of the topography is sufficiently short,

$$\lambda << 2\Pi\ (D/\rho cg)^{1/4}$$

Then the denominator of the above is larger than 1, so that $w_o << h_o$, and a will cause negligible deformation of the lithosphere. The lithosphere can therefore be regarded as infinitely rigid for loads of this scale (after Hinze et al 1980).

The regional anticlines of Northumberland are 5-10km wavelength structures which are small compared to the elastic thickness of the lithosphere and can therefore be expected to have produced a negligibly small deflection, in which case the local isostatic model is a reasonable approximation to the effect of the inversion shortening on uplift in the basin.

3:2:3 Discussion of the simple model

The simple, local isostasy model can be expressed as (after Angevine, Hellar & Paola 1988);

$$\rho m\, g\, w = [\, 1/\beta - 1\,]\, \rho c\, tc\, g$$

where the first term is the deflection of the crust into the mantle and w = vertical deflection of crust and $1/\beta$ = the shortening factor involved.

This is simplified version of Chadwick's (1985) model for uplift related shortening as discussed in chapter three. The point has been made previously that if this is applied over the whole basin it takes no effect of the possibility for asymmetric deformation and hence uplift. In chapter two where examples of inversion were introduced, it is almost characteristic of inversion shortening that it is asymmetric and localised uplifts are very large in comparison with the remainder of a particular basin. By treating the basin as a series of line loads, in a simple isostatic scenario it would be possible to build up a variable uplift profile for the basin.

In the simple model the crustal lithospheric profile after inversion in the north of the basin is slightly over-thickened. This would perturb the geotherm and cause more uplift due to thermal re-equilibration. Not only therefore can inversion pre-mature a basin it could cause significant uplift on-top of that caused by the structural shortening. This is the second half of Chadwick's model (1985, see chapter three), and a logical consequence of excessive basin shortening. An uplift curve would therefore curve into an asymptote, the reverse of a subsidence curve.

If the product of inversion is a non-matured basin, then the basin must continue to subside after inversion has ceased, because it is still thermally un-equilibrated. If this is the case for the southern part of the Northumberland basin then post-Carboniferous (post inversion) subsidence should be expected. If the stress release following inversion is rapid or perhaps coincides with a new phase of crustal tension, then post inversion normal faulting may be expected.

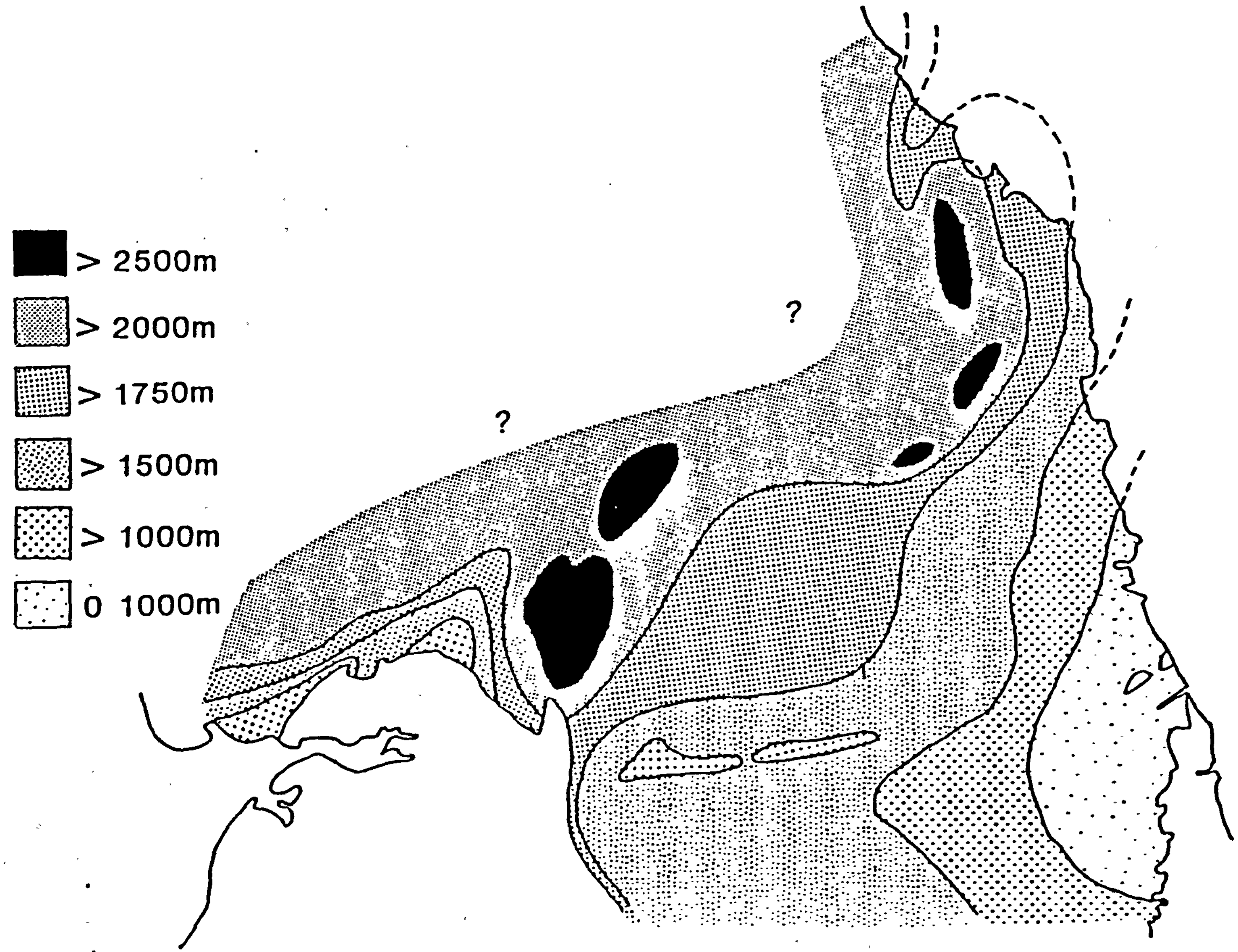


fig.122 Uplift variation over basin for Pre-Permian times, Inversion related.

i) The limitations of the simple model

The simple model is a limited application because it assumes that the basin was isostatically compensated at the time of the inversion event. If for any reason the basin was uncompensated the model cannot be applied. This will include;

a) Increased heat flow

This will affect the densities and therefore the thermal isostasy of the basin. A thermal event could conceivably produce local high heat flow, so that balancing between basin and stable block areas would be misleading. e.g. The Whin sill may have produced an increased heat flow in northern England prior to inversion. However the sill was intruded in both basin and block so effects seem to be regional compared with the area considered for the isostatic calculation.

b) Simple shear versus pure shear extension

If Northumberland was a product of simple-shear "Wernicke" type extension (Wernicke 1985), the extension in surrounding areas would be different for the basin and block in a pure shear model (McKenzie 1978). The centre of maximum heat flow in the former is displaced asymmetrically with respect to the basin (Buck, Martinez, Steckler & Cochran 1988) and therefore much as a) above, will invalidate or complicate the simple model.

c) Airy isostasy

Local isostatic compensation assumes that the lithospheric profiles (balance columns) act independently, separated as it were by vertical faults (airy isostasy). This is geologically unreasonable but as it has been demonstrated with approximation to the real, that regional models make too many estimates of variables that cannot be directly measured for the time considered. The simple model will overestimate uplift in the local, rather than distributing the effect over a wider (regional) area. However if the inversion load is very specific or localised, it is a reasonable approximation.

ii) Advantages of the simple model

The model is attractive as a starting point for estimating uplift in Northumberland because;

a) The regional model variables are difficult to estimate with any certainty.

b) The inversion load is so small and localised that the lithosphere is effectively infinitely strong and so supports the load without appreciable deflection of the lithosphere.

c) The simple model is capable of reproducing the asymmetric uplift of the basin on the same order of magnitude scale, and therefore provides insight into the shortening mechanism, .

Chapter Seven
PROJECT SYNTHESIS

7:0 Introduction

This concluding chapter takes the form of a synthesis, drawing together all the evidence from the authors work (chapters 4, 5 & 6) with previous publications (chapters 2 & 3) in a broad summary of the principal operating events during inversion, affecting Northumberland. The events and the processes are presented and their principal controls suggested. Detailed local event reconstruction was presented in the relevant chapters and so will not be repeated here. The synthesis is divided into two levels; a basin synthesis, integrating previous work with this study which falls into two sections. Firstly a summary of the areas studied in this work and secondly, the former is integrated with the basin review (chapter three). Both the previous are represented in three dimensional reconstructions of the basin, as part of the wider Carboniferous Iapetus province i.e those basins overlying the Caledonian suture.

The second half of this chapter expands the local basin, placing it in its regional context of the Carboniferous syn-orogenic complex. The relevance of the Northumberland basin will be discussed and used to review the regional characteristics of the Asturian event. Finally the continuing problems this study has raised will be introduced as possibilities for future research.

Part One
Basin synthesis

7:1:1 Summary of area interpretations

i) Age relations

Table 10 is a simplified summary of the principal events observed in the North Pennine and Stublick areas compared with the NE Coast. It is clear from the table that there is a broad similarity of events and timings. Both areas indicate normal fault activity was active during the Dinantian, with rifting starting possibly as early as the Tournaisian in the Stublick Fault area. Rifting was accompanied by abundant dewatering and synchronous slumping. No such structures were observed in the North Pennine Fault region or in the higher stratigraphic levels of the Stublick faults hanging-wall. This may suggest that there was no major basin margin active along the North Pennine fault, though its present position as a post-Carboniferous/Permian fault cuts into the foot-wall of the original Vale of Eden scarp. The Stublick fault on the other hand was clearly active as a syn-sedimentary fault until at least the Middle Limestone Group as the seismic

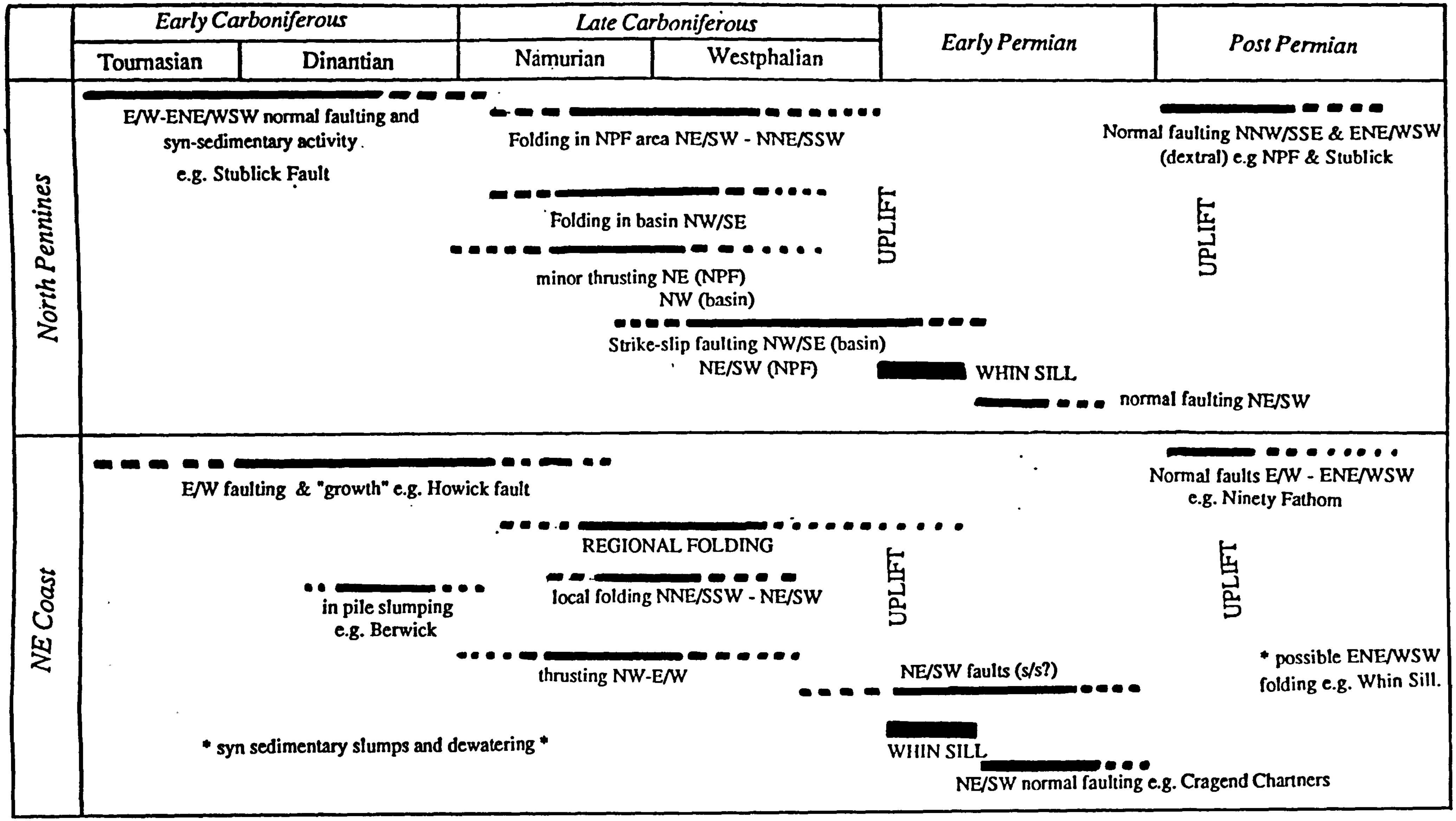


Table 10 Simplified summary of main tectonic events for the North Pennine Fault and Stublick areas, compared with the North-East Coast of Northumberland.

proves. This margin was step faulted, and buried during the transgression of the Alston Block though it may have continued to have been sporadically active after this time. The fault activity in the NE Coast area is more difficult to assess. Active fault positions can be surmised on the basis of the density and distribution of dewatering and slump structures and on their relations to local unconformities. It is concluded that the Tweed sub-basin was bounded to the south by a down-to-the-north normal fault, that was active until late Middle Limestone Group times (top Dinantian). This interpretation provides an explanation for the occurrence of "in-pile" gravitational folds. It fits with the age of minor "growth" faulting in the area (see chapter 5) and can explain the local unconformity at Spittal as consistent with erosion following back-rotation on a normal, down-north fault.

The Cheviot Alnwick ridge introduced in chapter three, appears to have been flanked by active faults in the Carboniferous. This is the unnamed S. Tweed basin margin fault (suggested above) and to the south of the ridge the Howick fault. The Howick fault, shows classic growth features that were active in the lower Upper Limestone Group (Namurian). This activity is late compared to the major growth on the Stublick fault and in relation to the Mid Dinantian inundation of the Cheviot Alnwick ridge, but it might reflect a persistent structural axis.

The inversion event falls within a wide time zone of 20-25my. Folding could have occured as early as base Upper Limestone Group age i.e. Namurian (oldest provable folding seen in the study areas) but could be as young as late Westphalian. This is a larger time window than has been previously suggested, but the absence of folding in the upper Namurian and Westphalian allows a no more precise relative age. Inversion commenced with layer parallel shortening, which produced vertical stylolites and minor intra-bed thrusts. These were followed by small scale folding and the onset of regional scale anticline formation in the NE Coast region.

In all cases the whin Sill was intruded after the small scale deformation folding, but may have been synchronous with continuing uplift and folding in the NE Coast region. The sill cuts up stratigraphy between the two inversion anticlines forming a series of laterally overlapping lensoids. These structures reflect either the extreme edges of the sill breaking away (Francis 1982) or else indicate dextral shear in the area. The change in intrusion horizon is consistent with the anticlines developing initially at the extreme N and S ends <u>before</u> the sill intrusion and then continuing to uplift (shorten) in the central area (around Alnwick) <u>after</u> the sill intrusion. The Whin Sill cuts pre-existing E/W faults appearing to utilise them as conduits for vertical "stepping". The Sill is cut by later NE/SW faults in both areas. In the NE Coast region the Sill forms a NE/SW shallow antiform offshore, between the Farne Isles and Cullernose Point (see fig. 128). This structure post-dates the Inversion (since it folds the Sill) and may represent a Mesozoic phase of mild tectonism. Similar structures are observed in sedimentary successions in the Southern North Sea (Leeder pers. comm.) where they are interpreted as Mesozoic inversion axes. The NE/SW to NNE/SSW direction of the post inversion antiform is a direction not observed in the basin, however there are a number of gentle N/S flexures in the Tynemouth area that persist over the 90 Fathom fault which may yet prove to be Post Carboniferous (?Mesozoic).

The inversion related folding and Whin sill intrusion were post-dated by ENE/SWS and NE/SW faulting. These appear to have reactivated earlier E/W faults e.g. the Howick fault, though it may be that some of the NE/SW faulting was synchronous with regional scale folding. Late stage NW/SE faulting occurred in the Stublick region, which largely offset the Whin Sill but is associated with minor folding on the NE sides of the faults (see chapter three, Trotter & Hollingworth 1928). Some of the fault offsets for NW/SE and ENE/SWS structures are greater than the offset of the Whin Sill e.g the Belford fault (see enclosure 7), which implies displacement prior to the Sill existed and may be inversion related. This would then explain the folding previous workers have recorded for the faults (see above), i.e. related to inversion.

A three dimensional reconstruction of the Northumberland basin in the Iapetus province during the Early Dinantian is given in figure 123. The basin was largely controlled by E/W syn-sedimentary growth faults which are illustrated schematically in fig. 123. The detailed activity of the faults mentioned are summarised in figure 129, and also the principal structures e.g. inversion axes.

ii) Deformation distribution

Folding deformation in the basin occurs on two scales;

1) Regional folding.

This is confined to the northern extremes of the basin. In the NE Coast the regional anticlines have sub-parallel flexures of an intermediate scale on their eastern flanks. The anticlines are associated with large scale, steep, reverse faults with displacements up to 2km. This gives an estimate of shortening over the width of the basin of 10-15%.

2) Small scale folding.

This is developed almost ubiquitously in all the areas selected for study. The character of the folding is fairly homogeneous over an area, but between areas shows little similarity of style. The North Pennine fault is associated with variable geometries, amplitudes and wavelengths that show a direct relationship with distance from the NPF. This author suggests that the NPF area represents a major crustal lineament. This lineament does not break surface in the study area as it is cut out by the Post Permian NPF. The structure is probably a symmetrical zone of deformation localised around a region of dextral strike-slip. This bears a strong resemblance to the structures identified in the Dent fault and Dent line system (Underhill et al 1988). Oblique strike-slip would provide a means of producing inliers in the fault system bounded by steep normal /strike-slip faults.

Small scale folding is confined in the Stublick area to the basinward or hanging-wall side of the fault system. Folding is most intense close to the fault and quickly dies out with distance away from it. The Alston block is largely undeformed, minor thrusts occurring only in the immediate foot-wall to the Stublick system.

The emerging picture is of a compressional event leading to uplift and deformation in the Late Carboniferous. The above can be integrated with data from the rest of the basin to fully describe the products, controls and mechanisms of the inversion event.

7:1:2 Basin integration.

i) Inversion mechanism

Taking a wider look at the whole basin, a pattern of asymmetric deformation emerges. Regional scale inversion anticlines exist in the north of the basin, whilst the southern normal faulted margin is associated with small scale folding. Estimates for pre-Permian uplift are also asymmetric over the basin with maximum values coinciding with the positions of regional anticlines. A broad 3:1 ratio between the north and south of the basin exists (see chapter 6) which needs to be explained in conjunction with the deformation pattern.

Exploratory modelling of the basin in chapter six, demonstrated that the same broad pattern of asymmetric uplift can be generated for the basin by simple Airy isostatic compensation calculations. The results of this modelling explained the uplift as a fundamental function of;

1) the thickness ratio of sedimentary cover to thinned crustal lithosphere,

2) the mechanism of shortening by which the inversion process operated.

It was concluded that the regional anticlines were either areas of extreme thin-skinned shortening or regions of minimal shortening of sedimentary cover and basement (crustal lithosphere). The latter alternative is geologically more acceptable, as there is no evidence for major thin-skinned shortening. The southern margin of the basin, however is characterised by the absence of significant reverse fault reactivation and the presence of basin confined folding corresponding to the inversion event. This margin suffered much less pre-Permian uplift and is therefore interpreted as alternatively;

1) a region of limited shortening i.e. less than that for the regional anticlines (<10%).

2) a region of minimal reactivation during inversion where shortening is taken up by butressing of the sedimentary cover against a rigid foot-wall.

3) a region of thick skinned shortening where renewed fault activity was not reversed but still permitted limited uplift. The smaller value of uplift seems to be related to the fact that a greater sediment to basement ratio is involved.

The geological evidence favours the second alternative, which is supported by the presented seismic lines (enclosures 3 & 4), displaying no reverse reactivation of the basin margin fault system. The only exception to this is in the region of the 90 Fathom fault where the margin runs more NE/SW (see later for explanation). Reverse reactivation may have occurred, but any post Carboniferous movement on the fault has produced a net normal offset geometry to the present day. If this does not reflect total gross motion of the fault it therefore must have enjoyed *three* periods of reactivation. The structure is a relatively simple step faulted margin (imaged on seismic), which is not consistent with bidirectional multiple reactivations.

The foot-wall of the Stublick fault may have acted as a rigid block for the following reasons:

i) The fault system was not in a suitable orientation to favour reactivation during inversion.

ii) The fault is a crustal scale planar structure, and so is mechanically unfavourable for reactivation even provided it was perpendicular to the deforming stress.

iii) The fault bounds a block cored by a still buoyant granite.

All the available data for the basin presented in chapter three tends to support a "butressing" model for end Carboniferous deformation. Nowhere on the fault is there evidence for significant foot-wall deformation, except where minor structural short-cuts have occurred e.g. figs. 21 & 22 (Kimbell et al 1989). Frost and Holliday described how "folding increased to the SE as the margin of the basin (was) approached", in connection with the Bellingham district.

Late breaching of the Stublick foot-wall may have occured with continued shortening, producing high angle reverse structures in the hanging-wall, such as described for A1 in enclosure 3.

The North Pennine Fault, although outside the basin, connects with the Stublick system. It shows that a post-Permian displacement occured on the Stublick system. The NPF region is not associated with regional anticlines or major low angle thrusts. As previously mentioned the present day fault dissects the Carboniferous structure, but whilst this obscures matters a number of conclusions can be drawn:

i) The NPF lineament is either not perpendicular to the principal compressive stress, or is not a suitable mechanical structure for large scale reactivation (Sibson 1982).

ii) The lineament shows a clear relationship between intensity of deformation and distance from the fault.

iii) The deformation is unlike that found in the basin, being associated with fold-synchronous high angle reverse and strike-slip faults, which is consistent with a strike-slip zone.

iv) The lineament shows striking similarities to the Dent system (Askrigg block) although less intensely developed.

v) The presence of the zone at right angles to areas of deformation of the same age i.e. the Stublick fault, implies that the regional event causing the deformation is overall compressional (although locally the structures can be produced in both a transtensional and transpressional regime, see table 11).

On the basis of data presented in chapter three and four, this author interprets the NPF lineament as a long lived crustal lineament. This lineament controlled deformation in a strike-slip zone during Late Carboniferous inversion and can be described as a positive flower structure. The zone was reactivated as a discrete large scale normal fault in the Permian and post-Permian, which cut obliquely through the flower structure. The lineament appears to die out towards the Iapetus province and may have acted as a transfer zone between the Northumberland and Solway basins during the Carboniferous. Table 11 shows how the possible interpretations for the deformation on the NPF region compares with deformation recorded for the basin.

