"THE SEDIMENTOLOGY AND DIAGENESIS OF COPPER-BEARING ROCKS OF THE SOUTHERN MARGIN OF THE DAMARAN OROGENIC BELT, NAMIBIA AND BOTSWANA"

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by

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ABSTRACT

Late Proterozoic sediments of the Doornpoort, Klein Aub and Ghanzi Formations outcrop on the southern foreland of the Damaran Orogenic Belt, and contain stratiform copper ore deposits. This thesis presents sedimentological, diagenetic and isotopic studies of these sediments, defines the controls on copper mineralization and presents a model for ore genesis. The above-mentioned Formations are reclassified into the Doornpoort Formation, which is divided into the Klein Aub, Dordabis, Eskadron and Lake Ngami Members.

The Doornpoort sediments were deposited between c. 1,000 MYR and c. 850 MYR age, unconformably on a mineralized basement which yields Eburnian (2,000 ± 200 MYR) and Kibaran (1,100 ± 200 MYR) ages. They consist of alluvial fan, lacustrine, aeolian, playa and mud flat sediments, deposited in a semi-arid to arid climate. Four types of alluvial fan complex are recognized and divided into two morphological groups: 1) thick conglomeratic fans with rapid lateral facies changes into aeolian, lacustrine and playa deposits, and 2) thin laterally persistent complexes with intercalated mud flat and lacustrine sediments. Fan complexes of differing morphological type can be correlated using megasequences (10's to 100's m. thickness of sediment). Thin, broad fans were probably formed by regional uplift and unconfined sediment discharge, whereas thick, narrow fan complexes were produced by localized uplift with sediment discharge through stable, restricted feeder zones.

Despite the destructive mineralogical and textural effects of Damaran deformation and associated lower greenschist facies metamorphism, a generalized diagenetic sequence is identified for the

formation of red and green Doornpoort sediments. Red sediments formed in alkaline, oxidizing diagenetic conditions and contain evidence of dissolution and replacement of detrital grains. In situ alterations probably led to the release of various elements into interstitial waters, which later recombined to form authigenic minerals and overgrowths. A paragenetic sequence of authigenic minerals is recognized in the aeolian Red Bed sandstones of the Witvlei fan complex, parts of which can be identified in surrounding fluviatile and playa sediments. Green sediments may contain copper and iron sulphides, which are intergrown with diagenetic minerals in the Witvlei playa sediments.

Copper mineralization is restricted to reduced playa and marginal lacustrine sediments, which are closely associated with Red Bed deposits. Sedimentological evidence suggests that copper distribution was determined by ground and surface water drainage and then controlled by lacustrine palaeocurrents. Textural and sulphur isotopic data indicates that copper was fixed in the sediments during diagenesis, as sulphides, by the bacterial reduction of groundwater sulphate. Both sedimentological and isotopic data point to a basement origin for the copper and silver.

A model for ore genesis is proposed, involving the release of copper and silver from mineralized basement rocks during Late Proterozoic semi-arid to arid weathering and the transport of metals in solution as copper sulphate, which on contact with neutral or alkaline aqueous solutions, was converted to insoluble basic copper carbonate and carried in suspension. Metalliferous waters collected in topographically low areas on the alluvial fan surface, in playas and lakes. Particulate basic carbonates were deposited

with the suspended sediment load and reworked by lacustrine palaeocurrents, forming placer deposits. The metals were subsequently fixed as sulphides during diagenesis.

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CHAPTER I

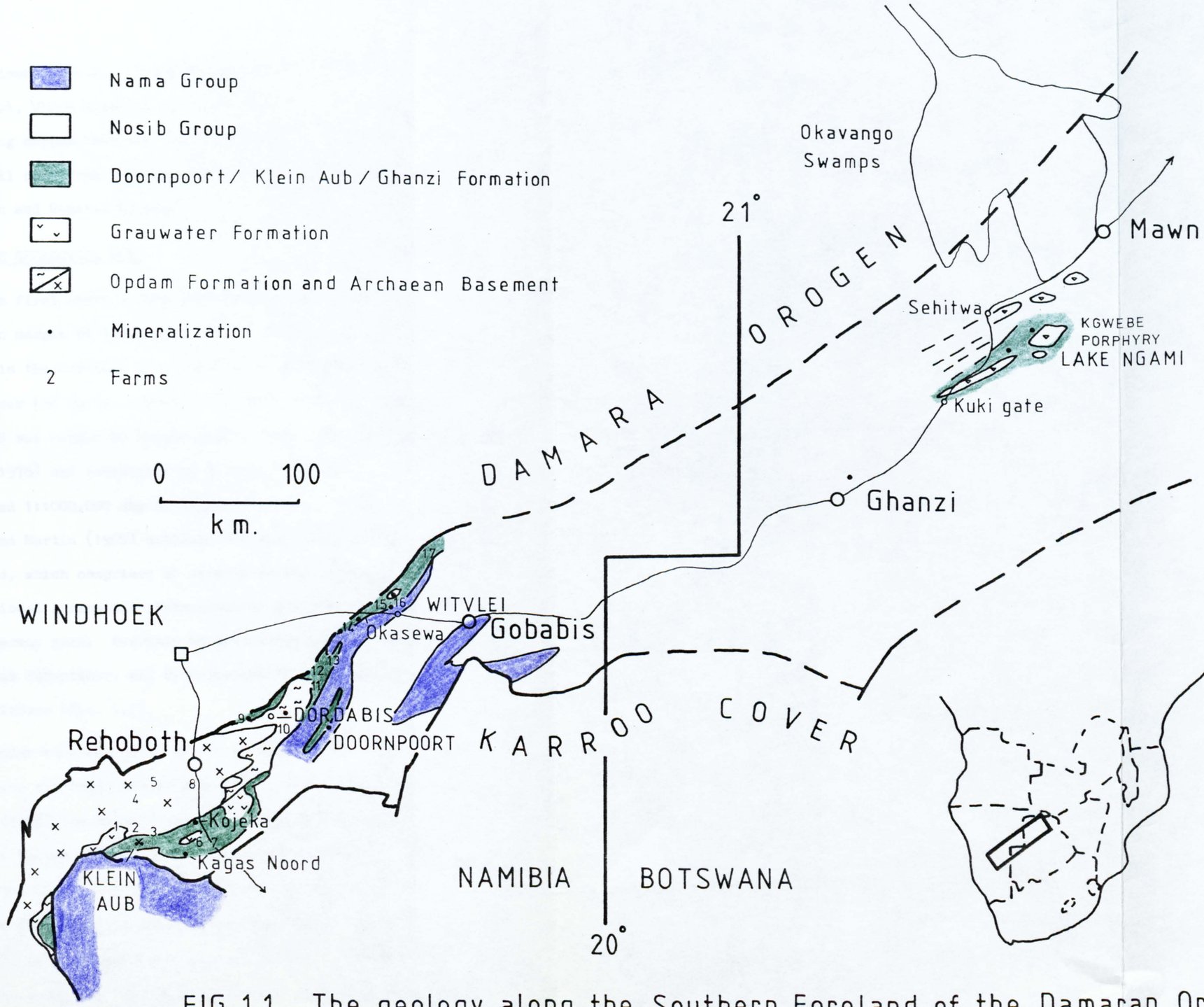
INTRODUCTION

PREFACE

Late Proterozoic sediments of the Doornpoort and Klein Aub Formations outcrop along the Southern Margin of the Damaran Orogenic Belt. They rest unconformably on a Kibaran basement (1,100 MYR), in an outcrop zone which extends from S.W. of Windhoek (Namibia) to the Botswana/Zimbabwe border (Fig. 1.1), between longitudes 16° to 24°E and latitudes 18° to 24°S, a total area of about 115,000 square kilometres. The sediments form a molassic sequence which contains stratiform copper deposits. This thesis describes the sedimentology and diagenesis of the Doornpoort and Klein Aub sediments and includes detailed studies of their copper ore deposits.

Various mining companies have undertaken extensive prospecting in the region, in the hope that these sediments may contain extensions of Zambian Copper belt mineralization. Problems of poor exposure and rapid lateral sedimentary facies changes have led to difficulties in correlation and exploration. Rock outcrop is generally obscured by a veneer of Kalahari sand which reaches a thickness of over 30 m. on the edge of the Kalahari Basin in N.W. Botswana. However, low ridges and hills bring rocks close, or onto the surface. Due to the lack of exposure much of the initial prospecting was carried out using geobotanical techniques (Cole and Le Roex, 1978). Sediment sampling and trenching are only useful in areas where rock is close to the surface. Diamond drilling is the most usable technique elsewhere.

Since exposure is generally poor in this region, specific areas were chosen for detailed studies and connected by widespread



FARMS

1. Grauwater
2. Dymoeb
3. Einpaal
4. Kobos
5. Marienhof
6. Witkop
7. Tsumis
8. Swartzmodder
9. Hamis
10. Skumok
11. Dunes
12. Bitterwater
13. Peperkorpel
14. Christiodore
15. Eskadron
16. Okatjirute West
17. Kehoro

FIG. 1.1. The geology along the Southern Foreland of the Damaran Orogenic Belt: Namibia and Botswana.

reconnaissance work. Two areas were analysed in detail: firstly, Klein Aub, where exposure is relatively good and there is a producing copper mine and secondly, Witvlei, where exposure is poor but drill core from several locations was made available by Anglo-American and General Mining.

PREVIOUS GEOLOGICAL WORK

The first works of any geological significance along the southern margin of the Damara Belt in Namibia were done by Gevers (1934) in the Dordabis area, Handley (1965) around Klein Aub and Anhaeusser and Button (1973) in the Witvlei area. The southern foreland was mapped by Schalk (1960, 1961, 1973) and Hedenberger (1960, 1978) and summarized in Schalk (1970) and on the recently published 1:1000,000 map of Namibia (1980). Schalk (1960, 1961, 1970) and Martin (1965) outlined the complex nature of the southern foreland, which comprises of several different volcano-clastic depositional cycles with intrusions of granites and granodiorites of different ages; overlain unconformably by the Doornpoort and Klein Aub Formations, and subsequently by the Nosib, Nama and Karroo Groups (Fig. 1.2).

Copper mineralization of the Doornpoort and Klein Aub Formations was first noted by Rimann (1915) and subsequently by Martin (1965) and Holtz (1967), who suggested a syngenetic origin, with the copper derived from mineralized basement. Anhaeusser and Button (1972) and Toens (1975) described cupriferous sediments from the Witvlei area, noticed the association of copper and coarse sediment, and supported a syngenetic origin. Handley (1966) outlined the geology of the Klein Aub area, skilfully avoiding any discussion of the mineralization. Toens (1975) was the first to

THE STRATIGRAPHY OF THE SOUTHERN MARGIN OF THE DAMARAN OROGENIC BELT

KLEIN AUB/KARANUS	DORDABIS	WITVLEI	LAKE NGAMI
KARROO G.	KARROO G.	KARROO G.	KARROO G.
NAMA G.	NAMA G.	NAMA G.	
BLAUBECKER F.	NOSIB G.	NOSIB G.	
NOSIB G.			UPPER GHANZI F.
KLEIN AUB F.	DOORNPOORT F.	ESKADRON F.	
DOORNPOORT F.			LOWER GHANZI F.
GRAUWATER F.	SKUMOK F.		? KGWEBE PORPHYRY ?
UBIB or NÜCKOPF F.	OPDAM F. a) PROTEA b) KUPFERBERG		
MARIENHOF F.		MARIENHOF F.	
ELIM F.			

FIG. 1.2: Stratigraphy of the southern foreland base on the work of Schalk, Hedenberger, Toens and Martin (see Appendix I).

(F = Formation : G = Group)

report copper from the Ghanzi Formation of N.W. Botswana and suggested a correlation between the Doornpoort, Klein Aub and Ghanzi Formations. This correlation was confirmed by Cole and Le Roex (1978), who outlined the importance of geobotany in exploration for copper over the whole region.

The geology of the Lake Ngami area, N.W. Botswana, was outlined by Passarge (1904), Boocock and Van Straten (1962) and mapped by Thomas (1969). The Ghanzi sediments are exposed on the flanks of the Kgwebe Porphyry, which lies in the core of a large domal fold.

Additional geological work by various mining companies has contributed much useful information, which provided a broad base for this thesis, and is contained within unpublished mining company reports. The Witvlei area was initially prospected by Anglovaal and subsequently by John Main of Anglo-American. Additional prospecting by General Mining covered the farms Okasewa, Gemsbokkvlei and Christiodore in addition to several farms North of Witvlei and South of the Black Nossob river (e.g. Okasandu, Ottawa). General Mining also own the Klein Aub Copper Mine and have drilled on the farm Kagas Noord.

Prospecting in N.W. Botswana was initially undertaken by a consortium dominated by Anglovaal, but detailed studies by United States Steel (Essex Minerals) under Doug Greig, led to the discovery of mineralization in the Lake Ngami area.

Exploration activity has not been confined to the Doornpoort and Klein Aub sediments themselves, several companies are at present prospecting in pre-Doornpoort, basement rocks.

AIMS OF THIS THESIS

The prime aim of this work was to determine the genesis of deposits of the Red Bed/stratiform copper association in the Doornpoort and Klein Aub Formations, in the hope of increasing the understanding of similar deposits throughout the world. Since early workers suggested that the ores are of syngenetic origin and that there is an association between mineralization and coarse sediment, a sedimentological approach was adopted. The initial aims were to describe the sedimentology of these sediments, paying particular attention to mineralized areas, and to study the textures of the ore minerals. In order to do this it was necessary to understand the effects of deformation and metamorphism and separate them from the diagenetic and depositional textures and structures.

Sedimentological and textural studies suggested that the distribution and concentration of copper was controlled by sedimentary processes and that the copper was fixed as sulphides during diagenesis. In addition, the results indicate that the copper, and the sediments, were derived from basement rocks.

Several questions arose from these discoveries:

1) How was the copper released from the basement?
2) In what form was it transported?
3) How was it concentrated in the sediments?
4) Under what circumstances was the copper fixed under diagenesis?

Sulphur, lead, carbon and oxygen isotopic studies were undertaken to qualify the sedimentological and textural results and to help try and answer these and other questions. Piecing all this evidence together and with the help of work by Strakov (1970, III),

Rickard (1974) and others, a model outlining the origin of these ore deposits was constructed. This thesis describes the evidence and information leading to the formulation of this model.

THESIS PLAN

Chapters I and II introduce the study area and describe the geological context of the Doornpoort and Klein Aub Formations, in terms of their stratigraphy, structure and metamorphism. A brief outline of some important aspects of the underlying basement rocks is included.

Chapters III and IV describe the sedimentology of the deposits across the whole of the southern foreland of the Damaran Orogenic Belt, with particular reference to the Witvlei and Klein Aub areas. As well as a detailed facies analysis (Chapter III), different facies associations are delineated (Chapter IV) and the problems of correlation of these sediments expounded. Palaeogeographic reconstructions and sedimentation processes are discussed.

Chapter V outlines the diagenesis of the Doornpoort and Klein Aub sediments and pays particular attention to Red Beds, which make up approximately 80% of the deposits. The diagenesis of non-red sediments is briefly described and their relationship to Red Beds discussed.

A paragenetic sequence of authigenic minerals is recognized in the aeolian sandstones of the Witvlei area. Parts of this sequence are identified in the alluvial fan sediments of Witvlei and Klein Aub, and also in the reduced playa deposits of the Witvlei fan complex.

From the evidence presented, speculations are made concerning the chemistry of interstitial solutions during the diagenesis of both red and green sediments.

Chapter VI considers the problem of ore genesis and thus contains the main conclusions of this thesis. Mineralized horizons are discussed with reference to sedimentological, textural and isotopic evidence. Sulphur, lead, carbon and oxygen isotopic evidence is presented and their implications on ore genesis discussed.

A model, explaining the origin of these ore deposits, is presented in the light of all the available evidence. The relationship between the genesis of the Doornpoort ores and that of other Red Bed/copper mineral associations throughout the world, is briefly discussed.

LOGISTICS

Fieldwork was carried out in the summers of 1978 ($2\frac{1}{2}$ months) and 1979 ($6\frac{1}{2}$ months). Anglo-American and Leeds University kindly provided landrovers, which enable the reconnaissance of vast land areas. Information was gathered by the author from bush traverses and field mapping, the logging of exploration drill core (approximately 2-3 month's work) and underground mapping and logging (about 1 month's work). Excursions were made into the field with the following geologists: J. Barnes, H. Clemmey, R. Corrans, M. Coward, K. Downing, C. Hawkesworth, H. Hedenberger, J. Main, A. Marlow, R. Miller, T. Ranson, K. Schalk, A. Tennant and R. Yaldwin.

INHERENT PROBLEMS

Poor and non-continuous rock exposure hampered the precise description of sedimentary facies and the construction of facies maps. In several areas the rock outcrop was inadequate to enable facies identification or mapping (e.g. Lake Ngami area). Although drill core sections were available in the Witvlei, Klein Aub, Kagas Noord and Lake Ngami areas, information was often insufficient to deduce specific sedimentary facies. In addition, the selective nature of mine development and exploration drilling gives a biased sedimentary picture.

Intense Damaran deformation and associated metamorphism obliterated many sedimentary and diagenetic structures, reducing the amount of useful rock.

Other Models

Concepts which relate the genesis of stratiform orebodies to processes such as basinal brines, scavenging of sedimentary piles, and volcanogenic activity are acknowledged in the text and the list of references (Annels 1974,1979 a & b; Binda 1975; Brown 1971,1974 Garlick 1972; Raybould 1978; Renfro 1974;Rose 1976. etc.). A general review of these, however, would have required more exhaustive treatment than is warranted in view of the objectives of this thesis outlined on p.6 and by the title - that is, to place the occurrence of a group of specific Cu-Ag ores within their sedimentary and diagenetic framework.

CHAPTER II

GEOLOGICAL SETTING

2.1 GEOLOGICAL CONTEXT

On the southern margin of the Damaran Orogenic Belt, the Doornpoort and Klein Aub Formation sediments form part of the northern arm of the Rehoboth Magmatic Arc (Watters, 1974, 1976): itself located on the N.W. margin of the Kalahari Craton (Clifford, 1970; Toens, 1975) (Fig. 2.1). The Magmatic Arc consists of several volcano-clastic depositional cycles and intrusive plutonic rocks of pre-Pan-African (pre-Damaran, 600 ± 200 MYR) age (Martin, 1965; Schalk, 1970), estimated at between 1,350 to 900 MYR by Watters (1976). The rocks are bounded to the North by overthrust Damaran metasediments and metavolcanics, and to the South by cover rocks of the Nosib, Nama and Karroo Groups. The geology of the Rehoboth Arc is complex and at present the lithostratigraphic correlation and nomenclature are confused (Fig. 2.2) (Appendix I). A classification was attempted by Schalk, presented on geological maps 2316D, 2317B, 2317C and 2317D, and summarized in Schalk (1970). This classification is used here and summarized in Figure 2.2. Copper mineralization is reported from plutonic and volcano-clastic rocks of each depositional cycle.

The Doornpoort and Klein Aub Formations form the last cycle of sedimentation of the Rehoboth Magmatic Arc. They lie unconformably on underlying rocks and are directly overlain by rocks of the Nosib, Nama and Karroo Groups.

2.2 AGE RELATIONS

All rocks below the basal unconformity of the Doornpoort Formation are considered as basement. Ages from this basement

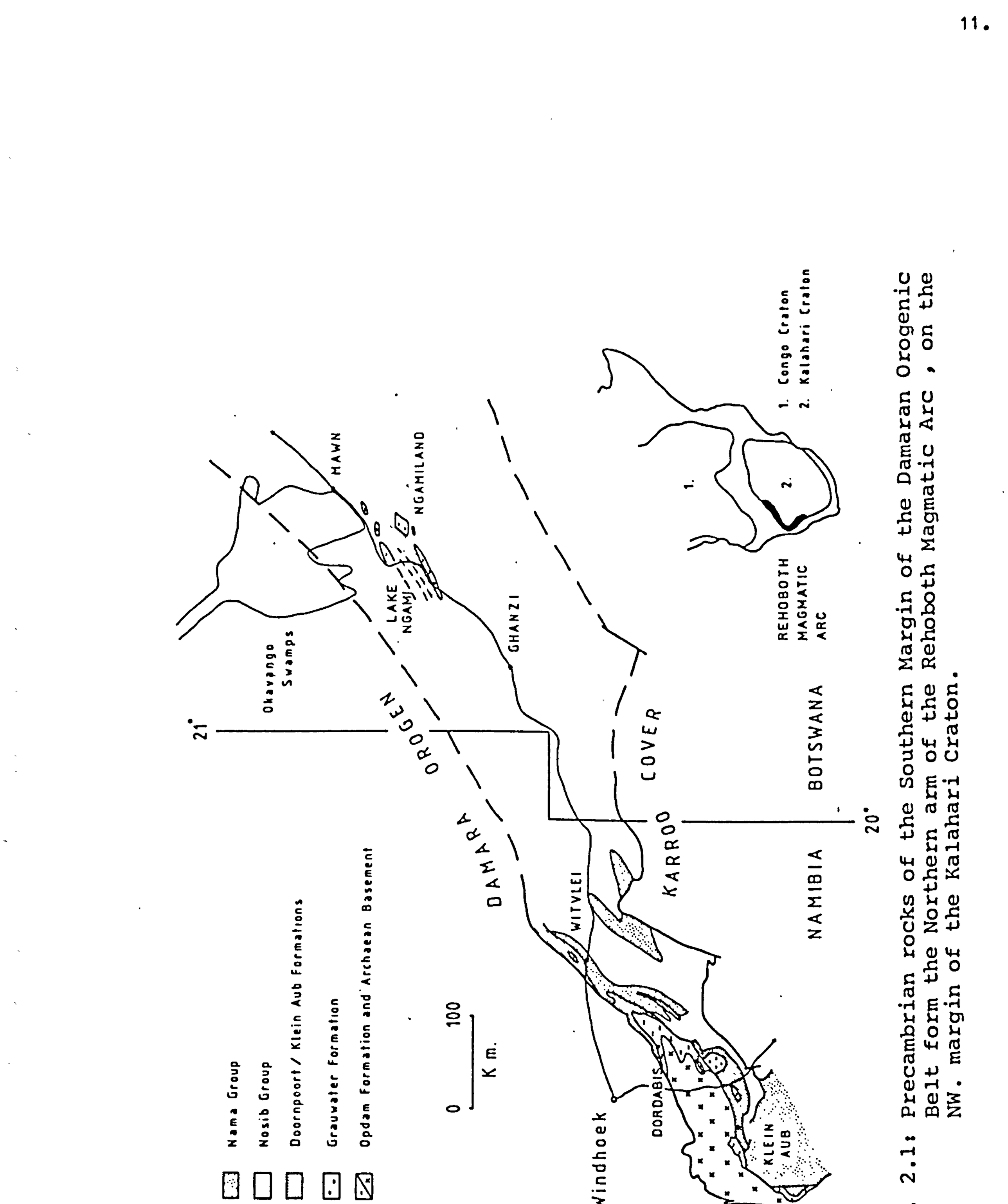


FIG. 2.1: Precambrian rocks of the Damaran Orogenic Belt form the Northern arm of the Rehoboth Magmatic Arc, on the NW. margin of the Kalahari Craton.

STRATIGRAPHY OF THE SOUTHERN MARGIN OF THE DAMARAN OROGENIC BELT (GENERALIZED)

		MYR		
PAN-AFRICAN OROGENY (600 ± 200 MYR)	NAMA GROUP		(unconformity)	COVER
		c530		
		c750		
	DAMARAN GROUP		BLAUBECKER FORMATION	
			NOSIB FORMATION	
		c850		
	DORDABIS (NUWEDAM) GROUP		KLEIN AUB FORMATION	
			DOORNPOORT FORMATION	
KIBARAN OROGENY (1100 ± 200 MYR)		c1000		REHOBOTH MAGMATIC ARC
			GRAUWATER FORMATION	
			UBIB OR NÜCKOPF FORMATION	
	REHOBOTH GROUP	?1600	BILLSTEIN FORMATION	BASEMENT
			DORDABIS FORMATION	
			GAUB VALLEY FORMATION	
			MARIENHOF FORMATION	
EBURNIAN OROGENY (2000 ± 200 MYR)		c1900	ELIM FORMATION	
			CHAMASIS FORMATION	

Fig. 2.2: A generalized stratigraphic sequence for the Southern Margin of the Damaran Orogenic Belt taken from Schalk (1970) and the South African Committee for Stratigraphy (Geological Survey, 1979). See Appendix I for further details.

range between 1,900 to 900 MYR.

The oldest basement age of 1,900 MYR was recorded using lead isotopes from a galena-bearing vein complex on the farm Marienhof (N. of Klein Aub, Fig.6.1), analysed by Nicolaysen and reported in Martin (1965, p.13). This age is confirmed by lead isotopic evidence presented in this thesis (Chapter VI). Pyrite from the Kobos volcanogenic massive sulphide mine, North of Klein Aub, yielded a model lead/lead age of 1,900 ± 30 MYR (Fig. 6.28). In addition, strontium and neodymium data from the central zone of the Damaran Orogenic Belt, suggest a similar age (2,000 MYR), which is interpreted by Hawkesworth, Kramers and Miller (1981) as indicating an early crustal-forming event.

Ages of 2,000 ± 200 MYR are attributed to the Eburnian tecto-genetic event and are evident from many parts of the African Craton (Kroner, 1977). Presumably, in this region, rocks of Eburnian age formed basement rocks, onto which the volcano-clastic sequences of the Rehoboth Magmatic Arc were deposited.

Additional dates from the granitic and volcanic rocks of the basement indicate a series of events between 1,100 MYR and 900 MYR, corresponding to the deposition of the volcano-clastic deposits and the intrusion of plutonic rocks of the Rehoboth Magmatic Arc. Schalk (1970) reports an age of 1,132 ± 75 MYR (analysis: Van Niekerk, U/Pb on zircon) from granitic rocks on the farm Kunineib 378, and Hugo and Schalk (1971-2) ages from acid lavas and granites from basement, North of Klein Aub (Fig. 2.3), all falling between 1,100 and 900 MYR's. Harding and Snelling (1972) dated the Kgwebe Porphyry of the Lake Ngami area, using whole rock Rb/Sr and produced an age of 906 ± 36 MYR's. This represents the youngest age

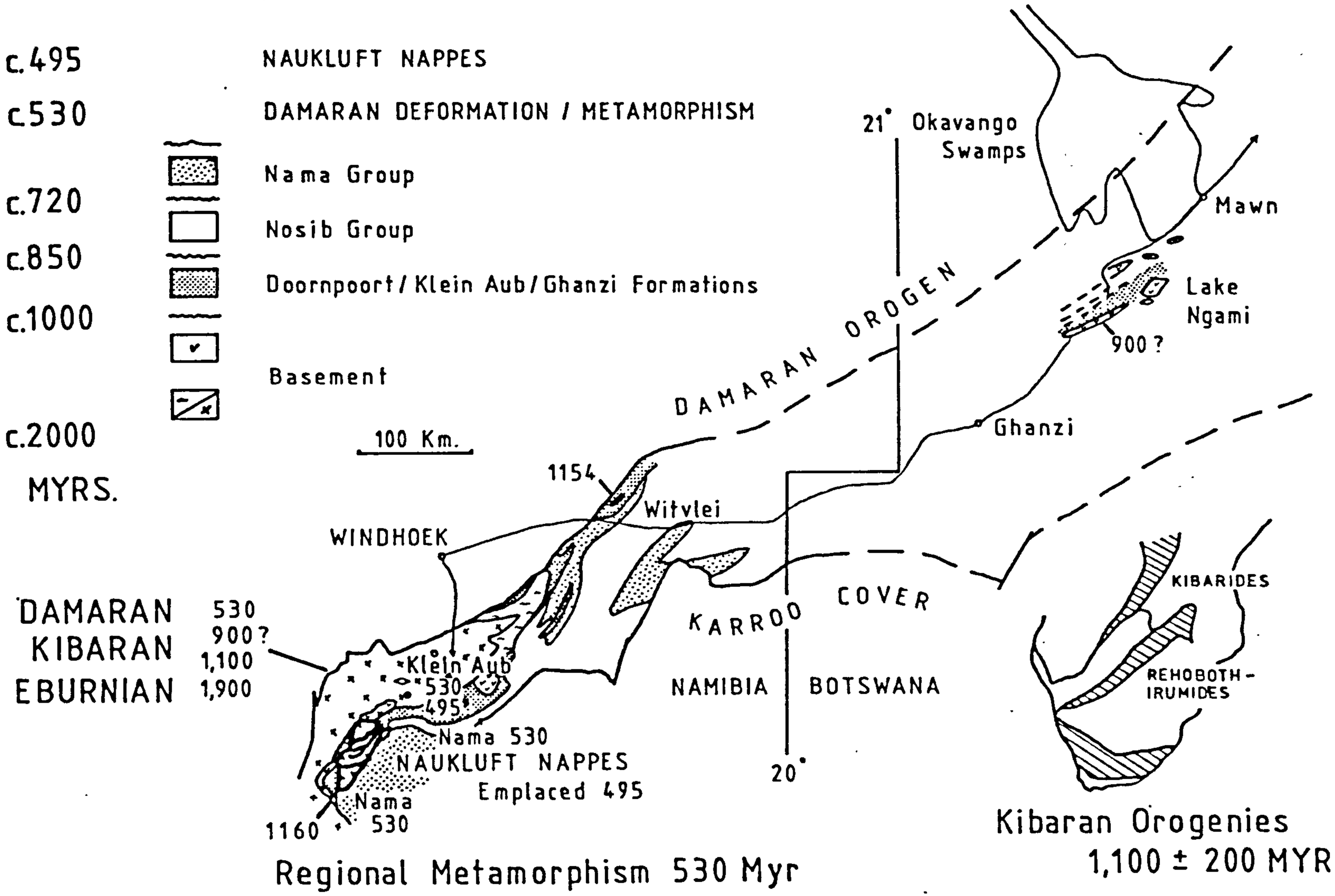


FIG. 2.3: Ages and events along the Southern Margin of the Damaran Orogenic Belt - which froms part of the REHOBOTH-IRUMIDE BELT (Kibaran 1,100 ± 200 Myr).

obtained from Doornpoort basement rocks.

Many of these ages from the southern margin are provisional dates, calculated from one sample of zircon, determined by uranium/lead and lead/lead ratios. They must therefore be considered of limited use as precise age indicators.

Ahrendt et al (1978) present an age of about 1,160 MYR's, using K/Ar methods on muscovite from just South of the Nauklupf Mountains. Considering this age, along with those reported by Schalk (1970), Hugo and Schalk (1971-2) and Harding and Snelling (1972), it appears that basement rocks of this area were affected by the Kibaran Orogenic Event (1,100 ± 200 MYR) (see Cahen, 1970; Kroner, 1977). De Villiers and Simpson (1974) correlated these ages with dates and structures from southern Zambia and suggested the existence of a laterally continuous belt - the Rehoboth-Irumide belt (1,100 ± 200 MYR's) (Fig. 2.3).

The Doornpoort sediments lie unconformably on this Eburnian and Kibaran basement. As yet, no direct ages have been obtained from the Doornpoort or Klein Aub Formations. However, they are overlain by sediments of the Nosib Group which, according to Kroner (pers. comm. in Hawkesworth et al, 1981), were deposited prior to the Matchless Amphibolite (dated at 765 ± 35 MYR using the Rb/Sr Whole Rock method)which is contained within the Nosib sediments. Nosib sedimentation is generally considered to have been between 850 and 750 MYR (Hawkesworth et al, 1981). The Nosib Group was subsequently overlain by the Nama Group, which was deposited between 719 ± 28 MYR and 530 MYR (see Germs, 1972; Ahrendt et al, 1978).

Sediments of the Doornpoort and Klein Aub Formations were probably deposited between 1,000 and 850 MYR, during the later stages of the Kibaran orogeny (Summary, Fig. 2.3).

2.3 STRUCTURE AND METAMORPHISM

All pre-Karroo Group rocks on the southern margin have been affected by late stage Damaran deformation and metamorphism. The geology is dominated by N.E. trending anticlines, synclines and domal folds, and N.E. striking thrusts and faults (Fig. 2.4). Two phases of deformation are evident.

At Lake Ngami, intense isoclinal folding, pressure solution and cleavage are associated with tight dome and basin folds. Sediments of the Ghanzi Formation (Lake Ngami Member - this thesis) outcrop on the flanks of the Kgwebe Porphyry, which is exposed in the core of a large domal fold. Due to the intensity of deformation, many of the primary sedimentary and diagenetic textures of these rocks have been obliterated. It is because of this, and the appalling rock exposure in the area, that no detailed sedimentological and diagenetic study was undertaken.

In the Witvlei area basement rocks of the Marienhof Formation are exposed in the core of a domal fold (Fig. 4.6). Although the rocks of this area are clearly deformed, the folding is more open and the effects of cleavage and pressure solution entirely localized to fold hinges. Sedimentary and diagenetic features of these sediments are therefore often preserved.

The Dordabis area illustrates f1 folds being refolded by later f2 phases forming broad, open structures. Further complications arise from frequent faulting and thrusting (Fig. 4.10).

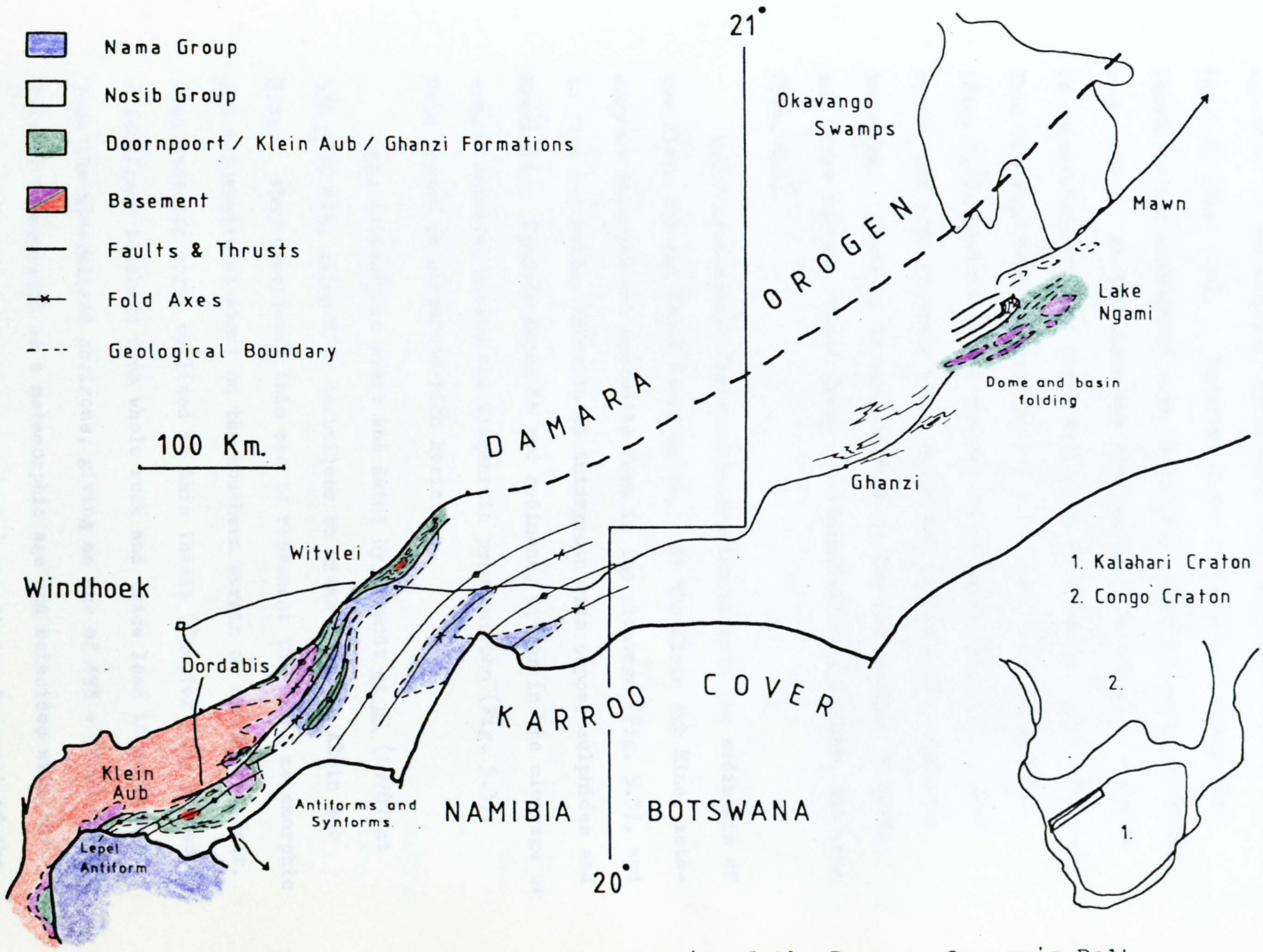


FIG. 2.4: A structural map of the Southern Margin of the Damaran Orogenic Belt.

Around Klein Aub and in the Kagas Noord and Witkop areas the structure is dominated by three major fold axes which trend towards the N.E. (Fig. 2.4). Numerous minor folds and localized dislocations are associated with these axes, best recognized in finer rock units. At the Klein Aub Mine a strong penetrative cleavage is associated with the Lepel anticline and related folds (Fig. 2.4). This cleavage destroys sedimentary structures in conglomerates (Fig. 3.4), sandstones and shales, remobilizes and reorientates copper and iron minerals (Fig. 6.13) and breaks down diagenetic textures. Cleavage is most intense in the fold hinges of minor and major folds. Domal folds are recognized in the Klein Aub area (Fig. 4.2).

Lower Greenschist facies metamorphism affects the sediments of the Klein Aub and Kagas Noord areas. At the Klein Aub Mine, metamorphic chlorite and muscovite form in the cleavage (Fig. 5.3), and in fine sediments, chlorite is intergrown with copper sulphides and haematite. Epidote forms in red sediment, either in the cleavage or around detrital grains and diagenetic pseudomorphs (Fig. 5.3). Talc occurs in carbonate-rich horizons.

This metamorphic event was dated by Ahrendt et al (1978) at 530 ± 10 MYR, using K/Ar techniques on micas from the Klein Aub Mine. They considered this age to represent the final metamorphic and deformational event on the southern margin of the Damara Belt. Lead isotopic work, outlined in this thesis (Chapter VI), produced a lead/lead isochron from whole rock and trace lead in sulphides from the mineralized horizons, giving an age of 493 + 57-60 MYR. This is interpreted as a metamorphic age and coincides with the date suggested by Ahrendt et al (1978) for the emplacement of the

Nauklupf nappes, situated 30 km. S.W. of Klein Aub. The dates presented here are summarized in Figure 2.3.

The affect of metamorphism and the intensity of deformation are variable across the southern margin, hardly surprising when considering its strike length. This has enabled diagenetic and sedimentary studies on relatively undeformed and unmetamorphosed sediments (from Witvlei) to be compared with more deformed, metamorphosed sediments of Klein Aub. More detailed affects of deformation and metamorphism on red and non-red sediments are presented in Chapters V and VI.

2.4 DOORNPOORT, KLEIN AUB AND GHANZI FORMATIONS

Sediments and the small volume of volcanics of the Doornpoort, Klein Aub and Ghanzi Formations extend from a few kilometres West of Klein Aub up into the Lake Ngami area of N.W. Botswana. They rest unconformably on basement rocks. Exposure of the unconformity is rare but was observed on the farm Diergaards Aub 454, 8 km., East of Kojeka (Fig. 2.5). Relief on the unconformity is generally low, less than 100 m., and was first described by Handley (1966) just North of Klein Aub. Sediment-type directly above the unconformity is variable, from coarse conglomeratic facies (Fig. 2.5) to coarse-grained Red Bed sandstones with occasional grit bands. Coarse conglomerates usually occur in areas of basement relief and may represent scree accumulations or small valley fills.

Volcanics and Intrusives

Volcanic and intrusive igneous rocks occur towards the base of the sedimentary pile in the Kagas Noord, Witkop, Dordabis and Lake Ngami areas. On the farms Skumok and Autabib Ost, S.E. of Dordabis,

FIG. 2.5: A photograph illustrating the basal unconformity (-) of the Doornpoort Formation - from the farm Diergaards Aub. 454. (Fig. 4.2).

an intrusive laccolith of micro-granodiorite outcrops (see Maps 2217D, 2317B and Schalk, 1973) (Fig. 4.10). This is the only intrusive rock recognized. Amygdaloidal felsic and intermediate lavas occur on farms Mountain View and Bitterwater, N.E. of Dordabis, and also on the farm Doornpoort, itself, where the lavas contain copper sulphide and oxide amygdale fills. Olivine basalts and intermediate flows outcrop near Witkop and also in the Lake Ngami area.

It is important to emphasise that in contrast to the basement volcano-clastic cycles of the Rehoboth Magmatic Arc, the volume of igneous rocks in the Doornpoort, Klein Aub and Ghanzi Formations is very low. The total proportion of volcanic to sedimentary rocks is less than 1%. In addition, it must be stressed that volcanic rocks occur only in the basal parts of the sedimentary successions, contained within alluvial fan sediments. No igneous material was associated with any occurrences of stratiform copper observed by the author.

An attempt was made to classify these volcanic rocks in terms of their geological significance, i.e. Island arc, Continental or Calc-Alkaline, using the method proposed by Pearce and Cann (1973). This method enables the classification of volcanic igneous rocks, despite the effects of metamorphism. However, due to the lack of samples, and their highly weathered nature, the results obtained were meaningless (Appendix II). The volcanics probably suffered Late Proterozoic as well as present-day weathering.

Sediments

The sediments consist of a series of alluvial fan deposits which are interdigitated and intercalated with lacustrine, playa,

mud flat and aeolian facies. They were derived from uplift of the Kibaran basement to the North and deposited in a slowly-subsiding southern basin. At Klein Aub the sedimentary succession is 3 km. thick and laterally extensive (Fig. 4.2). in contrast to Witvlei, where the sediment pile is 11 km. thick and typified by rapid lateral facies changes (Fig. 4.7). Correlation of the sediments from the Klein Aub area to Witvlei and Lake Ngami was first proposed by Schalk (1970) on the basis of lithology, mineralization and the relative lack of metamorphism. He separated the Klein Aub succession into the Doornpoort and Klein Aub Formations on the evidence of a dividing unconformity. On close inspection, this unconformity separates red alluvial fan deposits from red and non-red lacustrine sediments and is therefore probably not a time-significant break. It is therefore proposed to abolish the term Klein Aub Formation and classify these lacustrine sediments as part of the Doornpoort Formation. Since different areas along the southern foreland of the Damara Belt contain differing sedimentary facies and sediment morphologies, the terms Klein Aub Member, Dordabis Member, Eskadron Member (Witvlei) and Lake Ngami Member are proposed (Fig. 2.6). This new classification will apply from this point on in the text.

2.5 STRATIFORM COPPER MINERALIZATION

Stratiform copper mineralization occurs within reduced sediments of the Doornpoort Formation, which are surrounded by alluvial fan Red Bed deposits. The main ore deposits are found in the Klein Aub, Witvlei, Okasewa and Lake Ngami areas, with less-important horizons at Kagas Noord and Kojeka. The ores occur as disseminated sulphides with an average grade of between 1.5 to 2.0% copper (Toens, 1975), containing minor amounts of silver.

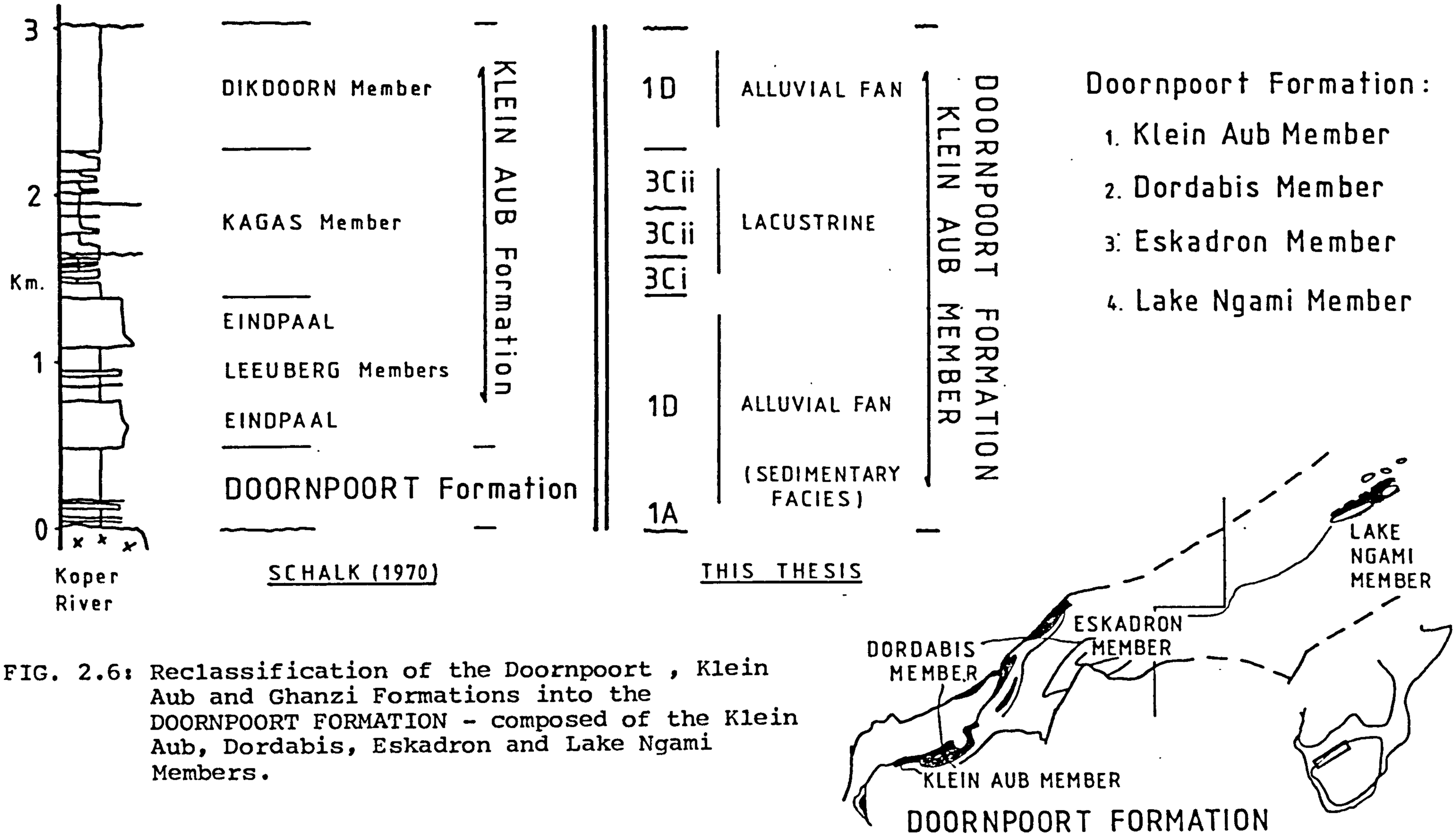


FIG. 2.6: Reclassification of the Doornpoort , Klein Aub and Ghanzi Formations into the DOORNPOORT FORMATION - composed of the Klein Aub, Dordabis, Eskadron and Lake Ngami Members.

Following the study of all mineralized deposits, the Klein Aub and Witvlei areas were chosen for detailed research - partly because marginal lacustrine sediments host the copper at Klein Aub, whereas playa sediments are mineralized at Witvlei, and partly since they are the best exposed and prospected areas.

2.6 BASEMENT ROCKS - MINERALIZATION

Several different types of mineralization of various ages occur in pre-Doornpoort rocks. A brief outline of these mineralized rocks and various aspects of the basement are discussed here and referred to in Chapter VI.

Two ore deposits of Eburnian age (1,900 MYR) occur in the basement North of Klein Aub: the Rehoboth Inlier (Martin, 1965), on the farms Kobos and Marienhof (Fig. 2.3); Stratabound, massive sulphide deposits on the farm Kobos contain copper, lead and zinc and are probably of volcanogenic origin. This origin is supported by lead isotopic work presented in this thesis, since the sample Kobos plots on the two-stage growth curve of Stacey and Kramers (1975), along with other stratabound volcanogenic ore deposits from all over the world (see Stanton, 1972, p.195, Doe, 1970). Galena-bearing quartz veins on the farm Marienhof give an age of 1,900 MYR (Nicolaysen in Martin, 1975). Lead isotopic studies from this work yield a more radiogenic result than that of Nicolaysen, since the sample galena plots above the growth curve (Fig. 6.28). However, sulphur isotopic evidence from both deposits, suggests that they are of primary magmatic origin (Chapter VI).

Stratiform copper deposits occur within sheared metasediments, and are common, attaining economic significance on the farm Swartzmodder, North of Kojeka (Fig. 2.3). Sulphur isotopes from

this deposit and a similar copper showing on the farm Dymoeb (North of Klein Aub), indicate a juvenile source. Copper occurs in sandstones on the farm Dordabis, forming part of a mineralized volcanoclastic sequence.

Copper-bearing lavas and granodioritic rocks are common around Dordabis and occur in the Witvlei inlier. Granodioritic rocks on the farm Eskadron (Witvlei) are extensively epidotized and sericitized and contain copper sulphides (bornite), chrysocolla, malachite and azurite. Alteration of this granodiorite is variable and may represent the metamorphosed equivalents of copper porphyry alteration (argillitic and propylitic) similar to that described from El Salvador, Chile (Gustafson and Hunt, 1975). In this Chilian analogue, copper is initially contained as sulphides and released by weathering processes to form chrysocolla, malachite and azurite. Additional evidence for the weathering of these basement rocks is that they contain feldspars which are often extensively sericitized and epidotized - perhaps metamorphic equivalents of kaolinized feldspars formed during semi-arid/arid weathering in the late Proterozoic.

CHAPTER III

SEDIMENTOLOGY : FACIES ANALYSIS

In this chapter sediments of the Doornpoort Formation are divided into facies, depicting specific sedimentary environments of deposition. Three main facies are recognised and further divided into subfacies. Chapter IV goes on to describe the various facies associations and the factors effecting the evolution of the Doornpoort sedimentary successions.

3.1 FACIES 1

Sediments of facies 1 are predominantly coarse grained, often conglomeratic, poorly sorted and usually red. They form approximately 80% of the exposed Doornpoort sediments and may be divided into five subfacies.

Facies 1A

These sediments are red, poorly sorted, parallel laminated, conglomerates and grits which form discontinuous deposits, found only in the Klein Aub area, above the basal Doornpoort Unconformity. The clasts are highly angular (Fig. 3.1), usually less than 100 mm. in diameter, consisting of locally-derived basement rock types. Angular rock fragments (feldspar and quartz grains) and large clasts surround and suggest the development of an exfoliation breccia. This indicates long periods of time during which clasts were mechanically broken down by weathering processes.

The sediments were probably formed on a pediment surface by in situ breakdown of local rock fragments, which were periodically transported by sheet-wash run-off.

FIG. 3.1: Parallel laminated conglomerates of Facies 1A illustrating the INSITU brecciation and exfoliation of contained clasts.

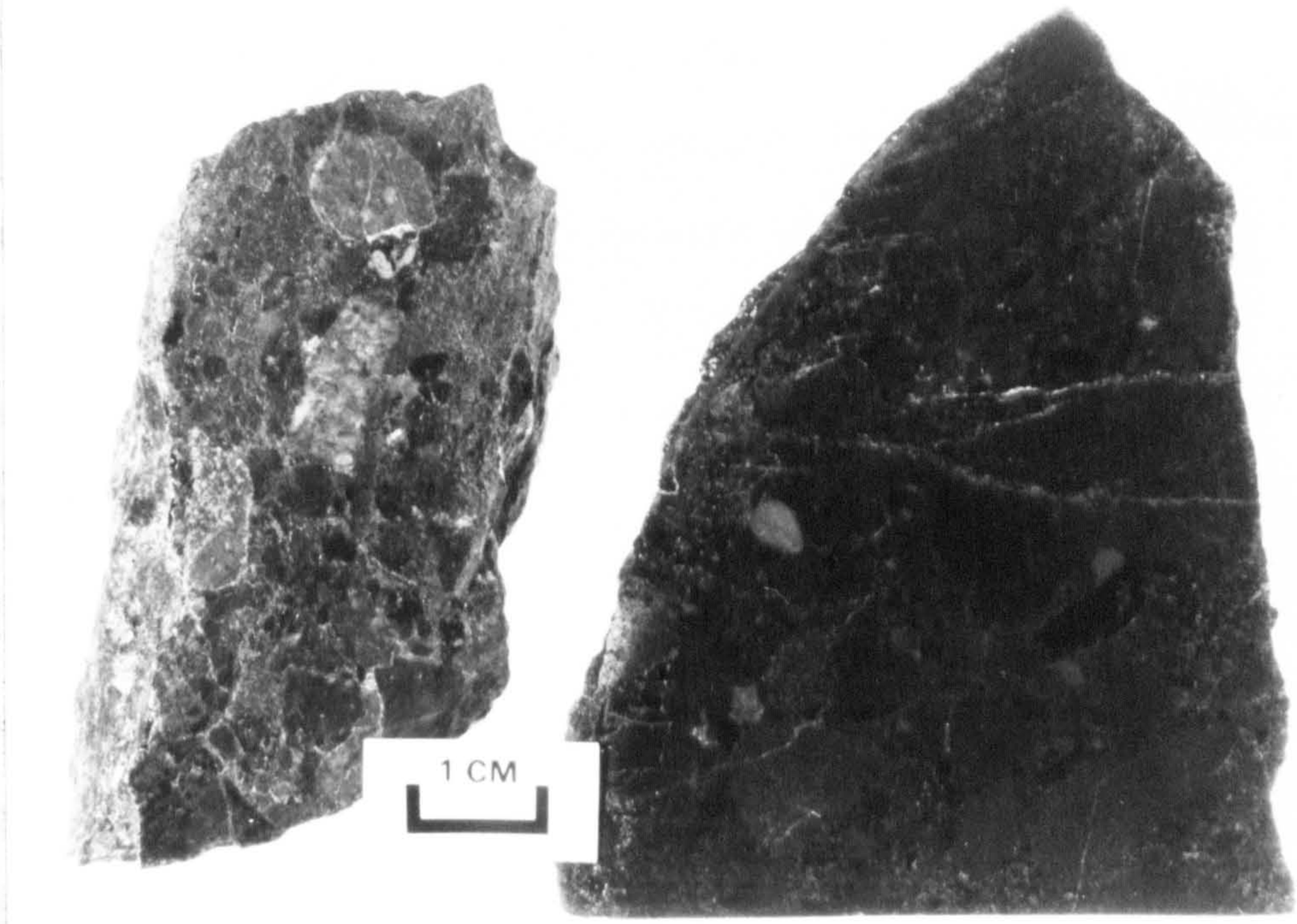


FIG. 3.2: Angular, poorly sorted conglomerates of Facies 1C(i) with basement clasts only, in contrast to the more rounded, better sorted conglomerates of Facies 1C(ii),with sedimentary and basement clasts.