The structures described above and in 7:1:1 as regional folds (inversion axis) and small scale deformation (butressing) and the NPF area are typical of deformation in the Iapetus province. A fourth type of structure is also observed that is important during inversion deformation. These are the regional monoclines, e.g. Berwick-Upon-Tweed and the Gilsland monocline (Brampton district and described for A1 in enclosure 3). In the case of the Gilsland monocline seismic reflection revealed that the structure was associated with a zone of near vertical faulting (with some reverse displacements) and syn-sedimentary growth during the LBG. The monoclinal flexure occurred after the syn-sedimentary activity and may have started as a hingeline accommodating massive "growth" on the Stublick system. The structure was subsequently uplifted and deformed, producing a monocline at the surface and a rather lop-sided positive flower structure at depth. The structure breaches basement but with no significant offset which may indicate a strike-slip sense of motion.

The Berwick monocline has an unusual trend if it too is to be interpreted as a basement controlled structure. The structure differs from the Gilsland structure in that to the north the monocline is dissected by a steep reverse N/S fault, whose displacement increases northwards. The monocline may well reflect deformation of an original syn-sedimentary fault which was extensively reactivated or breached during shortening deformation. Unfortunately there is no seismic data to aid interpretation in this respect.

Basement trends therefore seem to play a much more significant role in inversion than do the E/W syn-sedimentary growth faults. The E/W faults show early Carboniferous offsets and limited deformation, though folding does seem to concentrate between regions of E/W faulting. These faults have not suffered reverse reactivation during inversion, but show post-Carboniferous displacements, producing what have been termed Permian roll-overs (Collier 1989; Leeder et al 1989). Such roll-overs may be post-Permian in age corresponding to the post-Permian age for normal (or slightly oblique) reactivation of the E/W Stublick system.

Basement trends were discussed in some detail in chapter three (part 3:1:1) and it becomes apparent that some of the major structures in Northumberland have unusual orientations. These may be due in part to the reactivation of structures not wholly perpendicular to the maximum compressive stress during inversion, but nevertheless some discussion of basin feature trends is relevant here.

In the north of the basin many of the subsidiary normal faults and regional anticlines are NW/SE directed, which is similar to the Lower Palaeozoic structural grain of the Southern Uplands. However the Holburn anticline and the Berwick monocline have more N/S to NNW/SSE orientations. These trends may reflect several controls:

i) The trends are structural components determined during initial rifting of the Northumberland and Tweed basins. They may reflect connecting faults between normal fault bounded blocks.

ii) They may represent older structures related to the Devonian formation of intermontane basins, following the collapse of the Scottish Caledonides.

iii) The trends may reflect non-characteristic structural lineaments in the Caledonian accretionary prism.

iv) The trends may reflect the effect of the Cheviot granite acting as a rigid indenter, where the structural trend reflects deformation around the Cheviot block, or deformation controlled by ring faults formed by the intrusion of the Devonian granite.

It is difficult to determine the exact control from available data.

In summary therefore there are four principal structures and controls observed in the Late Carboniferous inversion event of the Northumberland basin (see fig. 127).

1) **Reactivation of basement trends,** that had no significant control on sedimentation during initial basin rifting, perpendicular to inversion compression e.g. the Bewcastle and Kershope anticlines.

2) **Reactivation of basin "hingelines"** as positive flower structures where significant syn-sedimentary growth occurred during the lifetime of the basin. These structures appear to have suffered some component of strike-slip motion during reactivation e.g. the Gilsland and Berwick monoclines.

3) **Butressing** of thick sedimentary hanging-wall piles against E/W faults or rigid basin margins foot-walls. The faults may not have been perpendicular to maximum shortening and so show no significant reverse reactivation movement e.g. The Stublick fault, the Antonstown and Sweethope faults.

4) Reactivation of crustal lineaments not perpendicular to maximum compression resulting in transpressional zones, and unassociated with major syn-sedimentary growth e.g. the NPF.

ii) The effects of inversion

Exploratory modelling in chapter six demonstrated that following inversion the Northumberland basin would have continued to subside under thermal isostasy. The regional anticlines developed over a long period of time during which they could have acted as local sources of sedimentation both during and after Initial shortening (inversion). The anticlines are sites of extreme pre-Permian peneplanation and must have supplied vast quantities of sediment to the basin and adjacent areas during their erosion. Carboniferous inversion anticlines in the Southern North Sea have been observed with synchronous depocentres (which are loosely described as growth synclines) which derived material from the eroded upland (Leeder & Hardman in press). In the Northumberland basin the state of preservation is such that no such relationship can be observed. However during late Carboniferous Westphalian C-D continental 'red' beds were deposited in the nearby Canonbie coalfield. These are adjacent to the Bewcastle anticline and this alone might suggest some uplift due to the Bewcastle inversion axes caused deposition of Barren Red Measures instead of coaliferous Westphalian beds. The sediments are mature sandstones with sporadic calcretes and may not have been derived directly from the anticline (Collier pers. comm). It is possible that locally derived sediments were eroded during continuing inversion uplift. The Namurian/Westphalian unconformity in the Canonbie district might indicate the first signs of uplift during incipient inversion. A schematic reconstruction of the Iapetus province during the Westphalian is presented in fig. 125.

Stephanian strata may have been deposited in the basin towards the end of the inversion event as localised deposits derived form nearby anticlines. There is evidence to suggest this is when the 90 Fathom fault was formed (see chapter 4). The 90 Fathom has an excess post-Westphalian displacement when the post-Permian displacement is removed. This displacement may post-date the inversion but could be synchronous with the later phases (the movement is at least post Westphalian C). Figure 126 illustrates how the basin might have appeared during the Stephanian, immediately after the inversion shortening, but prior to complete pre-Permian peneplanation.

Hypothetically the inversion process may have caused local overthickening of the crustal lithosphere (see chapter six) which in turn would have produced slow thermal re-equilibration uplift even after inversion had ceased. This would provide a suitable mechanism for the removal of Stephanian deposits and variable amounts of Carboniferous. Lower Carboniferous cores to inversion axes were exposed to be transgressed in the mid-Permian.

iii) Stress regimes

Previous suggested stress regimes are summarised in table 11. It is obvious there is a diversity of interpretations based largely on small areas within the basin. By taking the basin as a whole and it nearest neighbouring structures e.g the North Pennine Fault system, only one stress regime can reasonably explain most of the structures within the basin. This simple explanation is a basin wide NW/SE directed dextral transpressional regime. Figure 128 illustrates how the disparate elements of the basin fit into one interpretation.

The palaeomagnetism study presented in chapter six, cannot unequivocally prove a dextral strike-slip component to the inversion event. However it does indicate some anticlockwise rotation occurred over the Iapetus province between MBG and Whin Sill intrusion times.

In the suggested stress scenario, E/W faults suffer limited reactivation as strike-slip structures. the principal shortening direction is NW/SE with NE/SW folding, except where the folding is associated with strike-slip reactivated or deformation zones. Rotation of the stress elipsoid during the event produces NE/SW normal faults therefore most of anticlines, small scale folding are explained and the NE/SW folding on the southern margin around lines F1-F7 in enclosure 4 are the result of a restraining bend.

However there are difficulties with rationalising the Holburn and Berwick structures. It has been previously suggested that the Berwick monocline may be the result of compression imposed on a pre-existing fault. The Holburn anticline has been interpreted as the product of "shearing" or rotation during inversion but this is unsupported by the absence of provable strike-slip faults with significant sinistral offsets (which is what would be expected) in the area. It is unclear at this time how the Holburn anticline fits the Northumberland stress system unless, i) it is the product of a local stress system to the NE of the main basin i.e. part of a different crustal block scheme; or, ii) it is a fundamental basin fault which was reactivated during shortening.

Area	Suggested Interpretation	Comments
Bewcastle Day 1970	N/S compression (tension - ENE faults) E/W compression	Multiphased event invoked
Langholm Lumsden at al	E/W compression	90° difference between two interpretations
Langholm Anderson 1951	N/S compression and wrenching	
Tynemouth Land 1974 Collier 1989	Late Carboniferous compression E-W & NW/SE compression.	
Brampton Trotter & Hollingworth 32	E/W? compression with wrenching on NW faults (folds on NE sides)	All assigned to end Carboniferous
Cheviots Carruthers et al 1932	N/S folds & NE s/s faults	
Alnwick Carruthers et al 1930	"en-echelon" Holburn and Lemmington anticlines	No stress orientation given
Rothbury Fowler 1932	No folding ENE faults	Robson '53 observed NE folds
Bellingham Frost & Holliday 1980	N/S compression - tension - E/W compression	Multiphase event invoked.
NE Coast Shiells 1964	E/W compression	Not all folds are tectonic
NPF Ch. 4	N/S dextral transpression OR NW/SE dextral transpression	No muliphased event needed if NW/SE dex. Transpression is invoked
Stublick Ch. 4	E/W dex. transpression OR NW/SE compression	
NE Coast Ch. 5	NW/SE dex. transpression OR E/W dex. transpression OR NW/SE dex. transtension	
90 Fathom	E/W compression or NW/SE dex. transpression	
NE England Robson 1980	W/E compression (locally N/S)	Difficult to resolve separate stress locally

Table 11 Summary of suggested stress orientations for the Northumberland basin.

Part Two

Regional context

7:2:0 Introduction

The Northumberland basin is only one example in a syn-orogenic suite of basins over the northern Variscan foreland. Although the conclusions concerning the mechanisms of the of the inversion process may be relevant to other Carboniferous basins, it still remains to determine its relationship to the whole suite.

A compiled structural map for the British Carboniferous of Northern England is presented in figure 130. This shows the principal folds and faults for basins and blocks from the Midland Valley to the central Midlands, and was derived from a variety of published sources. Wherever possible recent publications were used to supplement existing BGS maps.

7:2:1 Northern England

i) The Iapetus basement province

Northumberland and its neighbour together form the basins of the Iapetus basement province. The trace of the Iapetus suture runs beneath the basins, and is thought to represent a crustal break between the former northern Caledonian continent and the southern "lake District" continent. Previous studies introduced in chapter two suggested that the crustal variation over the suture was from a relatively thick Lower Palaeozoic crust on the northern side to a thinner L. Palaeozoic succession overlying deeper, possibly Cambrian or Pre-Cambrian crust (Bott 1979, 1985).

In the Northumberland basin it has been demonstrated that a distinct difference in the distribution and style of deformation exists over the basin. Basement reactivation appears to be important for the bulk of the basin, except in the extreme south. It has been suggested that this reflects reactivation control by pre-Carboniferous "lineaments". This suggestion is further rationalised by inferring that the lineaments are Caledonian basement.

The Southern Uplands have been interpreted as an accretionary prism (McKerrow et al 1977; Legget & McKerrow 1979) exhibiting a NE/SW tectonic 'grain'. This author suggests that the bulk of the Northumberland basin is developed over the same NE/SW trending Lower Palaeozoic accretionary prism of the former northern Caledonian continent. Whereas the southern part of the basin straddles the former southern continent (it has been suggested by Chadwick & Holliday in press, that a continuation of the

Authors	Late Carboniferous	Post Carboniferous	Tertiary/Mesozoic
Robson '77	Hercynian W-E Compression Shear faulting	Whin Sill N-S compression	Tertiary dykes.
Shiells '64	W-E compression (dextral shear)	Dextral shear Whin Sill	Late normal faulting
Arthurton '76	E-W compression E thrusts in NPF	Tension Whin Sill	Normal faulting "Alpine" faulting.
Day '70	Early N/S compression - ENE tension - E/W compression & s/s E/W faults	Whin Sill	Perm/Trias faulting
Underhill et al '88	NW/SE compression	normal faults E/W extension	
Critchley '84	E/W compression (shear joints)	ENE/WNW normal faults Tension Uplift & Whin Sill	Renewed E/W compression ESE s/s faults
Land '74	E/W compression	Whin Sill	
Dunham '33	NNE "pressure" NE compression Shearing "clockwise" NE folds		
Collier '88	E/W compression (NW/SE?)	Transtension	(folding of Permo-mesozoic)

Table 12 Summary of suggested stress orientations for the Carboniferous inversion of basins in Northern England.

suture would intersect the surface around the northern edge of the Alston block). The principal control for the basin rift would therefore be a combination of the following;

1) the presence of a buoyant granite in the foot-wall block,

2) the extensional stress regime,

3) possible inheritance from the deep basement, though not necessarily Caledonian structures.

This incidentally might lend weight to the suggestion that the NPF line is a long lived basement lineament possible Cambrian in age.

The strong NE/SW structural expression in the Northumberland basin is not unique in the Iapetus province (B.West, Edinburgh Oil & Gas, pers.comm.) and this almost certainly reflects the influence of the Caledonian basement.

In summary therefore, the Iapetus province Carboniferous basins show evidence for Caledonian basement control during Late Carboniferous inversion, where the basin rests on the hanging-wall (former over-riding plate) of the Suture. South of the suture, the control is divided between several unique palaeoplate controls and the presence of major syn-sedimentary faults in the basin margins.

From the present work there is no sure way of linking the Iapetus province basins at deep seismic levels to the Suture. Chadwick & Holliday (1990) suggested such a model where the basin is an extensional reactivation of the suture. However Ord (1989) demonstrated that major syn-sedimentary normal faults active in the Dinantian exist on the north side of the Solway basin. The Northumberland basin (growing on the south side) is linked laterally with Solway over a transfer zone characterised by monoclines (flower structures) and Inversion axes e.g. Bewcastle. This complex pattern of basins "growing" along both the north and the south margins of one province causes geometrical problems in relating these basins to a simple extensional reactivated north dipping suture.

SF = Stublick fault, PNF = Precursor to 90 Fathom, VE = Vale of Eden, SF'= Solway fault, SU = Southern Uplands, KT = Kelso Trapps (early plateau basalts and vents) ORS = Devonian intermontane basins (relic) CAR = Cheviot Alnwick ridge TSB = Tweed sub-basin, BL = Birrenswark lavas (early).

Note: Schizo haline facies around Bewcastle, Annan and Whita sandstones around Langholm, and reduced sedimentation over the Cheviot - Alnwick ridge.

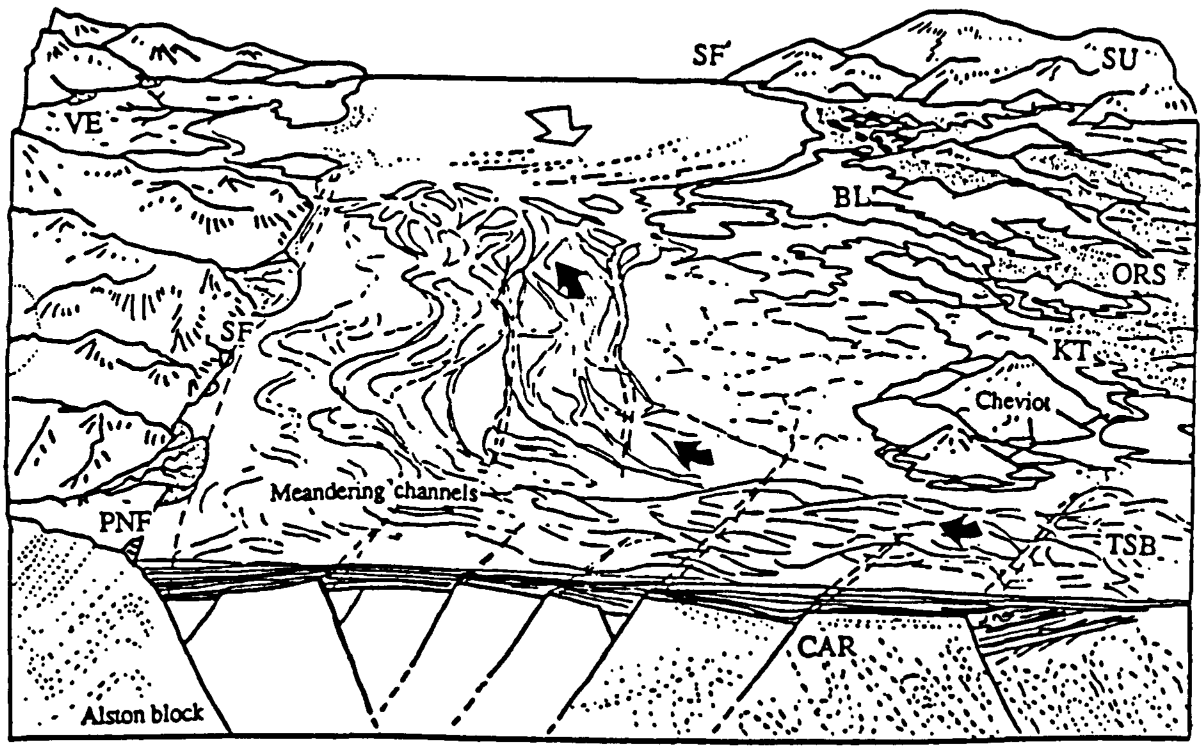


fig. 123 Three dimensional representation of the Iapetus province during the Lower Carboniferous, Border Group times.

BM = Buried basin margin, BA = Bewcastle anticline, LA = Lemmington anticline, HA = Holburn anticline, SU = Southern uplands (partially inundated), SBA Solway basin anticlines?

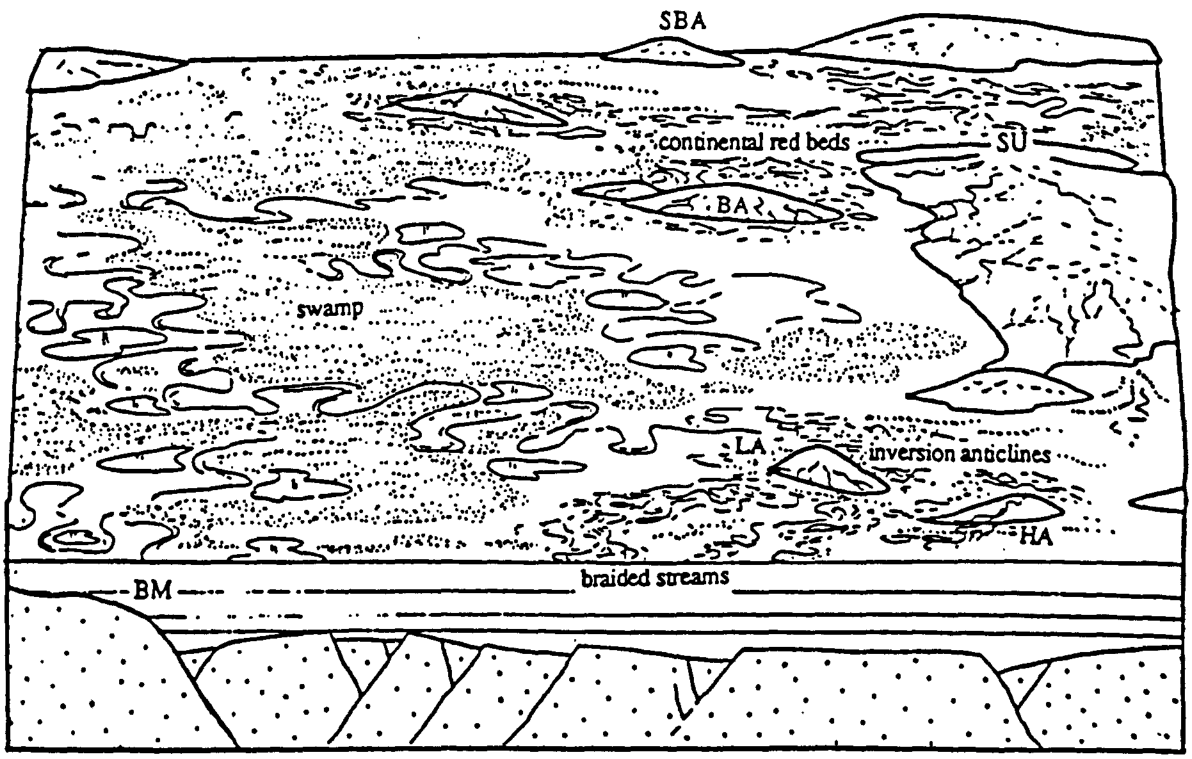
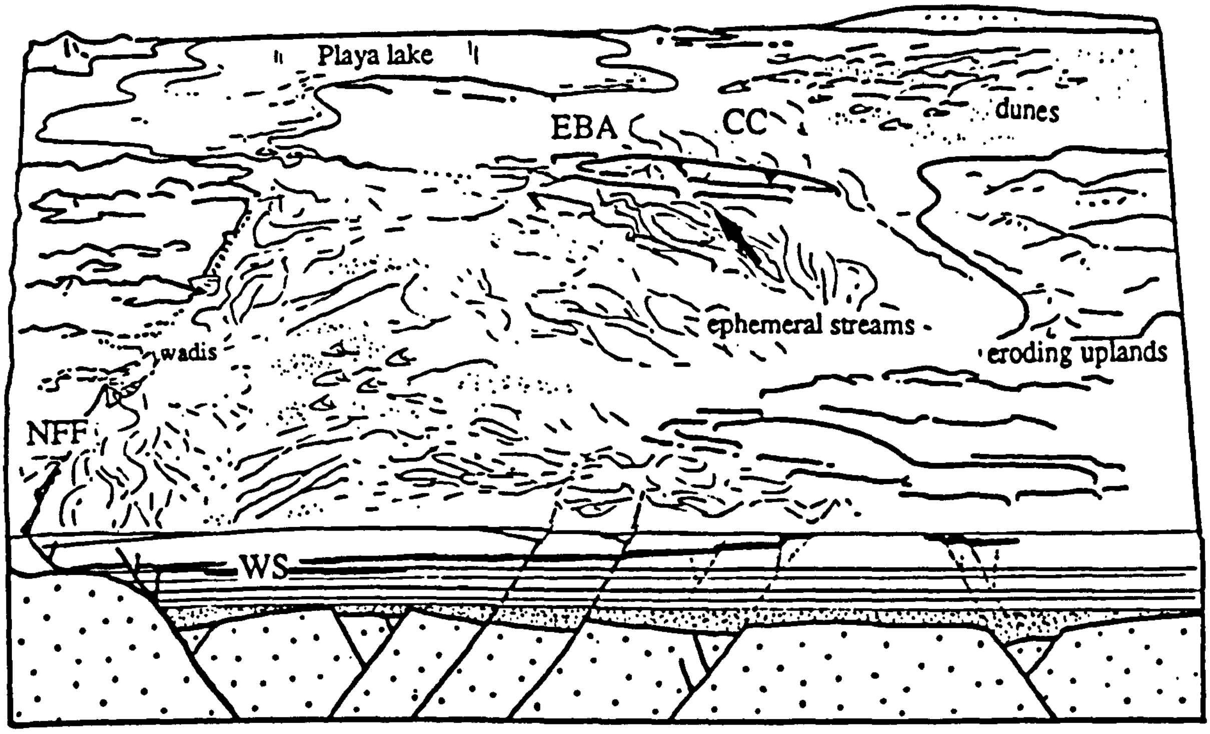


fig. 124 Three dimensional representation of the Iapetus province during inversion, Westphalian B-C times.

WS = Whin Sill, NFF = Ninety Fathom Fault, EBA = Eroded Bewcastle Anticline,
CC = Canonbie Coalfield.



Reactivated basin margin

fig. 125 Hypothetical three dimensional representation of the Iapetus province immediately post-inversion, Stephanian times.