Facies 1B

Facies 1B consists of large basement and sedimentary clasts (< 300 mm. diameter), supported in a red mudstone matrix, recognised only from drill core sections on the farm Okasewa. The proportion of matrix and the angularity of the clasts is variable, with individual units up to an apparent thickness of 20 m.

Sediments of facies 1B are interpreted as mudflow and debris flow deposits, which are typically unsorted and associated with alluvial fan sediments (Bull, 1964; Bluck, 1967; Steel, 1974; Collinson, 1978). They are deposited in laterally-persistent sheets with flat bases, from high viscosity flows. Experimental evidence suggests that debris and mudflows are produced by sudden rainfall, which flushes sediments from the source and fan-head region of alluvial fans (Weaver, 1976; Schumm, 1977). Their occurrence indicates periodic sediment discharge and rainfall - common features in arid to semi-arid climates (Bull, 1964; Lustig, 1965; Schumm, 1977). Many such deposits have been described from modern desert areas (Bull, 1964; Denney, 1965; Blissenback, 1954) and according to Schumm (1977) they typify dry alluvial fan sedimentation.

Facies 1C

These sediments consist of poorly-sorted, red conglomerates and sandstones which are intercalated with localized shale horizons of facies 3A, outcropping in the Okasewa, Witvlei and Kehoro region. Two divisions are made on the basis of clast types and the degree of sorting.

1C(i): Conglomerates of the 1st cycle are very poorly-sorted, have angular clasts (Fig. 3.2a) which are less than 250 mm. in

diameter and are composed entirely of basement rock types. They may be matrix- or clast-supported, the matrix consisting of smaller clasts and/or a red to purple sandstone. Conglomeratic horizons below shale lenses are often cemented by calcite, which may also brecciate clasts.

The intercalated sandstones are bedded with trough cross-stratification and display occasional small scale ripple cross-stratification. Red mudstone flakes and balls (20-40 mm. diameter) are common lithoclasts in these sandstones and are interpreted as rip-up clasts from adjacent desiccated lacustrine sediments (Glennie, 1972).

1C(ii): Conglomerates of the 2nd cycle are more mature - with better sorting and rounder clasts - than facies 1C(i) (Fig. 3.2b) and are further characterized by the appearance of sedimentary clasts.

These deposits are more extensive than those of facies 1C(i) and better exposed. Thick conglomeratic zones pass laterally into intercalated sheets of sandstone and conglomerates and finally into red sandstones. Conglomerate units have erosive bases and often fine upwards into trough cross-stratified sandstones which may also contain small scale current ripple stratification (Fig. 3.3). Clasts are dominantly supported in a matrix of red sandstone and finer rock fragments are generally less than 350 mm. in diameter. Relative percentages of clast types vary from 0 to 100% basement rocks. Sedimentary clasts are composed of stratified, lithified red sandstones, usually of finer grain size than the matrix surround.

Interpretation: The poor degree of sorting in both sediment cycles, the lenticular depositional geometry and possible reverse grading in the conglomerates (Fig. 3.3) suggest deposition from

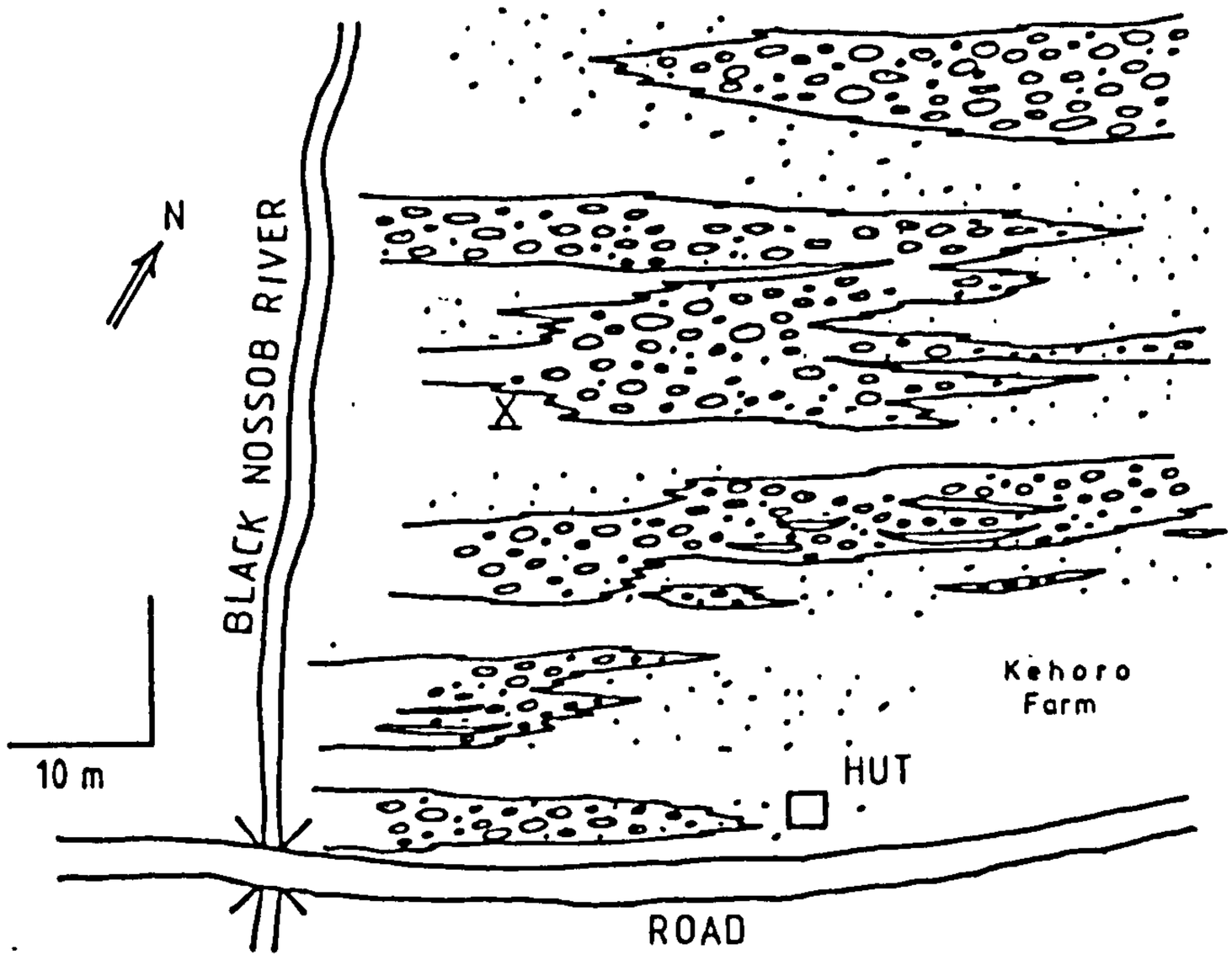
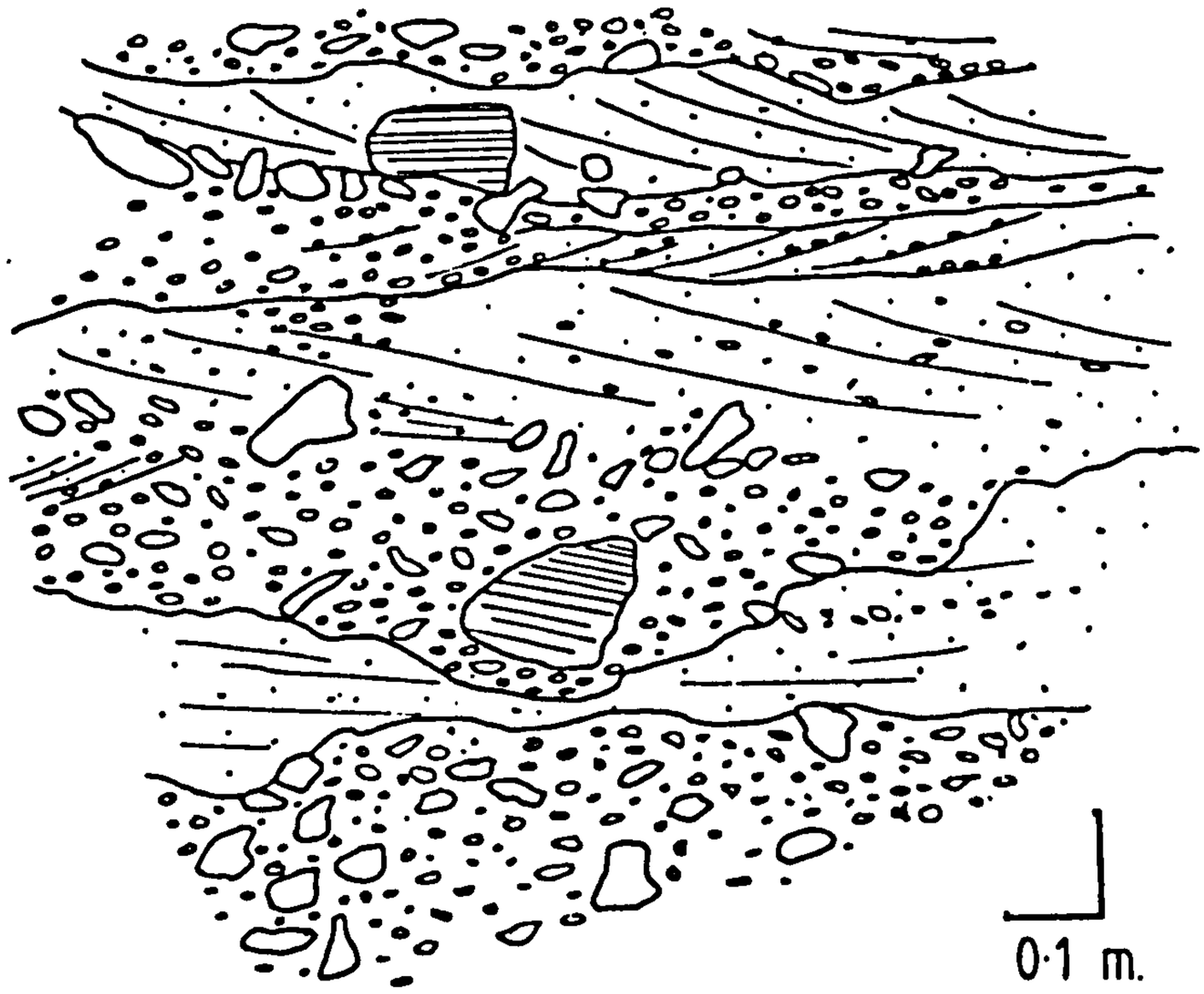


FIG. 3.3; a) Laterally inpersistant sheets and wedges of conglomerates and sandstones - Facies 1C (ii), farm Kehoro, Black Nossob Fan, Eskadron member.

X.



b) INSET: (X) Detail of conglomerates - note the erosive bases of each conglomeratic unit , the separation of conglomerates and sandstones and the inverse grading.

high to medium viscosity flows. A degree of turbulence in these flows, however, produced the separation of fines and partial separation of conglomerates and sandstones. The deposits are similar to the type A and B conglomerates of Bluck (1967) and interpreted to be of sheetflood and streamflood origin. Sediments of facies 1C(i) are more proximal than those of facies 1C(ii), since they are not as well sorted and contain more angular clasts. The presence of lithified sedimentary clasts in facies 1C(ii) indicates either interformational reworking or the erosion of an earlier sedimentary cycle.

The fan-shaped nature of facies 1B and 1C deposits (Fig. 4.7) and the close association of coarse and fine sediment, clearly suggests that deposition took place on alluvial fans (see Bull, 1964; Denney, 1965; Bluck, 1967).

Facies 1D

Facies 1D consists of poorly-sorted, highly-stratified conglomerates and sandstones differing from 1C in that they form laterally extensive deposits (over 30 km.) with a marked absence of shale. They outcrop in the Klein Aub, Karanus and Witkop areas.

Conglomerate bands are up to 1 km. thick, consisting of numerous laterally extensive lenses, of the order of 5-6 m. thick and 20-30 m. wide, recognized by a variation in clast size, from large in the centre to finer clasts at the margins. Towards the base of the succession at Klein Aub, these lenses can easily be identified in thin persistant (over 1 km.) bands (Figs. 4.3, 4.4). In some areas, clasts of similar sizes are common giving a bimodal grain-size distribution (clasts and matrix), but elsewhere large isolate clasts (Fig. 3.4) and areas of variable clast size occur. When unaffected

by the strong penetrative cleavage, conglomerates are highly stratified; trough cross-stratification is the dominant form. Clasts vary in size up to 0.5 m., are subrounded to rounded and predominantly basement-derived. They are supported in a matrix of smaller clasts and yellow/brown/red medium to coarse grained sandstone.

Highly stratified yellow/brown sandstones are intercalated with conglomerate bands, forming irregular boundaries on a small scale (Fig. 3.6, B and C) but smooth contacts on a larger scale (Fig. 4.3). Near the base of the succession at Klein Aub, trough cross-bedding develops in relatively small wedging sets (Fig. 3.6A), whereas towards the top of the conglomeratic/sandstone member (Fig. 4.3), very large wedging sets formed (Fig. 3.5; over 20 m. across).

Interpretation: Sediments of this facies are more mature than facies 1C, with rounded clasts, the absence of shale horizons and evidence of reworking. Trough cross-bedded conglomerates and sandstones suggest deposition on a series of bars and dunes (Coleman, 1969; Collinson, 1978), indicating cut and fill of migrating channel zones. Planar cross-stratified sandstones (Fig. 3.6D) are interpreted as transverse sediment bar deposits; planar sets (shown in Fig. 3.6D) have been eroded and filled with finer sediment - probably during low stage. The occurrence of clay rip-up clasts suggests that fine sediments were deposited, but removed by subsequent erosion and reworking.

Sediment reworking by migration of channel zones points to deposition from a turbulent flow. The occurrence of large clasts and the lack of obvious channel lag deposits suggest a degree of

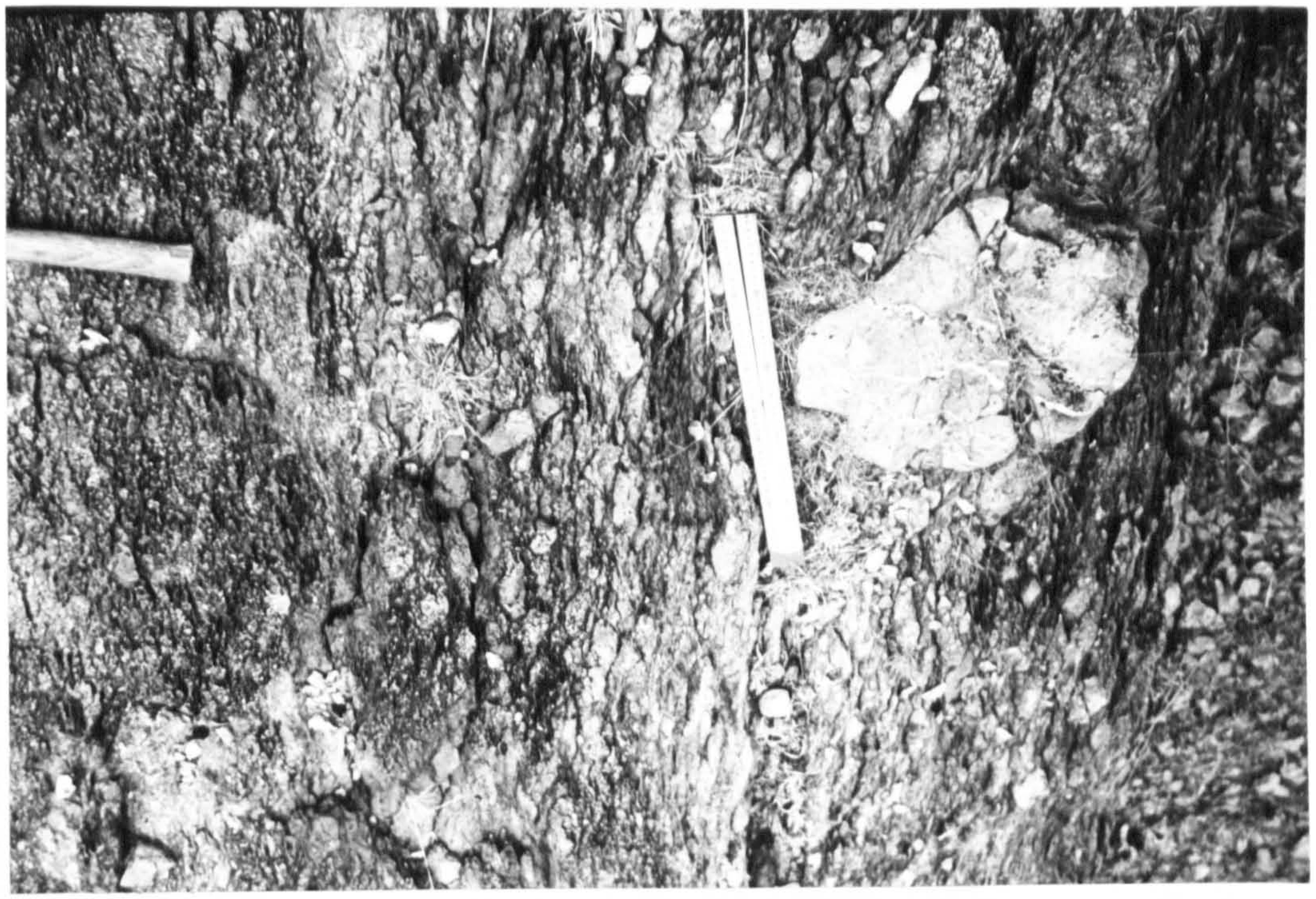


FIG.3.4: Large isolated clast in conglomerates of Facies 1D (0.5m) - note the strong cleavage in the surrounding finer conglomerates. (Koper River, Klein Aub).

FIG. 3.5: Large scale trough cross-stratification in the sandstones of Facies 1D - note the strong cleavage (top left-bottom right). (Koper River, Klein Aub, ruc sac for scale).

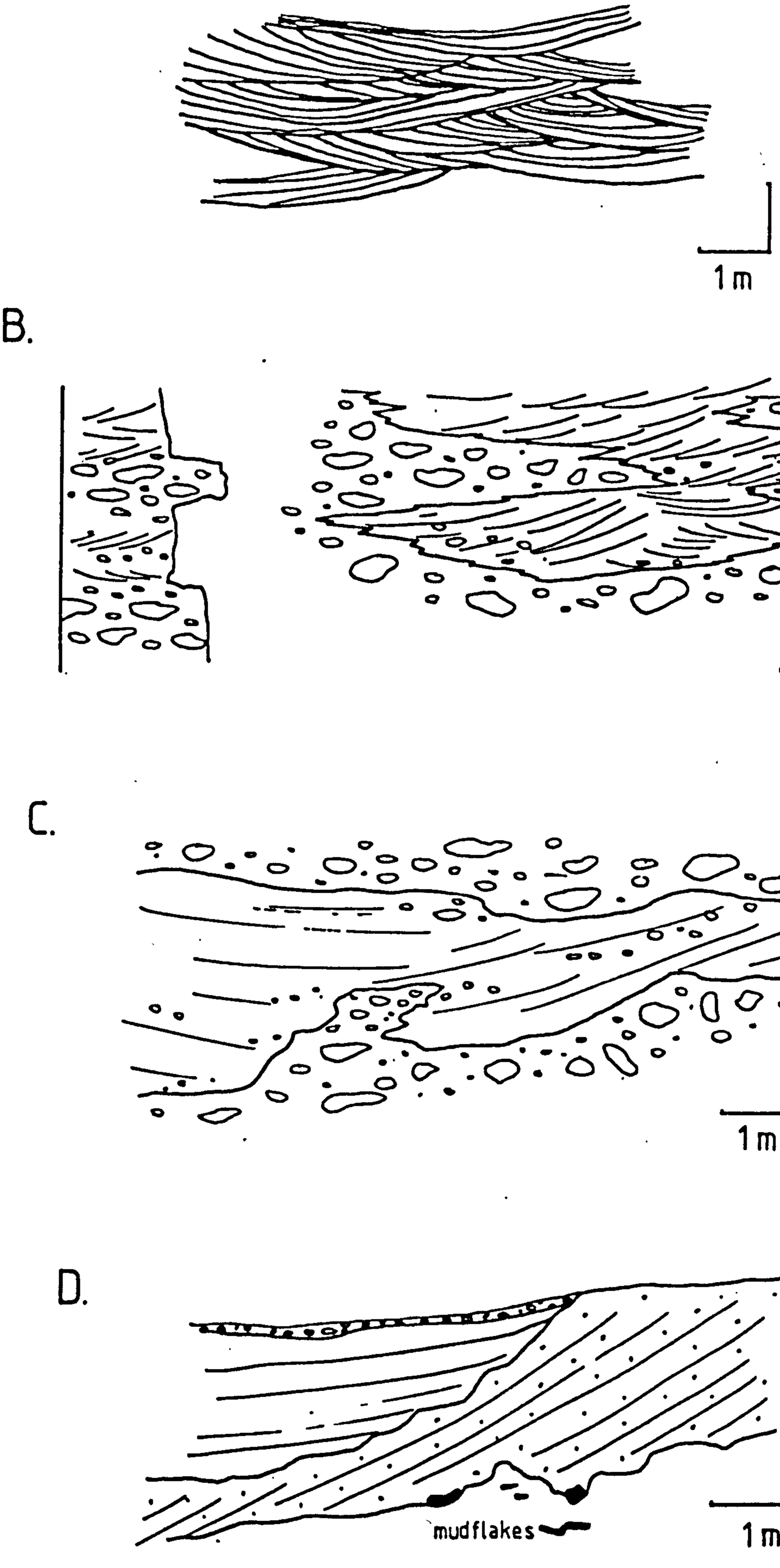


FIG. 3.6: Conglomerate - sandstone relations, Facies 1D. :A. Trough cross-bedded sandstones, Koper River, Klein Aub. B. Interdigitated conglomerates and sandstones. C. & D. Pebble and sandbar margins. (B.C.D. Kalf River, Witkop).

viscosity to the flow. These deposits are interpreted as streamflood/braided stream sediments similar to the "Conglomerate B" deposits of Bluck (1967) and "streamflood" deposits of Steel (1974). The lateral persistence of the conglomerate and sandstone bands is consistent with broad zones of lateral migrating channels and bars, typical of streamflood and braided stream sedimentation (Collinson, 1978).

Facies 1E

Sediments of facies 1E are well sorted in comparison with other facies 1 sediments, are highly stratified (Fig. 3.8), laterally persistent and contain pebble lags. They occur predominantly in the Dordabis and Doornpoort areas on the Okasewa farm and possibly in the Lake Ngami region.

The deposits are laterally persistent, over several kilometres, consisting predominantly of red sandstone with thick conglomeratic bands (500 m. thick and approximately 4 km. wide) and smaller lenses ($\lesssim$ 30 m. across) (Fig. 4.10). Conglomeratic units are well sorted, highly-stratified, containing numerous fining upward cycles (Fig. 3.8). Clasts are well rounded, up to 100 mm. in diameter and made up exclusively of basement rock-types in the Dordabis area but may contain sedimentary clasts also on the Okasewa farm. Pebbles commonly line foresets and form lags (Fig. 3.7).

Associated red sandstones contain trough cross-stratification, which is often complex with multiple truncations and reactivation surfaces (Fig. 3.8).

Interpretation: Abundant cross-stratification, the high degree of sorting and evidence for erosion and reworking suggest that these sediments were deposited by braided streams (see Bluck, 1967; Steel,

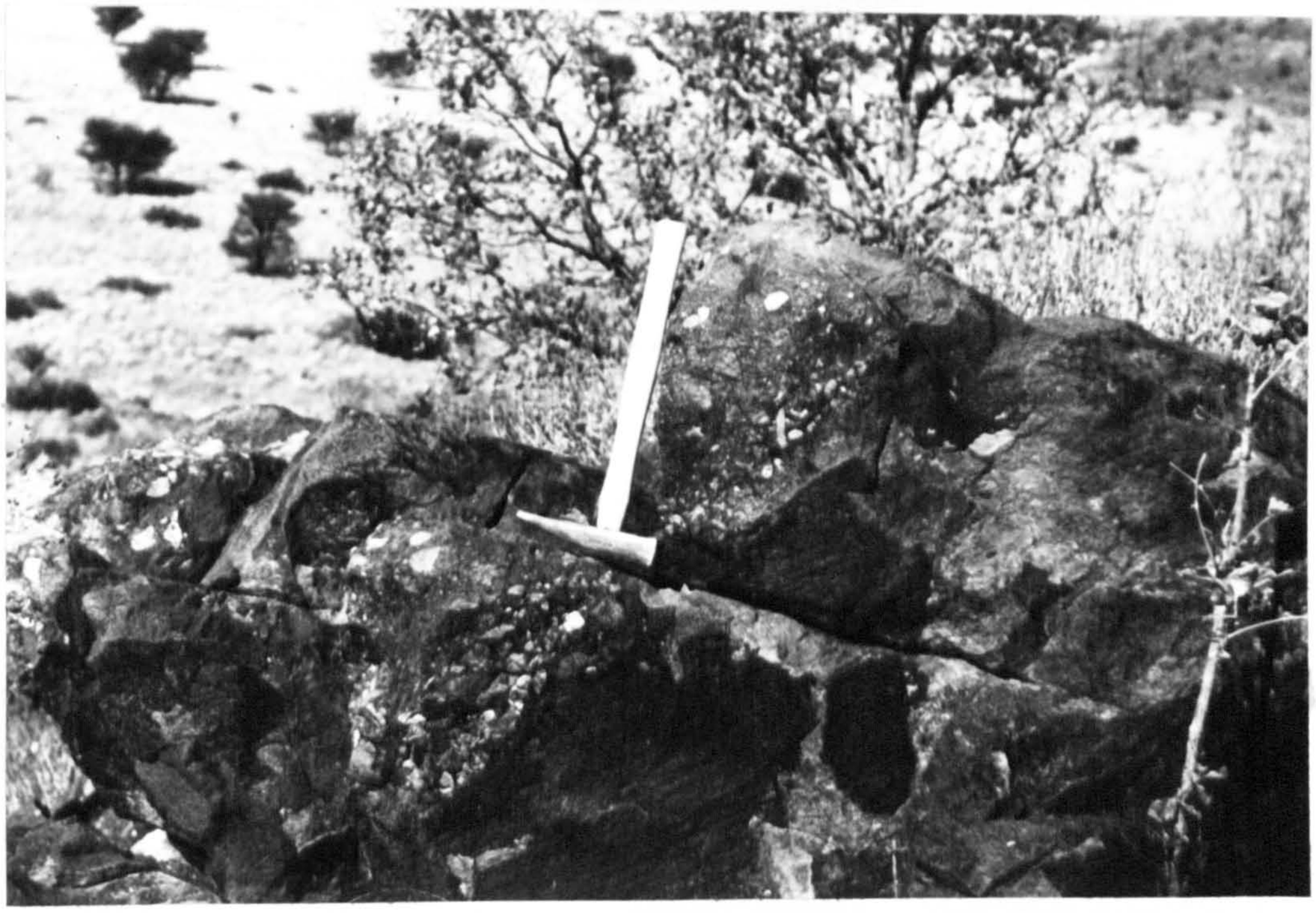


FIG. 3.7: a) Facies 1E conglomerates - pebble lag. (Dunes, Dordabis).