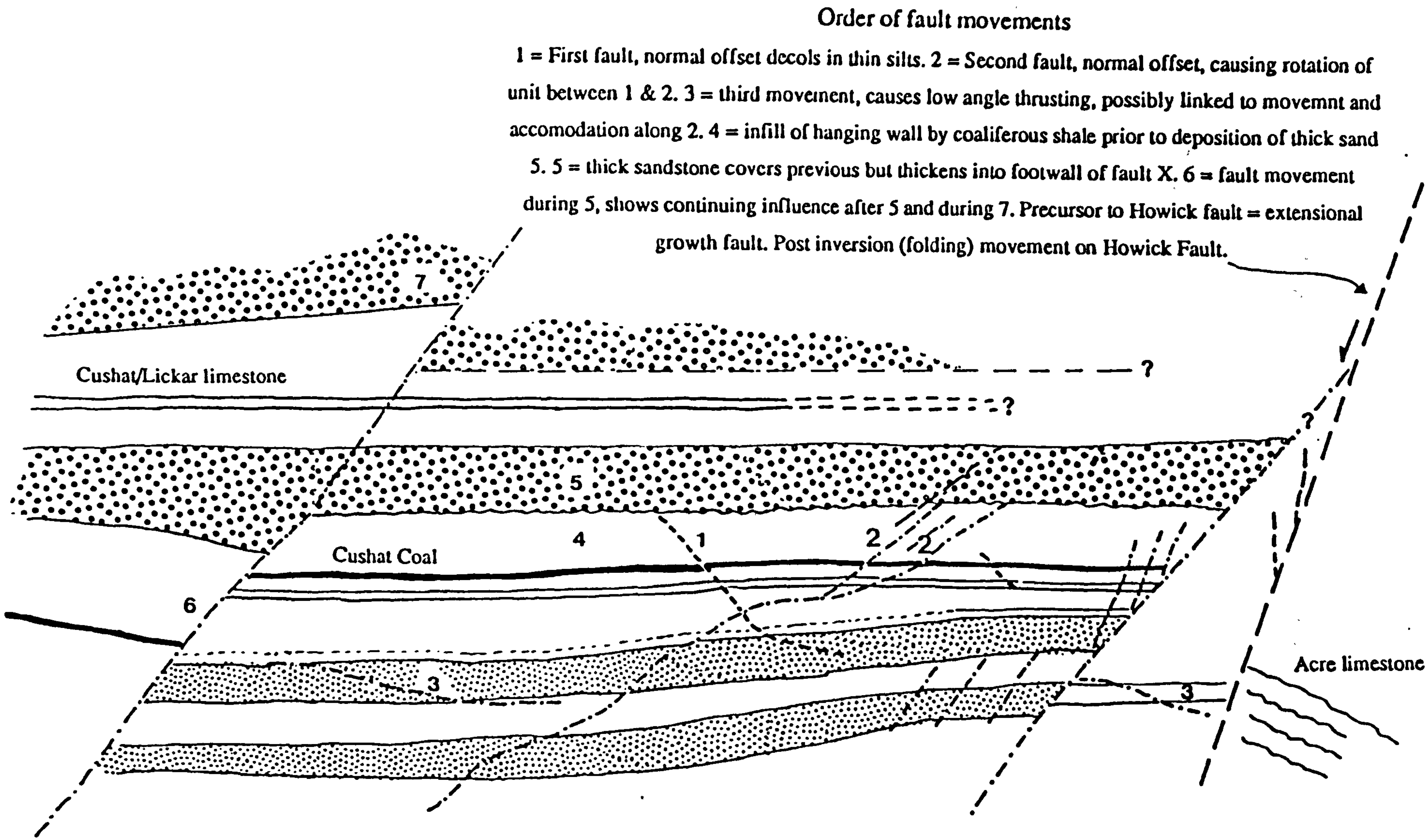


fig. 126 Fault restoration of the the Howick fault to demonstrate its syn-sedimentary character.

ii) Regional relevance

The Northumberland basin is relevant to other British Carboniferous basins in demonstrating the intricate interplay of controls, during both its extensional development and subsequent inversion. The Iapetus province basins are unique in their placement and sub-basin crustal profiles, and therefore should not be taken as a general model for Carboniferous inversion. The author suggests that Northumberland has proved the inaccuracies of a premature basin or regional assessment without a basin wide integrative approach. A regional stress interpretation should only be considered if the individual basin controls and inversion structures are known. In the case of the Northumberland basin apparently large scale scale folding was reinterpreted as the product of gravitational slumping and therefore irrelevant to the inversion stress regime.

If the whole Carboniferous extensional province shows basement reactivation, great care must be taken when interpreting local stress regimes e.g. monoclines. Clearly an extensional province of such a size as the British Carboniferous will be composed of numerous crustal blocks, which will rotate in extensional and compressional regimes. This "jostling" will almost certainly produce local stress regimes and inferring a regional would then be academic.

The Asturian event therefore in the British Carboniferous northern foreland is a broadly time equivalent Late Carboniferous compression. It produced mild regional deformation and widespread basin inversion. The mild tectonism shows strong local basement control which is essentially unique for each basin in the province. This due to the superimposition of a complex extensional suite on an equally complex non-parallel Caledonian Arc and Suture.

If deformation proves to be Namurian in age in the future this is similar to the age of deformation suggested for initial inversion in the Midland Valley of Scotland (see Read 1988 for review) and may be linked to along strike deformation relating to North American Hercynian events roughly coincident with the European Asturian event.

Other effects that deserve consideration in this synthesis are considered in the following sections. These are processes that have not been studied in detail for this study and were strictly outside the original scope of the project but for completeness they are introduced here.

iii) The seismic-aseismic transition zone

One consequence of inversion that may prove important for inversion events, is the migration of the aseismic-seismic transition zone during extension. England and Jackson (1987) discussed this phenomenon in during uniform (pure shear) and non-uniform (simple shear) extension of continental lithosphere. They concluded that the migration of the transition zone (15-20km) caused basement structures that previously deformed aseismically (ductilely) to enter a new depth range in which they would deform seismically (brittlely).

This process may bring basement structures into seismic deformation depths after initial rifting (zone transition is effectively lowered) which would then be "available" for reactivation during an inversion event (provided the event occurred before thermal subsidence had restored the transition zone to its pre-rift depth range. Hence deep crustal tectonic lineaments may undergo repeated reactivation, producing new structural trends uncharacteristic of the previous extensional province.

This process may not have been crucial in the case of Northumberland as the transition zone would have been within the Caledonian basement during extension and so is unlikely to have produced any "new" controls. However this may be an important process in other continental extension provinces.

iv) Pure Shear versus Simple Shear

It is widely acknowledged that the Carboniferous syn-orogenic basin complex (Northern England) was initiated by crustal tension in the Late Devonian/Early Tournaisian. What is less widely understood is the principal mechanism of that extension. There is a general consensus for a "pure shear" (McKenzian) stretching model, but recent papers have suggested an alternative "simple shear" (Wernickian) model. This was discussed in chapter three (3:1:2). This debate is important when modelling the inversion process. If the latter holds true then a simple isostatic model cannot be applied (see chapter six, part two, for discussion). The extension mechanism is of particular relevance in the Iapetus province where the Whin Sill intrusion event has to be accounted for in an integrative basin model.

White (1990) discussed alternative models in reference to lithospheric extension in the North Sea. As with many of the Carboniferous basins much of the observational data could equally support either model. White used the thermal subsidence "rift" geometry relative to initial rifting sediment thicknesses to distinguish between the two models. Predicted geometries for the "pure shear" model have a 3:1 ratio of thermal subsidence sedimentary thicknesses over initial basin rifting thicknesses. The "simple shear" predictive model however, has a 1:3 or 0.3 ratio.

This approach can be adopted with the British Carboniferous, provided no basin is taken in isolation and an accurate estimate of the thermal subsidence sediment thickness can be obtained. On the edges of a wide extensional province ratios will approach unity as rift geometry changes. This is the case for Northumberland where of a total estimated thickness of 5-6km of sediment almost 3km can be accounted for in the Dinantian. A review of the literature would seem to support a "pure shear" model for the whole

Northern England extension suite as Upper Carboniferous sediment thickness greatly exceed those of the Lower Carboniferous.

v) Heat flow and the Whin Sill

The Whin Sill has yet to be satisfactorily explained in terms of on-going Carboniferous basin evolution. It is outside the scope of this work to study the matter in detail but a preliminary discussion is relevant here, especially as heat flow in the basin has important consequences for inversion process modelling (see chapter six, part two).

The Sill is a member of the tholeiitic suite and therefore requires a tholeiitic melt to be emplaced. The melt can be produced from extensive basaltic melt extraction and differentiation, or from melting at higher levels in the Lower Lithosphere. To generate a tholeiitic melt Dixon and colleagues (Dixon, Fitton & Frost 1981) suggested that suitable magmas could be produced by;

1) widespread attenuation (stretching) in the crust by listric normal faults overlying a relatively localised of Lower Lithosphere attenuation i.e. simple shear.

2) stretching over a wide zone at the base of the lithosphere reflected by similar extension in the upper crust i.e. normal or pure shear rifting. In this case tholeiitic melts are only produced if;

a) the extension is sufficiently high, b) the crust is abnormally thin (hot) to start with, and c) the rift is narrow compared to the zone of extension in the Lower lithosphere.

3) Stretching that is even throughout the lithosphere but confined to a "sharp upward asthenospheric bulge" e.g. basins bounded by active or reactivated strike-slip faults which penetrate deeply into the lithosphere.

Latin (1990) remodelled the production of basaltic melts in the North Sea. By using a non-instantaneous rifting model large quantities of melts could be extracted at lower extension values than otherwise believed. If the extension for the Iapetus province was sufficiently high this might generate tholeiites but at the onset of rifting not during thermal subsidence. The Whin sill is so closely linked in time to the Asturian inversion event that it is hard not to believe the two are unrelated. The appropriate melt could be produced by reactivation of crustal scale normal faults in a strike-slip regime related to the inversion event. This certainly applies to the strike-slip dominated Midland Valley and might provide a mechanism for the production of the Midland Valley sills. In the case of the Northumberland basin the presence of a non-equilibrated basin with a strike-slip reactivated crustal scale margin might just be sufficient to generate the required melt.

The puzzle of the Whin Sill requires extensive heat flow modelling for the basin's geohistory and modelling of the generation of tholeiite melts.

7:2:2 Reccomendations for future research

It is clear from the preceding work and the above discussions that there is much scope for continued research in the Carboniferous basins of Northern England. A few suggested avenues of study are listed below.

1) Modelling of the production of the Whin Sill.

The mechanism of production of the Whin Sill in the Inversion and extensional context is not fully understood.

2) Heat flow modelling through time for an extensional basin affected by an inversion event and the intrusion of a major igneous body.

This is a regional and general study needed to model inversion accurately and to determine the subsidence mechanism for any extensional suite/province, but is of particular relevance to the British Carboniferous.

3) A regional study of the deep structure of the British Carboniferous extensional province. Either by seismic or gravity modelling. Some excellent studies have shown the potential for this work (Lee 1988).

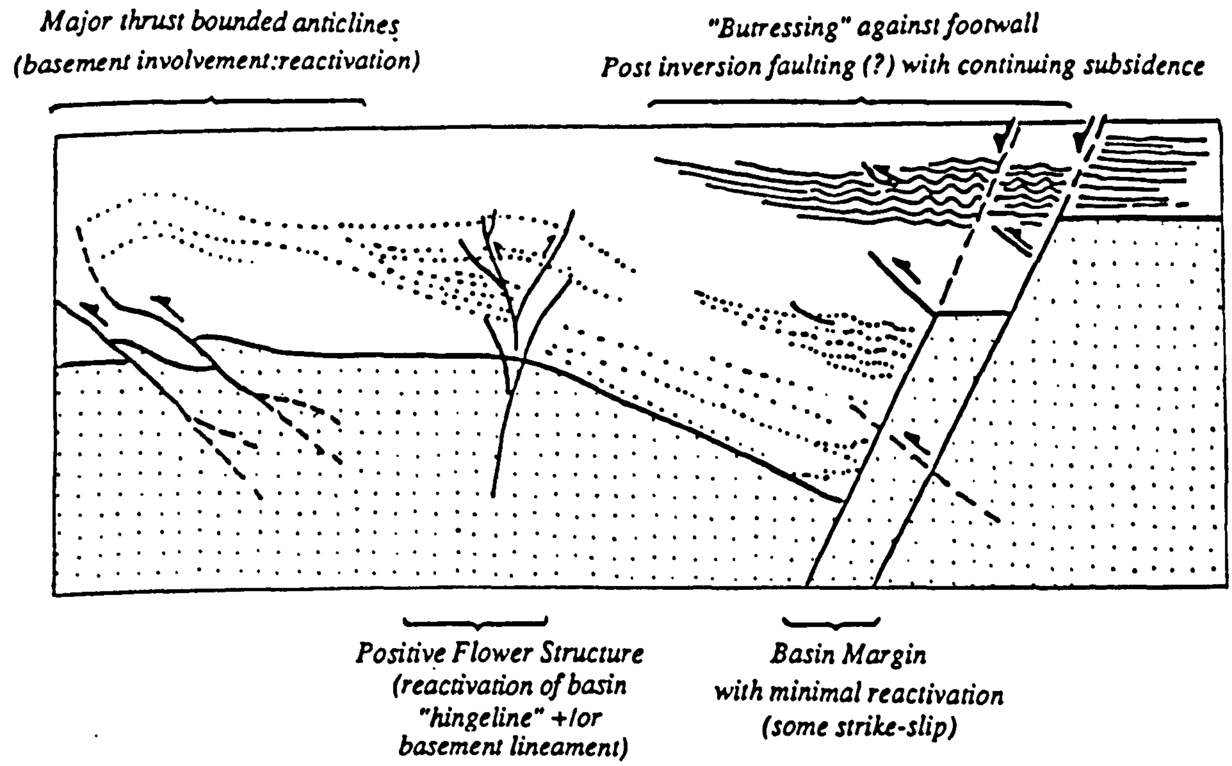
4) A regional study of Carboniferous tectonic rotations by palaeomagnetism.

5) The dating of non-metamorphic epeiorogenic tectonism, i.e. basin inversions (perhaps dated through fission track analysis for uplift events).

The last suggestion is the biggest area of doubt in the study of Late Carboniferous inversion in Northumberland. There is no sure method of accurately dating the onset and culmonation of the inversion except relatively. This means that regional applications are limited. Uplift dating is a particular problem in Northumberland as massive Mesozoic uplift has stripped the basin of its Permo-Trias and younger cover. There is no way therefore of estimating accurately maximum burial depths (from vitrinite and spore colour index) or inversion uplift during the Carboniferous and then during the Mesozoic. Hence the geotherm cannot be reconstructed and this severely limits quantitative modelling.

7:2:3 Concluding Remarks

The study of the Northumberland basin has revealed that although the Asturian (late Carboniferous) inversion was widespread throughout the Carboniferous basins of Northern England, no generalised stress regime or characteristic structures can be concluded. This is amply demonstrated by the unique structural character of the Iapetus basement province basins and the expression of the inversion there. The Northumberland basin aids the general study of inversion events and processes by showing how one basin of known structure, geohistory and geodynamic environment responded in a regional compression event. However the structures observed in Northumberland may or may not be typical of inversion deformation in the Carboniferous. The processes by which they formed in the basin were discussed but these controls must expected to vary in relative



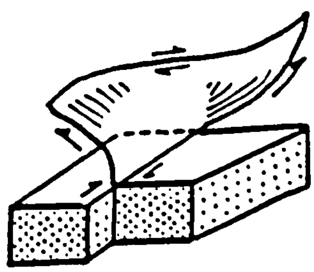


fig. 127 Schematic representation of the principal structures and their controls characteristic of Late Carboniferous inversion in Northumberland.

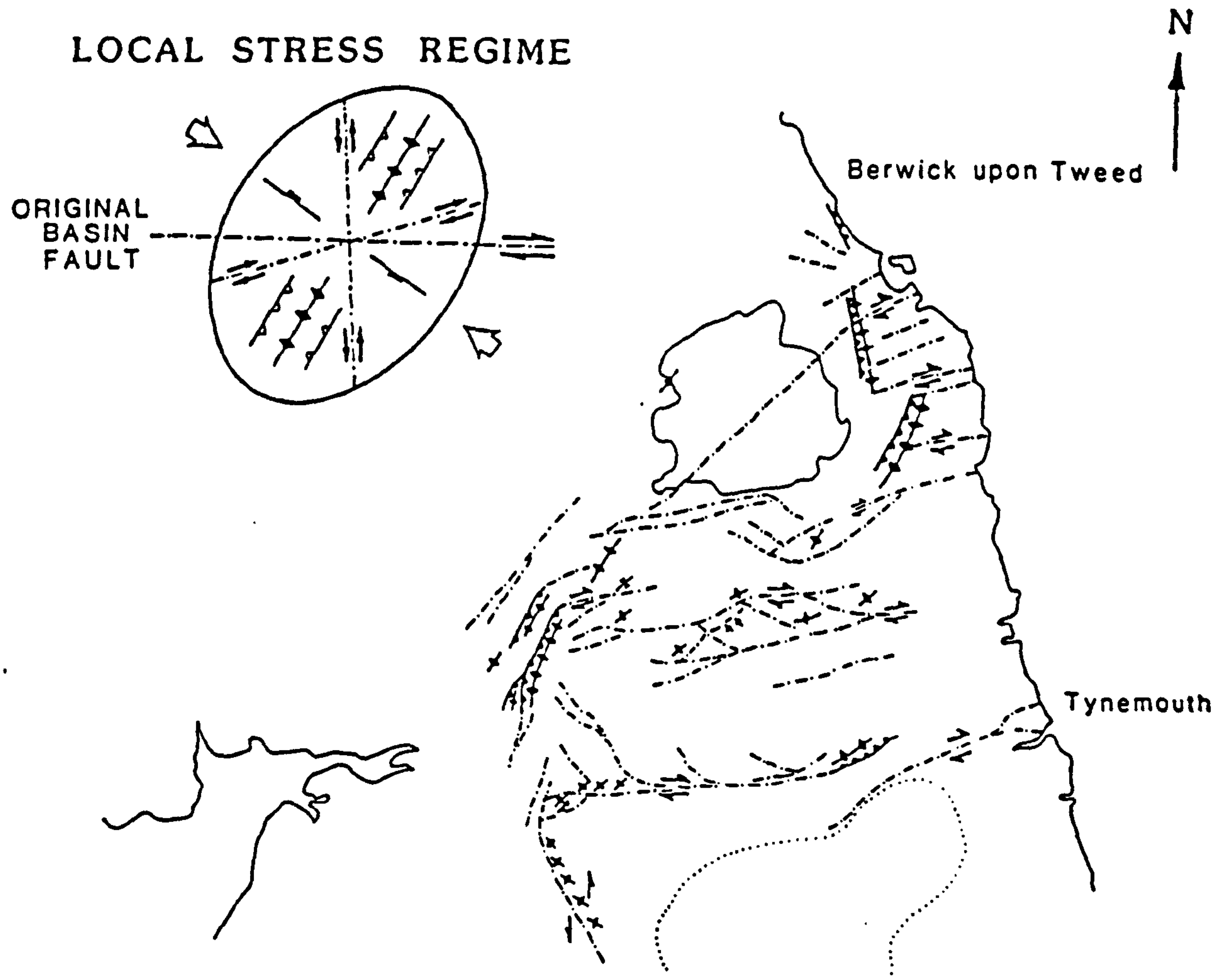


fig. 128 Suggested local stress regime for the Northumberland at the time of Carboniferous basin inversion.

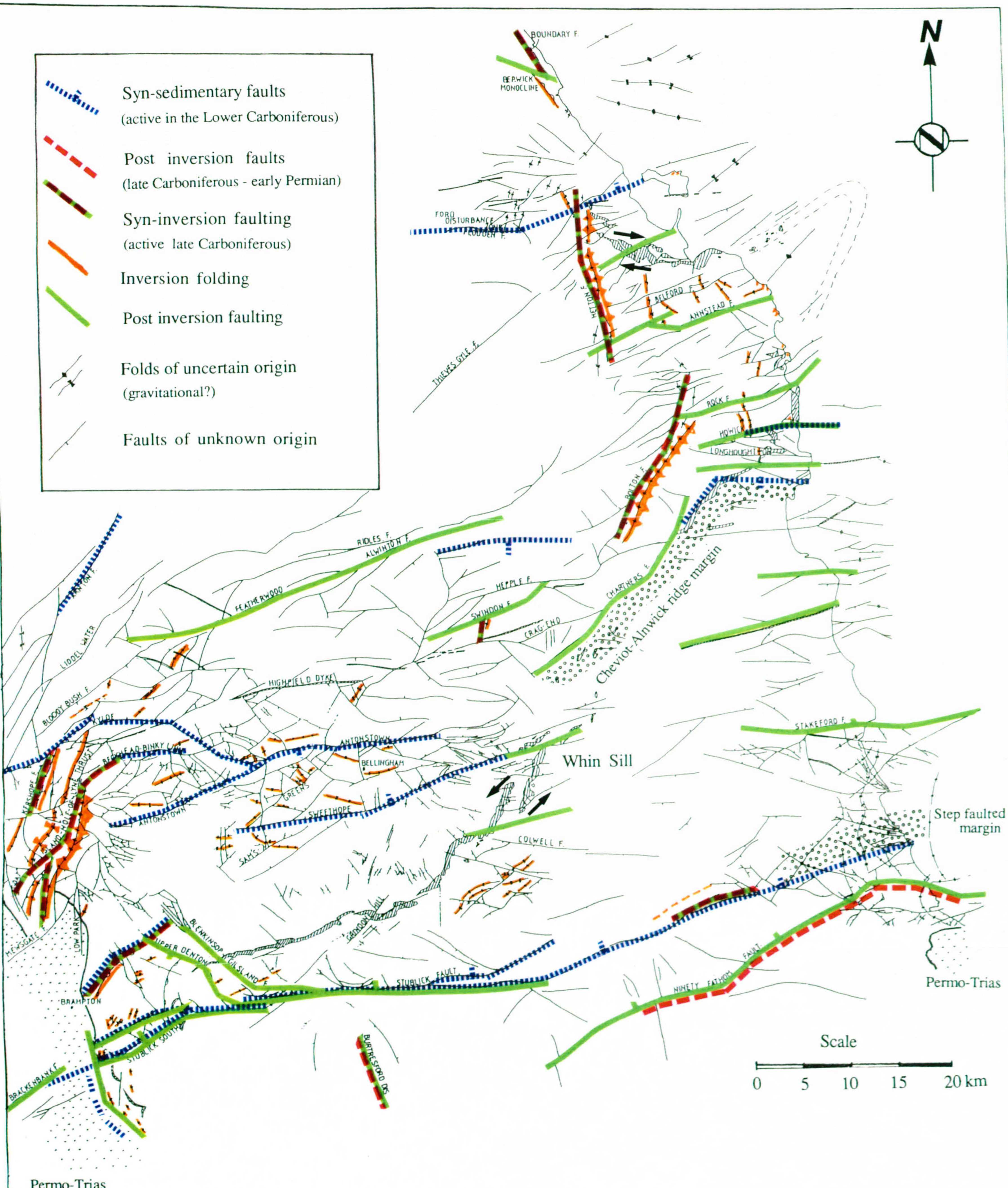


fig. 129 Summary structural map for Northumberland, showing principal fault activities. Compiled from all published sources and the present work.

importance between basins. This is a consequence of the interplay of local stress regimes on basins sited in different crustal geometries. Nevertheless several general predictions can be made concerning other basins and other inversion events, not only those of the British Carboniferous:

1) Basement structure is an important controlling factor in the reactivation and non-reactivation of basin features.

2) Not all basin syn-sedimentary growth faults will be involved in significant uplift and reactivation during inversion. This is especially true if the faults are large crustal scale planar structures, or are in positions oblique to the stress regimes responsible for the inversion. In cases were faults bound major crustal blocks and/or low density bodies (granites) butressing is likely to be the dominant shortening mechanism.

3) Major inversion anticlines may be completely unassociated with previous "growth" faulting when the basin was extending. Such regional scale structures can be expected to be sites of major uplift and erosion if crustal shortening was involved.

4) Inversion as a crustal shortening process may pre-maturely equilibrate a basin. If shortening is not involved or is insufficient to restore the lithosphere to pre-rift thicknesses, subsidence will continue after inversion has ceased. Excessive shortening will produce regional thermal uplift due to thermal isostacy after initial uplift and shortening.

5) It is possible to model the effects of inversion in a simple way for most geologic situations. However accurate regional modelling will only be possible where the thermal history, the flexural rigidity and its variation with geohistory and the load geometry is known.

6) Detailed structural analysis is required in inversion studies to distinguish between deformation as a result of basin extension processes e.g.slumps, and inversion related structures e.g. flower structures and inversion axes. This will particularly critical where inversion is not caused by regional compression e.g. strike-slip basins. Structural analysis is important to date the ages of basin structures, i.e. in the case of Northumberland two periods of uplift have occured and the present day 90 Fathom fault has proved to be a post-inversion fault (nucleated on the original margin).

7) Integration of all available datasets is vitally important in basin inversion studies. Without the deep structure data afforded by seismic reflection, structures and processes are uncertain. A comprehensive background of the extensional basin history is vital in determining which of the inversion structures are related to extensional basin structures (or not as the case may be).

8) The Asturian phase was a period of regional compression in the northern Variscan foreland. It produced regional basin inversion of which one expression was the Northumberland basin.

9) Inversion in the Northumberland basin didn't curtail subsidence, merely interrupting it temporarily. Subsidence after inversion may be a common feature of the event for the

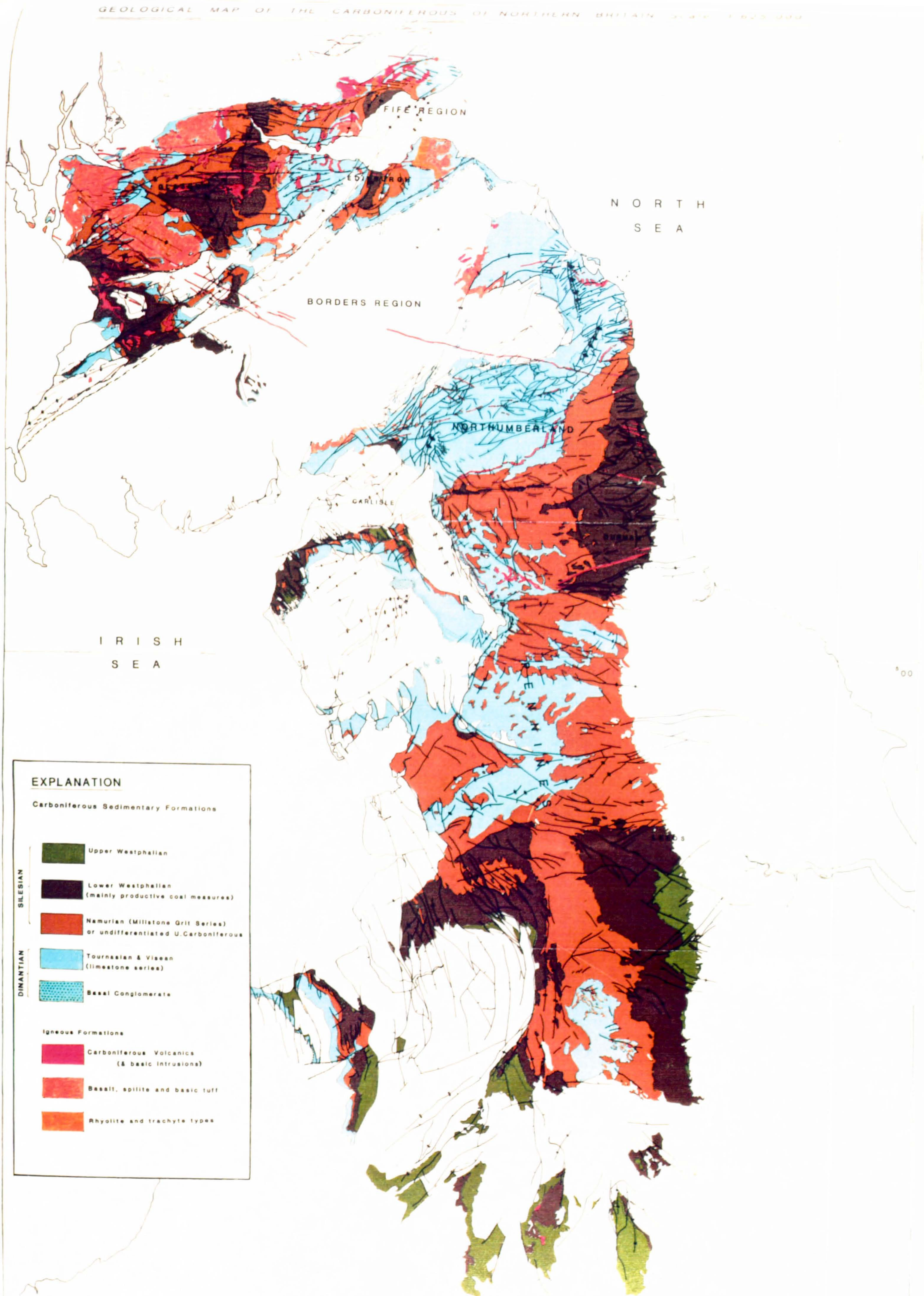


fig. 130 Summary structural map for the British Carboniferous of Northern England. Compiled from published work (see chapters 2 & 3 for sources).

APPENDIX I

List of abbreviations and symbols

AG = Alston Group
BB = Basement Beds
CsG = Cementstone Group
FSG = Fell Sandstone Group
LBG = Lower Border Group
LGS = Longhoughton Grit Series
LLG = Lower Limestone Group
MBG = Middle Border Group
MGS = Millstone Grit Series
MLG = Middle Limestone Group
NFF = Ninety Fathom Fault
NPF = North Pennine Fault
OG = Orton Group
SCG = Scremerston Coal Group
SF = Stublick Fault
StG = Stainmore Grit Series
UBG = Upper Border Group
ULG = Upper Limestone Group

Palaeomagnetism terms

AFDM Alternating Field Demagnetisation.
TDM Thermal Demagnetisation.
NRM Natural Remanent Magnetism: The total of all magnetisations found in the rock in the field, due to natural geologic processes.
TRM Thermal RM: Magnetisation acquired by cooling in magnetic field over a wide range of temperatures, usually from above the Curie temperature down to room temperature - applies to igneous rocks.
CRM Chemical RM: Magnetisations acquired as a result of chemical changes e.g. exsolution of magnetic minerals in igneous rocks, weathering etc.
VRM Viscous Remnant Magnetisation: Acquired as a function of time alone.

Laboratory induced magnetism

IRM Isothermal RM: Induced in an applied direct filed e.g. electromagnet or lightening (though is more complex).
ARM Anhysteric RM: Simultaneous application of an alternating field and a direct magnetic field i.e. during Alternating Field Demagnetisation.

RRM Rotational RM: Acquired by rotation in an applied alternating electrical field.

Dec. Declination (+ve east, -ve west).
Inc. Inclination (+ve down, -ve up).
Lat. Latitude of site or pole (+ve North, -ve South).
Long. Longitude (+ve East, -ve West).
N or n = number of observations.
R = Length of resultant vector giving weight to each other.
k = Fischerian estimate of true precision (K).
α = radius of cone/circle of 95% confidence about the mean (angular measure of precision)
σ = radius of cone/circle containing 63% of observations; a measure of scatter analogous to standard deviation.
mA/m = milli amp per metre - unit of intensity of magnetisation.
mT = milli Tesla - unit of field strength in AFDM.

Stereonet symbols
Small dots = slickensides and slickencrysts
Small crosses = slickensides for faults specified in text
Filled circles = Fold axis
Direction arrows = Direction of fault motion
Single arrow = transport direction on thrust planes from slickensides
Open circles = pole to axial plane (fold)

Additional symbols (maps)
Rose diagrams = joint plots
ScL = Scar limestone
4FL = Four Fathom limestone
3YL & 5YL = Three Yard and Five Yard limestones respectively
GtL = Great limestone
SmL = Smiddy limestone
SPL = Single Post limestone
TBL = Tyne Bottom limestone
JL = Jew limestone
MScL = Melmerby Scar limestone

APPENDIX II

a) Amoco UK (Al & A2)

PROCESSING PARAMETERS

PROCESSING 60 FOLD CDP STACK	PROCESSING SAMPLE RATE 4MS.
DEMULTIPLEX	FROM SEGD 6250 BPI FIELD TAPES RESAMPLE TO 4 MS. ZERO PHASE ANTI-ALIAS FILTER APPLIED
AMPLITUDE RECOVERY	SPHERICAL DIVERGENCE CORRECTION [illegible]
TRACE AND SHOT RECORD EDITING	FROM QC DISPLAYS
CROOKED LINE GEOMETRY	FROM FIELD [illegible] CDP LINE [illegible] SCATTER
COMMON DEPTH POINT GATHER	60 FOLD NOMINAL
FIELD STATIC CORRECTIONS	TO FLOATING DATUM PLANE. VALUES FROM FIELD SURVEY.
PHASE FILTERING	VIBROSEIS MINIMUM PHASE CONVERSION. FILTER DERIVED FROM SYNTHETIC SWEEP DYNAMITE DATA FILTERED WITH ZERO PHASE EQUIVALENT
DECONVOLUTION BEFORE STACK BAND PASS OPERATOR LENGTH DESIGN GATE [illegible]	[illegible] SPIKING DECONVOLUTION [illegible] MINIMUM PHASE [illegible]
NORMAL MOVEOUT CORRECTION	FROM FINAL CONSTANT VELOCITY STACKS
RESIDUAL STATIC APPLICATION	SURFACE CONSISTENT STATICS [illegible]
CDP CONSISTENT STATICS	[illegible] MS MAXIMUM STATIC [illegible]
FIRST BREAK SUPPRESSION	OFFSET [illegible] TIME MS [illegible]
TRACE EQUALISATION	[illegible] BALANCE GATES [illegible] OVERLAP
COMMON DEPTH POINT STACK	60 FOLD NOMINAL
TRACE EQUALISATION	1000 MS BALANCE GATES
WAVE TIME MIGRATION	[illegible] STACKING VELOCITIES
TIME VARIANT FILTER	FILTER LENGTH [illegible] MS. [illegible]
TRACE EQUALISATION	1000 MS BALANCE GATES
STATIC CORRECTION	FROM FLOATING DATUM TO DATUM [illegible]

DIGITAL EXPLORATION LIMITED.
EAST GRINSTEAD.
W. SUSSEX. RH19 4HG
ENGLAND

PROCESSED ON A VAX 11/780.
USING DIGICON'S PROPRIETARY SOFTWARE

b) Fina Exploration (F1 to F7)

CGG - DATA PROCESSING SERVICES

47-55, THE VALE, ACTON, LONDON, W3 7RR

PROCESSING PARAMETERS

SEQUENCE IN 4MS

DEMULTIPLEX FROM SEG-B FORMAT TO CGG FORMAT
ANTI ALIAS FILTER AND RESAMPLE TO 4MS
AMPLITUDE RECOVERY
NOISE EDITION
PRE-FILTER HIGH PASS 12.18HZ
SLALOM LINE*
CDP GATHER
PREDICTIVE DECONVOLUTION

DESIGN GATE	OPERATOR	GAP	WHITE NOISE
0.2-2.0S	120MS	20MS	5 PERCENT

FIELD STATIC CORRECTION
RELATIVE TO NEAR SURFACE FLOATING DATUM PLANE (F.D.P.)
1ST VELOCITY ANALYSIS
CONSTANT VELOCITY STACKS-VSCAN**
NMO CORRECTION**
MUTING**
FIELD STATIC CORRECTION FROM NEAR SURFACE FDP TO DP
AUTOMATIC RESIDUAL STATICS-SATAN IV (PHASE 1 MV)
2ND VELOCITY ANALYSIS WITH SATAN IV RESIDUAL STATICS APPLIED
CONTINUOUS CONSTANT VELOCITY STACKS-VSCAN**
REVISED NMO CORRECTION**
MUTING**
DYNAMIC TRACE EQUALISATION**
AUTOMATIC RESIDUAL STATICS-SATAN IV (PHASE 2 SV)
AUTOMATIC RESIDUAL STATICS-SATAN IV (PHASE 3 SS)
STACK NOMINALLY 4800PERCENT
PREDICTIVE DECONVOLUTION**

DESIGN GATE	OPERATOR	GAP	WHITE NOISE
0.2-1.7S	240MS	20MS	5 PERCENT
0.8-2.3S	240MS	32MS	5 PERCENT

WAVE EQUATION MIGRATION-WEMIG-90PERCENT STACK VELOCITIES
TIME VARIANT FILTER**

TIME	BAND PASS
0.0-1.2S	12.18.55.65HZ
1.8-3.0S	12.18.45.55HZ

DYNAMIC TRACE EQUALISATION**

GATE	OPERATOR
0.0-1.2S	200MS
1.2-3.0S	400MS

DISPLAY

* CGG RTM
** ORIGIN OF TIME IS AT THE NEAR SURFACE F.D.P.

DISPLAY PARAMETERS

DISPLAY IN DOT MODE PLOTX	
HORIZONTAL SCALE	1:12500
VERTICAL SCALE	20CM/SEC
DATUM PLANE	MSL
POLARITY	SEG: UPWARD DISPLACEMENT OF GEOPHONE RECORDED AS A NEGATIVE NO. AND DISPLAYED AS A WHITE TROUGH
SECURITY NO.	132L208
TAPE NO.B10976.F1=TSD1	

References

Addison, F.T., Turner, P. & Tarling, D.H. (1985) Magnetic studies of the Pendleside limestone: evidence for remagnetisation and late diagenetic dolomitization during a post Asbian normal event. J.Geol. Soc. Lond. 142 p.983-994.

Allen, J.R.L (1960) The Mam Tor sandstones: A "turbidite: facies of the Namurian Deltas of Derbyshire, England. J. Sedim. Petrology. 30 p.193-208.

Alvarez, F., Vivieux, J & Le Pichon, X. (1984) Thermal consequences of lithospheric extension over continental margins: The initial stretching phase. Geophys. J. R. Astron. Soc. 78 p.389-411.

Anderson (1951) The Dynamics of faulting and dyke formation with applications to Britain. Edinburgh.

Anderson, E, M. (1951) The Dynamics of faulting (2nd ed.) Oliver & Boyd, Edinburgh.

Anderton, R. (1985) Sedimentology of the Dinantian of Foulden, Berwickshire, Scotland. Trans. Royal Soc. Edin. 76 Earth Sciences p.7-12.

Anderton, R., Bridges, P.H., Leeder, M.R. & Sellwood, B.W. (1979) A Dynamic stratigraphy of the British Isles. Allen & Unwin. London.

Anglier, J. & Colleta, B. (1983). Tensional fractures and extensional tectonics. Nature 301 pp.49-51.

Armstrong, H.A. & Purnell, M.A. (1987) Dinantian conodont biostratigraphy of the Northumberland trough. J. Micropalaeontology 6 p.97-112.

Arthaud F. & Matte, P (1975) Les derochements tardi-Hercyniens du sud-ouest de L'Europe. Geometrie at essai d reconstitution des conditions de la deformation. Tectonophysics 25 p.139-171

Arthaud, F. & Matte, P. (1977). Late Palaeozoic strike-slip faulting in southern Europe and northern Africa: Result of a right lateral shear zone between the Appalachians and the Urals. Bull. Geol. Soc. Am. 88 p.1305-1320.

Arthurton, R. S. & Wadge, A. J. (1981) Geology of the country around Penrith. Mem. Geol. Soc. Gt. Britain sheet 24.

Arthurton, R. S. (1983). The Skipton Rock fault - an Hercynian wrench fault associated with the Skipton anticline, NW England. Geol. Jour. 18 p.105-114.

Arthurton, R. S. (1984). The Ribblesdale fold belt NW England - a Dinantian-early Namurian dextral shear zone. In: Hutton, D. H. W. & Sanderson, P. J. (eds). Variscan Tectonics of the North Atlantic Region. Geol. Soc. Lond. Spec. Publ. 14.

Badham, J.P.N. (1982). Strike-slip orogens - an explanation of the Hercynides. Jour. Geol. Soc. Lond. 139 p. 493-504.

Balance, P. F & Reading H. G (1980) Sedimentation in oblique slip mobile zones. Spec. Publ. Int. Assoc. Sed. 4, 337pp.

Bally, A. W., Bernouli, P., Davies, G.A. & Montadat, L.(1981) Listric normal faults. Oceanal, Acta. Proc. 26th International Geol. Congres. "Geol. Cont. Margins Symposium" Paris, colloque C3 p.87-101.

Bally, A.W. (1982) Musings over sedimentary basin evolution. Phil. Trans. R. Soc. Lond. A305 p.325-338.

Bamford, D., Faber, S., Jacob, B., Kaminski, W., Nunn, K., Prodehl, C., Fuchs, K., King, R. & Wilmore, P. (1976) A lithospheric seismic profile in Britain - I Preliminary results. Geophys. J. R. Astron. Soc. 44 p. 145-160.

Bamford, D., Nunn, K., Prodehl, C. & Jacob, B. (1978). Crustal structure of northern Britain. Geophys. Jour. Res. Astron. Soc. 54 p.43-60.

Banks, R. J. & Gurbuz, C. (1984) An investigation of the crustal structure of north-west England using quarry blasts as seismic sources. Proc. Yorks. Geol. Soc. 45 p. 19-25.

Banks, R. J. (1986) The interpretation of the Northumberland trough geomagnetic variation using two-dimensional current models. Geophys. J. Royal Astron. Soc. 87 p.595-616.

Bard, Burg, J. P. Matte, Ph & Ribeiro, A. (1980) La chaine Hercynienne d'Europe occidentale en termes de tectonique des plaques. Int. Geol. Congr. 26th Paris C6 p.234-246.

Barfety, C. & Gidon, M. (1984) Un exemple de sedimentation sur un abrupt de faille fossile; le Lais du versant du massif du Taillefer (zone Daupinois, Alpes Occidentales). Revue de Geologie Dynamique et Geographie physique 25 p.267-276.

Bartely & Gidon (1984)

Bassett, G. (1984) Lower Palaeozoic Wales - A review os studies in the past 25 years. Proc. Geol. Ass. 95 pt4.

Beach, A. (1984) Structural evolution of the Witch Ground graben. J. Geol.\Soc. 141 621pp.

Beach, A. (1987) A regional model for linked tectonics in NW Europe. In: Pet. Geol. NW Europe (eds) J. Brooks & K. Glennie. p.43-48.

Beaumont, C. (1979) On rheological zonation of the lithosphere during flexure. Tectonophysics 59 p.347-365.

Beaumont, C. (1981) Foreland basins. Geophys J Royal Astron. Soc. 65 p. 291-329

Behr, H. J., Engel, E., Franke, W., Giese & Weber (1984) Variscan belt in Europe.

Tectonophysics 109 p.15-40.
Bembrose, H. H. A. (1894) On the microscopical structure of the Carboniferous dolerites and tuffs of Derbyshire. Q. J. Geol. Soc. Lond. 50 p.603-644.
Besly, B. M. (1988) Palaeogeographic implications of late Westphalian to early Permian red-beds, Central England. In: Besly, B. M. & Kelling (eds) Sedimentation in a syn-orogenic basin complex: The Upper Carboniferous of NW Europe. Blackie, Glasgow & London p. 200-221.
Bless et al (1980) Palaeogeography of Upper Westphalian deposits in NW Europe with reference to Westphalian C north of the mobile Variscan Belt. Meded. Rijks. geol. Diest. NS 28 p.101-147.
Bluck, B. J. (1978) Sedimentation in a late orogenic basin: The ORS, Scotland. In: Crustal evolution in NW Britain and adjacent regions. (eds) Bowes, D.R & Leake, B.E Geol. J. Spec. Issue 10.
Bosworth (1985) Discussion on the structural evolution of extensional basin margins; reply by A. D. Gibbs. J. Geol. Soc. Lond. 142 p.939-942.
Bott, M H P. (1974) The geological interpretation of the gravity survey of the English Lake District and the Vale of Eden. J. Geol. Soc. Lond. 130 p.309-331.
Bott, M.H.P & Mithend, P. (1983) Mechanism of graben formation - The wedge subsidence hypothesis. In: P. Morgam & B. H. Baker (eds) Process of Continental Rifting. Tectonophysics 94 p.11-22.
Bott, M.H.P (1961) Geological interpretations of magnetic anomalies over the Askrigg block. Q. J. Geol. Soc. Lond. 117 p.481-495.
Bott, M.H.P (1987) Subsidence mechanisms of Carboniferous Basins in Northern England. In: Miller, J., Adams, A.E. & Wright, V.P. (eds) European Dinantian Environments.
Bott, M.H.P. (1967) Geophysical investigations of the northern Pennine basement rocks. Proc. Yorks. Geol. Soc. 36 p.139-168.
Bott, M.H.P. (1976) Formation of sedimentary basins of graben type by extension of the continental crust. Tectonophysics 36 p.77-86.
Bott, M.H.P. (1978) Deep structure In: Moseley, F. (ed) The geology of the Lake District. Yorks. Geol. soc. Occ. Publ. 3 p.25-40.
Bott, M.H.P., Long, R.E., Green, A.S.P., Lewis, A.H.J., Sinha, M.C. & Stevenson, P.L. (1985) Crustal structure beneath northern England. Nature 314 p.724-7.
Bott, M.H.P., Swinburn, P.M & Long, R.E (1984) Deep structure and origin of the Northumberland and Stainmore troughs. Proc. Yorks. Geol. Soc. 44/4 p.479-495.
Bradley, P. C. (1982) Subsidence in late Palaeozoic basins in the Northern Appalachians. Tectonics 1 p.107-123.
Briden, J.C., Robertson, D.J & Smethurst, M.A. (1989) Short paper: Terrane rotations in the Irish Caledonides. J. Geol. Soc. 146 p.909-911.
Broadhurst, F.M., Simpson, I.M & Hardy, P.G (1980) Seasonal sedimentation in the Upper Carboniferous of England. J. Geol. 88 p.639-651.
Brooks, J., Goff, J. C. & Van Hoom, B. (1983) Habitat of Palaeozoic Gas in NW Europe. Spec. Publ. Geol. Soc. 23.
Browne, M. A.E., Hargreaves, R.L. & Smith, I.F. (1985) The Upper Palaeozoic basins of the Midland Valley of Scotland. Invest. Geotherm. Potent. UK British Geol. Surv. BGS Keyworth, Notts.
Brune, J.P & Burg, J.P. (1982) Combined thrusting and wrenching in the Iberico-Armorican arc: a corner effect during continental collision.. E.P.S.L. 61 p.319-332.
Buck, W.R., Martinez, F., Steckler, M.S. & Cochran, J.R. (1983) Thermal consequences of lithospheric extension: pure and simple. Tectonics 7(2) p.213-234.
Buckowicz, C. & Ziegler, P.A (1985) Tectonic development of Mid-Norway continental margin. Marine & Petroleum Geology 2(1) p.12-22.
Burg, J.P. & Matte, P. H. (1978) A cross section through the French Massif Central and the scope of its Variscan geodynamic evolution. Z. Deutsch, Geol. Ges. 129 p.429-460.
Burgess, I. C. & Holliday, D. W. (1979) Geology of the country around Brough-Under-Stainmore. Mem. Geol. Surv. Great Britain.
Burgess, I.C & Mitchell, M. (1976) Visean lower Yoredale limestones on the Alston and Askrigg blocks and the base of the D2 zone in northern England. Proc. Yorks. Geol. Soc. p.613-630.
Burgess, I.C & Wadge, A.J. (1974) The geology of the Cross Fell area: explanation of the 1:25 000 Geol. Sec. sheet. HMSO London.
Burgess, I.C (1986) Lower Carboniferous sections in the Sedburgh District, Cumbria. Trans. Leeds Geologists Ass. 11 p.1-18.
Burke, K. & Dewey, J.F. (1973) Plume generated triple junctions: Key indicators in applying plate tectonics to older rocks. J. Geol. 81 p.406-433.
Butler, R.W.H. (1982) The terminology of structures in thrust belts. J. Struct. Geol. 4 p.239-245.
Butler, R.W.H. (1989) The influence of pre-existing basin structure on thrust system evolution in the western Alps. In: Cooper, M.A. & Williams, G.D (eds) Inversion tectonics. Spec. Pub. Geol. Soc. 44.
Calver, M.A (1969) Westphalian of Britain Cr. 6me Congr. Int. Strat. Geol. Conb.Sheffield 1967 1 p.233-254.