FIG. 3.7: b) Facies 1E conglomerates - pebbles aligned along foresets. (Dunes, Dordabis).

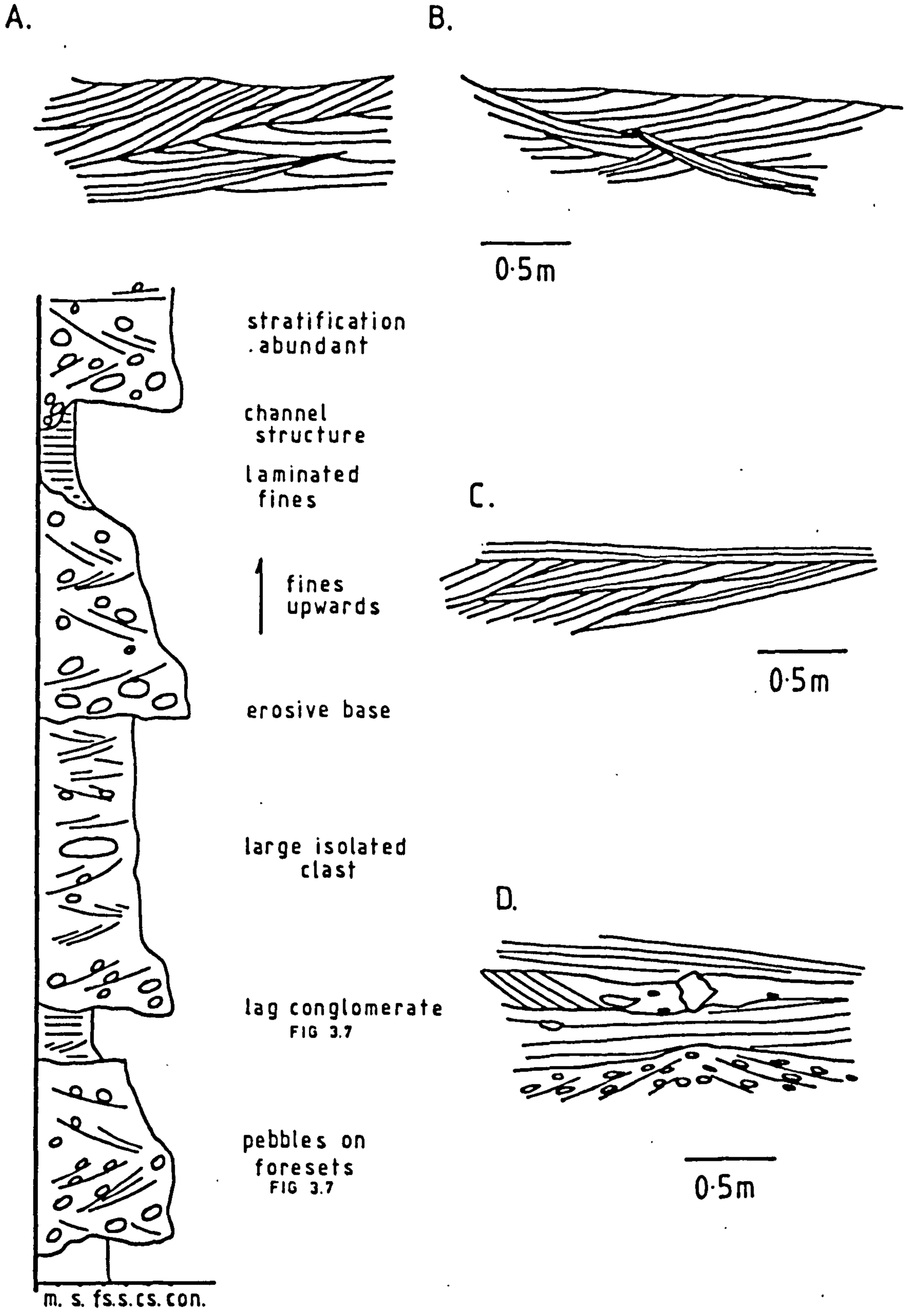


FIG. 3.8: Log of Facies 1E conglomerates and sandstones (farm Dunes), with sketches showing the complexity of sandstone cross-stratification. (A. from the farm Bergzicht, B.C.D. from Skumok, Dordabis).

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1974; Collinson, 1978). Deposition occurred on complex bar forms, probably on lingoidal and transverse dunes indicated by numerous reactivation surfaces, planar and trough cross-stratification. The flow was probably highly turbulent, effecting the separation of fines and sandstones from conglomerates.

3.2 ALLUVIAL FAN SEDIMENTATION

Alluvial fans are accumulations of sediment at the boundary between high and lowland areas (Blissenback, 1954; Bull, 1964(a); Steel, 1976). They are generally concave upwards and show a decrease in particle size downfan (Lustig, 1965; Denney, 1965; Hooke, 1967). Single fans form cone-shaped deposits, whereas several fans combine to form a bajadas (Blackwelder, 1931). Deposition takes place as a result of a change in slope (Bull, 1964), the infiltration of water into the fan surface or due to the dispersal of sediment-laden waters onto the fan surfaces from an "intersection point" or channel mouth (Hooke, 1967). Deposition takes several forms in response to high or low viscosity flows (Bluck, 1967). Debris and mudflows are deposited from high viscosity flows (Bluck, 1967) as a result of spasmodic rainfall in the hinterland and rapid sediment discharge (Schumm, 1977). Braided stream sediments are, on the other hand, deposited by continuous waterflow in migrating discharge zones, that rework earlier fan deposits. Braided stream sediments are therefore well sorted and highly-stratified, whereas debris and mudflow deposits, unsorted and poorly-stratified. Sheetflood and streamflood sediments lie between these two end-members. Schumm (1977) pointed out that laterally-extensive braided stream deposits are more common in humid climates, on wet fans, as opposed to the dominance of debris/mudflows on semi-arid to arid climatic (or dry) fans. Since successive mud

and debris flows tend to form thick, small alluvial fans (Hooke, 1967; Schumm, 1977) and braided stream sedimentation forms laterally persistent, thin fans; alluvial fans in humid climates tend to be larger than those of arid regions (Gole and Chitale, 1966; Lustig, 1965; Miall, 1970).

Bluck (1967) and Steel (1974) described ancient fan deposits with a zonation from proximal debris and mudflows to distal braided stream sediments. This zonation is a product of decrease in flow viscosity and grain size down the fan. The style of sediment deposition on alluvial fans is therefore related to position on the fan but is dominated by climatic effects (Schumm, 1977).

3.3 FACIES 2

Facies 2 contains well sorted, medium to coarse-grained, red sandstones, arranged in large-scale wedging sets of planar cross-stratification (Fig. 3.9). These sediments outcrop in the Witvlei area and are entirely surrounded by alluvial fan sediments (Fig. 4.6 and 4.7).

This facies interfingers with conglomerates and sandstones of facies 1C(ii), differing from them in their well sorted nature, rounded grains and lack of micas. The deposits are well-stratified, displaying large-scale wedging sets of planar cross-stratification - up to 1-2 m. thick and 10-20 m. wide. Truncation angles between sets are up to 35° (Fig. 3.9A). Planar lamination is formed by the intercalation of medium and coarse grained sandstones on a scale of 1-10 mm. Large scale slump structures are found at the margins of the deposits (Figs. 3.9B and 4.7), whereas at the top, large clay balls (up to 100 mm. in diameter) are incorporated.

A.

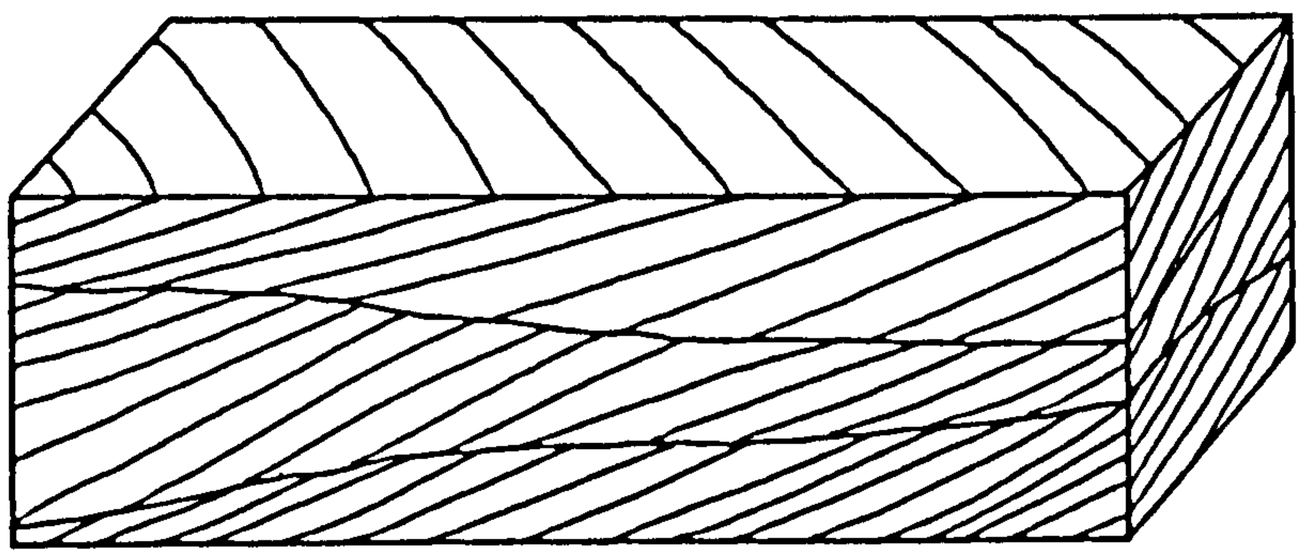
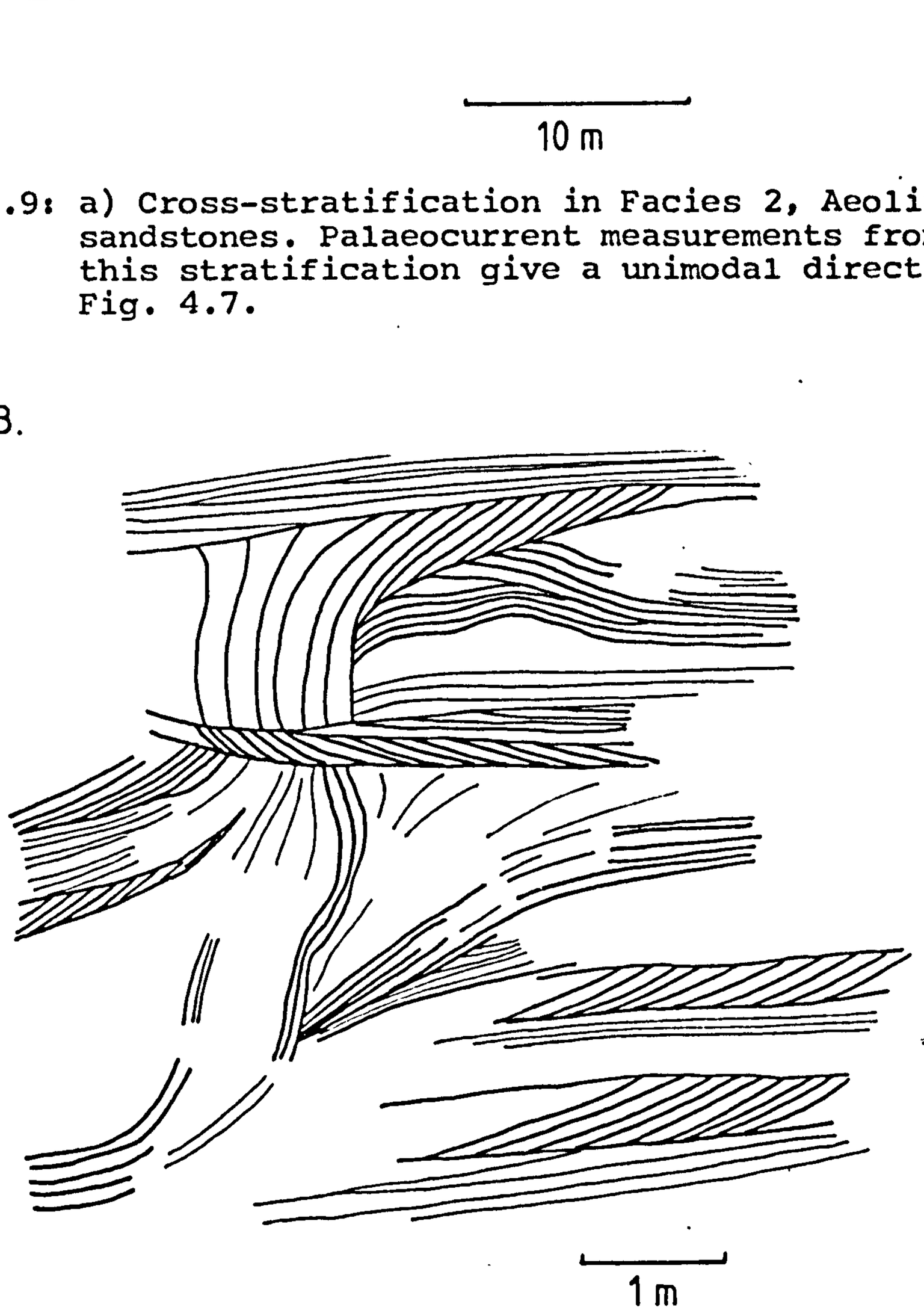


FIG. 3.9: a) Cross-stratification in Facies 2, Aeolian sandstones. Palaeocurrent measurements from this stratification give a unimodal direction, Fig. 4.7.

B.



b) Large scale slumping at the margins of the aeolian deposits. (Both diagrams from the Okatjirute West/Witvlei Townlands farm boundary, Witvlei (see Fig. 4.7.)).

Palaeocurrent measurements from the steep sides of planar cross-stratification define a unimodal distribution (Fig. 4.7).

Interpretation: The wedging planar cross-stratified sets, unimodal palaeocurrent direction and maturity of these sandstones suggest an aeolian origin (Collinson, 1978). The fine scale laminations of medium and coarse sandstones indicate variable wind strength and winnowing, supported by the absence of micas (Glennie, 1972). Unimodal palaeocurrents and high truncation angles suggest deposition on transverse or barchan sand dunes (Shotton, 1956; Wright, 1956; Glennie, 1970; 1972). Slumping at the margins of sand dunes and the incorporation of laterally-equivalent playa mudstones are common (Collinson, 1978).

3.4 FACIES 3

Facies 3 contains sandstones, siltstones and mudstones, often well laminated and sorted. The sediments lie within or adjacent to facies 1 deposits. Four divisions are made.

Facies 3A

These deposits consist of mudstones and siltstones, plus rare limestones, intercalated with conglomerates and sandstones of sheet-flood and streamflood alluvial fan origin of facies 1C. They crop-out in the Witvlei and Okasewa areas mainly, but also at Kojeka. Two divisions are made: in the first, the sediments are red and desiccated, and in the second, green or black with subaqueous dewatering structures and algal remains.

3A(i): These sediments are red, well laminated with grain sizes from mudstone to medium-grained sandstone (Fig. 3.10). Desiccation cracks, up to 15 cms. in length (Fig. 3.11), are

abundant, indicating exposure and dewatering of the sediment. These cracks may cut across numerous laminations formed by the alternation of coarse and finer sediment (Fig. 3.10A). Laminations have a variable thickness, from a few mm's to cm's; thick laminations usually contain coarser sediment. Each lamination probably indicates one depositional event with a coarser basal unit, which may have an erosive base and a finer upper unit. The laminations may fine upwards or contain a break between the coarse and fine members, produced as the fines settle out of suspension from the flow. Small scale current ripple cross-stratification is common in siltstones and sandstones. The sediments may also contain syn-sedimentary faults, syneresis cracks and carbonate layers and nodules, all of which are more commonly associated with facies 3A(ii).

3A(ii): Black, grey and green sediments, essentially mudstones and siltstones, and pink limestone bands typify this facies. They are well laminated, similar to 3A(i) but contain syneresis rather than desiccation cracks (Figs. 3.10B and 3.12), and are of particular importance since they host the Okasewa, Witvlei and Kojeka "ore deposits".

Small scale current ripple cross-stratification and syn-sedimentary faults occur (Fig. 3.10). Evidence for algal growth is present in the form of mat structures which bind the sediment (Fig. 3.12A) and also small spheres which may represent tiny fossil forms (Fig. 3.12B). Thin carbonate layers and nodules are common, one occurrence on the farm Okatjirute West (N. of Witvlei) of layer carbonate contains lath-shaped pseudomorphs, *probably* after gypsum (Fig. 3.12D). On the farm Eskadron, vugs in green siltstones form honeycomb textures pointing to the removal of a soluble material

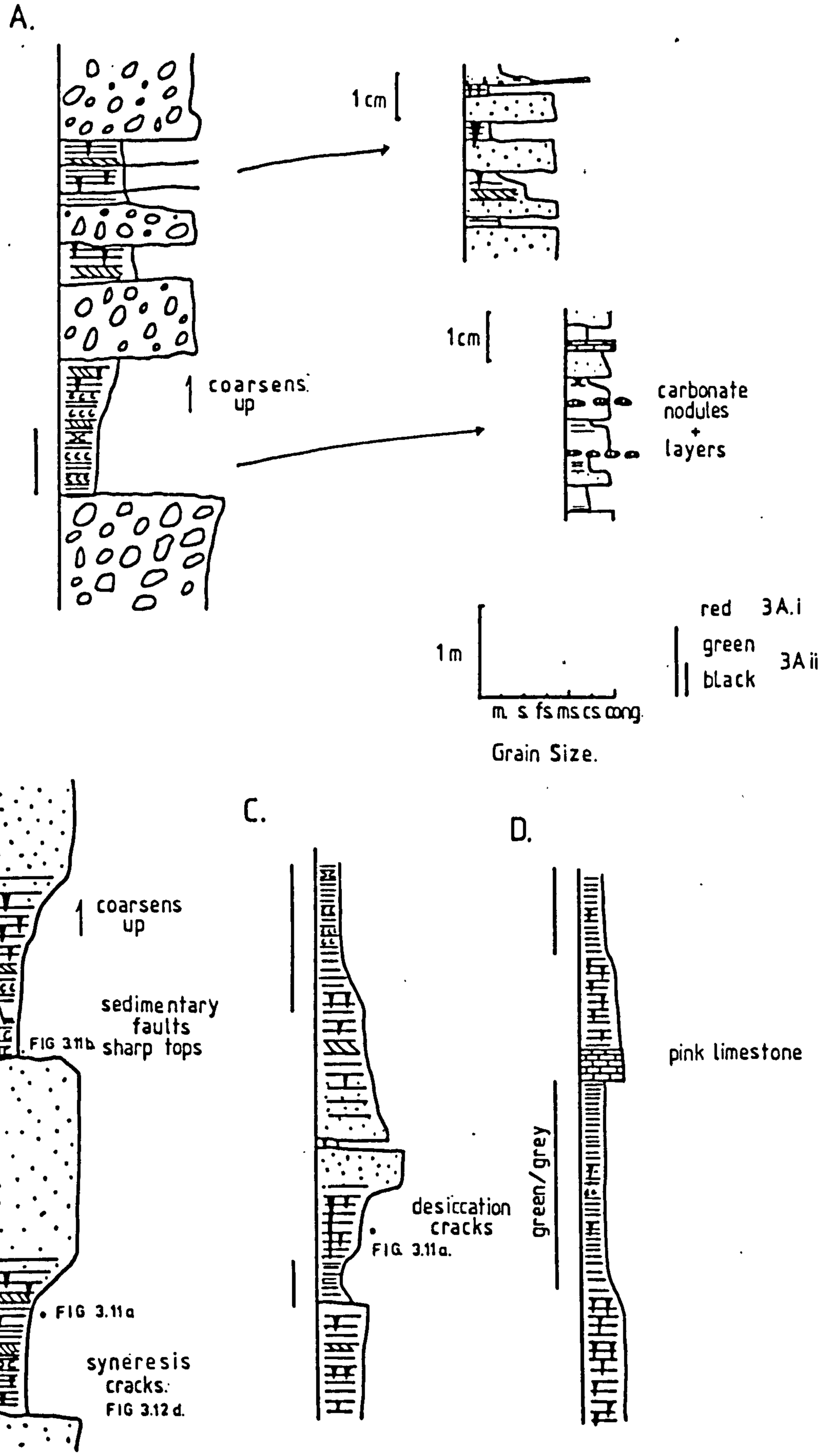


FIG. 3.10: Drill core sections of marginal and distal playa sediments (Facies 3A), intercalated with conglomerates and sandstones of Facies 1C. A. farm Okatjirute West, OKW. 5, B. farm Daheim, D1 ; Witvlei Fan ;and C. and D. farm Christiodore, CH. 11 ; Okasewa Fan.

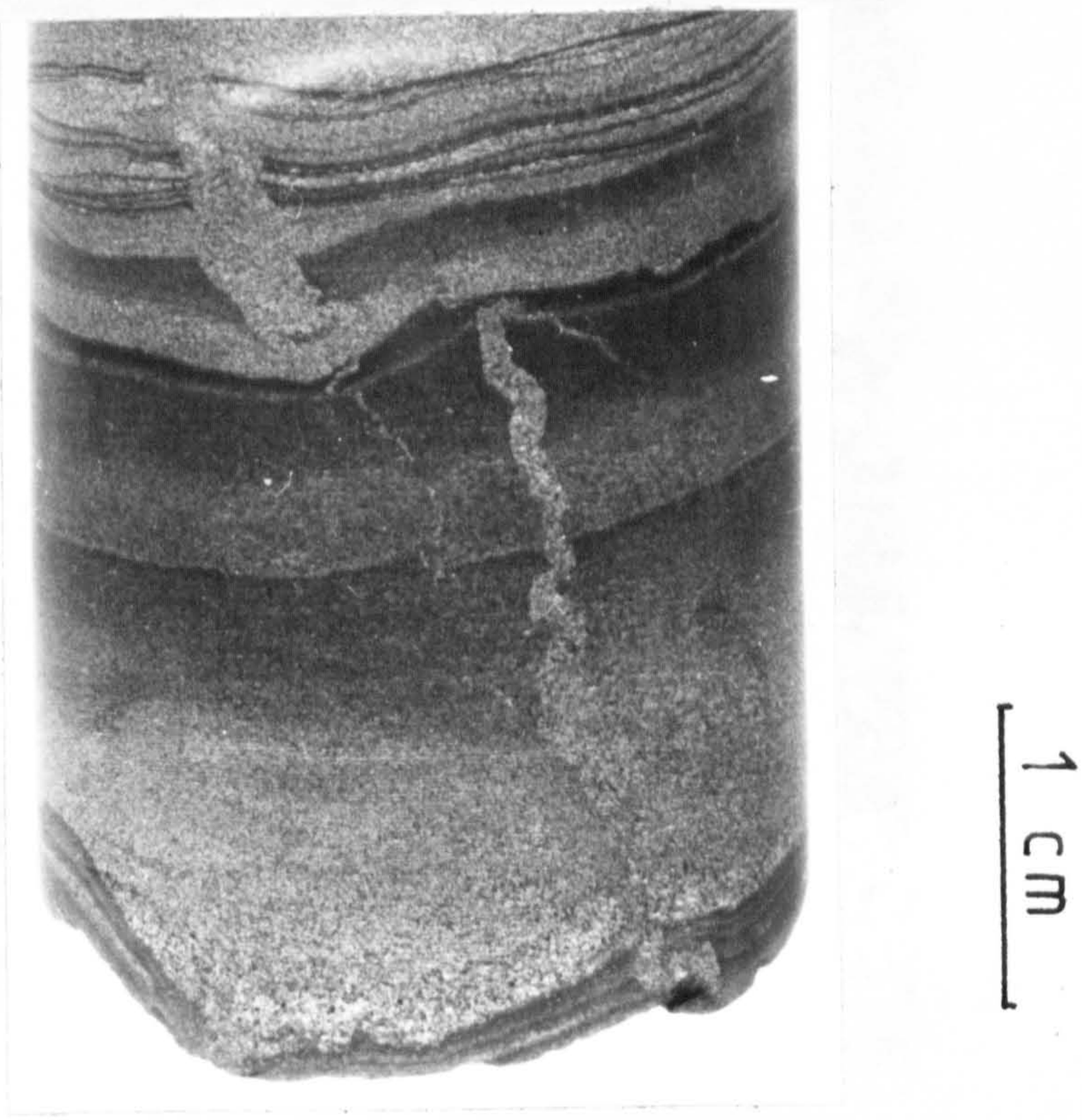
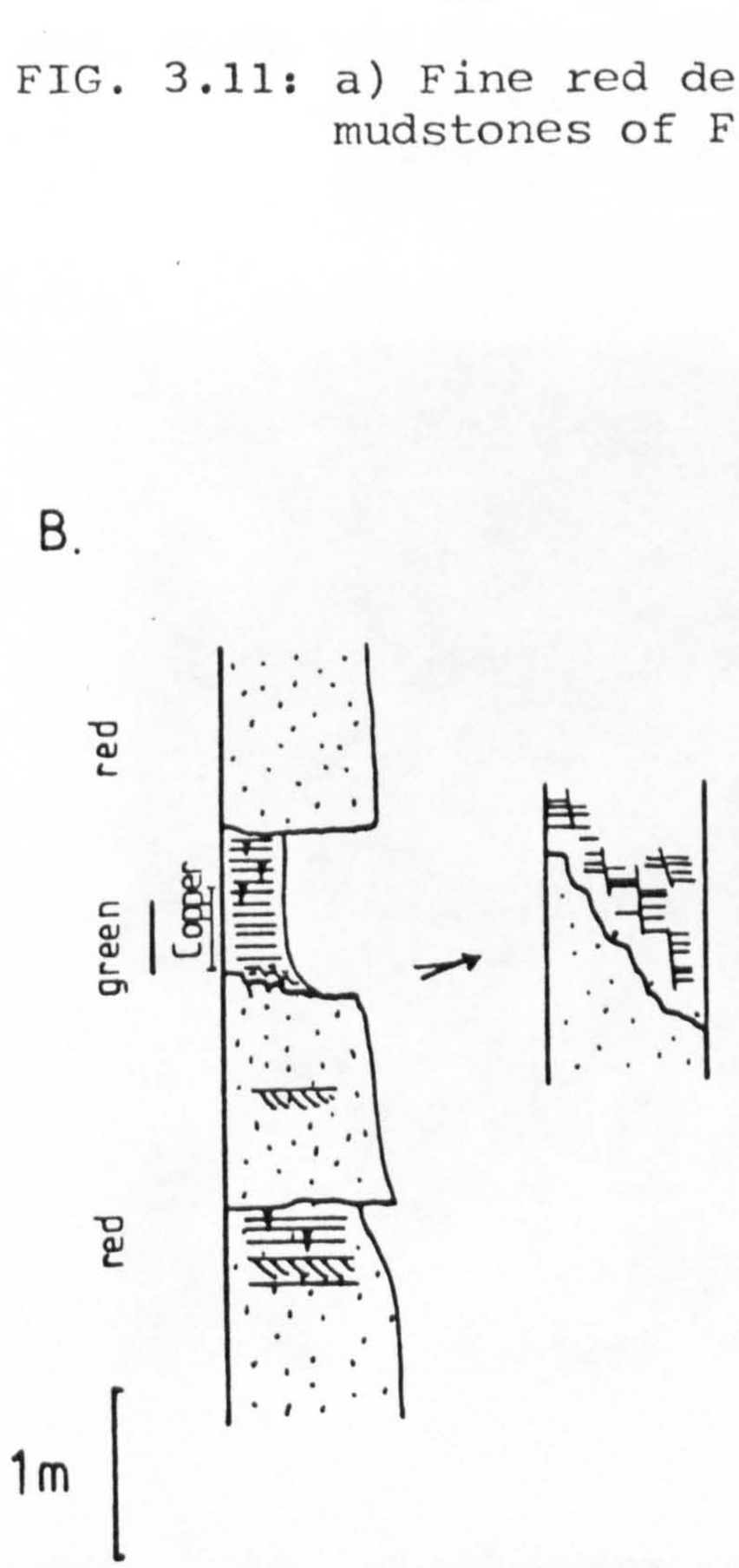


FIG. 3.11: a) Fine red desiccated siltstones and mudstones of Facies 3A (i). Drill core D1.