Carruthers, R.G., Burnet, G.A. & Anderson, W. (1930) The geology of the Alnwick district. Mem. Geol. Surv. Sheet 6.

Carruthers, R.G., Dunham, C.H., Burnett, G.A & Maden, J. (1927) Geology of Belford, Holy Island and the Farne Islands. (ed) W. Gunn Mem. Geol. Surv. Sheet 4.

Carter, J.S. & Moore, J, McM. (1978) Some major lineaments in the northern Pennine orefield. Trans. Instn. Min. Metall. 87B p.90-93.

Chadwick, R.A (1985) Cenozoic sedimentation, subsidence and tectonic inversion. In: Whittaker, A. (ed) Atlas of onshore sedimentary basins in England and Wales: Post Carboniferous tectonics and stratigraphy. Blackie, Glasgow.

Chadwick, R.A. (1985b) Permian, Mesozoic and Cenozoic structural evolution of England and Wales in relation to the principles of extension and inversion tectonics. As previous.

Chase, C.G. (1978) Extension behind island arcs and motions relative to hot-spots. J. Geophys. Res. 83/11 p.5385-5387.

Cheshire, S.G & Bell, J.D (1977) The Speedwell vent, Castleton Derbyshire: a Carboniferous litteral cone. Proc. Yorks. Geol. Soc. 41 p.173-184.

Chisholm, J.I. (1977) Growth faulting and sandstone deposition in the Namurian of the Stanton syncline, Derbyshire. Proc. Yorks. Geol. Soc. 41 p.305-323.

Clarke, A.M. (1962) Some structural, hydrological and safety aspects of recent developments in South East Durham. Trans. Inst. Min. Engs. 122 p.209-231.

Cloetingh, S. (1985) Intraplate stresses as a mechanism for sea-level variations. EOS Trans. Am. Geophys. Un. 1060pp.

Cloetingh, S., McQueen, H. & Lambeck, K. (1985) On a tectonic mechanism for regional sea-level variations. E.P.S.L. 75 p.157-166.

Cloos, H. (1939) Hebung - Spaltung - Vulkanisms. Geol. Rdsch. 30 p.405-527.

Cochran, J.R. (1983) Effects of finite rifting times on the development of sedimentary basins. E.P.S.L 66 p.289-302.

Cogne, J. (1976) La chaine Hercynienne ouest-European pour une interpretation geodynamique globale. Colloq. Int. CNRS p.111-129.

Collinson, J.D (1968) Deltaic sedimentation units in the Upper Carboniferous of northern Britain. Sedimentology 10 p.233-254.

Collinson, J.D (1976) Deltaic evolution during basin fill - Namurian of Central Pennine basin, England. B. A. A. P. G. 60 659pp.

Collinson, J.D. (1988) Controls on Namurian sedimentation in the Central province basins of northern England. In: Sedimentation in a synorogenic basin complex : the Upper Carboniferous of NW Europe (eds) Besly, B.M & Kelling. Blackie, Glasgow.

Conway, A., Dentith, M.C, Doody, J.J. & Hall, J. (1987) Preliminary interpretation of upper crustal structure across the Midland Valley of Scotland from two east-west seismic refraction profiles. J. Geol. Soc. 144(6).

Cooper, M.A., Williams, G.D., De Graciansky, P.C., Murphy, R.W., Needham, T., de Paor, D., Stoneley, R., Todd, S.P., Turner, J.P. & Ziegler, P.A. (1989) Inversion tectonics - a Discussion. In: Cooper, M.A. & Williams, G.D (eds) Inversion Tectonics. Spec. Publ. Geol. Soc. 44 p.335-347.

Coward, M.P. & Smallwood, S. (1984) An interpretation of the Variscan tectonics of the SW Britain. In: Variscan Tectonics of the North Atlantic Region. (eds) Hutton, D.H.W & Sanderson, D.J. Spec. Publ. Geol. Soc. Lond. p.89-101.

Coward, M.P. (1986) Heterogeneous stretching, simple shear and basin development. E.P.S.L. 80 p.325-336.

Coward, M.P., Enfield, M.A. & Fischer, M.W. (1989) Devonian basins of Northern Scotland: extension and inversion related to late Carboniferous - Variscan tectonics. In: Cooper, M.A & Williams, G.D (eds) Inversion Tectonics, Geol. Soc. Spec. Publ. 44 p.275-308.

Creaney, S., Jones, J.M., Holliday, D.W. & Robson, P. (1980) The occurance of Bitumen in the Great Limestone around Maften Northumberland - its characterisation and possible genesis. Proc. Yorks. Geol. Soc. 43 p.69-79.

Critchley, M.F (1981) Structure nd formation mechanisms of vein-fracture systems in the North Pennine orefield. Unpublished PhD Thesis. Uni. London.

Davison (1986) Listric Normal fault profiles: Calculations using bed length balance and fault displacement. J. Struct. Geol. 8 p.209-210.

Day, J.B.W. (1970) Geology of the country around Bewcastle Mem. Geol. Surv. Gt. Britain.

De Graciansky, P.C., Cardean, G., Lemoine, M. & Tricart, P. (1989) The inverted margin of the French Alps and foreland basin inversion. In: Cooper, M.A. & Williams, G.D (eds) Inversion Tectonics. Spec. Publ. Geol. Soc. 44.

De Souza (1978) Age data from Scotland and the Carboniferous time scale In: Odin, G.S (ed) Numerical dating in stratigraphy p.455-465. Wiley, New York.

Deegan, C.E (1973) Tectonic control of sedimentation at the margin of a Carboniferous depositional basin in Kirkcudbrightshire. Scott. J. Geol. 9 p.1-28.

Dewey, J.F & Burke, K.C.A. (1973) Tibetan, Variscan and Precambrian reactivation products of continental collision. J. Geology 81 p.683-692

Dewey, J.F & Kidd, W.S.F (1974) Continental collisions in the Appalachian-Caledonian orogenic belt: variations related to complete and incomplete suturing. Geology 2 p.543-546.

Dewey, J.F (1971) A model for the lower Palaeozoic of the southern margin of the early Caledonides of Scotland and Ireland. Scott. J. Geol. 7 p.219-240.

Dewey, J.F (1982) Plate tectonics and the evolution of the British Isles. J. Geol. Soc. Lond. 139 p.371-412.

Dewey, J.P. (1975) Finite plate evolution, some implications for the evolution of rock masses at plate margins. American J. Science. 2.75A p.260-284.

Dixon, J.E & Fitton, J.G. (1981) The tectonic significance of Post-Carboniferous igneous activity in the North Sea basin. In: Petroleum geology of the continental shelf of NW Europe, p.121-137 Institute of Petroleum, London.

Donaldson, C.H Petrology of the uppermost mantle deduced from spinel Lherzolite and harzburgite nodules at Carlton Hill, Derbyshire. Contrib. Mineral. Petrol. 65 p.363-377.

Dow, W.G. (1977) Kerogen studies and geological interpretations. J. Geochem. Exploration 1 p.79-99.

Drewery, S., Cliff, R.A & Leeder, M.R. (1987) Provenance of Carboniferous sandstones from U-Pb dating of detrital zircons. Nature 325 p.50-53.

Duff, P. McL. D. & Walton, E.K. (1962) Statistical basis for cyclothems: A quantitative study of the sedimentary succession in the East Pennine Coal field. Sedimentology 1 p.235-255.

Dunham, K.C & Johnson, G.A.L. (1962) Sub-surface data on the Namurian strata of Allenheads south Northumberland. Proc. Yorks. Geol. Soc. 33(3) p. 235-254.

Dunham, K.C & Wilson, A.A (1985) Geology of the Northern Pennine orefield II Stainmore to Craven. Mem BGS England & Wales.

Dunham, K.C (1933) Structural features of the Alston block. Geol. Mag. 69. 241-254.

Dunham, K.C. (1948) Geology of the Northern Pennine orefield: I Tyne to Stainmore. Mem. Geol. Surv. Gt. Britain.

Dunning, F.W (1977) Caledonian - Variscan relations in North-West Europe. Colloquium International, Centre National de le Recherche Scientifique Rennes 242 p.165-180.

Edwards & Trotter (1954) The Pennines and adjacent areas. Brit. Reg. Geol. H.M.S.O London.

Elliot, D. (1983) The construction of balanced cross-sections. J. Struct. Geol. 5 101pp.

Elliot, R.B. (1960) The Carboniferous volcanic rocks of the Langholm district. Proc. Geol. Ass. 71 p.1-24.

Elliot, T. (1975) The sedimentary history of a delta lobe from a Yoredale (Carboniferous) cyclothem. Proc. Yorks. Geol. Soc. 40 p.505-536.

Elliot, T. (1976) Sedimentary sequences from the Upper Limestone Group of Northumberland. Scott. J. Geol. 12 (2) p.115-124.

Enfield, M.A. & Coward, M.P (1987) The structure of the West Orkney basin, Northern Scotland. J. Geol. Soc. 144 p.871-884.

Engel. E. & Franke, W. (1983) Flysch sedimentation: Its relations to tectonism in the European variscides. In: Matin, H. & Eder, F,W (eds) Intracontinental fold belts p.289-322. Springer Verlag, Berlin.

England, P. & Jackson, J. (1987) Migration of the seismic-aseismic transition during uniform and non-uniform extension of the continental lithosphere. Geology 15 p.291-294.

England, P.C & Richardson, S.W (1980) Erosion and the age dependance of continental heat flow. Geophys. J. R. Astron. Soc. 62 p.421-437.

England, P.C. & Thompson, A.B, (1984) Pressure-temperature time paths of regional metamorphism I Heat transfer during the evolution of regions of thickened continental crust. J. Pet. 25 p.894-928.

Etheridge, M.A (1986) On the reactivation of extensional fault systems. Phil. Trans. R. Soc. Lond. 317 p.179-194

Evans, C.J., Kimbell, G.S & Rollin, K.E (1988) Hot Dry rock Potential in Urban areas. Investigation of the geothermal potential of the UK BGS.

Evans, A.D., Roberts, P.D. & Bateson, J.H. (1989) Magnetic and geochemical surveys in the area between Geltsdale, Cumbria, and Glendue Fell, Northumberland. Technical Report WF/89/1 M.R.P 97 Mineral Resources Series. British Geological Survey.

Fewtrell, M.D. & Smith, D.G (1980) Revision of the Dinantian stratigraphy of the Craven basin, N. England. Geol. Mag. 114 p.37-49.

Fielding. C.R & Johnson G.A.L. (1987) Sedimentary structures associated with extensional fault movement from the Westphalian of N.E. England. From: Coward et al (eds) Continental extensional tectonics. Geol. Soc. Spec. Publ. 28 p.511-516.

Fielding. C.R (1982) Sedimentology and stratigraphy of the Durham Coal Measures and comparisons with other British coalfields. Unpubl. PhD thesis Uni. Durham.

Fielding. C.R (1984a) Upper delta plain lacustrine and fluviolacustrine facies from the Westphalian of the Durham coalfield, N.E. England. Sedimentology 31 p.547-567.

Fielding. C.R (1984b) A coal depositional model for the Durham coal measures of N.E. England. J.

Geol. Soc. Lond. 141 p.919-931.
Fitch, F.J & Millar, J.A. (1965) Age of the Weardale granite. Nature 208 p.743-745.
Fitch, F.J, Millar, J.A. & Williams, S.C.(1970) Isotopic ages of British Carboniferous rocks. C.R. 6th Int. Congr. Carb. Strat. Geol. 2 p.771-789.
Fowler, A. (1966) The stratigraphy of the North TRyne basin, Northumberland. Bull. Geol. Surv. Gt. Britain. 24 p.57-104.
Francis, E.H. (1978) Igneous activity in a fractured craton: Carboniferous volcanism in N. Britain. In: D.R. Bowes & B.E. Leake (eds) Crustal evolution in NW Britain and adjacent regions. Geol. J. Spec. Issue 10 p.279-296.
Francis, E.H. (1978) The Midland Valley as a rift, seen in connection with the late Palaeozoic European rift system. In: Rambel & Neumann (eds) Tectonics & Geophysics of Continental Rifts. p.133-147.
Francis, E.H. (1983) Carboniferous In: Craig, G.Y "Geology of Scotland": 2nd ed. p.253-296. Edinburgh: Scottish Academic Press.
Francis, E.H. (1983) Magma and sediment II Problems of interpreting palaeovolcanics buried in the stratigraphic column. J. Geol. Soc. Lond. 140 p.165-184.
Frazer (1989)
Frazer, A.J., Nash, D.F., Steele, R.P. & Ebdon, C.C. (in press) A regional assessment of the intra-Carboniferous play of northern England.
Frost, D.V & Holliday, D.W. (1980) Geology of the country around Bellingham. Mem. Geol. Surv. Gt. Britain.
Frost, D.V (1969) The lower Limestone Group of Otterburn. Proc. Yorks. Geol. Soc. 37 277pp.
Frost, D.V (1984) New information on the Dinantian stratigraphy and structure of Tynedale, Northumberland. Proc. Yorks. Geol. Soc. 45(1) p.45-49.
Furlong, K.P & Londe, M.D (1986) Thermal-Mechanical consequences of Basin and Range extension. Spec. Publ. Geol. Soc. Am. 208 p.23-30.
Gardiner, A.R. (1983) Sedimentological structures of the Scremerston Coal Group and Lower Limestone groups in the Northumberland basin. Unpub. PhD thesis Uni. Leeds.
Garfunkel, Z. & Ron, H. (1985) Block rotation and deformation by strike-slip faults: II The properties of a type of macroscopic discontinuous deformation. J. Geophys. Res. 90 p.8589-8602.
Garwood (1931) The Tuedian beds of northern Cumberland and Roxburghshire east of the Liddel Water. Quart. J. Geol. Soc. Lond. 87 p.97-159.
Gawthorpe, R.L & Clemmey, H. (1985) Geometry of submarine slides in the Bowland basin (Dinantian) and their relation to debris flows. J. Geol.Soc. Lond. 142 p.555-565.
Gawthorpe, R.L (1986) Sedimentation during carbonate ramp-to-slope evolution in a tectonically active area: Bowland basin (Dinantian) N. England. Sedimentology 33 p.185-206.
Gawthorpe, R.L (1987) Tectono-sedimentary evolution of the Bowland basin, N. England during the Dinantian. J. Geol. Soc. Lond. 144 p.59-71.
Geology of Northumberland and Durham (1931) Proc. Geol. Ass. XLII (3) p.217-296.
George, T.N (1958) Lower Carboniferous evolution of the British Isles. Proc. Yorks. Geol. Soc. 31 p.227-318.
George, T.N., Johnson, G.A.L., Mitchell, M., Prentice, J.E., Ramsbottom, W.H.C., Sevastopulou, D. & Wilson, R.B. (1976) A Correlation of the Dinantian rocks in the British Isles. Spec. Rep. Geol. Soc. Lond. 7.
Gibbs, A. (1987a) Development of extension and mixed mode sedimentary basins. In: Continental Extensional Tectonics (eds) Coward, M., Dewey, J. & Hancock, P.L. Geol. Soc. Spec. Publ. 28 p.19-33.
Gibbs, A.D (1983b) Strike-slip basins and inversion: a possible model for the Southern North Sea Gas area. In: Brooks, J., Goff, J.C. & Van Horn, B. (eds) Spec. Publ. Geol. Soc. Lond. 23 p.23-36.
Gibbs, A.D (1984) Structural evolution of extensional basin margins J. Geol. Soc. Lond. 141 p.609-620.
Gibbs,A.D (1983) Balanced cross-section constructions from seismic sections in areas of extensional tectonics. J. Struct. Geol. 5 p.153-160.
Gillchrist, R., Coward, M. & Muenier, J.L. (1987) Structural inversion and its controls: examples from the Alpine foreland and the French Alps. Geodinamica Acta (Paris) 1(1) p.5-34.
Glennie, K.W & Boegner, P.L.E (1981) Sole Pit inversion tectonics In: Illing, L.V & Hobson, G.D. (eds) Petroleum geology of the continental shelf of Northwest Europe. Inst. Petroleum Lond. p.110-120.
Goldring (1962) The bathyal lull: Upper Devonian and Lower Carboniferous sedimentation in the Variscan geosyncline. In: Coe, K. (ed) Some aspects of the Variscan fold belt. Manchester University Press. P.75-92.
Goodchild, J.G (1920) The lower Carboniferous rocks of N. Britain. Trans. Geol. Soc. Glasgow. 12 p.17-39.
Grayson, R.F & Oldham, L. (1987) A new structural framework for the northern British Dinantian as a basis for oil, gas and mineral exploration. In: European Dinantian Environments

(eds) Miler, Adams & Wright.
Green, P.F (1986) On the thermo-tectonic evolution of Northern England: evidence from fission track analysis. Geol. Mag. 123 p.493-506.
Gunn, W. (1898) Notes on the correlation of the Lower Carboniferous rocks of England and Scotland. Geol. Mag. 35 p.342-349.
Haller, J. (1970) Tectonic map of East Greenland. Medd. Gronland, 11.
Hancock, P.L & Bevan, T.G (1987) Brittle modes of foreland extension. From: Coward, M.P., Dewey, J.F. & Hancock, P.L. (eds) Continental extensional tectonics. Geol. Soc. Spec. Publ. 28 p.127-137.
Harding, T.P (1985) Seismic characteristics and identification of negative flower structures, positive flower structures and positive structural inversion. B.A.A.P.G 69 p.582-600.
Hayward, A.B. & Graham, R.H. (1989) Some geometrical characteristics of inversion. In: Cooper, M.A. & Williams, G.D (eds) Inversion Tectonics. Spec. Pub. Geol. Soc. 44 p.17-39.
Hazeldine, R.S (1983a) Fluvial bars reconstructed from a deep straight channel , Upper Carboniferous coalfield of NE England. J. Sed. Pet. 53(4) p.1233-1247.
Hazeldine, R.S (1983b) Descending tabular cross-bed sets and bounding surfaces from a fluvial channel in the Upper Carboniferous coalfield of NE England. Spec. Publ. Inst. Sed. 6 p.449-456.
Hazeldine, R.S (1984a) Carboniferous North Atlantic plaeogeography: stratigraphic evidence of rifting, not megashear or subduction. Geol. Mag. 121 p.443-463.
Hazeldine, R.S (1984b) Muddy deltas in freshwater lakes and tectonics in the Upper Carboniferous coalfield of NE England. Sedimentology 31 p.811-822.
Hedemann & Teichmuller (1971)
Hellinger, S.J & Sclater, J.G (1983) Some comments on two-layer extensional models for the evolution of sedimentary basins. J. Geophys. Res. 88 p.8251-8261.
Helwig, J. (1976) Shortening of continental crust in orogenic belts and plate tectonics. Nature 290 p.768-770.
Hickling, H.G.A (1950) Prospects of undersea coalfield extension in the North East. Trans. Inst. Min. Engrs. 109 p.659-671.
Hill.E.S (1976) Morphotectonics and geomorphical sciences with special reference to Australia. J. Geol. Soc. Lond. 117 p.77-89.
Hinze, W.J., Braile, L.W., Keller, G.R. & Lidiak, E.G (1980) Models for midcontinent tectonism. In: Continental tectonics: studies in geophysics. Nat. Res. Council, Washington D.C National Academy of Sciences.
Hodgson & Scott (1970)
Hodgson, A.V. (1978) Braided river bedforms and related sedimentary structures in the Fell Sandstone Group (lower Carboniferous) of North Northumberland. Proc. Yorks. Geol. Soc. 41 (4) p.509-532.
Holliday, D.W, Burgess, I.C & Frost, D.V (1975) A recorrelation of the yoredale limestones (upper Visean) of the Alston block with those of the Northumberland trough. Proc. Yorks. Geol. Soc. 40(3) p.319-334.
Holmes (1964) Principles of physical geology. Ronald, New York.
Hossack, J.R (1984) The geometry of listric growth faults in the Devonian basins of Sunnfjord, N. Norway. J. Geol. Soc. Lond. 141 p.629-637.
Hudson, R.G.S (1927) A mid-Avonian reef limestone and conglomerate in the Craven lowlands. Geol. Mag. p.503-511.
Jackson, J. (1980) Reactivation of basement faults and crustal shortening in orogenic belts. Nature 283 p.343-346.
Jackson, J.A & McKenzie, D (1983) On the geometrical evolution of normal fault systems. J. Struct. Geol. 5 p.471-482.
Jackson, J.A (1987) Active normal faulting and crustal extension. In: Continental Extensional Tectonics (eds) Coward, M.P, Dewey, J.F. & Hancock, P.L. Spec, Publ. Geol. Soc. 28 p.3-17.
Jameson, J. (1987) Carbonate sedimentation on a mid-basin high: the Petershill formation, Midland Valley of Scotland. In: Miler, Adams & Wright (eds) European Dinantian Environments.
Jarvis, G.T & McKenzie, D.P (1980) Sedimentary basin formation with finite extension rates. E.P.S.L 48 p.42-52.
Johnson, G.A.L. & Marshall, A.E (1971) Tournaisian beds in Ravenstonedale, Westmorland. Proc. Yorks. Geol. Soc. 38 p.261-280.
Johnson, G.A.L. (1959) Carboniferous stratigraphy of the Roman Wall district in western Northumberland. Proc. Yorks. Geol. Soc. 32 p.83-130.
Johnson, G.A.L. (1967) Basement control of Carboniferous sedimentation in N. England. Proc. Yorks. Geol. Soc. 36 p.175-194.
Johnson, G.A.L. (1978) European plate movements during the Carboniferous. In: Tarling, D.H (ed) Evolution of the Earth's crust. Academic Press. Lond. p.343-360.
Johnson, G.A.L. (1981) Geographical evolution from Laurasia to Pangea. Proc, Yorks. Geol. Soc. 43 p.221-252.
Johnson, G.A.L. (1982) Geographical change in Britain during the Carboniferous Period. Proc.