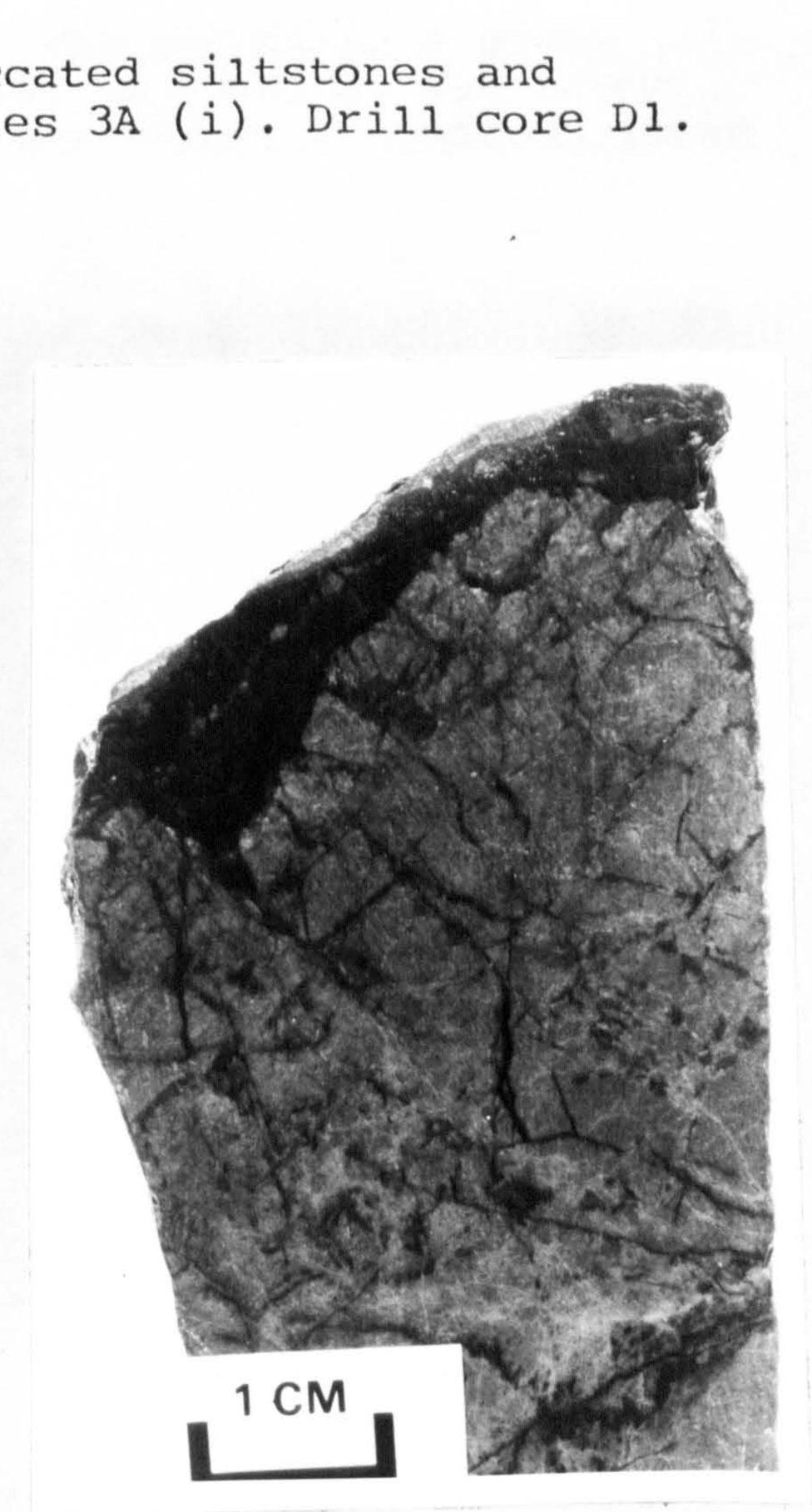


FIG.3.11: b) Flat top of a sandstone unit indicating an erosional boundary between Facies 1C sandstones and Facies 3A fine sediments. This boundary may represent a palaeoalluvial fan surface.

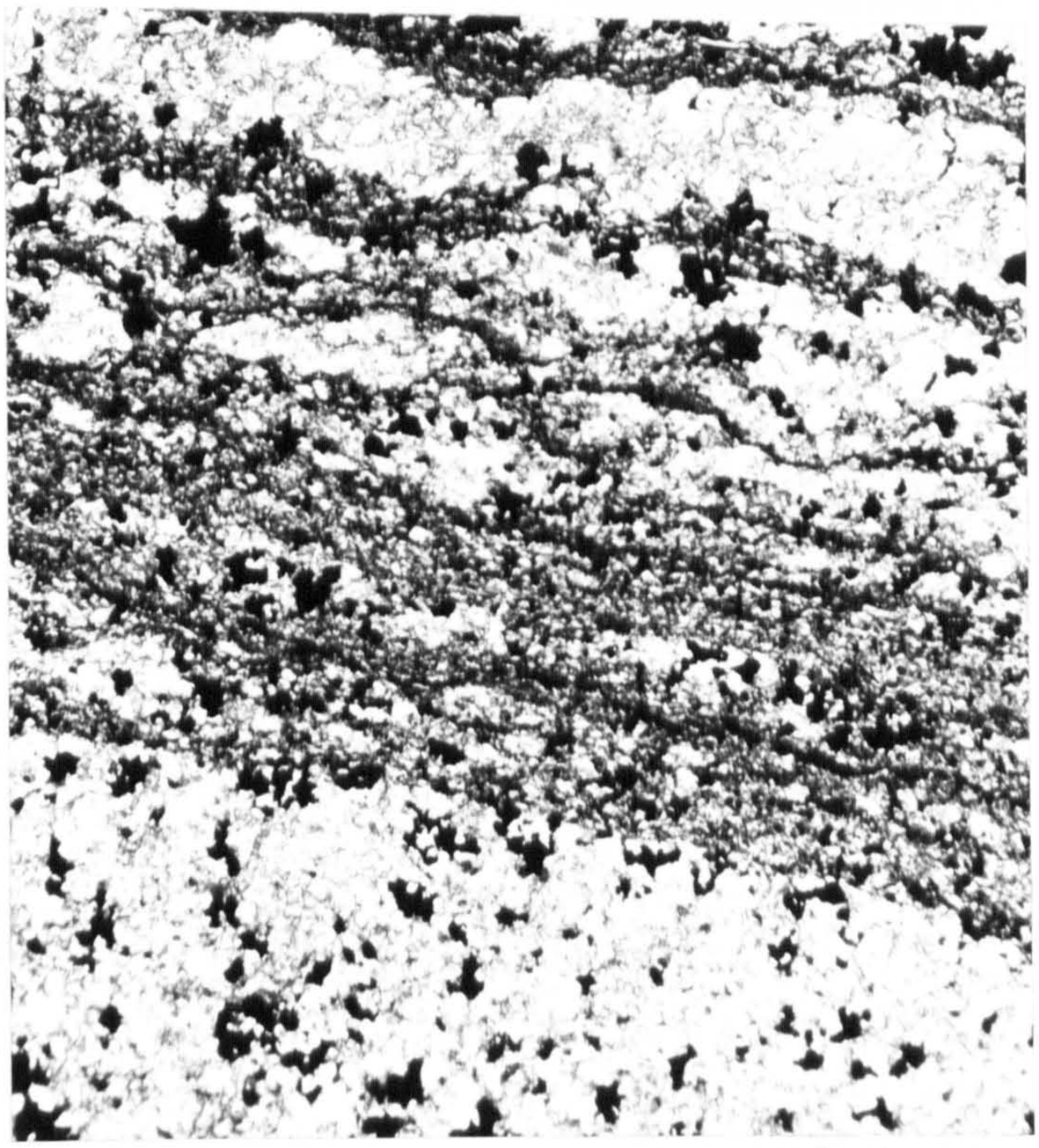


FIG. 3.12: a) Algal binding laminations in a green siltstone of Facies 3A (playa). The black irregular specks are copper sulphides. (core OKW. 5).

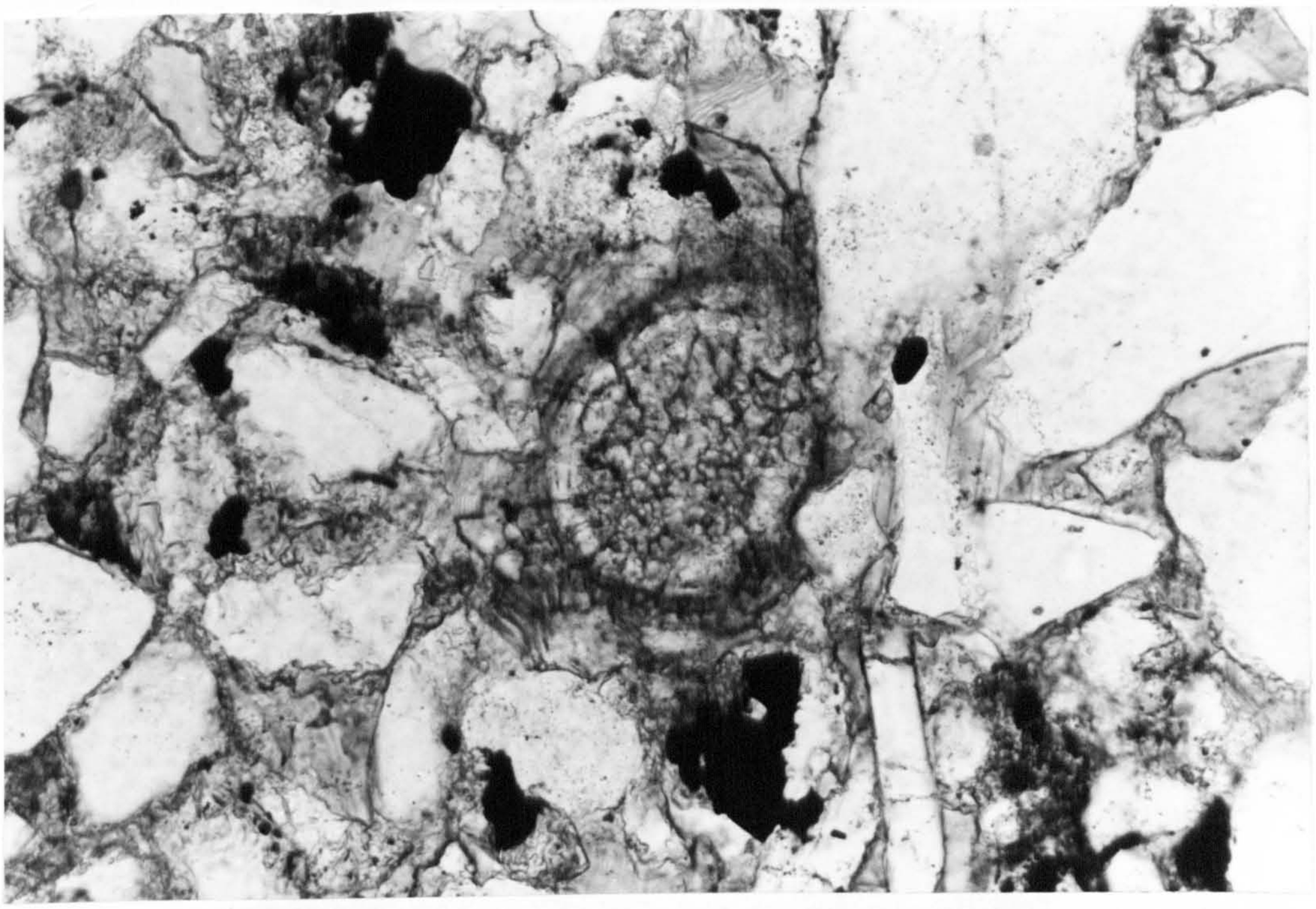


FIG. 3.12: b) Circular calcite forms which may represent Late Proterozoic microfossils. (core D1).

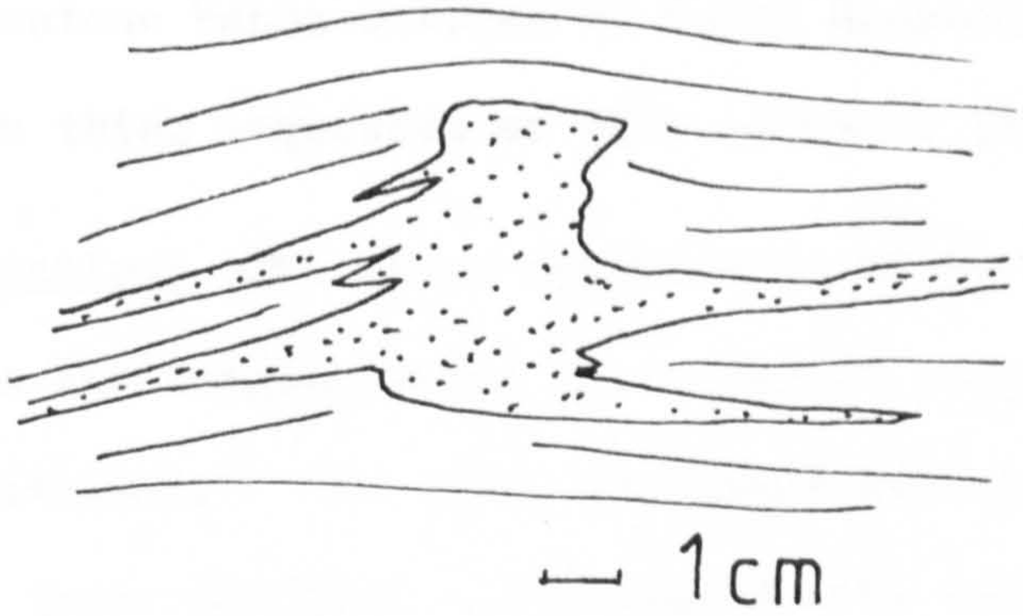


FIG. 3.12: c) Syneresis dewatering crack, deforming surrounding laminae. They are a common feature of Facies 3A(ii) sediments.

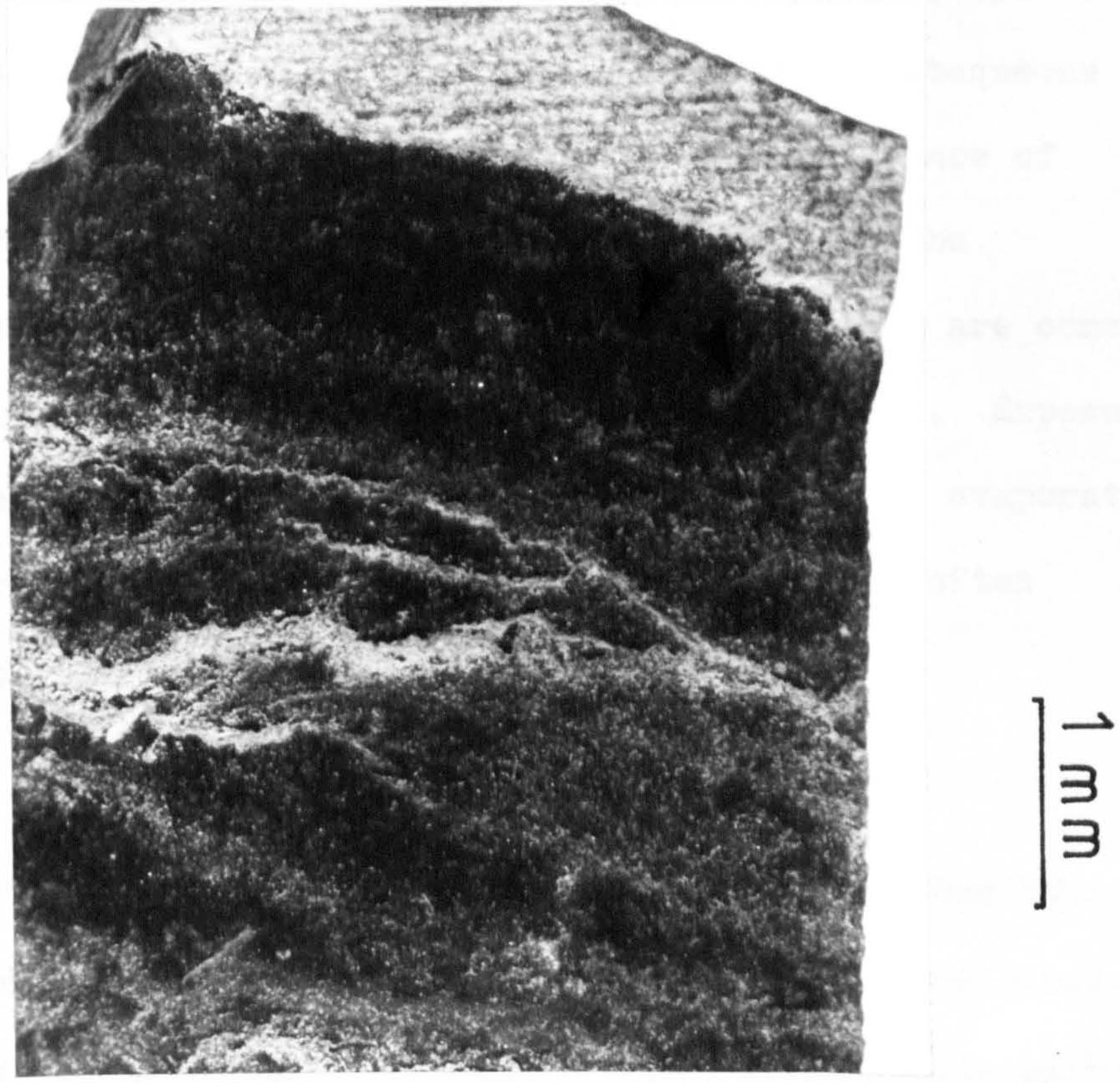


FIG. 3.12: d) A black carbonate layer containing lath-shaped pseudomorphs, probably after gypsum. The carbonate layer is interpreted as a replaced gypsum mat horizon (sample WC2/MAT analysed for it's carbon and oxygen isotope values).

during weathering. Similar structures described on the Zambian Copperbelt were found to contain anhydrite at depth (Annels, 1974; Clemmey, 1976).

Pink limestone bands outcrop on farms Gemsbokkvlei, Christiadore and Okasewa in thick sequences of fine sediment (Fig. 3.10D).

Interpretation: The close association of these sediments with the sandstones and conglomerates of facies 1C suggest that they are laterally equivalent. The often localized extent and thickness of facies 3A and their position intercalated with conglomerates and sandstones points towards a playa lacustrine origin. Similar laminated, desiccated fine sediments and green, algal bound carbonate-rich deposits are described by Hardie et al (1978), Link and Osbourne (1978) and Clemmey (1978). The occurrence of syneresis cracks in the laminated green sediments (3Aii) indicate subaqueous dewatering (Donovan and Foster, 1972), implying the existence of standing water during deposition. This is supported by the occurrence of algal mats and carbonaceous material; algae are common in temporary ponds of evaporitic climates (Sellwood, 1978). Exposure of these sediments led to desiccation and the formation of evaporative minerals and carbonate cements. Playa sedimentation was often interrupted by alluvial fan deposition (Fig. 3.10).

Facies 3B

Sediments of this facies are red, contain medium-grained sandstone to mudstone grain sizes and are well stratified. The scope of this facies group is expanded to encompass thin mud-partings, as well as 10's of meters of sediment thicknesses. The sediments outcrop in the Klein Aub/Witkop, Dordabis and Lake Ngami regions, adjacent to alluvial fan sediments of facies 1D and 1E (Fig. 4.2).

Numerous sandstone and siltstone units with erosive bases and flat or rippled tops, containing trough and some planar cross-stratification are evident within thicker sequences of this facies (Fig. 3.13). The separation of these coarser units from mudstones and fine siltstones indicates a break in deposition, from strong current to weaker current or suspension sedimentation.

Palaeocurrent measurements from the cross-stratified coarser sediment indicate a similar source area to the adjacent alluvial fan deposits. Small scale trough and planar cross-stratification indicate lingoid and tabular ripples, which together give variable palaeocurrent directions (Fig. 3.13). Further evidence for spasmodic current activity is indicated by migration ripples (Fig. 3.14D) and thin layers of cross-stratified sandstones and siltstones (Fig. 3.13). Symmetrical wave ripples and the occasional syneresis crack suggest periods of standing water. Desiccation cracks and mud-flakes and balls suggest emergence of the sediment. The common occurrence of convolutions, syn-sedimentary deformation and irregular lenses and blobs of sand in mudstones (Fig. 3.14) indicate liquifaction during deposition in the sediment pile. Such features denote rapid deposition.

Interpretation: These sediments are interpreted as mud flat deposits formed by periodic discharge of alluvial sediment. They represent the distal equivalents of facies 1D and 1E alluvial fan deposits. Syneresis cracks and symmetrical ripples indicate that there were periods of standing water although the sediments were probably dominantly exposed.

Facies 3C

These sediments are predominantly green, of variable grain size, contain regular laminites, carbonate and sulphides. Two

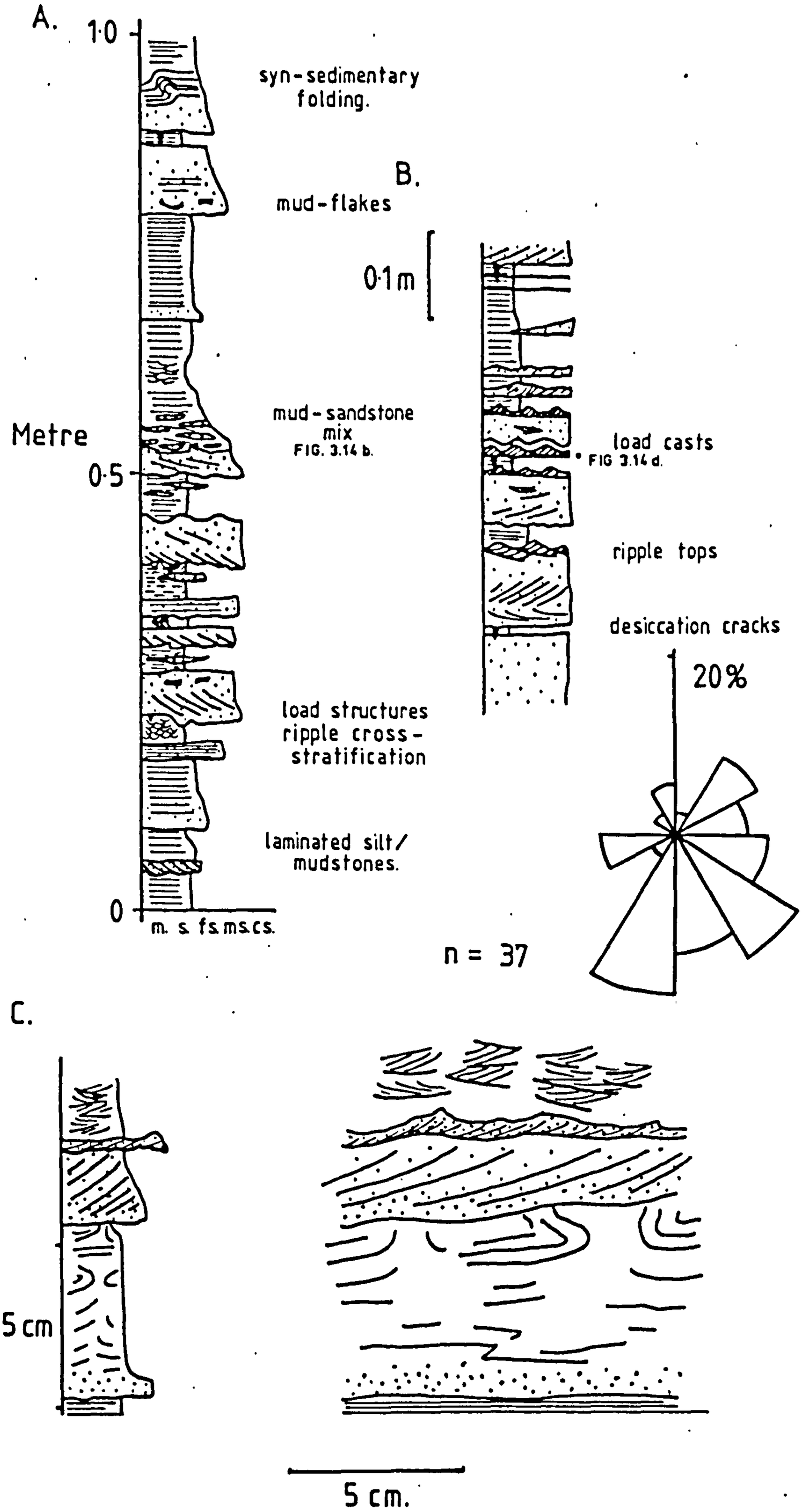


FIG. 3.13: Logs and palaeocurrent data of Facies 3B from the farms Peperkorpel (A.&B.) and Gemsbokkoppies (C).

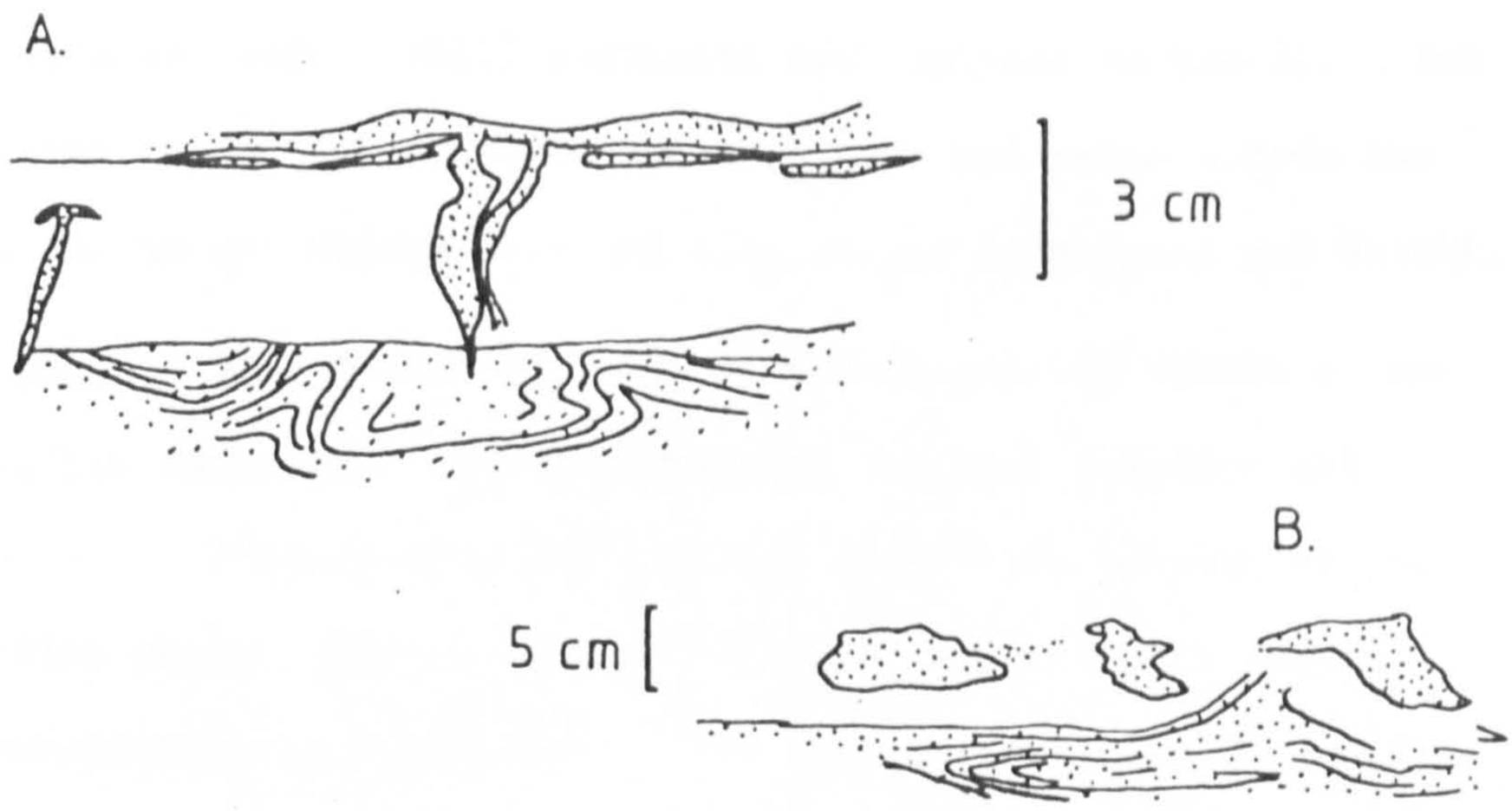


FIG. 3.14: a)Dewatering features of Facies 3B ; A. desiccation and convolutions (farm Bergzicht), B. mixing of sandstone and mudstone, and C. convolutions (farm Gemsbokkoppies).

FIG. 3.14: b) Photograph of migrating ripples in Facies 3B.

divisions are made: 3C(i) sediments are confined to the Klein Aub Mine area and 3C(ii) deposits are much more extensive - from the Klein Aub to the Witkop area and also around Lake Ngami and Ghanzi.

3C(i): This facies consists of medium-grained trough cross-stratified sandstones with intercalated bands of mudstone and siltstone. Figures 3.15 and 3.16 illustrate the content of these argillite bands, whereas the whole sediment sequence is shown diagramatically in Figure 4.4. The fine sediments of this facies host the Klein Aub ore horizons.

The trough cross-stratified sandstones are red, grey and green, contain some small scale current ripple cross-stratification, inter-formational mudstone rip-up clasts and have erosive bases and flat tops. Palaeocurrent data indicate that these sandstones were derived from the alluvial fan.

Intercalated argillite bands are up to 3 m. thick, separated by 5 to 20 m. thickness of medium-grained sandstones. They vary in type from red siltstones and mudstones to variegated red to green deposits which contain bands of nodular and layered carbonate, conformable to bedding (Fig. 3.15). The carbonate may be of primary origin or pseudomorphed after gypsum(?). Towards the top of the sequence, the argillite bands contain finely laminated, green to black, fine siltstones and mudstones, 1 to 2 mm. thick - each layer traceable over 20 to 30 m. (+) laterally. These units contain carbonaceous material and are interpreted as laminites (Fig. 3.16). Calcareous and carbonaceous laminites are abundant, separated by layers of marl, green mudstone or sandstone. Laminites are common lacustrine deposits; carbonaceous laminites have been described by Allen (1981) from the Caledonian Basin (ORS) of Scotland and calcareous

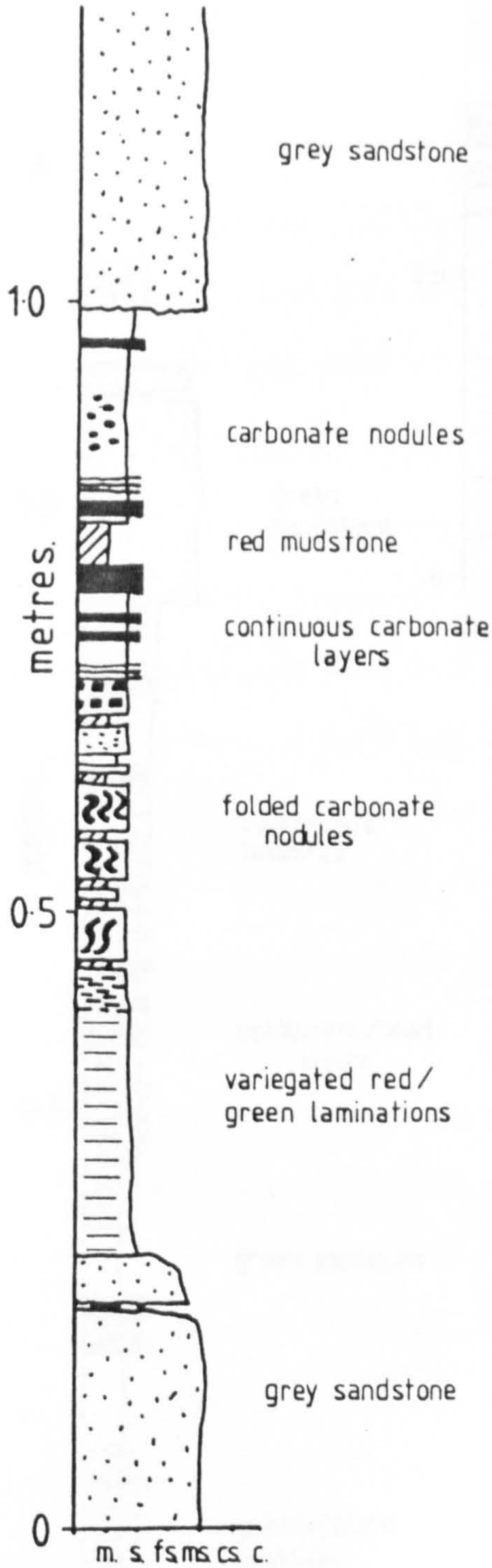


FIG. 3.15: Argillite band of Facies 3C (i) containing nodules of carbonate and layered carbonate (photos.) in a red/green coloured sequence of siltstones and mudstones. (Zero line, Level 6, Klein Aub Mine).

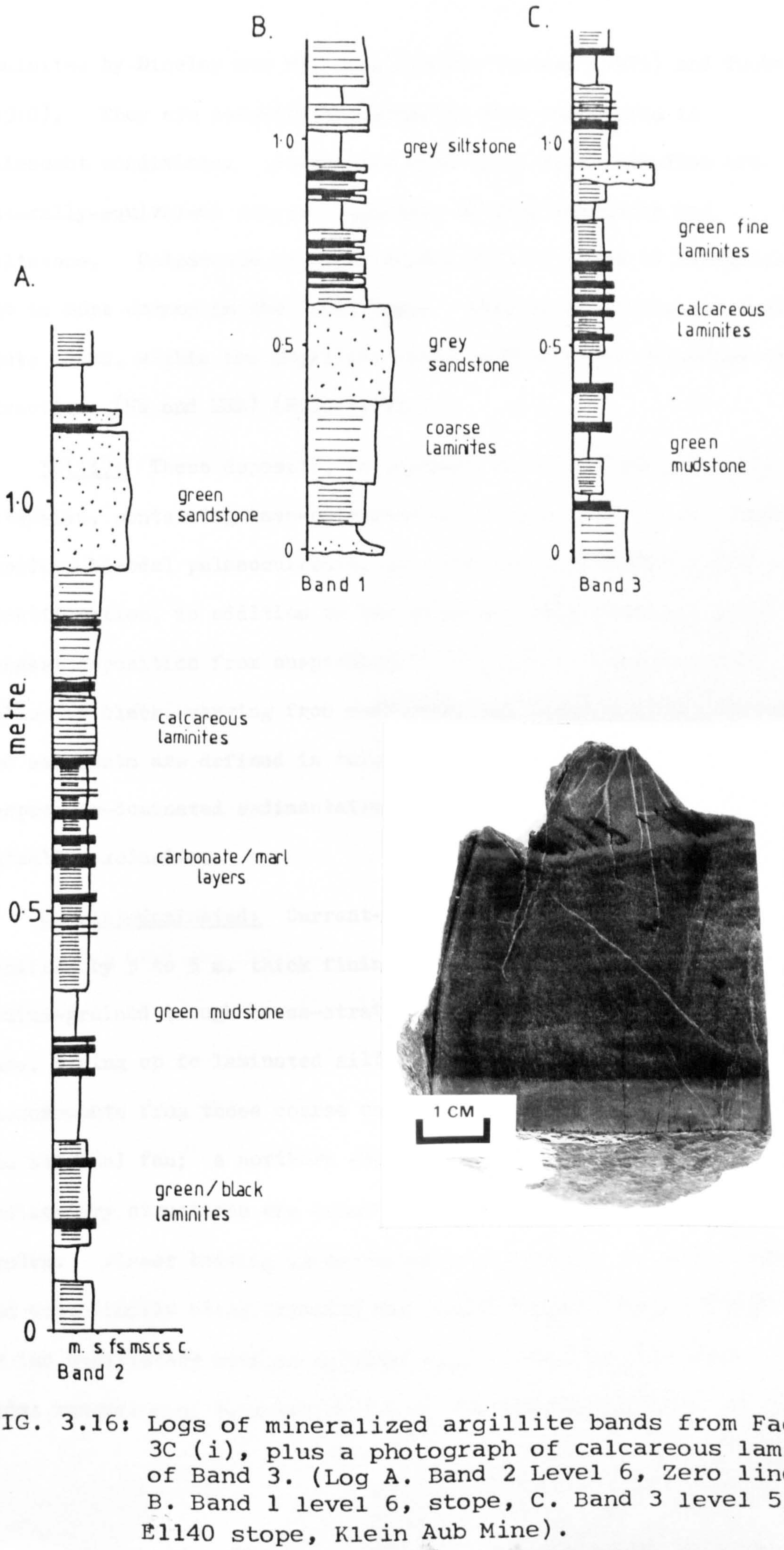


FIG. 3.16: Logs of mineralized argillite bands from Facies 3C (i), plus a photograph of calcareous laminites of Band 3. (Log A. Band 2 Level 6, Zero line, B. Band 1 level 6, stope, C. Band 3 level 5, E1140 stope, Klein Aub Mine).

laminites by Dineley and Williams (1968), Donovan (1975) and Tucker (1978). They are essentially deposited from suspension in quiescent conditions. Associated with these fine laminites are laterally-equivalent coarser laminites of fine sandstone and siltstone. Calcareous material occurs in both types of laminites but is more common in the finer type. Rare ripple-forms and small flute casts, within the argillite bands, indicate two palaeocurrent directions (NW and ENE) (Fig. 3.17).

3C(ii): These deposits, in contrast to 3C(i), are laterally extensive, containing wave-generated structures, such as oscillation ripples, bimodal palaeocurrents, undulose and wave-bundle cross-stratification, in addition to laminites and other features which suggest deposition from suspension. They are red, grey, green, yellow or black, varying from medium-grained sandstones to mudstones. The sediments are defined in terms of current-dominated and suspension-dominated sedimentation, although the two are by no means mutually exclusive.

Current-dominated: Current-dominated sedimentation is dominant, typified by 3 to 5 m. thick fining upward cycles (Fig. 3.17B). Medium-grained trough cross-stratified sandstones overlie an erosive base, fining up to laminated siltstones and mudstones. Palaeocurrent measurements from these coarse units indicate their derivation from the alluvial fan; a northern source (Fig. 3.17). Wave-generated sedimentary structures are common in the finer portions of the cycles. Flaser bedding is preserved as mud whisps in ripple troughs and occasionally along foresets and ripple backs. They are formed by the oscillatory motions of water bodies, usually attributed to tidal reworking of fine sediment with the mud fraction settling from

suspension during the turning of the tide (Reineck and Singh, 1973). Further evidence for oscillatory currents are provided by the presence of oscillation and symmetrical wave ripples and wave-bundle cross-stratification (Figs. 3.17, 3.18) (McKee, 1957; Boersma, 1970; Reineck and Singh, 1973; Donovan, 1975; Tucker, 1978; Allen, 1981 a,b, etc). Oscillation ripples have knife-sharp edges, the troughs filled with laminite sediments (Fig. 3.17A). Mud-drape structures forming over current and wave ripple forms, suggest deposition from oscillatory currents (Boersma, 1970; Reineck and Singh, 1973). The occurrence of micro-ripples, less than 1 cm. high with a wavelength less than 1 cm., indicate wave action in shallow water (Singh, 1969; Singh and Wunderlich, 1978). Linsen structure and migrating ripple forms occur, formed by currents moving fine sand over suspended sediment deposits (de Raaf et al, 1977).

Breaks in the sediment grain size are numerous (Fig. 3.17B) indicating variable current velocities. Ripple tops filled with suspension sediment suggest a rapid decrease in current velocity, followed by suspension deposition of fines. Laminites also point to settling from suspension. Ladder or run-off ripples indicate exposure of the sequence (Reineck and Singh, 1973), supported by the presence of desiccation polygons and mud rolls. Convolution dewatering structures in the coarser part of the fining upward cycle, indicate rapid deposition.

Suspension-dominated: Suspension sedimentation is typified by the extensive development of regular laminites (Fig. 3.17A), 1 to 2 mm. thick and persistent over 10 m. plus (Fig. 3.18B). They are composed of fine sandstone and siltstone layers, occasionally interrupted by knife-edged oscillation ripples and vugs.

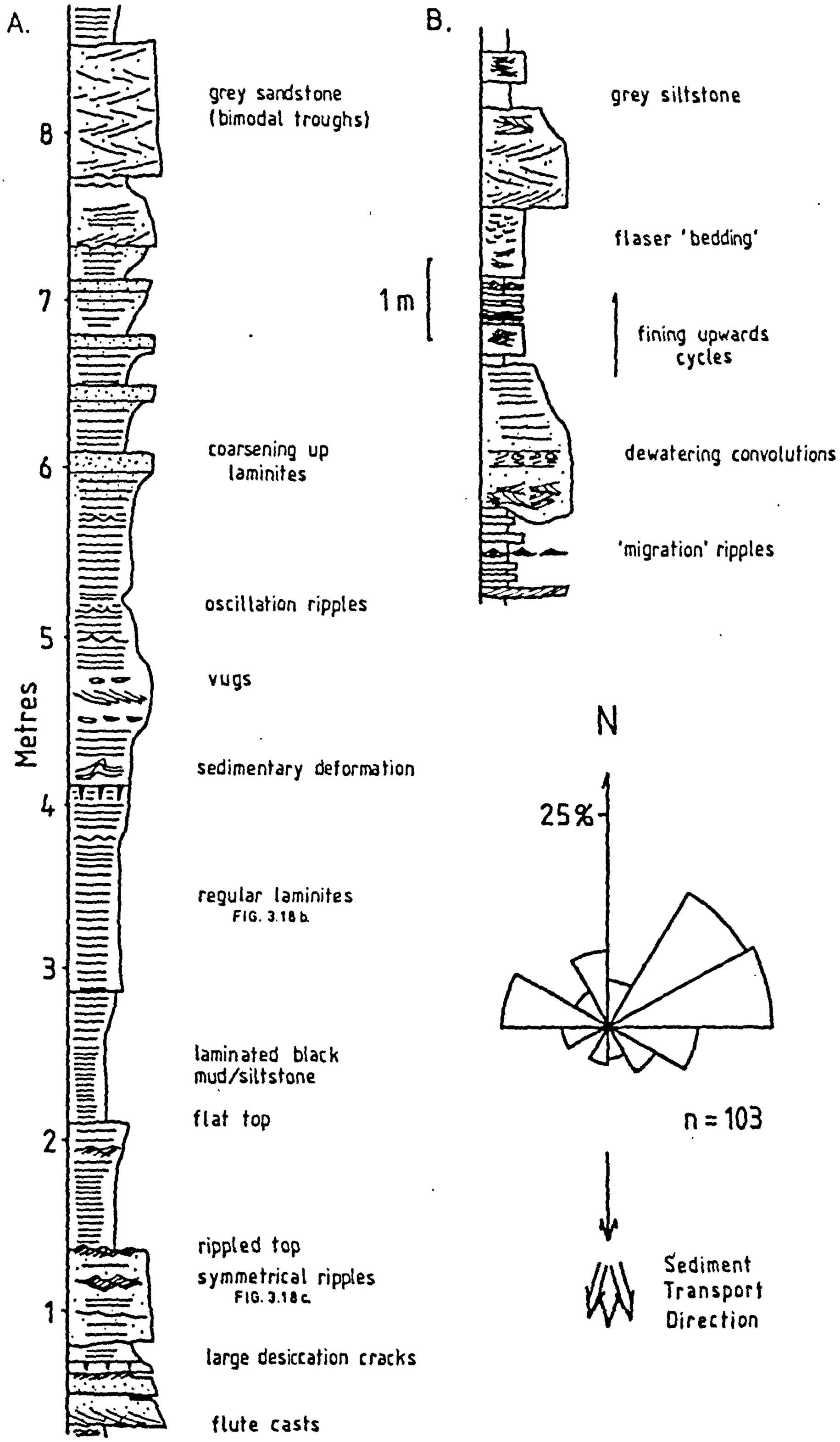


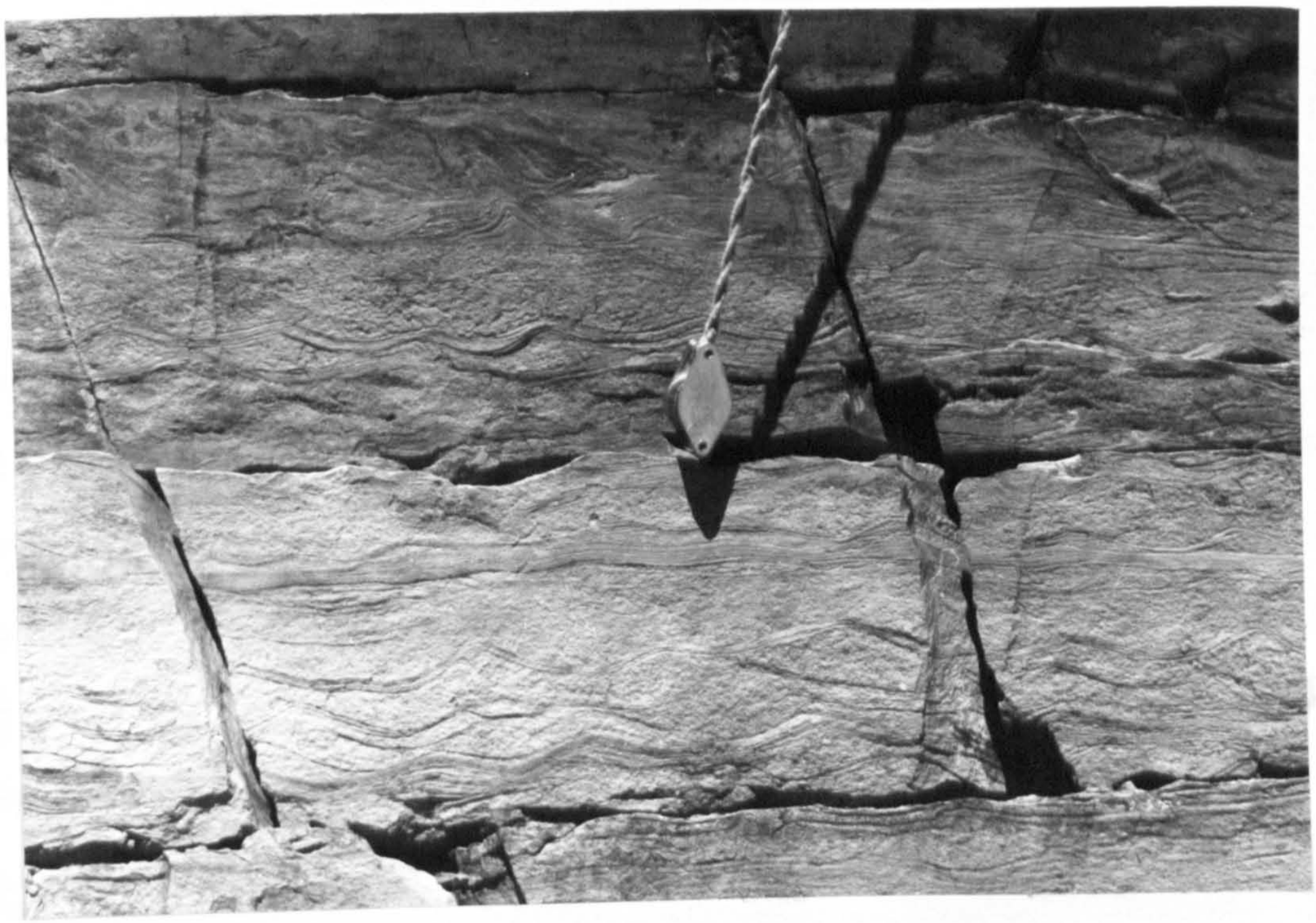
FIG. 3.17: Logs of Facies 3C(ii)sediments, A. "suspension-dominated and B. "current- dominated". Plus a palaeocurrent rose from small-scale ripples etc. and sediment transport direction from trough-cross-bedding. (Koper River)

FIG. 3.18: a) Wave-bundle ripple cross-stratification Facies 3C(ii), Kagas Noord.

b) Truncated regular laminites,Facies 3C (ii), Klein Aub.

c) Symmetrical ripples and laminites from suspension-dominated sediments of Facies 3C(ii), Klein Aub.

2 cm.



Laminites with irregular thickness indicate a variable suspended sediment influx, whereas coarsening upwards laminites a steady input of coarser material.

Laminites are common lacustrine features and have been reported in ancient lake sediments by Feth (1964), Donovan (1975), Link and Osbourne (1978) and Dineley and Williams (1968).

A few current structures are present in suspension deposits - e.g. current ripple forms, bimodal trough cross-stratification in medium-grained sandstones, indicating lacustrine current reworking of coarser sediment and also flute casts (Fig. 3.17A).

Interpretation: Trough cross-stratification, present in the medium-grained sandstones of facies 3C, indicates that they were derived from a similar source to the alluvial fan sediments of facies 1D beneath. Wave-generated structures, suspension deposits and bi-modal palaeocurrent roses suggest that the finer sediment was deposited in standing water bodies, which were subjected to periods of oscillatory current motion and periods of quiescence. The evidence suggests that deposition took place on, or adjacent to, fluviatile deltas which prograded into a lake or shallow sea. Similar deposits are described by Link and Osbourne (1978), Stanley and Sundam (1978), Allen (1981a) and modelled by Wright (1977). Many of the structures present in the finer sediment fraction are common to both shallow marine and lacustrine environments (Allen, 1981a). The distinction between these two facies environments in Phanerozoic rocks is heavily dependent upon the recognition of fauna and flora (Reineck and Singh, 1973; see Reading, 1978). Phanerozoic shallow marine deposits often contain extensive burrowing and benthonic fauna, recognisable as marine-dwellers, in contrast to lacustrine sediments, which

commonly contain fish or dinosaur remains. Precambrian marine sediments, however, contain no recognisable fauna or flora and distinction from lacustrine deposits must be purely based on lithofacies analysis. Since marginal marine and lacustrine environments are essentially very similar, their distinction in Precambrian sediments is difficult. This dilemma is evident in the recognition of facies 3C sediments. However, the combination of different features (with additional indicators from adjacent facies), in addition to isotopic data, suggest that the finer sediment fraction are lacustrine deposits. These factors include the lack of persistent tidal activity, as indicated by suspension-dominated deposition; the fact that lacustrine sediments are enclosed by alluvial fan deposits (Fig. 4.2), with no evidence of sand bars and extensive reworking of alluvial sediment; and that sulphur isotopic analysis on sulphides, from copper/iron sulphides and pyrite in facies 3C(i) and pyrite in facies 3C(ii), indicate that all the sulphur was derived from basement sources and was not of marine origin (see Chapter VI).

Sediments of facies 3C(i) were dominated by alluvial fan deposition, lacustrine sediments forming during periods of lobe abandonment. The finer lacustrine sediments are principally suspended sediment deposits with little sign of wave activity. The fining upwards cycles of facies 3C(ii) possibly indicate initial alluvial deposition, followed by a mixture of current-dominated and suspension-dominated lacustrine sedimentation. The numerous sharp changes in grain size within the fining upward sequences indicate breaks in alluvial and lacustrine current deposition, suggesting periodic alluvial and lacustrine currents. The fining upward

cycles probably again indicate lobe abandonment sedimentation on the alluvial fan. Several metres thickness of suspension-dominated sediment, intercalated with the more numerous fining upward sequences, probably indicates long periods of lobe abandonment or deposition in adjacent areas to the lacustro-fluvial delta.

Facies 3D

Facies 3D is essentially similar to 3C but contains a wider range of lithologies (conglomerates, sandstones, siltstones, mud-stones, marls and limestone bands) and more evidence of wave action. These sediments outcrop in the Witvlei area, closely associated with 1C (and 1B) alluvial fan deposits. Two sub-divisions are made.

3D(i): Well sorted, fine to medium-grained, red sandstones, containing low angle planar cross-stratification, typify this facies (Fig. 3.19A). A sequence of sedimentary structures from planar-laminated to flaser-bedded sandstone units exists. The low angle planar laminations are depicted by slight changes in grain size and heavy minerals (haematite dominantly). Low angle truncation cut-offs form between the sets (Fig. 3.19A). They pass up into small scale trough cross-stratification and into flaser-bedded units, indicated by heavy mineral concentrations along ripple foresets and in ripple troughs. Flaser-bedding indicates oscillatory current movements reworking and depositing fine sand, whereas low angle planar stratification suggests sedimentation and reworking by waves in a nearshore environment (Elliot, 1978). Flat-topped ripples occur, suggesting sediment exposure in a nearshore environment (Reineck and Singh, 1973). Rapid deposition is indicated by convolution and sand volcano, dewatering structures. Desiccation cracks, found in rare fine mudstone partings and mud-rolls, indicate

exposure. Mud-roles are curls of mudstone which enclose sandstone, forming branching stringers with variable thickness, width and often with a polygonal habit, lying on bedding surfaces.

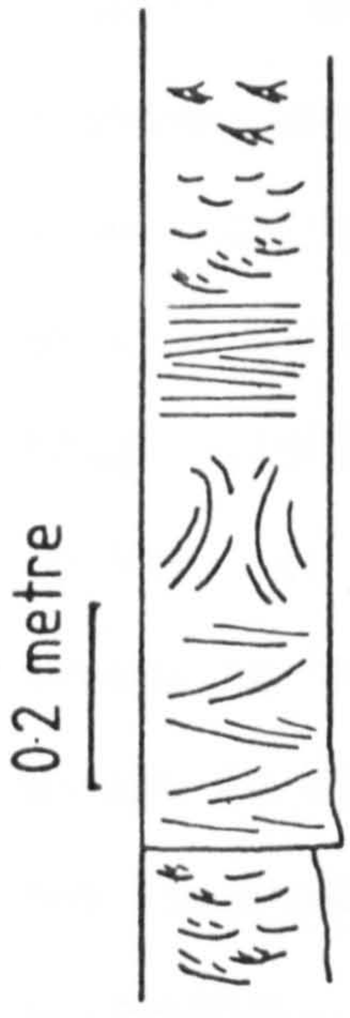
Interpretation: This facies was probably deposited in a marginal marine or lacustrine environment. Horizontal and low angle planar laminations are produced in the breaker and swash zones of foreshore and backshore environments in both marine (McKee, 1957) and lacustrine (Allen, 1981) sediments. Flaser-bedding forms as a result of oscillatory currents below the breaker zone, in the build-up or shoaling zone (Shepard and Inman, 1950; Elliot, 1978) and flat-topped ripples and desiccation cracks on exposed beach surfaces.