Yorks. Geol. Soc. 44 p.181-204.
Johnson, G.A.L. (1984) Subsidence and sedimentation in the Northumberland trough. Proc, Yorks. Geol. Soc. 45 p.71-84.
Johnson, G.A.L., Nudds, J.R & Robinson, D. (1980) Carboniferous stratigraphy and mineralisation at Ninebanks, West Allendale, Northumberland. Proc. Yorks. Geol. Soc. 43 p.1-16.
Jones, J.M., Murchison, D.G & Saleh, S.A (1973) Reflectivity and anisotropy of vitrinites in some coal seams from the coal measures of Northumberland. Proc. Yorks. Geol. Soc. 39(4) p.515-526.
Jones, N.E & Preston, R.M.F (1987) eds: Deformation of sediments and sedimentary rocks. Spec. Publ. Geol. Soc. Lond.
Karner, G.D. (1986) Effects of lithosphere in plane stresses on sedimentary basin stratigraphy. Tectonics. 5 p.573-588.
Kendall (1911)The geology of the district around Settle and Harrogate. Proc. Geol. Ass. 22 p.27-60.
Kent & Opdyke (1978)
Kent, D.V. & Opdyke, N.D. (1978) Palaeomagnetism of the Devonian Catskill Red beds: evidence for motion of the coastal New England - Canadian Maritime province relative to cratonic North America. J. Geophys. Res. 83 p.4441-4450.
Kent, P.E (1966) Structure of the concealed Carboniferous rocks of NE England. Proc. Yorks. Geol. Soc. 35 p. 323-352.
Kent, P.E (1974) Structural history In: Rayner D.H & Hemmingway, J.E (ed) The geology and mineral resources of Yorkshire. Yorks. Geol. Soc. Leeds.
Kent, P.E (1975) Review of North Sea basin development J. Geol. Soc. Lond. 131 p.435
Kent, P.E (1975) The tectonic development of Great Britain and the surrounding seas. From: Petroleum and the continental shelf of NW Europe. 1 p.3-28.
Kent, P.E (1980) Subsidence and uplift in east Yorkshire and Lincolnshire: a double inversion. Proc. Yorks. Geol. Soc. 42 p.502-524.
Kent, P.E , Bott, M.H.P., McKensie, D.P. & Williams, C.A. (1982) The evolution of sedimentary basins. Phil. Trans. Roy. Soc. Series A 305 p.325-338.
Khramov, A.N. (1987) Palaeomagnetology. Springer Verlag, Berlin. p.308.
Kimbell, G.S., Chadwick, R.A., Holliday, D.W. & Werngren, O.C. (1989) The structure and evolution of the Northumberland trough from new seismic reflection data and its bearing on modes of continental extension. J. Geol. Soc. 146 p.775-787.
Kirton, S.R (1984) Carboniferous volcanicity in England with special reference to the Westphalian of the est and west Midlands. J. Geol. Soc. Lond. 141 p.160.
Kisch, H.J. (1983) Mineralogy and petrology of burial diagenesis (burial metamorphism) and incipient metamorphism in clastic rocks. In: G. Larsen and G.V. Chilinger (eds) Diagenesis in sediments and sedimentary rocks rocks 2. Developments in sedimentology. Elseiver, Amsterdam p.289-493.
Klemperer, S.L Metthus, D,H. (1987) Iapetus suture located beneath the North Sea by BIRPS deep seismic reflection profile. Geology 15 p.195-198.
Klingspar, I. (1976) Radiometric age-determination of basalts, dolerites and related syenites in Skane, southern Sweden. Geol. Foren. Stockh. Fordh. 98 p.195-215.
Knipe, R.J. (1982) Interaction of footwall geometry and folds during detachment faulting. In: Frost, E.G & Matin, D.L. (eds) Mesozoic-Cenozoic Tectonic evolution of the Colorado river region, California, Arizona & Nevada. Cordilleran publishers, San Diego. p.608.
Koons, P.O. (1987) Some thermal and mechanical consequences of rapid uplift an example from the Southern Alps, New Zealand. E.P.S.L 86 p.307-319.
Koopman, A. (1987) Sand box studies of inversion tectonics. Tectonophysics 137 p.379-388.
Kossmat, F. (1927) Gliederung desvaristiden Gebirgsbaues. Abn. Sachs. Geol. Landesamtes. p.1-39.
LaJoie, J. (1972) Slump fold axis orientations: an indication of palaeoslope. J. Sedim. Petrol. 42 p.584-586.
Lampulgh, G.W. (1920) Structure of the Weald and analogue tracts.Quart. J. Geol. Soc. 75 LXXIII-XCV (anniversary address).
Land. (1974) Geology of Tynemouth District. Mem. Geol. Survey. Gt. Britain. Sheet 15.
Lawrence, S.R., Coster, P.W. & Irelan, R.J (1987) Structural development-petroleum potential of the N flank of the Bowland basin (Carboniferous) NW England. In: Petroleum geology of north-west Europe. (eds) J. Brooks & K. Glennie. p.225.
Le Fort, J.P & Van der Voo, R. (1981) A kinematic model for the collision and complete suturing between Gondwanaland and laurasia in the Carboniferous. J. Geol. 89 p.537-550.
Le Pichon, X. & Alvarez, F. (1984) From stretching to subduction in back-arc regions: Dynamic considerations. Tectonophysics, 102 p.343-357.
Le Pichon, X. & Sibuet, J.C.(1981) Passive margins: A model of formation. J. Geophys. Res. 86 p.3708-3720.
Lee, M.K., Pharaoh, T.C. & Soper, N.J. (1990) Structural trends in central Britain from images of gravity and aeromagnetic fields. J. Geol. Soc. Lond. 147 p.241-258.

Leeder, M.R (1974) The origin of the Northumberland basin. Scottish Journal of Geology 10 p.283-296.

Leeder, M.R (1975) Lower Border Group (Tournaisian) stromatolites from the Northumberland basin. Scott. J. Geol. 11 (3) p.207-226.

Leeder, M.R (1976) Sedimentary facies and the origins of basin subsidence along the northern margin of the supposed Hercynian ocean. Tectonophysics 36 p.167-179.

Leeder, M.R (1982) Upper Palaeozoic basins of the British Isles: Caledonide versus Hercynian plate margin processes. J. Geol. Soc. Lond. 139 p.481-494.

Leeder, M.R (1987) Sediment deformation structures and the palaeotectonics analysis of extensional sedimentary basins. In: Jones M. & Preston, R.M.F (eds). Deformation of sediments & sedimentary rocks. Spec. Publ. Geol. Soc. Lond.

Leeder, M.R. & Gawthorpe, R.L. (1987) Sedimentary models for extensional tilt-block / half-graben basins. In: Continental Extensional Tectonics (eds) Coward, M.P, Dewey, J.F. & Hancock, P.L. Spec, Publ. Geol. Soc. 28 p.139-152.

Leeder, M.R. & Hardman, M. (1991) In press. Carboniferous geology of the Southern North Sea and controls on hydrocarbon prospectivity.

Leeder, M.R. & Strudwick (1987) Delta-marine interactions: A discussion of sedimentary models for Yoredale type cyclicity in the Dinantian of N. England. In: European Dinantian Environments. (eds) Miller, Adams & Wright.

Leeder, M.R. (1987) Devono-Carboniferous river systems and sediment dispersal from the orogenic bets and cratons in NW Europe. In: Evolution of the Caledonide/Appalachian orogen (ed.) A. Harris. Spec. Publ. Geol. Soc. Lond.

Legget, J.K (1987) The Southern Uplands as an accretionary prism: The importance of analogues in reconstructing palaeogeography. J. Geol. Soc. Lond. 144 p.737-752.

Lewis, K.B (1971) Slumping on a continental slope inclined at 1° to 4°. Sedimentology 16 p.97-100.

Lumsden, G.I., Tulloch, W., Howells, M.F. & Davies, A. (1972) The geology of the neighbourhood of Langholm. Mem. Geol. Soc. Gt. Britain.

MacDonald, R. & Walker, B.H. (1985) Geochemistry and tectonic significance of the lower Carboniferous Cockermouth lavas, Cumbria. Proc. Yorks. Geol. Soc. 45 p.141-146.

MacDonald, R., Gass, K.N., Thorpe, R.S & Gass, I.G. (1984) Geochemistry and petrogenesis of the Derbyshire Carboniferous basalts. J. Geol. Soc. Lond. p.147.

MacDonald, R., Gottfried, D., Farrington, M.J., Brown, R. & Skinner, N. G. (1981) Geochemistry of continental tholeiite suite: late Paleozoic Qtz-Dolerite dykes of Scotland. Trans. Roy. Soc. Edinb. Earth Sci. 72 p.57-74.

MacDonald, W.D (1980) Net tectonic rotation, apparent tectonic rotation and the structural tilt correction in Palaeomagnetic studies. J. Geophys. Res. 85 p.3659-3669.

Matte, P. & Burg, J.P. (1981) Sutures, thrusts and nappes in the Variscan arc of western Europe: Plate tectonic interpretations. In: K. McClay (ed) Thrust and nappe tectonics. Geol. Soc. Lond. Spec. Publ. p.353-358.

McClay, K.R & Ellis, P.G (1987) Analogue models of extensional fault geometries. In: Coward et al (eds) Continental Extensional Tectonics Geol. Soc. Lond. Spec. Publ. 28.

McClay, K.R. (1989) Analogue models of inversion tectonics. In: Cooper, M.A. & Williams, G.D (eds) Inversion Tectonics. Spec. Pub. Geol. Soc. 44.

McGretchin, T.R., Burke, K.C., Thompson, G.A & Yong, R.A (1980) In: Dynamics of plate interiors (eds) A.W. Bally, P.L. Bender, T.R. McGretchin & R.I Walcott. Am. Geophys. Union & Geol. Soc. Am. Boulder, Colorado.

McKensie, D.P (1978a) Some remarks on the development of sedimentary basins. E.P.S.L 40 p.25-32.

McKensie, D.P (1984) Possible mechanism for epeiorogenic uplift. Nature 307 p.316-318.

McKensie, D.P. (1972) Active tectonics of the Mediterranean region. Geophys. J. R. Astrn. Soc. 40 p.25-32.

McKensie, D.P. (1978b) Active tectonics of the Alpine Himalayan belt: the Aegean Sea and surrounding areas. Geophys. J. R. Astron. Soc. 55 p.217-254.

Mercier, J.L (1987) Change from late Tertiary compression to Quarternary extension in S.Tibet during the India-Asia collision. Tectonics 6(3) p.275-304.

Millar, J. & Grayson, R.F (1972) Origin and structure of the Lower Visean 'reef' limestones near Clitheroe, Lancashire. Proc. Yorks. Geol. Soc. p.607-638.

Miller & Turner (1931) The lower Carboniferous succession along the Dent fault and the Yoredale beds of the Shap District. Proc. Geol. Ass. 42 p.1-28.

Miller, J. & Grayson, R.F. (1982) The regional context of Waulsortian Facies in Northern England. Symposium on palaeoenvironment setting and distribution of the Waulsortian facies. El Paso, Texas.

Miller, J., Adams, A.E. & Wright. (1986) Eds: European Dinantian Environments. Wiley, London.

Mitchell, M. (1978) Dinantian In: Moseley, F (ed) The Geology of the Lake District. Yorks. Geol. Soc. Occ. Publ. 3 p.168-177.

Molnar, P. (1986) The structure of mountain ranges. Scientific American 255 p.70-79.

Moseley, F. (1962) The structure of the south western part of the Sykes anticline, Bowland, west Yorkshire. Proc. Yorks. Geol. Soc. 33 p.287-315.

Moseley, F. (1972) A tectonic history of NW England. J. Geol. Soc. Lond. 128 p.561-598.

Muraoka, H. & Kamata, H. (1983) Displacement distribution along minor fault traces. J. Struct. Geol. 5 p.483-495.

Murphy (1989) as Cooper et al (1989).

Myers, J.D & Wardell, J. (1967) The gravity anomalies of the Askrigg block south of Wensleydale. Proc. Yorks. Geol. Soc. 36 p.169-173.

Ord, D.M., Clemmey, H. & Leeder, M.R (1987) Palaeotectonic analysis of faults in the Carboniferous Solway basin in SW Scotland. J. Geol. Soc. 144.

Ord, D.M., Clemmey, H. & Leeder, M.R. (1988) Interaction between faulting and sedimentation during Dinantian extension of the Solway basin, SW Scotland. J. Geol. Soc. Lond. 145.

Palister, J.W (1952) The Birrenswark lavas, Dumfrieshire. Trans. Edin. Geol. Soc. 14 p.336-348.

Pantin, H.R & Evans, C.D.R (1984) Quarternary history of the Celtic sea. Marine Geology.

Perroud. H. (1986) Palaeomagnetic evidence for tectonic rotations in the Variscan mountain belt. Tectonics, 5 p.205-214.

Pharaoh, T.C., Merriman, R.J., Webb, P.C. & Beakinsale, R.D (1987) The concealed Caledonides of eastern England: Preliminary results of a multidisciplinary study. Proc. Yorks. Geol. soc. 46 .355-369.

Pin, C.& Peucat, J.J (1986) Ages des episodes de metamorphisme palaezoiques dans le Massif Central et l Massif Armoricain. Bull. Soc. Geol. France 8 p.461-469.

Pollard, J.E (1969) Three ostracod-Mussel bands in the Coal Measures (Westphalian) of Northumberland and Durham. Proc. Yorks. Geol. Soc. 37 p.239-276.

Price, N.J (1977) Aspects of gravity tectonics and the development of listric faults. J. Geol. Soc. Lond. 133 p.311-327.

Ramsbottom, W.C.H (1973) Transgressions and regressions in the Dinantian: a new synthesis of British Dinantian stratigraphy. Proc. Yorks. Geol. Soc. 39 p.567-607.

Ramsbottom, W.C.H (1974) Namurian. In: Rayner, D.H & Hemmingway, J.E (eds) The geology and mineral resources of Yorkshire. Yorks. Geol. Soc. p.73-87.

Ramsbottom, W.C.H (1981) ed: Field guide to the boundary stratotypes of the Carboniferous stages in Britain. Proc. Subcommission on Carboniferous Stratigraphy. Leeds. p.1-146.

Ramsbottom, W.C.H., Grossens, R.F., Smith, E.G. & Calver, M.A. (1974) Carboniferous In: Rayner, D.H. & Hemmingway, J.E (eds) The geology and mineral resources of Yorkshire. Leeds. Yorks. Geol. Soc. p.45-114.

Rast, N. (1983) Variscan Orogeny In: The Variscan fold belt in the British Isles (ed) Hancock, P.L. p. 1-17.

Read, J.F (1982) Carbonate platforms and passive (extensional) continental margins: Types, characteristics and evolution. Tectonophysics. 81 p.195-212.

Read, W.A (19) Controls on Silesian sedimentation in the Midland Valley of Scotland.

Read, W.A (19') The interplay of sedimentation, vulcanicity and tectonics in the Passage Group - in the (Arnsbergian, E2 to Westphalian A) Midland Valley of Scotland.

Read, W.A. & Dean, J.M (1976) Cycles and subsidence: their relationship in different sedimentary and tectonic environments in the Scottish Carboniferous. Sedimentology. 23 p.107-120.

Reading, H.G (1957) The stratigraphy and structures of the Cotherstone Syncline. Q. J. Geol. Soc. Lond. 113 p.27-56.

Reading, H.G (1980) Characteristics and recognition of strike-slip fault systems. In: Balance P.F & Reading, H.G. Sedimentation in oblique slip mobile zones. Spec. Publ. Int. Assn. Sedimentologists 4 p.7-26.

Reading, H.G (1982) Sedimentary basins and global tectonics. Proc. Geol. Ass. 93 p.321-350.

Ridd, M.F., Walker, D.B. & Jones, J.M (1970a) A deep borehole in the North of England: a Review. Proc. Yorks Geol. Soc. 28 p.231-315.

Ridd, M.F., Walker, D.B. & Jones, J.M (1970b) A deep borehole at Harton on the Margin of the Northumberland Trough. Proc. Yorks. Geol. Soc. 38 p.75-103.

Robinson, D., Wade, D.N. & Burnet, R. (1987) Correlation between organic and inorganic thermal maturation indices in Palaeozoic basins of Britain. In: Brooks, J. & Glennis, K. (eds) Petroleum Geology of NW Europe. pp.245.

Robson, D.A (1977) The structural history of the Cheviot and adjacent regions. Scott. J. Geol. 13 p.255-262.

Robson, D.A (1980) The geology of NE England. Spec. Publ. of the Nat. History Soc. of Northumbria.

Ron, H., Freund, R., Garfunkel, Z. & Nur, A. (1984) Block rotation by strike-slip faulting:

Structural and palaeomagnetic evidence.

Rowell, A.J & Scanlon, J.E (1957) The Namurian of the north-west quarter of the Askrigg Block. Proc. Yorks. Geol. Soc. 31 p.1-38.

Royden, I & Karner, G.D (1984) Flexure of the lithosphere beneath the Appennines and Carpathian foredeep basins. AAPG Bulletin 68 p.704-712.

Royden, L. & Keen, C.E (1980) Rifting process and thermal evolution of the continental margin of Canada determined from subsidence curves. E.P.S.L 51 p.343-361.

Russell, M.J (1974) A possible lower Permian age for the onset of ocean floor spreading in the northern North Atlantic. Scott. J. Geol. 4 p.315-323.

Sanderson, D.J (1984) Structural variation across the northern margin of the Variscides in NW Europe. In: Hutton, D.H.W & Sanderson, D.J (eds) Variscan tectonics of the North Atlantic region. Spec. Publ. Geol. Soc. 14.

Sclater, J.G & Christie, P.A.F (1980) Continental stretching: An explanation of the post-mid-Cretaceous subsidence of the Central North Sea basin. J. Geophys. Res. 85 p.3711-3739.

Scott, G. (1984) Variations in the coastal deposits formed during the mid-Dinantian marine transgression over the Askrigg Block, North Yorkshire. European Dinantian Environments 1st meeting abstracts, Dept. Earth Sci. Open Uni. p.56-58.

Scott, W.B. (1987) Nodular Carbonates in the Lower Carboniferous cementstone Group of the Tweed Embayment, Berwickshire: evidence for a former sulphate evaporite facies. Scott. J. Geol. p.325-345.

Shiells, K.A.G (1962) The Geological structure of North East Northumberland. Phil. Trans. R. Soc. Edin. 65(18) p.449-480.

Shotton, F.W (1935) The stratigraphy and tectonics of the Cross Fell inlier. Quart. J. Geol. Soc. Lond. 91 p.639-704.

Sibson, R.H (1981) Fluid flow accompanying faulting: field evidence and models. In: D.W. Simpson & P.G. Richards (eds) Earthquake prediction : an international review. Am. Geophys. Union, Maurice Ewing Series 4 p.593-603.

Sibson, R.H (1985) A note on fault reactivation. J. Struct. Geol. 7 p.751-754.

Simpson, I.R., Gravestock, M., Ham, D., Leach, H. & Thompson, S.D. (1989) Notes and cross sections illustrating inversion tectonics of the Wessex basin. In: Inversion Tectonics. Spec. Publ. Geol. Soc. Lond.

Simpson, S. (1962) Variscan orogenic phases In: K.Coe (ed) Some aspects of Variscan fold belts. Manchester University Press. p.65-73.

Smith, A.G., Briden, J.C. & Drewery, G.E (1973) Phanerozoic world maps. In: Hughes, N.F (ed) Organisms and continents through time. Palaeont. Soc, Spec. Paper 12 p.1-42.

Smith, D.I & Watson, J,V (1983) Scale and timing of movements on the Great Glen fault. Geology 11 p.523-526.

Smith, D.I. & Watson, J.V. (1983) Scale and timing of movements on the Great Glen fault. Geology 11 p.523-526.

Smith, K., Smith, N.J.P. & Holliday, D.W (1985) The deep structure of Derbyshire. Geological Journal 20 p.215-225.

Smith, N.J.P (1957) The deep geology of Central England: The prospectivity of the Palaeozoic rocks. In: Brooks, J. & Glennie, K. (eds) Petroleum geology of NE Europe. Graham & Trotman, London.

Smith, R.B & Bruhn, R.L (1984) Intraplate extensional tectonics of the eastern Basin-Range: Inferences on structural style from seismic reflection data, regional tectonics and thermal - mechanical models of brittle-ductile deformation. J.Geophys. Res. 89 (B7) p.5733-5762.

Soper, N.J., Webb, B.C. & Woodcock, N.H (198) Late Caledonian transpression in NW England: Timing, geometry and geotectonic significance. Proc. Yorks. Geol. Soc.

Spencer, J.E (1984) Role of tectonic denudation in warping and uplift of low-angle normal faults. Geology 12 p.95-98.

Steckler, M.S. & Watts, A.B (1978) Subsidence of the Atlantic type continental margin of New York. E.P.S.L 41 p.1-13.

Stedman, C. (1988) Namurian E1 tectonics and sedimentation in the Midland Valley of Scotland: rifting versus strike-slip influences. In: B.M. Besly & G. Kelling (eds) Sedimentation in a syn-orogenic basin complex: the Upper Carboniferous of North-West Europe. Blackie, Glasgow & London. p.53-68.

Stone, P., Floyd, J.D., Barnes, R.P. & Lintern, B.C (1987) A sequential back-arc and foreland basin thrust duplex model for the Southern Uplands of Scotland. J. Geophysics Scot. Lond. 144 p.753-764.

Stonely (1989) In: Inversion tectonics. Cooper, M.A. & Williams, G.D (eds). Spec. Publ. Geol. Soc. 44.

Strank, A.R.E (1987) The stratigraphy and structure of Dinantian strata in the East Midlands, UK. In: Miller, Adams & Wright (eds) European Dinantian Environments.

Tanner, G.P.W (1989) The flexural slip mechanism. J. Struct. Geol. 11 p.635-655.

Tate & Dobson (1989)

Tate (1867)

Taylor, B.J., Burgess, I.C., Land, D.H., Mills, D.A.C., Smith , D.B. & Warren< D.T. (1971) British regional geology: northern England (4th Ed) H.M.S.O. London.

Trotter, F.M & Hollingworth, S.E (1928) The Alston Block. Geological magazine 65 p.433-448.

Trotter, F.M & Hollingworth, S.E (1932) Geology of the Brampton district. Mem. Geol. Surv. Gt. Britain. Sheet 18.

Turcotte, D.L & Schubert, G. (1982) Geodynamics: Applications of continuum physics to geological problems. John Wiley & Sons.

Turner, J,S (1927) The lower Carboniferous succession in the Westmorland Pennines and the relations of the Pennine and Dent faults. Proc. Yorks. Geol. Ass. 38 p.339-374.

Turner, J,S (1935) Structural geology of Stainmore, Westmorland an notes of the late Palaeozoic (late Variscan) tectonics of the north of England. Proc. Geol. Ass. 46 p.121-151.

Turner, J,S (1949) The deeper structure of Central and Northern England. Proc. Yorks. Geol. Soc. 27 p.280-297.

Turner, P & Tarling, D.H (1975) Implications of new palaeomagnetic results from the Carboniferous system f Britain. J. Geol. Soc. Lond. 131 469pp.