3D(ii): Sediments of this facies generally form fining upward cycles (Fig. 3.19B) and contain conglomerates, sandstones, siltstones, mudstones, marls and limestone bands. The deposits are dominantly red, grey, containing rare green horizons and yellow marls, plus black limestones.

The base of the fining upwards cycles are normally erosive, overlain by medium to coarse-grained sandstones or conglomerates. Conglomerates contain sub-rounded to rounded clasts ($<$100 mm. in diameter), of basement and sedimentary rock types, which are supported in a red sandstone matrix; they can, in fact, be traced laterally into conglomerate bands of the alluvial fan facies 1C and differ from them only in a slight increase in sorting.

Conglomerates and sandstone units are usually trough cross-stratified, with palaeocurrents indicating an alluvial fan source. Medium to fine-grained, red sandstones containing low angle planar cross-stratification are attributed to facies 3D(i).

A.



B.

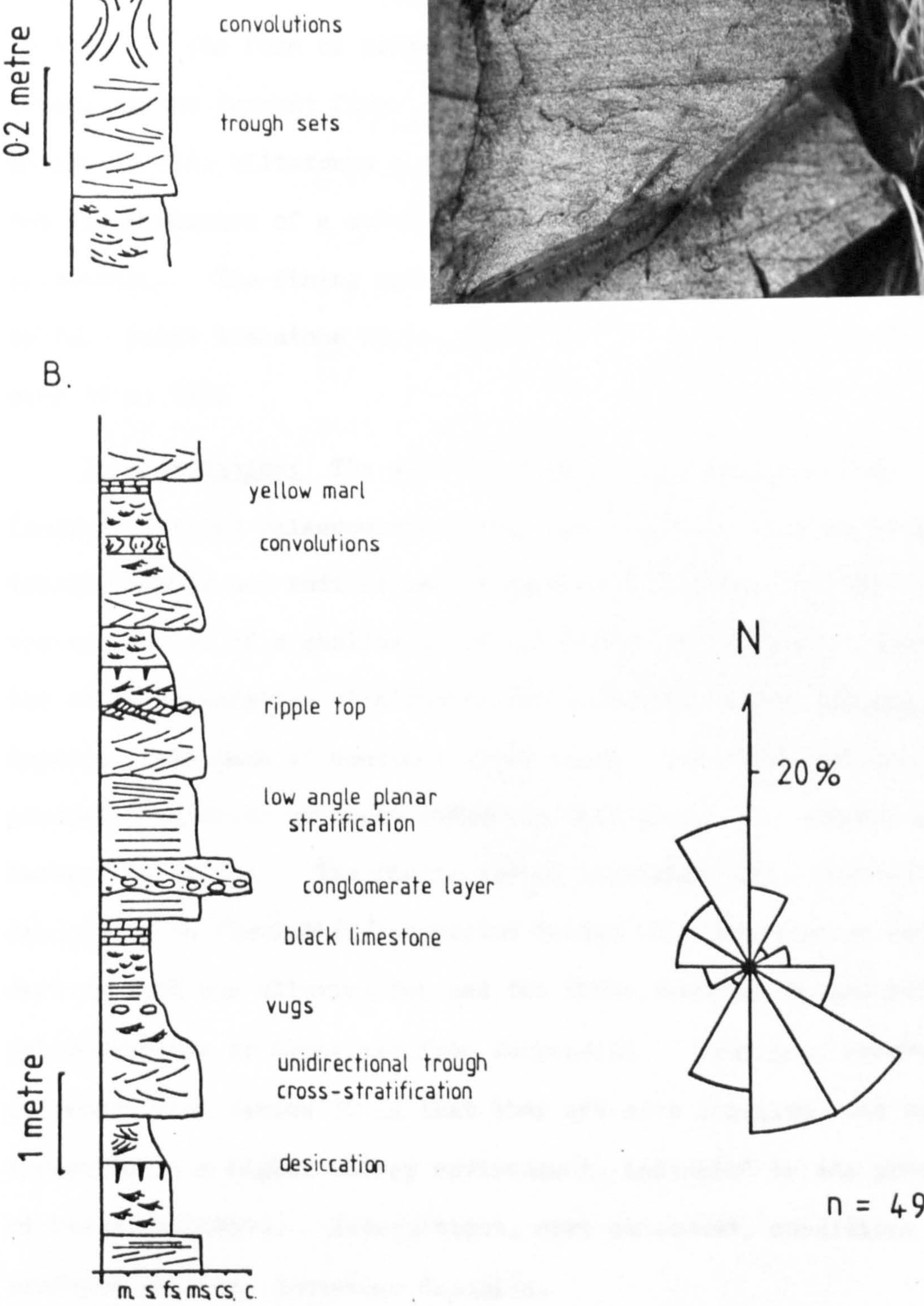


FIG.3.19: Facies 3D. A. 3D(i) beach deposits, log and photograph of flaser bedding and planar low angle laminations (Eskadron). B. Log of 3D(ii) and palaeocurrent rose (Okatjirute West/Eskadron).

Finer sediments of these cycles contain oscillation, current, lingoidal and micro-ripples. Tabular cross-stratified, oscillation ripples, suggest the reworking of current ripples by oscillatory water motions. Directional measurements of ripple forms and cross-stratification indicate a bimodal palaeocurrent distribution (Fig. 3.19B). Breaks in grain size within the fining upward cycles - in the form of ripple tops and planar boundaries - indicate breaks in the current flow. Flaser-bedding, delineated by mud whisps in fine siltstones and sandstones, is common. Vugs indicate the disappearance of a soluble material and convolutions suggest rapid deposition. The fining upward cycles may be capped by yellow marl or thin black limestone bands, which are often laterally persistent over 30 m. (+).

Interpretation: The wide variation in lithology, bimodal (current ripple) palaeocurrent rose, the occurrence of beach deposits (facies 3D(i)) and indications of current and suspension deposition, are suggestive of a shallow marine or lacustrine origin. However, the close association of alluvial fan sediments, which enclose these deposits, the lack of constant tidal current reworking and the general similarity of these sediments with facies 3C, suggest a lacustrine origin. The fining upward sequences again indicate deposition on fluviatile/lacustrine deltas with the coarser sediment derived from the alluvial fan and the finer, reworked by lacustrine palaeocurrents or deposited from suspension. They are, however, different from facies 3C in that they are more oxidized and were deposited in a higher energy environment, indicated by the presence of beach sediments. Intermittent, more quiescent, conditions produced marl and limestone deposits.

Sedimentation was probably dominated by alluvial fan processes, principally lobe abandonment resulting in the production of fining upwards sequences. Transgressive lobe events are recognised by coarse sediment influx and rare coarsening upward units.

SUMMARY

FACIES 1	ALLUVIAL FAN SEDIMENTS
1A	Pediment, alluvial sediments
1B	Mudflow + Debris flow deposits
1C	Sheetflood/Streamflood deposits
1D	Streamflood/Braided stream deposits
1E	Braided stream deposits
FACIES 2	AEOLIAN SEDIMENTS
	Transverse or Barchan dune
FACIES 3	LACUSTRINE, MUD FLAT AND PLAYA SEDIMENTS
3A	Playa sediments
3B	Mud flat deposits
3C	Fluvo-lacustrine deltaic and suspension sediments
3D	Beach and lacustrine deposits

CHAPTER IV

SEDIMENTOLOGY - FACIES RELATIONS

4.1 INTRODUCTION

The Doornpoort Formation consists of alluvial fan, aeolian, mud flat, playa and lacustrine sediments, which outcrop along the Southern Foreland of the Damaran Orogenic Belt. Three specific facies associations and one of unknown affinity, occupy distinct geographical positions along the margin (Fig. 4.1). Facies association A outcrops in the Klein Aub area, B around Witvlei, C near Dordabis and Doornpoort, and D in the Lake Ngami area. Association A, C and D are typified by laterally extensive but relatively thin deposits, in contrast to association B which comprises thick, laterally impersistent sediments.

This chapter outlines the different facies associations giving possible reasons for their differences, using analogues described from modern and ancient alluvial fans.

4.2 FACIES ASSOCIATION A

Facies association A is composed of facies 1A, 1D, 3B, 3C and rarely 3A (Fig. 4.1), outcrops south of Rehoboth and is called the Klein Aub Member. Alluvial fan sediments of facies 1A and 1D lie unconformably on basement rocks and consist of a lower sequence of conglomerates and sandstones and an upper sequence of sandstones, separated by a zone of mud flat and lacustrine deposits (facies 3B and 3C) (Fig. 4.2). The fact that the lacustrine and mud flat sediments are laterally extensive and that the lacustrine palaeo-current directions are similar along strike, suggest that deposition took place in large inland lakes and on broad mud flats (Fig. 4.2).

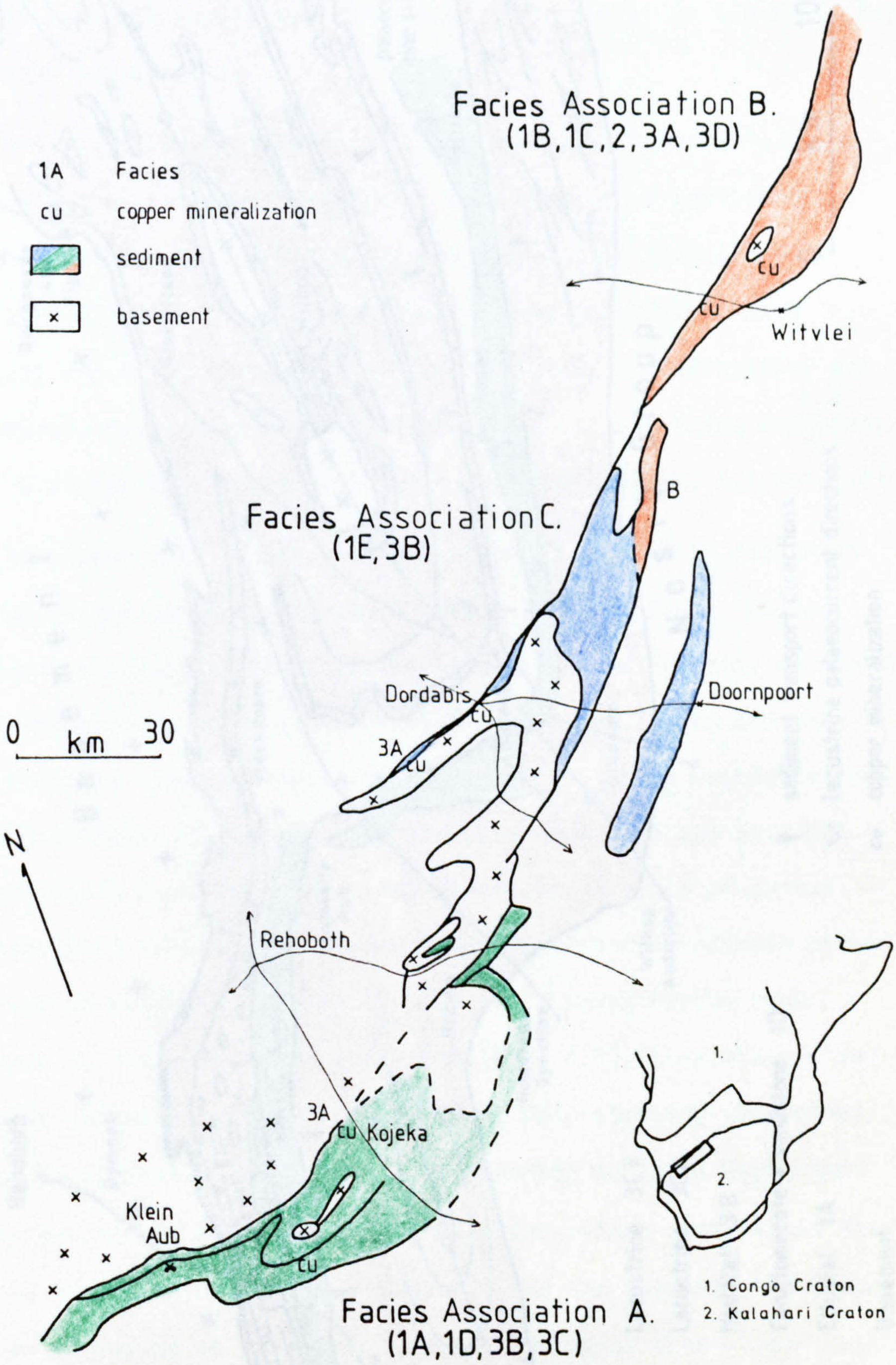


FIG. 4.1: The geographical distribution of Facies Associations along the Southern Margin of the Damara Belt and the Facies they contain.

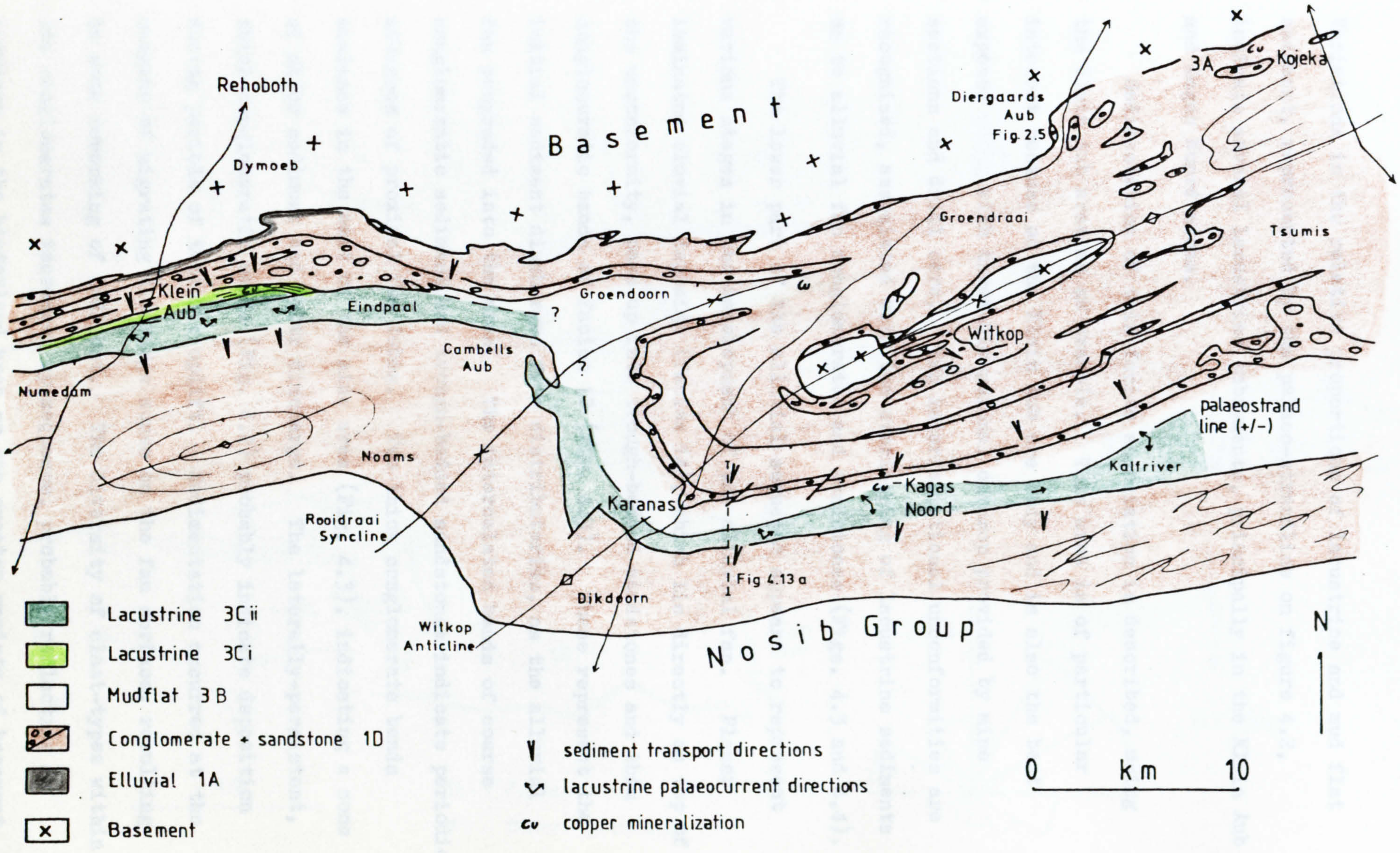


FIG. 4.2: Facies Association A, the KLEIN AUB MEMBER, containing Facies 1A,1D,3B, and 3C (+3A at Kojeka).

Variations in the relative proportions of lacustrine and mud flat sediment, represented by the palaeo-strandline on figure 4.2, indicate several lacustrine embayments, principally in the Klein Aub and Kagas Noord areas.

Sedimentation of this facies association is described, using the Klein Aub area as an example. This area is of particular interest because of the Klein Aub ore body and is also the best exposed with three-dimensional outcrop provided by mine sections and drill core. Two interformational unconformities are recognised, associated with the overlapping of lacustrine sediments on to alluvial fan conglomerates and sandstones (Figs. 4.3 and 4.4).

The lower part of the alluvial sequence appears to represent various stages in the development of the alluvial fan. Planar laminated eluvial deposits (facies 1A), which lie directly on top of the unconformity, pass up into trough-bedded sandstones and thin conglomeratic bands of facies 1D (Fig. 4.3). These represent the initial sediment discharges from distributaries, as the alluvial fan prograded into the area. The intercalated bands of coarse conglomeratic sediment and trough-bedded sandstones indicate periodic advances of proximal fan lobes. Two thick conglomerate bands coalesce in the east of the mine area (Fig. 4.3), indicating a zone of major sediment and water discharge. The laterally-persistent, thick conglomeratic bands (Fig. 4.2) probably indicate deposition during periods of tectonic uplift. Sedimentation occurred at the margins of migrating discharge zones on the fan surface, resulting in some reworking of sediment. The diversity of clast-types within the conglomerates increases up-sequence, probably reflecting an increase in the hinterland area or the greater variety of basement

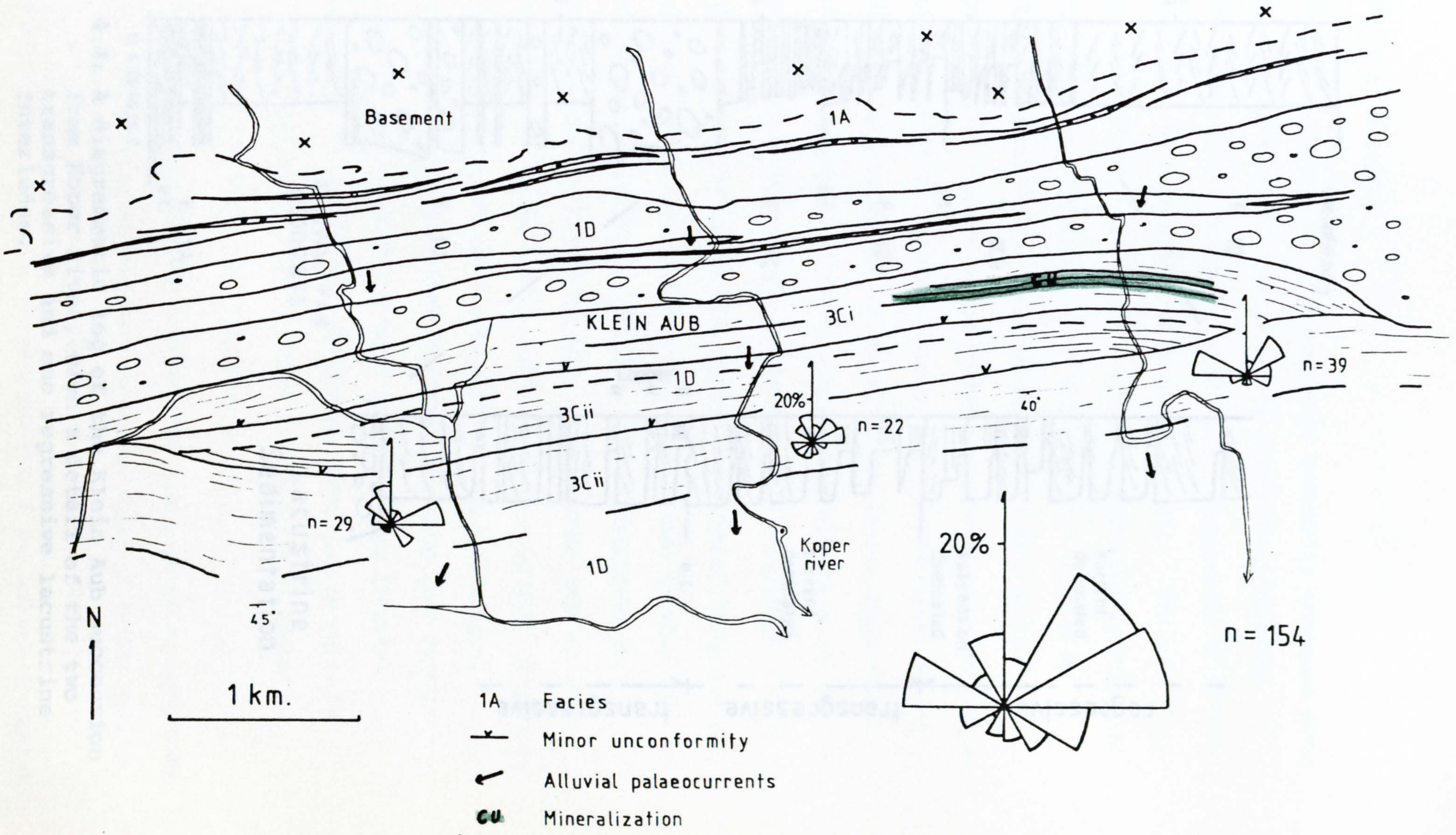


FIG. 4.3: Detailed Facies map of the Klein Aub area plus palaeocurrent rose.

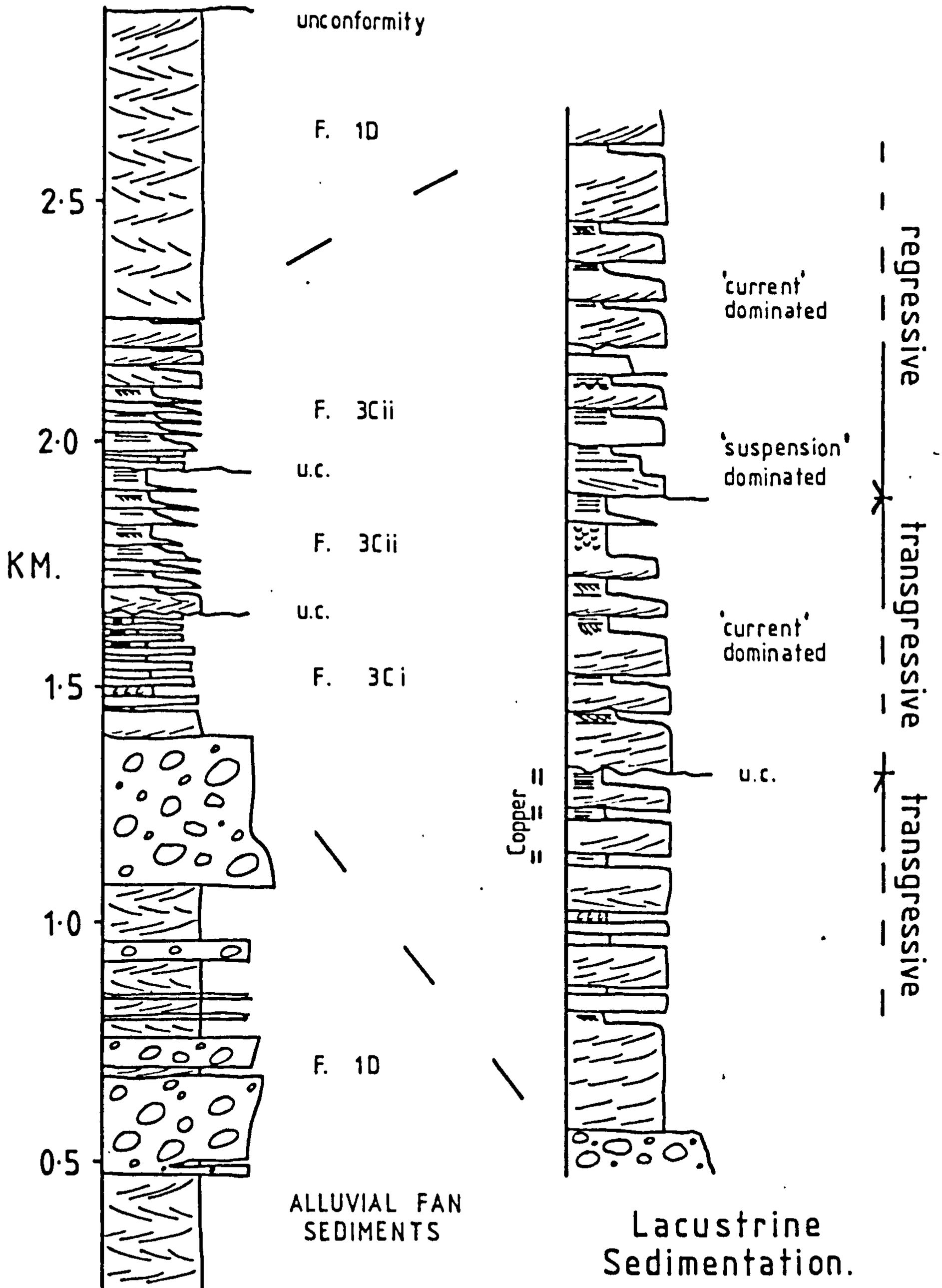


FIG. 4.4: A diagrammatic log of the Klein Aub succession from Koper River, with a detail of the two transgressive and one regressive lacustrine interludes.

rock-types with depth.

Two transgressive and one regressive lacustrine sequences occur at Klein Aub (Fig. 4.4). Sediments of facies 3C(i) form the initial transgressive sequence, consisting predominantly of alluvial fan sandstones with intercalated lacustrine bands. The unit fines upwards from alluvial sandstones and conglomerates and is truncated by a low angle unconformity ($< 10^{o}$ dip change). Many mine geologists have considered this unconformity to be a fault. However, detailed studies of the aerial photographs, the recognition of granitic clasts in the 'fault zone', and the occurrence of red alluvial fan sandstones (facies 1D) above the break, suggest that it is an interformational unconformity. Unconformities are not uncommon features at lake margins (Donovan, 1975; Collinson, 1978).

The alluvial sandstones are approximately 150 m. thick and pass upwards into lacustrine sediments of facies 3C(ii), forming the second transgression (Figs. 4.3, 4.4). These sediments are initially fluviatile-deltaic deposits which overlap onto alluvial fan sandstones in the West (Fig. 4.3). They pass up into suspension deposits, consisting of finer grey siltstones and mudstones. A second minor unconformity separates these sediments from coarser laminites and suspension deposits of the regressive lacustrine sequence (Figs. 4.3 and 4.4). Sediments above this unconformity overlap onto facies 3C(i) and alluvial fan deposits of facies 1D, in the east of the Klein Aub area (Fig. 4.3).