Turner, P (1988) Remagnetisation in Permo-Triassic red-beds of Northwestern Europe. Cuardernos Geologica Iberico.

Turner, P. (1987) Magnetostratigraphy. Geology Today p.127-132.

Turner, P., Vaughan, D.J. & Besly, B. (1985) Remanence acquisition in red beds from the Coal Measures of Central England. J. Geol. Soc. Lond. p.1015-1028.

Upton, B.G.S (1982) Carboniferous to Permian volcanism in the stable foreland. In: Sutherland, D.S (ed) Igneous rocks of the British Isles. John Wiley & Sons. p.255-275.

Uyed, S (1986b) Facts, ideas and open problems on trench - arc - backarc systems In: Wezel, F.C (ed) The origin of arcs: Developments in geotectonics 21 435pp.

Uyeda, S. (1986a) Origin of back-arc basins. In: Proc. USSR-Japan symposium on geology and geophysics of East Asian marginal seas. Khabarovsk.

Van der Voo, R. (1982) Pre-Mesozoic palaeomagnetism and plate tectonics. Ann. Rev. Earth Planet. Sci. 10 p.191-220.

Vaughan, R.D & Adams, A.E (1984) Chadian and Arundian sedimentation in the Furness and Millam areas, South Cumbria. Eur. Dinant. Envir. 1st Mtg 1984. Abstract Dept. Earth Sci. Open Uni. p.120-124.

Wade, D.N & Robinson, D. (1987) Diagenetic studies of lower Carboniferous mudstones from the Alston block and Northumberland Trough, Northern England. In: Brooks, J. & Glennie, K. (eds) Petroleum geology of NW Europe. 245pp.

Wadge, A.J., Harrison, R.K. & Snelling, N.J (1972) Olivine - Dolerite intrusions near Melmerby, Cumberland, and their age determination by the Potassium-Argon method. Proc. Yorks. Geol. Soc. 39 p.59-70.

Walkden, G.M (1977) Volcanic and erosive events on an upper Visean carbonate platform, north Derbyshire. Proc. Yorks. Geol. Soc. 41 p.347-367.

Walters, S.G & Ineson, P.R (1981) A review of the distribution and correlation of igneous rocks in Derbyshire, England. Mercian Geol. 8 p.81-132.

Watts, A.B (1982) Tectonic subsidence, flexure and global changes of sea level. Nature 297 p.469-497.

Weber, K. & Behr, H.J (1983) Geodynamic interpretation of the Mid-European Variscides. In: Martin & W. Eder (eds) Intracontinental fold belts. Springer Verlag p.427-469.

Weber, K. (1984) Variscan events: Early Palaeozoic continental rift metamorphism and late Palaeozoic crustal stretching. In: Variscan tectonics of the North Atlantic region. Geol. Soc. Lond. Spec. Publ.

Welbon, A. T (1988) The influence of intrabasinal faults on the development of a linked thrust system. Geologische Rundschau 77(1) p.11-24.

Wernicke, B & Berchfiel (1982) Modes of extensional tectonics. J. Struct. Geol. 4 p.105-115.

Wernicke, B. (1981) Low angle normal faults in the Basin & Range province: Nappe tectonics in an extending orogen. Nature 291 p.645-648.

Westell et al (1955) A guide to the geology of the district around Alnwick, Northumberland. Proc. Yorks. Geol. Soc. p.61-100.

White, N.J. (1989) The nature of lithospheric extension in the North Sea. Geology 17 p.111-114.

White, N.J., Jackson, J.A. & McKensie, D.P (1986) The relationship between the geometry of normal faults and that of the sedimentary layers in their hanging walls. J. Struct. Geol. 8 p.897-909.

White, P.H.N (1949) Gravity data obtained in Great Britain by the Anglo-American Oil Company limited. Q. J. Geol. \Soc. Lond. 104 p.339-364.

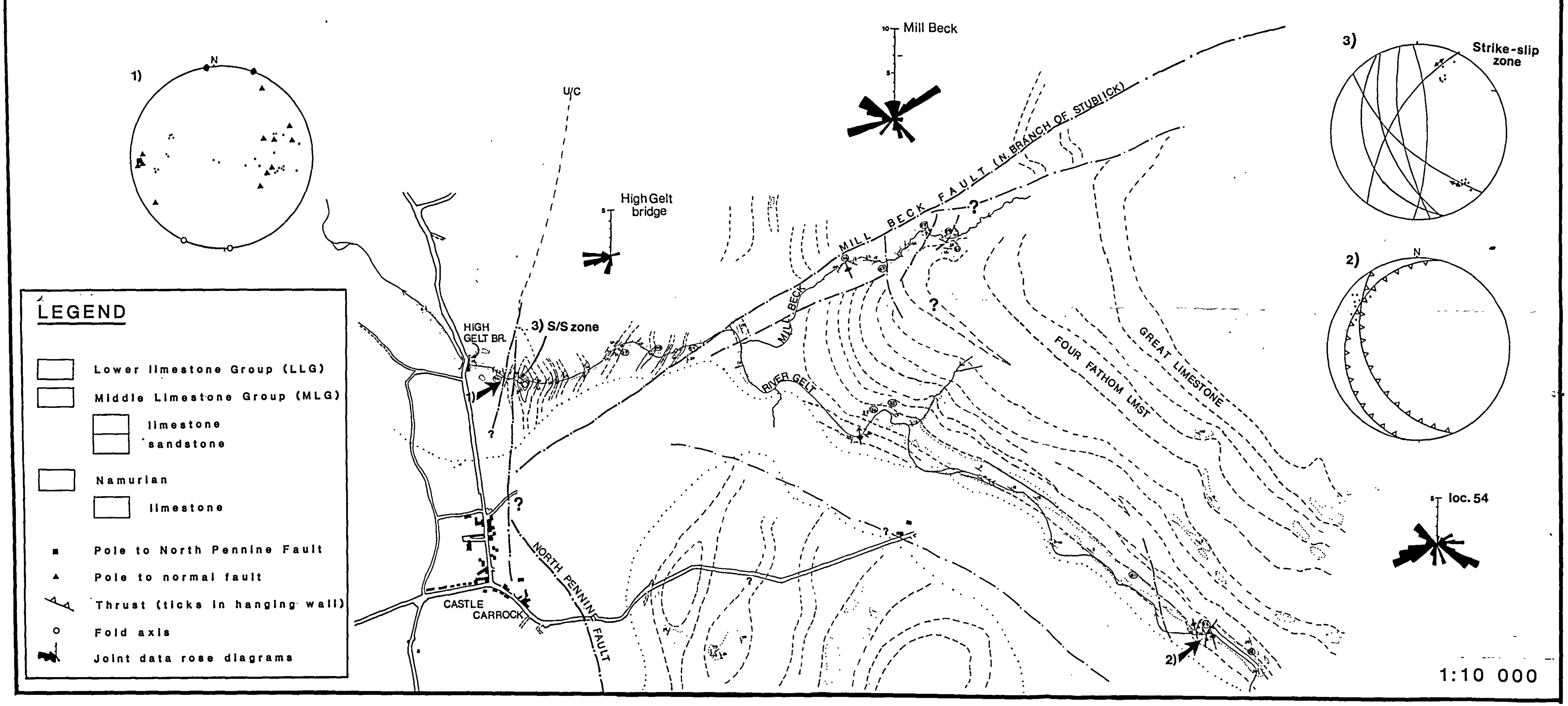
Whittaker, A. (1985) Atlas of onshore sedimentary basins in England and Wales: Post-Carboniferous tectonics and stratigraphy. B. G. S. 150th Anniversary, Blackie, Glasgow & London.

Williams & Vann (1987) The geometry of listric normal faults and deformation in their hanging

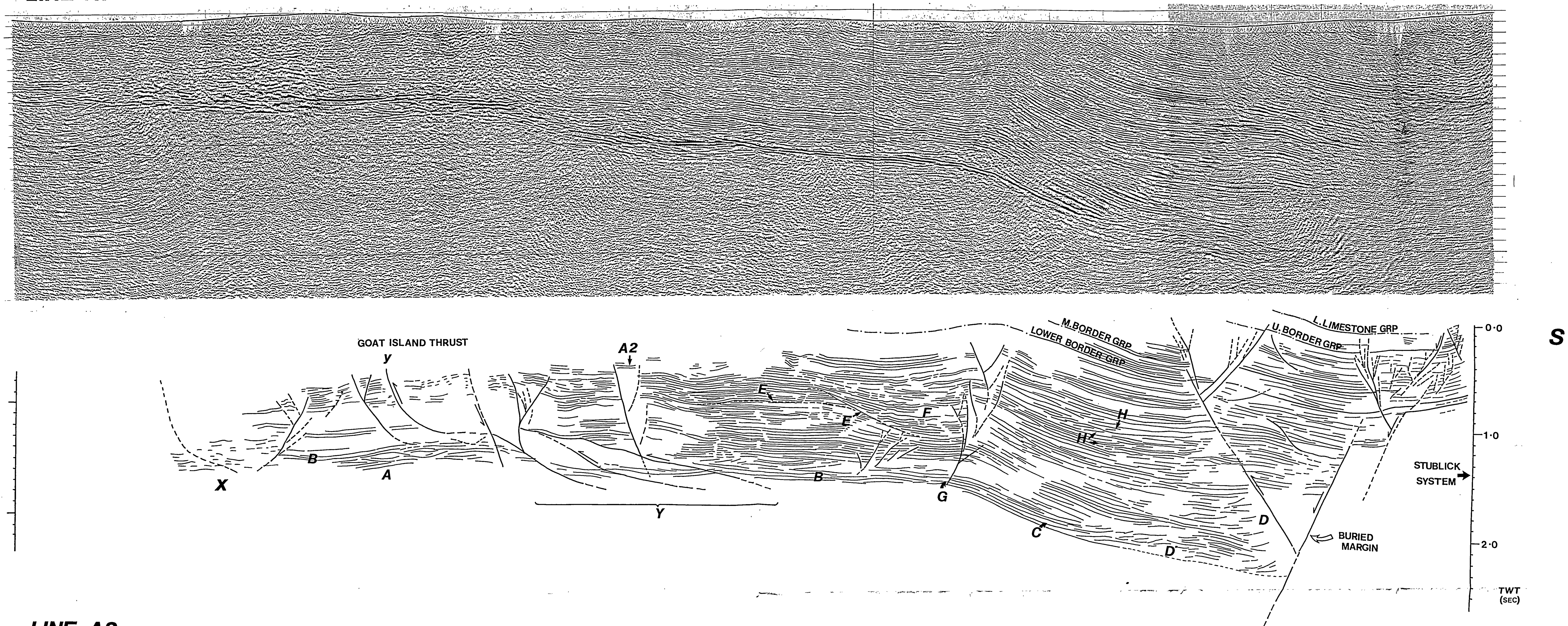
walls. J. Struct. Geol. 9 p.789-795.
Williams, G.D., Powell, C.M. & Cooper, M.A. (1989) Geometry and kinematics of inversion tectonics In: Cooper, M.A. & Williams, G.D (eds) Inversion Tectonics. Spec. Publ. Geol. Soc. 44 p.3-15.
Williams, J.E (1971) Carboniferous miospores from the Brampton district, northern England and the Archerbeck borehole, Dumfrieshire. Unpub. PhD Thesis. Uni. Sheffield.
Wills, L.J (1978) A palaeogeographical map of the Lower Palaeozoic floor below the cover of Upper Devonian, Carboniferous and later formations. Mem. Geol. Soc. Lond. 8.
Wilson, A.A. & Cornwell, J.D. (1982) The institute of geological sciences borehole at Beckermonds Scar, North Yorkshire. Proc. Yorks, Geol. Soc. 44 59pp.
Wiltschko & Eastman (1983) The role of basement warps and faults in localising thrust fault ramps. In: Hatcher, Jr, R.D., Williams, H. & Zeitz, I. (eds) Contributions to the tectonics and geophysics of mountain chains, Geol. Soc. Am. memoir. 158.
Winslow, M.A (1981) Mechanism for basement shortening in the Andean fold belt of South America. In: K.R. McClay & N.J. Price (eds) Thrust and Nappe tectonics Spec. Publ. Geol. Soc. 9 p.513-528.
Wortel, M.J.R & Cloetingh, S.A.P.L (1986) On the dynamics of convergent plate boundaries and stress in the lithosphere In: F.C Wezel (ed) The origin of Arcs: Developments in Geotectonics 21 115pp.
Zeigler, P.A (1978) North-western Europe: Tectonics and basin development. Geologie en Mijnbouw 57(4) p.589-626.
Zeigler, P.A (1981) Evolution of sedimentary basins in north-west Europe. In: L.V. Illing & G.D. Hobson. Petroleum geology of the continental self of NW Europe p.3-39.
Zeigler, P.A (1982) Geological atlas of western and Central Europe. Elsevier Press, Amsterdam.
Zeigler, P.A (1983) Inverted basins in the Alpine foreland In: Seismic expression of structural styles - a picture and work atlas. A.A.P.G. Studies in Geology 15 (3) p.3.3-3 to 3.3-12.
Zeigler, P.A (1985) Crustal thinning and subsidence in the North Sea. Nature 304 p.561.

GEOLOGICAL MAP OF PART OF THE NORTH PENNINE FAULT SYSTEM
(from Castle Carrock to Croglin, E . Cumbria.)

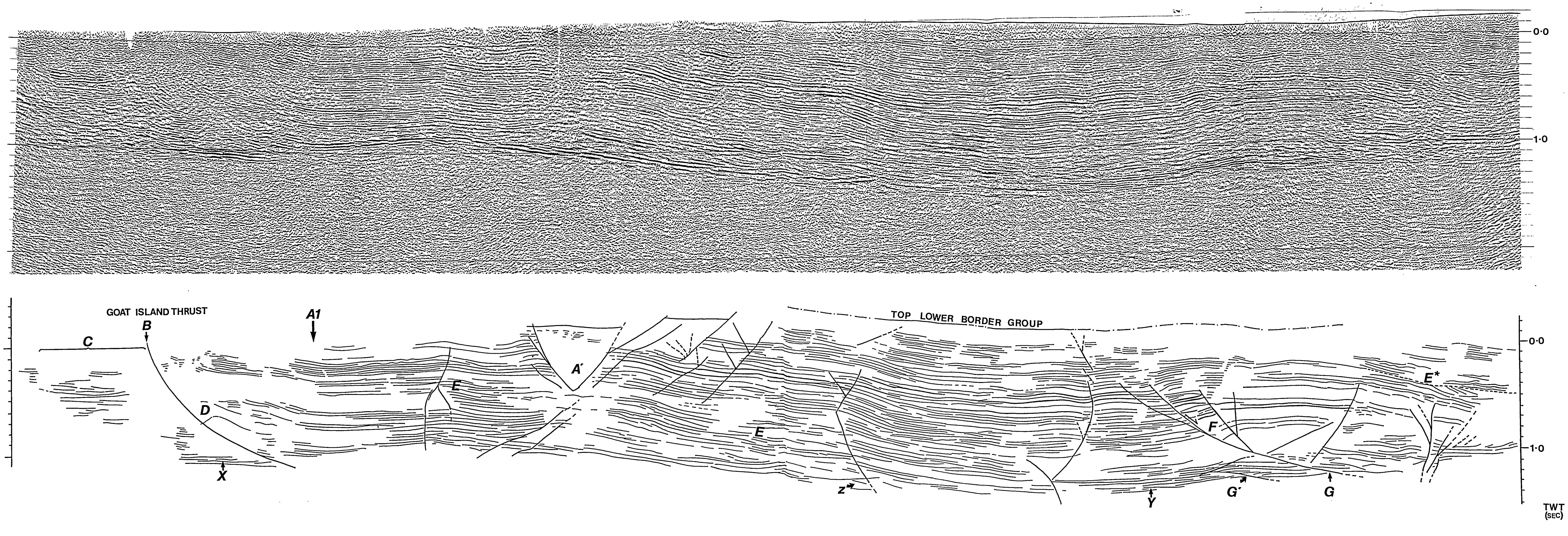
GEOLOGICAL MAP OF THE JUNCTION BETWEEN THE NORTH PENNINE AND STUBLICK FAULT SYSTEMS, CASTLE CARROCK, E. CUMBRIA.



LINE A1

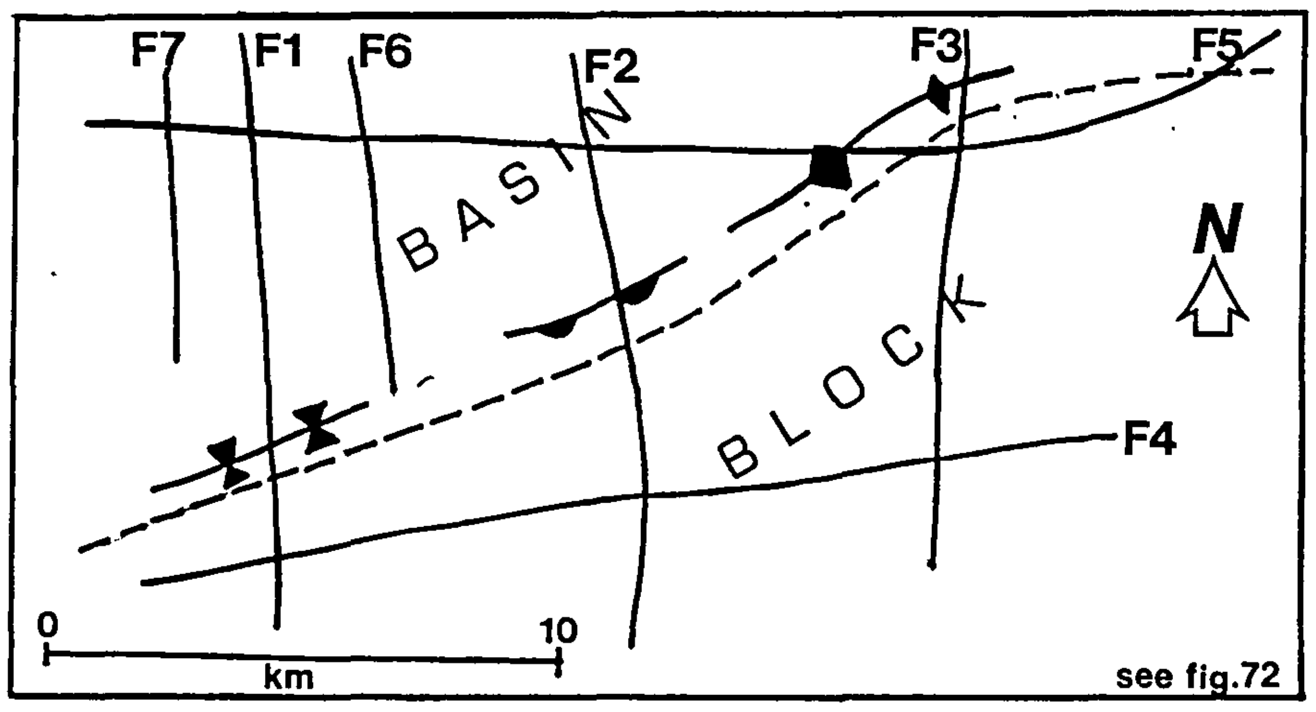


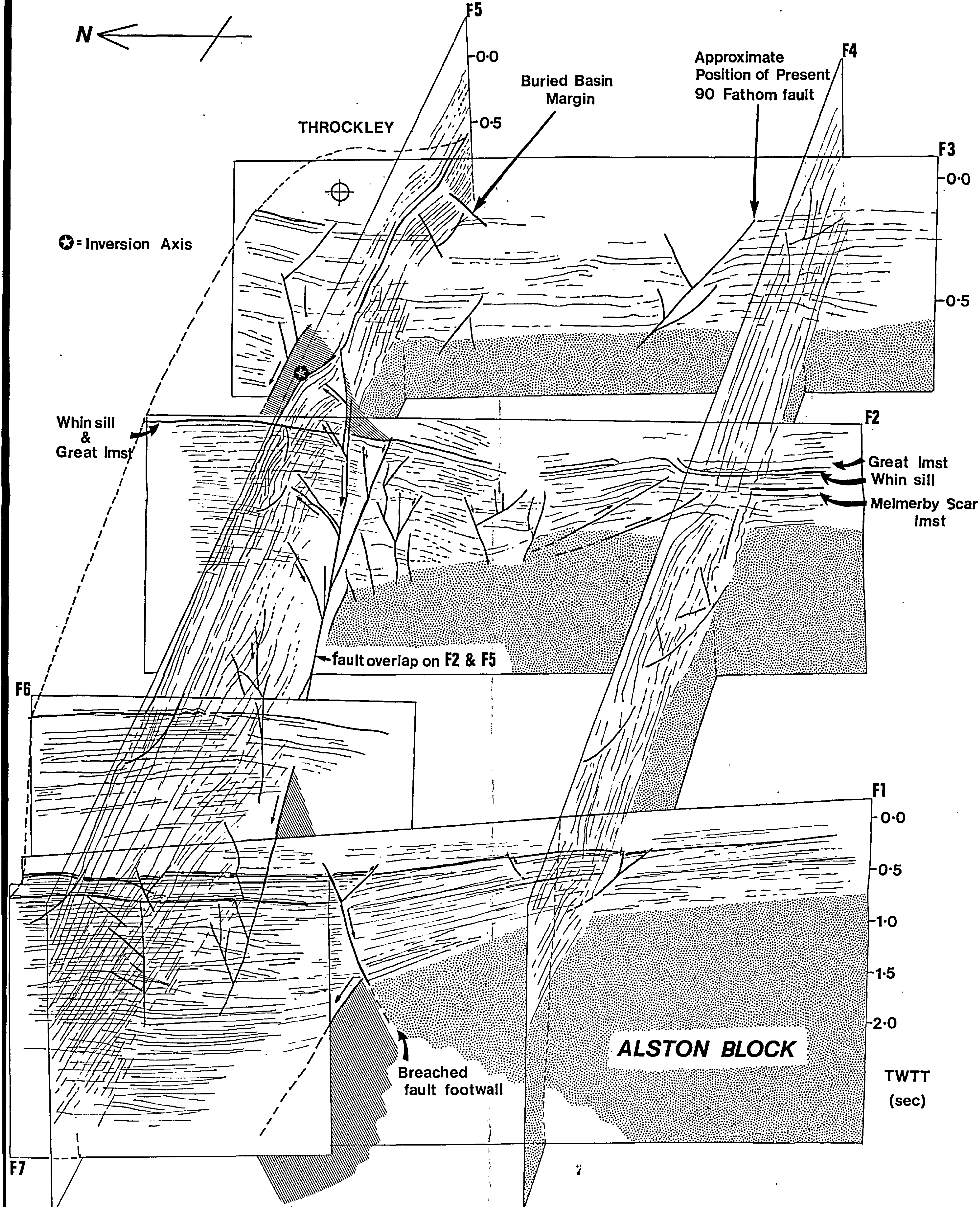
LINE A2



ENCLOSURE 4:

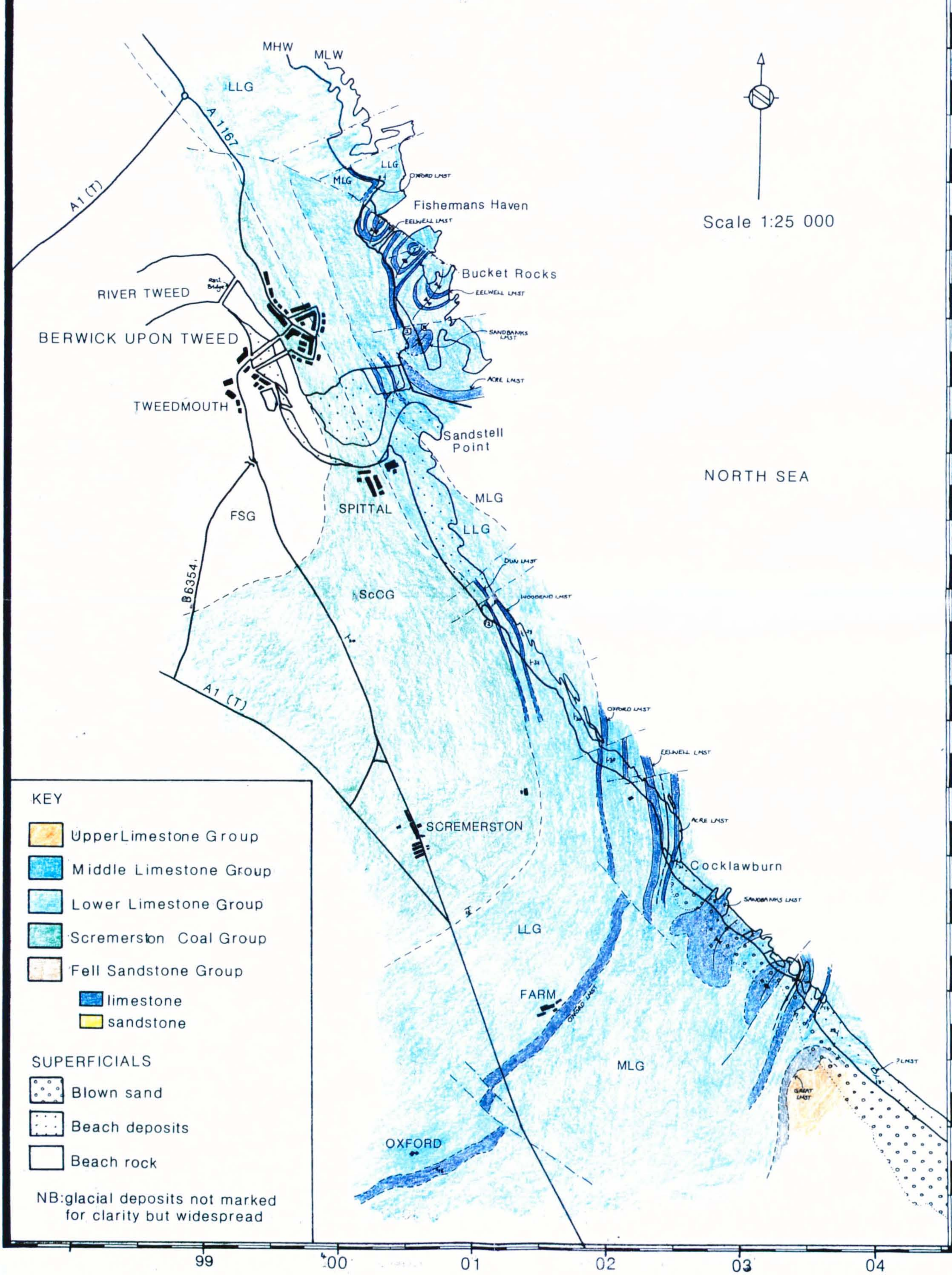
FENCE DIAGRAM INTERPRETATION OF SEISMIC REFLECTION LINES F1 - F7



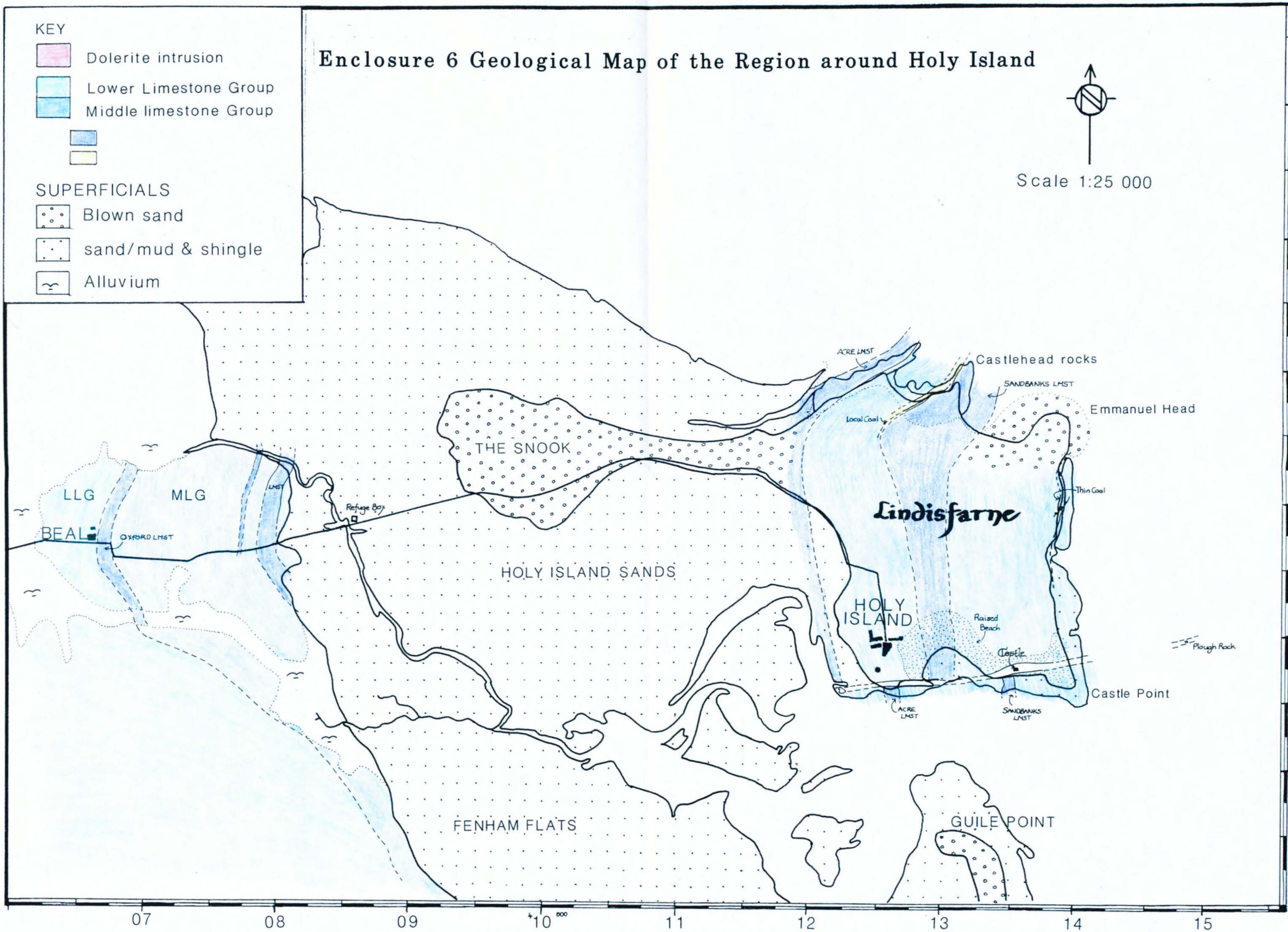


SCALE APPROX.

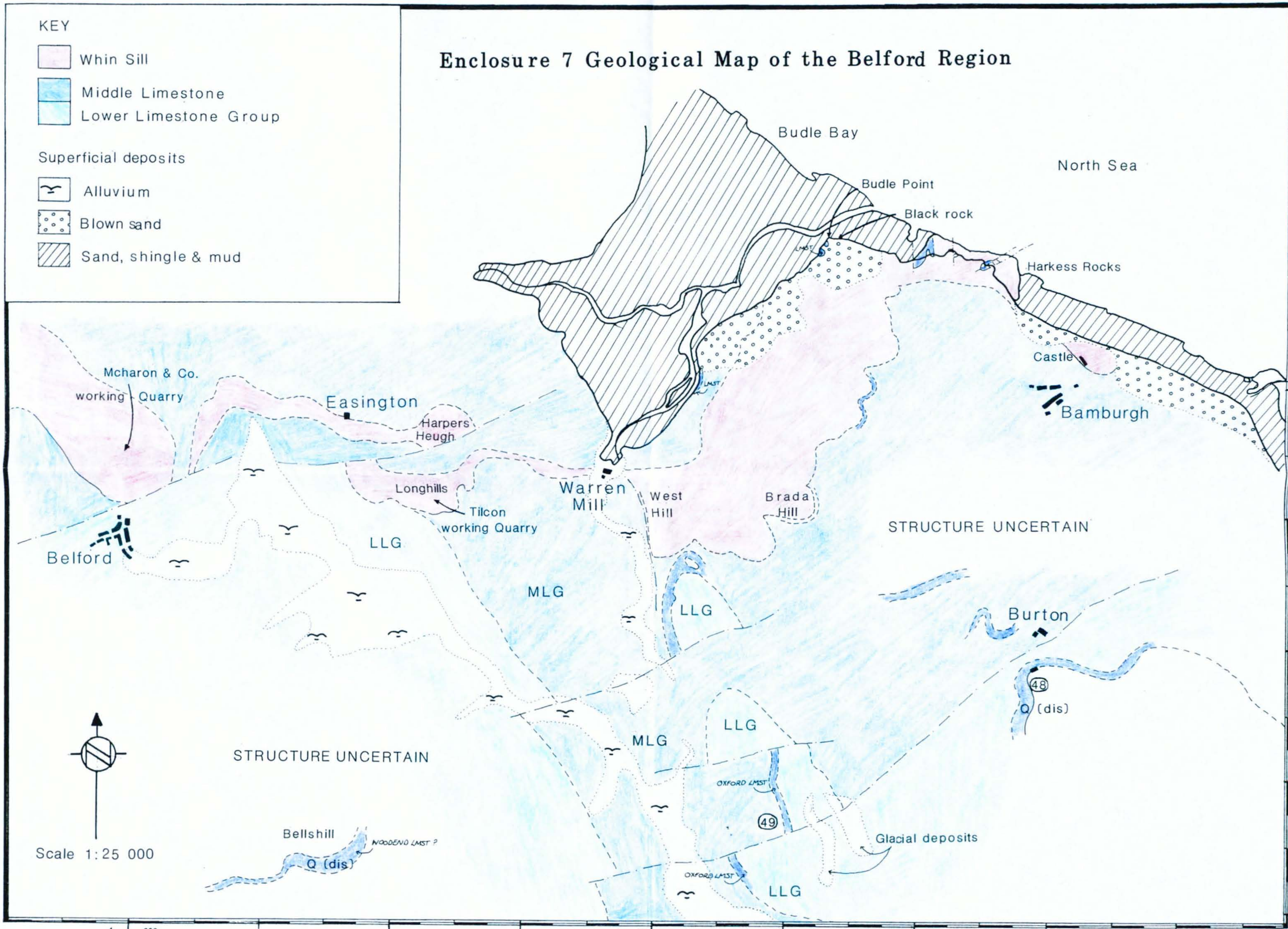
Enclosure 5 Geological Map of the Berwick Upon Tweed Region



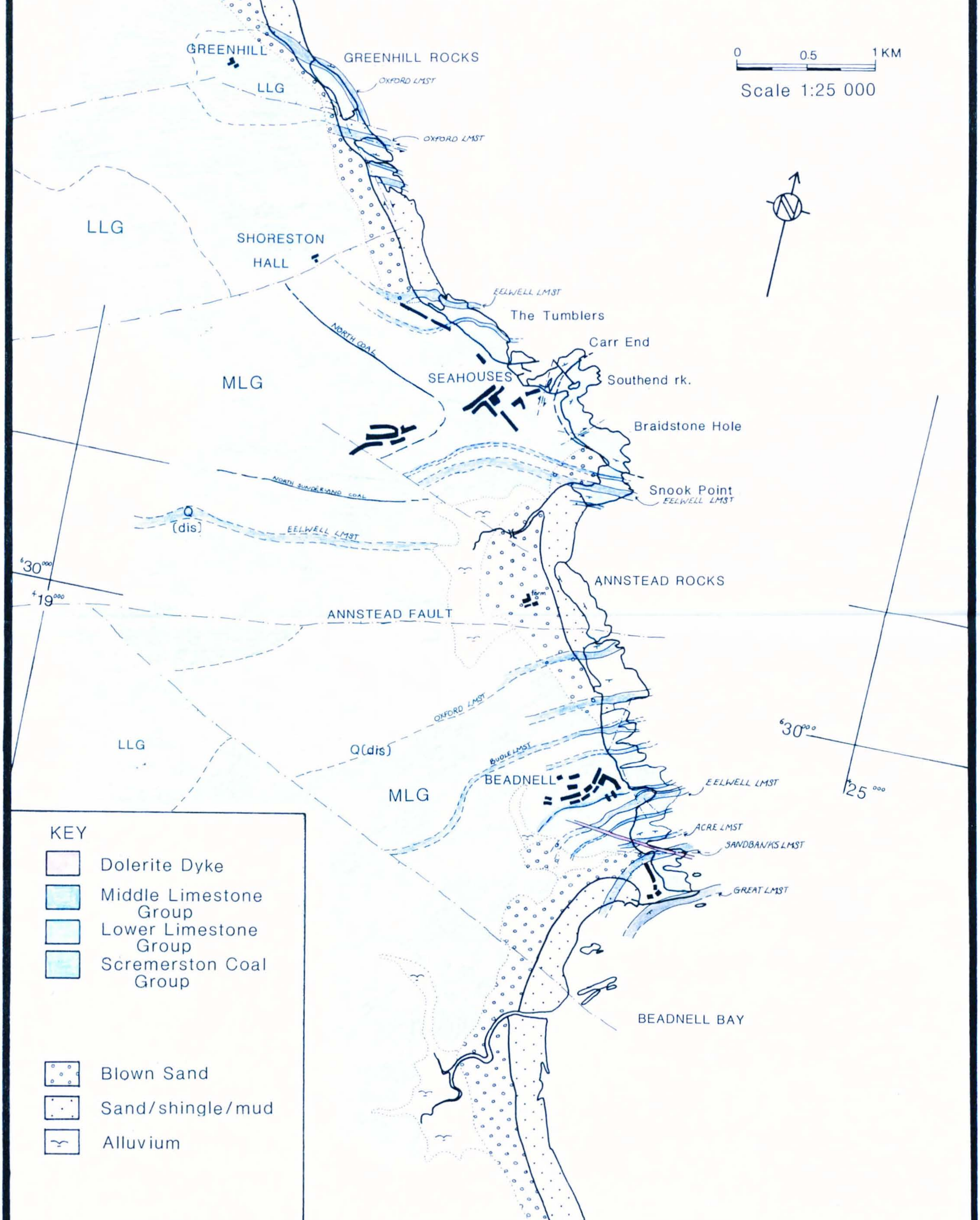
Enclosure 6 Geological Map of the Region around Holy Island

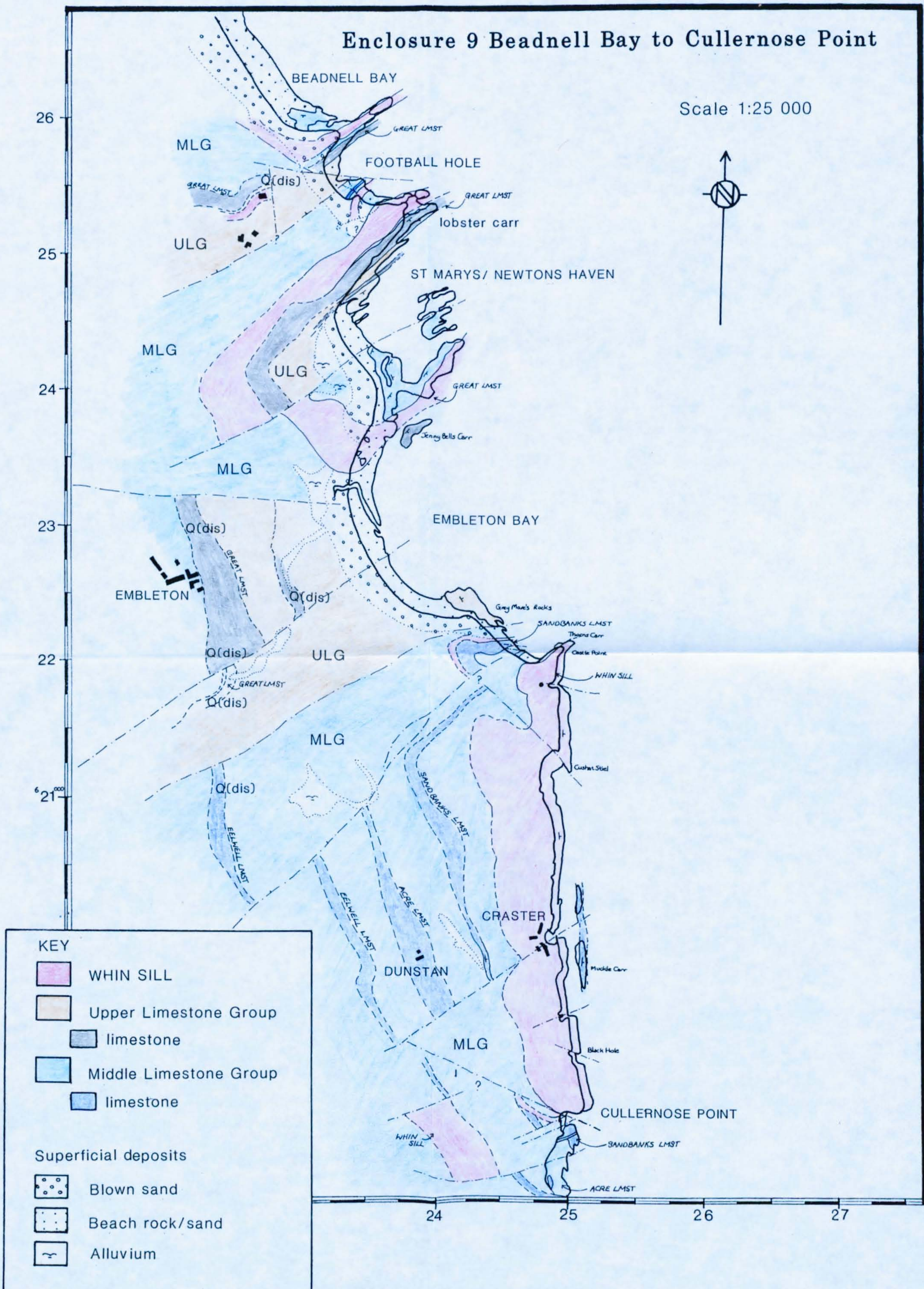


Enclosure 7 Geological Map of the Belford Region

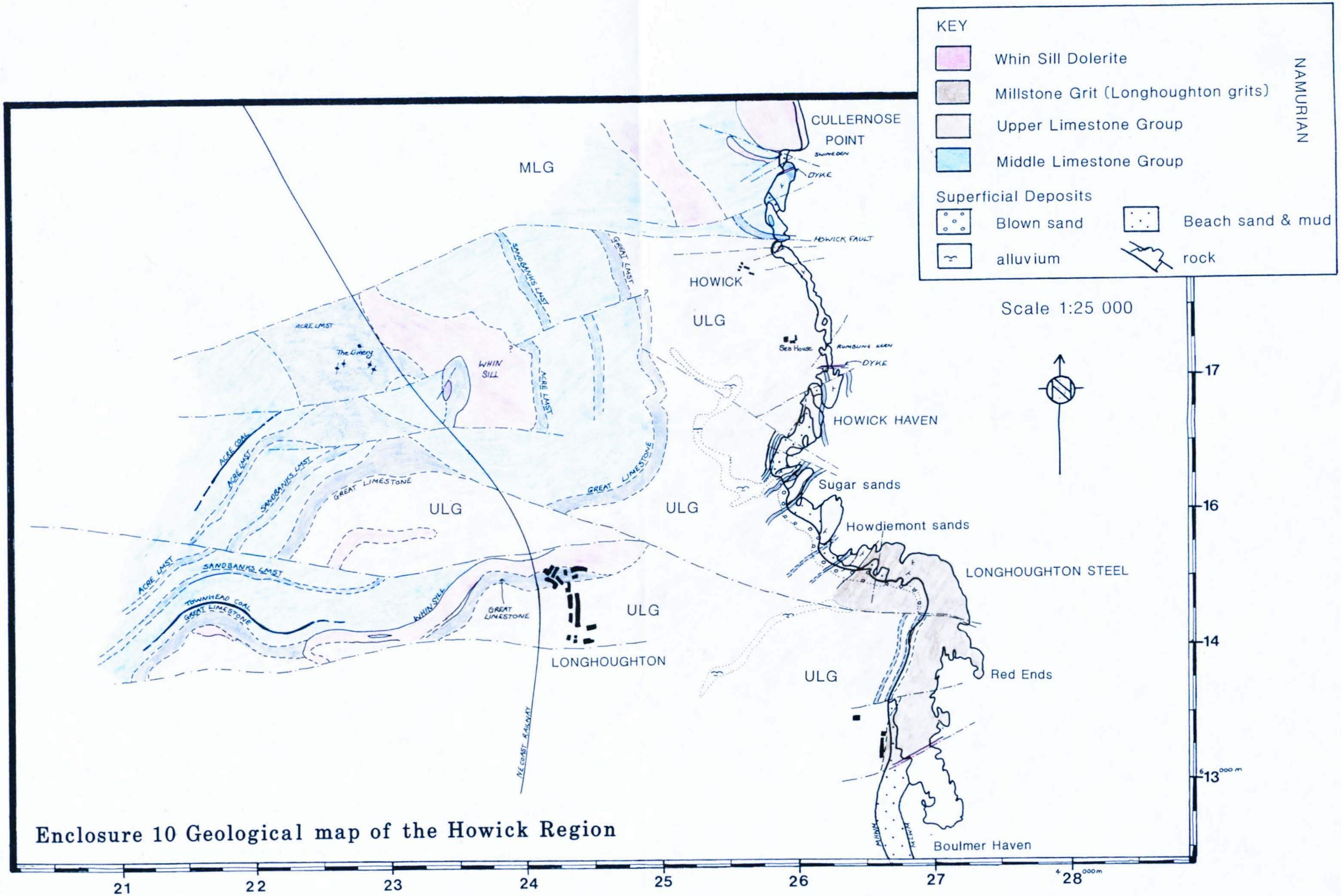


Enclosure 8 Seahousese to Beadnell Bay





Enclosure 9 Beadnell Bay to Cullernose Point
Scale 1:25 000
BEADNELL BAY
GREAT LMST
FOOTBALL HOLE
MLG
Q(dis)
ULG
lobster carr
ST MARYS/ NEWTONS HAVEN
Jenny Bells Carr
EMBLETON BAY
EMBLETON
Q(djs)
Grey Mare's Rocks
SANDBANKS LMST
Castle Point
WHIN SILL
Cushat Stiel
EELWELL LMST
ACRE LMST
CRASTER
DUNSTAN
Muckle Carr
Black Hole
CULLERNOSE POINT
26
25
24
23
22
21
27
KEY
WHIN SILL
Upper Limestone Group
limestone
Middle Limestone Group
limestone
Superficial deposits
Blown sand
Beach rock/sand
Alluvium



Enclosure 10 Geological map of the Howick Region