The suspension-dominated sediments of this regressive lacustrine unit give way to current-dominated deposits, which gradually pass up into alluvial fan sandstones of facies 1D. These alluvial sediments attain a thickness of approximately 1 km. and are truncated

by a major unconformity, on top of which the Nosib Group were deposited (Schalk, 1970).

In other areas where the Klein Aub Member is found, the volume of conglomerates is reduced and the mud flat sediments of facies 3B occur, which indicate a more distal environment. At Kagas Noord (Fig. 4.5), alluvial sandstones, grits and conglomerates fine upwards to mud flat sediments (3B) and then into lacustrine deposits of facies 3C(ii). Only one transgressive and regressive event is documented here.

At Kojeka, playa sediments of facies 3A occur in alluvial sandstones of facies 1D and are significant, since they contain copper mineralization (Fig. 4.2).

Palaeocurrents: Trough-beds from alluvial sandstones (1D) indicate that the Klein Aub Member was derived from the North (Fig. 4.2). Minor variations in direction reflect slight variations in basement typography and the morphology of the alluvial fan sediments during deposition.

Small-scale directional indicators (e.g. ripple forms and cross-stratification, flute casts, etc) indicate a northerly source for the mud flat (3B) sediments and three dominant palaeocurrent directions from lacustrine deposits (3C); of N to S; S.E. to N.W.; and W.S.W. to E.N.E. (Fig. 4.2). The former lacustrine direction indicates alluvial influence during deposition and the latter two directions, lacustrine palaeocurrents. At Klein Aub (Fig. 4.3), the W.S.W. to E.N.E. direction is dominant but individual palaeocurrent roses from different localities indicate a degree of variation. The origin of these lacustrine palaeocurrents is discussed later.

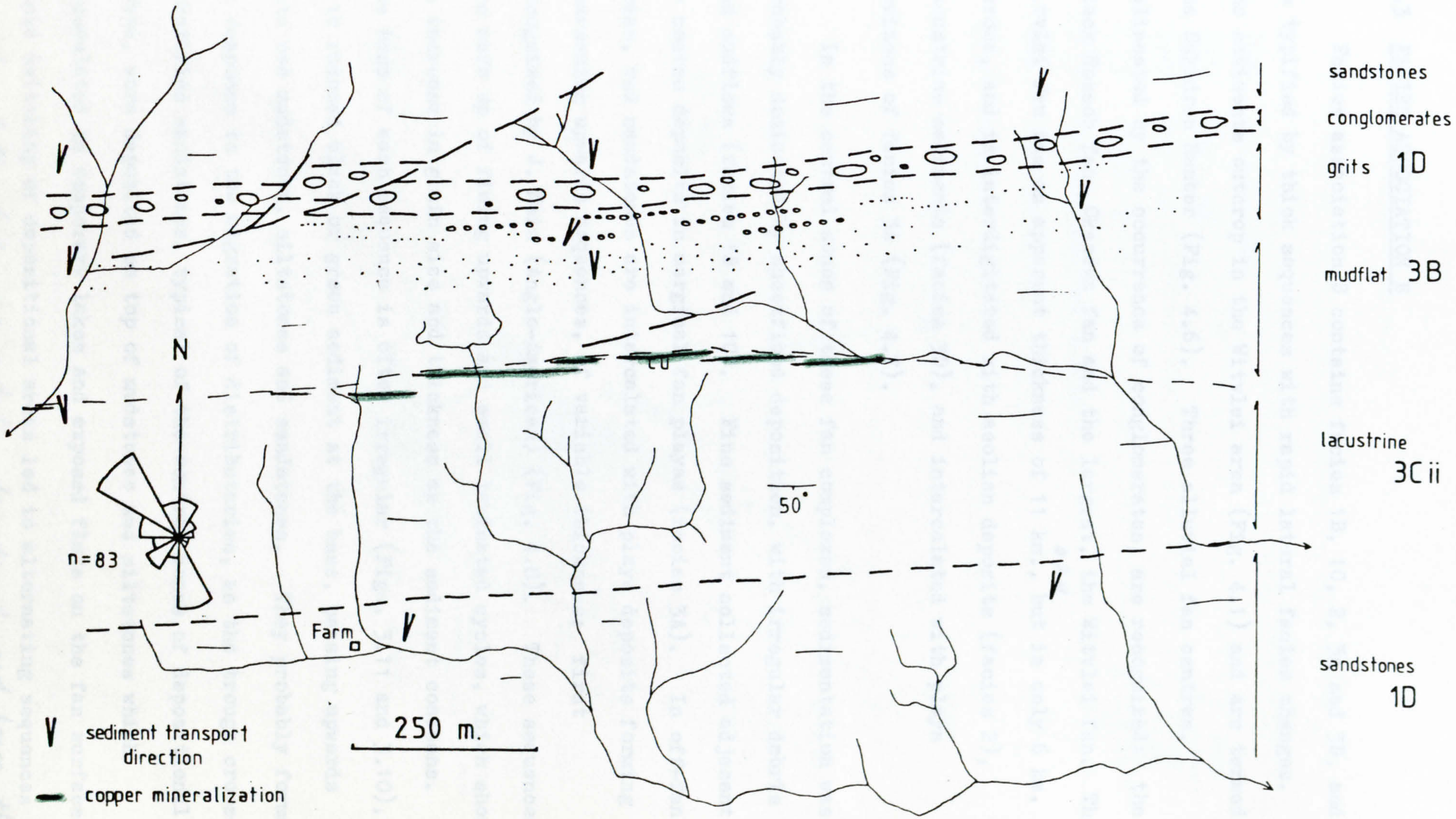


FIG. 4.5: Detailed Facies map of the Kagas Noord area, indicating a lacustrine embayment onto alluvial fan sediments.

4.3 FACIES ASSOCIATION B

Facies association B contains facies 1B, 1C, 2, 3A and 3D, and is typified by thick sequences with rapid lateral facies changes. The sediments outcrop in the Witvlei area (Fig. 4.1) and are termed the Eskadron Member (Fig. 4.6). Three alluvial fan centres, delineated by the occurrence of conglomerates, are recognized: the Black Nossob fan, Okasewa fan and the largest, the Witvlei fan. The Witvlei fan has an apparent thickness of 11 km.*, but is only 6 km. across, and is interdigitated with aeolian deposits (facies 2), lacustrine sediments (facies 3D), and intercalated with playa horizons of facies 3A (Fig. 4.7).

In the central zones of these fan complexes, sedimentation was probably dominated by sheetflood deposition, with irregular debris and mudflows (facies 1B and 1C). Fine sediment collected adjacent to coarse deposits in marginal fan playas (facies 3A). In off-fan areas, red sandstones are intercalated with playa deposits forming coarsening upwards sequences, of variable thickness; first recognized by J. Main (Anglo-American) (Fig. 4.8). These sequences are made up of fining upwards and small laminated cycles, which show an increase in grain size and thickness as the sediment coarsens. The base of each sequence is often irregular (Figs. 3.11 and 3.10), with reduced black or green sediment at the base, passing upwards into red mudstones, siltstones and sandstones. They probably formed in response to the migration of distributaries, as the trough cross-stratified sandstones, typical of the central zones of depositional lobes, were deposited on top of mudstones and siltstones which accumulated in temporary lakes and exposed flats on the fan surface. Rapid switching of depositional areas led to alternating sequences

* F.N. Dip angles of the strata are probably depositional and hence thickness measurements reflect the extent of fan progradation rather than true sediment thickness.

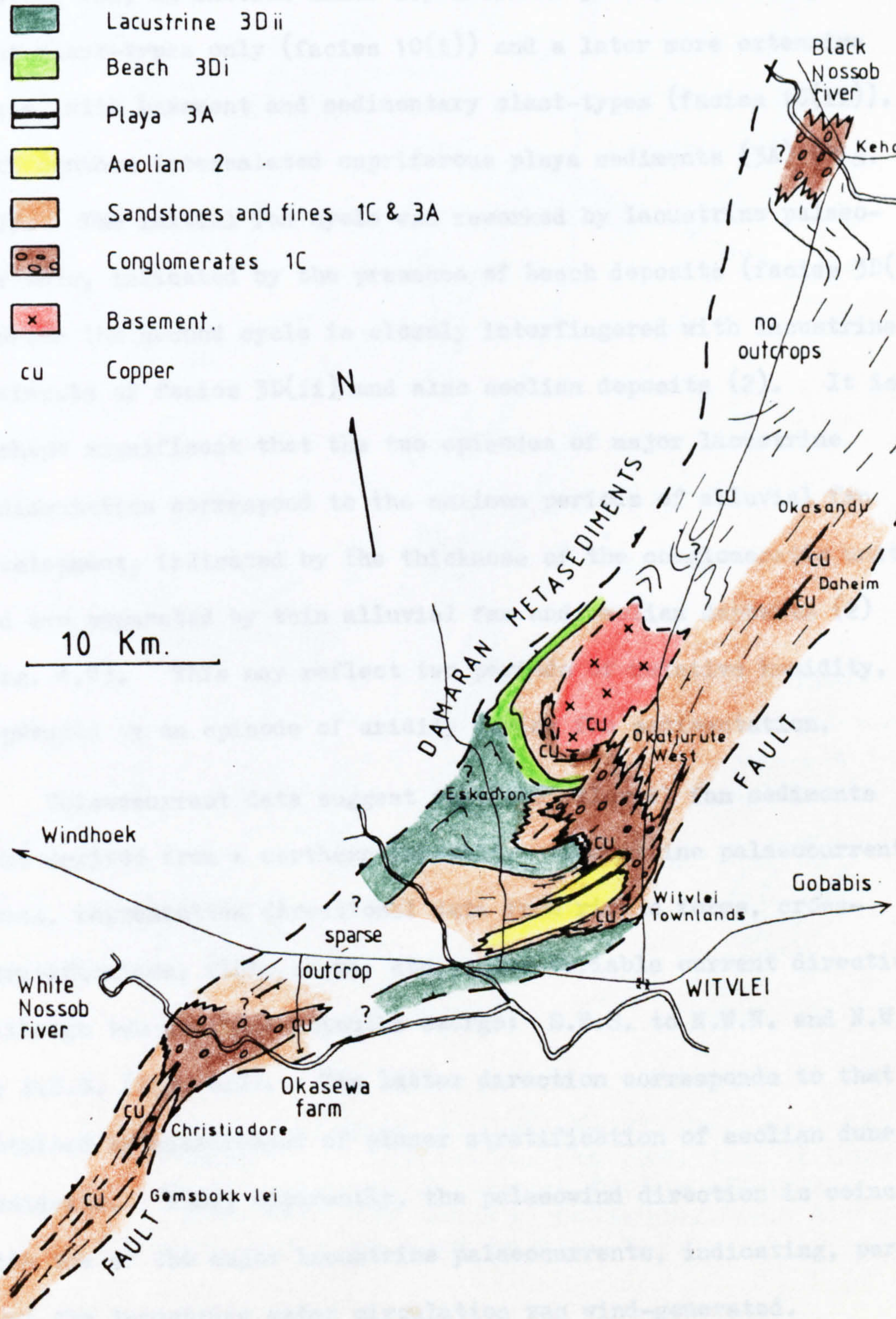


FIG. 4.6: Facies Association B, the ESKADRON MEMBER, containing Facies 1B, 1C, 2, 3A, and 3D (+1E on the Okasewa Fan).

of playa and alluvial sediment.

Two cycles of alluvial fan sedimentation are evident on the Witvlei fan, an initial minor depositional phase, containing basement clast-types only (facies 1C(i)) and a later more extensive phase, with basement and sedimentary clast-types (facies 1C(ii)). Both contain intercalated cupriferous playa sediments (3A) (Fig. 4.7). The initial fan cycle was reworked by lacustrine palaeocurrents, indicated by the presence of beach deposits (facies 3D(i)), whereas the second cycle is closely interfingered with lacustrine sediments of facies 3D(ii) and also aeolian deposits (2). It is perhaps significant that the two episodes of major lacustrine sedimentation correspond to the maximum periods of alluvial fan development, indicated by the thickness of the conglomeratic unit, and are separated by thin alluvial fan and aeolian deposits (2) (Fig. 4.7). This may reflect two periods of relative humidity, separated by an episode of aridity during fan sedimentation.

Palaeocurrent data suggest that the alluvial fan sediments were derived from a northern basement. Lacustrine palaeocurrent roses, representing directional data from ripple forms, cross-stratification, flute casts, etc., give variable current directions, although two dominant azimuths emerge: S.E.S. to N.W.N. and N.W.N. to S.E.S. (Fig. 4.7). The latter direction corresponds to that obtained by measurement of planar stratification of aeolian dune sediments. Thus, apparently, the palaeowind direction is coincident with one of the major lacustrine palaeocurrents, indicating, perhaps, that the lacustrine water circulation was wind-generated.

Wind currents in lakes are common and, along with geostrophic events, dominate lacustrine water circulations (Beadle, 1974;

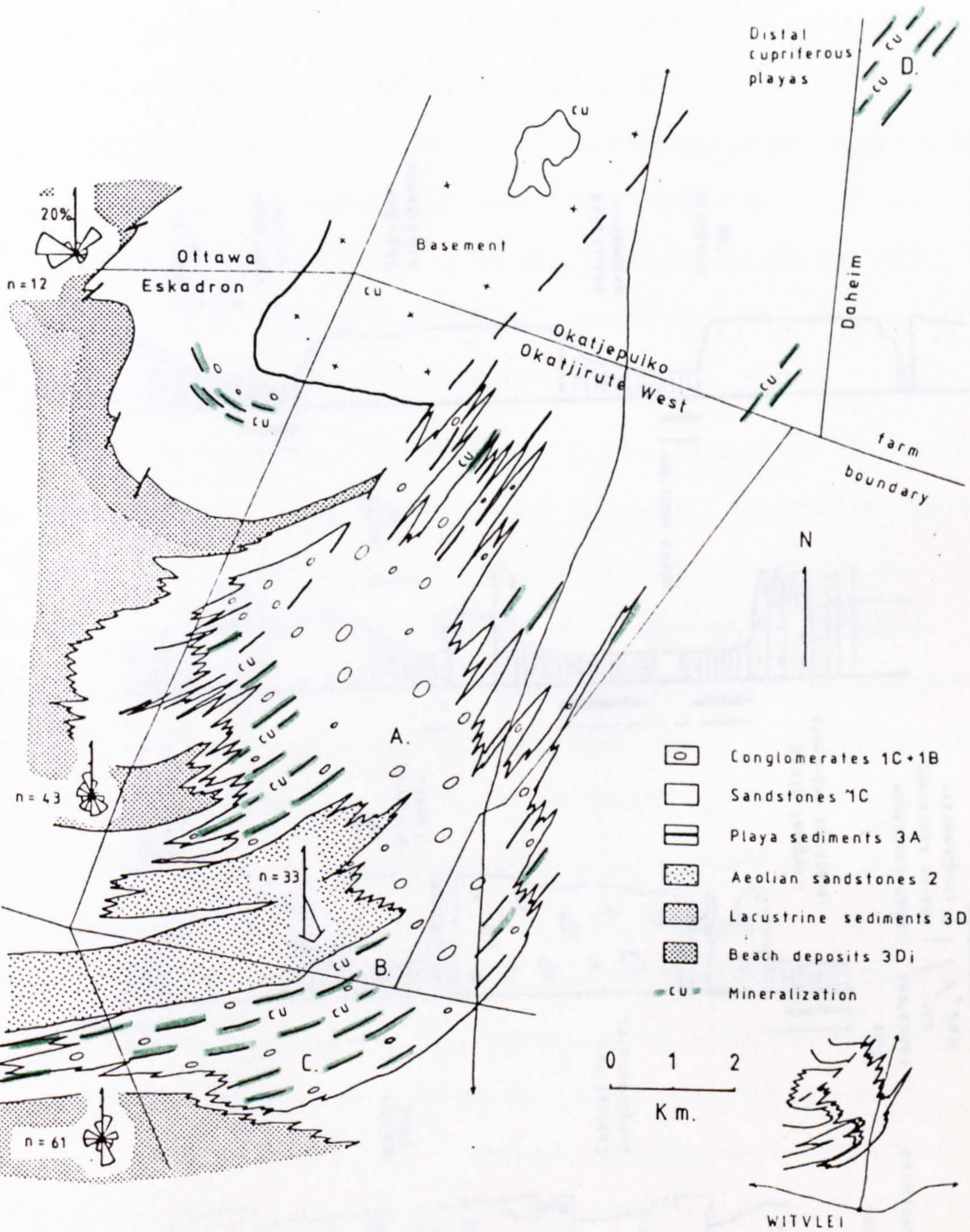


FIG. 4.7: Detailed Facies map of the Witvlei area (Fan complex), illustrating the position of Cupriferous playas and rapid lateral facies changes. Lacustrine and Aeolian palaeocurrents are shown. A-D. refer to logs in Fig. 4.8.

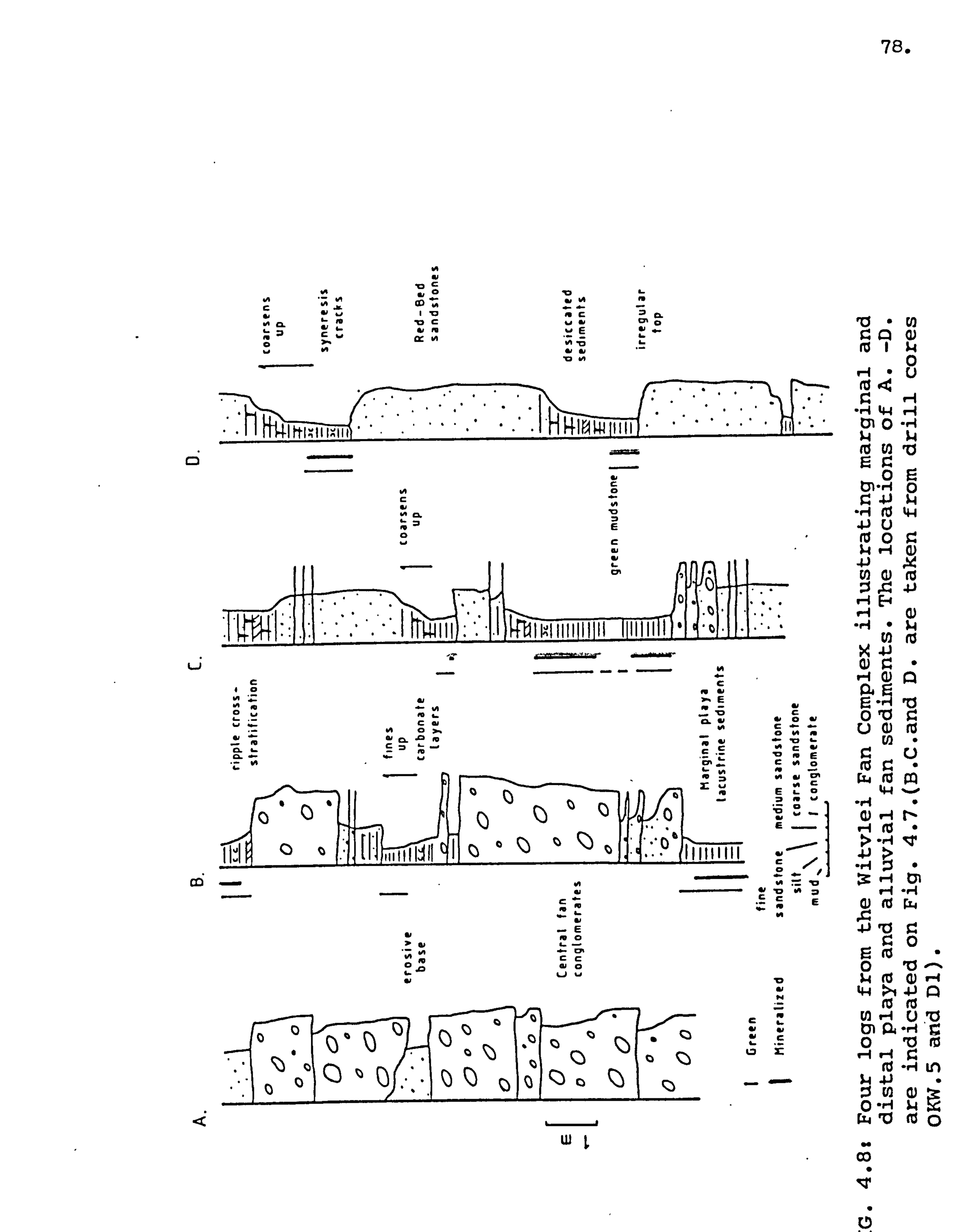


FIG. 4.8: Four logs from the Witvlei Fan Complex illustrating marginal distal playa and alluvial fan sediments. The locations of A. are indicated on Fig. 4.7.(B.C.and D. are taken from drill cores OKW.5 and D1).

Collinson, 1978). Evidence of lacustrine currents is apparent in ancient sediments, described by Donovan (1975), Hubert et al (1976), and Allen (1981 a and b). Wind-generated currents are often intermittent and lead to variable palaeocurrent directions. Allen (1981b) estimated the depth (10 m. max.) and width (20 km. max.) of the Ocadian basin in the Shetlands of Scotland, using wind-generated wave ripples and cross-stratification.

The Okasewa fan contains facies 1C, 3A, as well as 1B and 1E. Debris and mudflow deposits (1B) tend to occur in coarse fan areas, intermixed with sheetflood/streamflood deposits of facies 1C. The braided stream (3E), highly stratified, conglomeratic material occurs at the fan margins, thus suggesting a zonation of unsorted to well sorted conglomeratic units, from proximal to marginal fan areas; a feature previously reported by Bluck (1967) and Steel (1974). (See Chapter 3.2). Clast-types vary from basement only to sedimentary and basement types (Fig. 4.9), although the distribution of sedimentary clasts is complex and variable (from 0 - 100%). Two stages of fan development are suggested; an early fan with basement clast-types, followed by a later fan with complex mixtures of basement and sediment types. Figure 4.9 illustrates the upper part of the Okasewa fan where conglomeratic units are interfingered with playa sediments. A variation of basement clast-types only, to sedimentary types only, up into a mixture, is indicated. Contours for copper ore grade within intercalated playa horizons indicate the formation of ore shoots, towards the S.W. in the lower (basement clast-type) unit and towards S.E. in the upper (mixed sedimentary/ basement clast-type) unit. This probably indicates different sediment source directions.

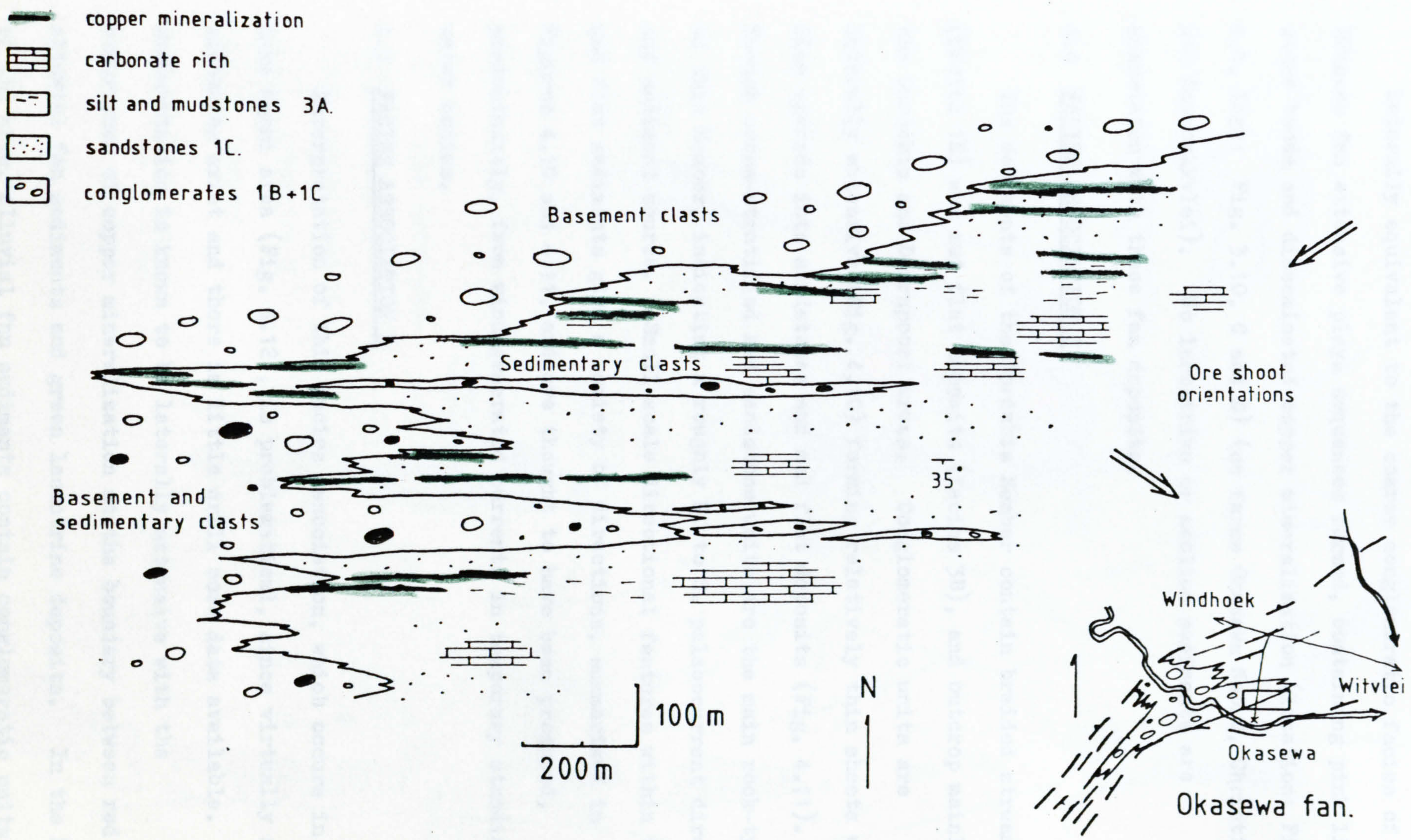


FIG. 4.9: A Facies map of part of the Okasewa Fan Complex constructed from drill core correlation made by the author and from information provided by General Mining.

Laterally equivalent to the coarse conglomeratic facies of the Okasewa fan extensive playa sequences formed, containing pink limestone bands and disseminated copper mineralization (location: Fig. 4.6, logs: Fig. 3.10, C and D) (on farms Okasewa Noord, Christiodore and Gemsbokkvlei). No lacustrine or aeolian sediments are associated with these fan deposits.

4.4 FACIES ASSOCIATION C

The sediments of the Dordabis Member contain braided stream (facies 1E) and mud flat deposits (facies 3B), and outcrop mainly in the Dordabis and Doornpoort areas. Conglomeratic units are laterally extensive (Fig. 4.10) forming relatively thin sheets which fine upwards into sandstones and mud flat deposits (Fig. 4.11). Trough cross-stratified red sandstone units are the main rock-type of this Member, indicating a roughly N. to S. palaeocurrent direction and sediment source. Small scale directional features within the mud flat sediments give a variety of directions, summarised in Figures 4.10 and 4.11, and are thought to have been produced, predominantly, from wind-generated currents in temporary standing water bodies.

4.5 FACIES ASSOCIATION D

Interpretation of this facies association, which occurs in the Lake Ngami area (Fig. 4.12), is problematical, since virtually no exposures exist and there is little drill core data available. Sedimentation is known to be laterally extensive with the occurrence of copper mineralization at the boundary between red alluvial fan sediments and green lacustrine deposits. In the N.E. of the area, alluvial fan sediments contain conglomeratic units,

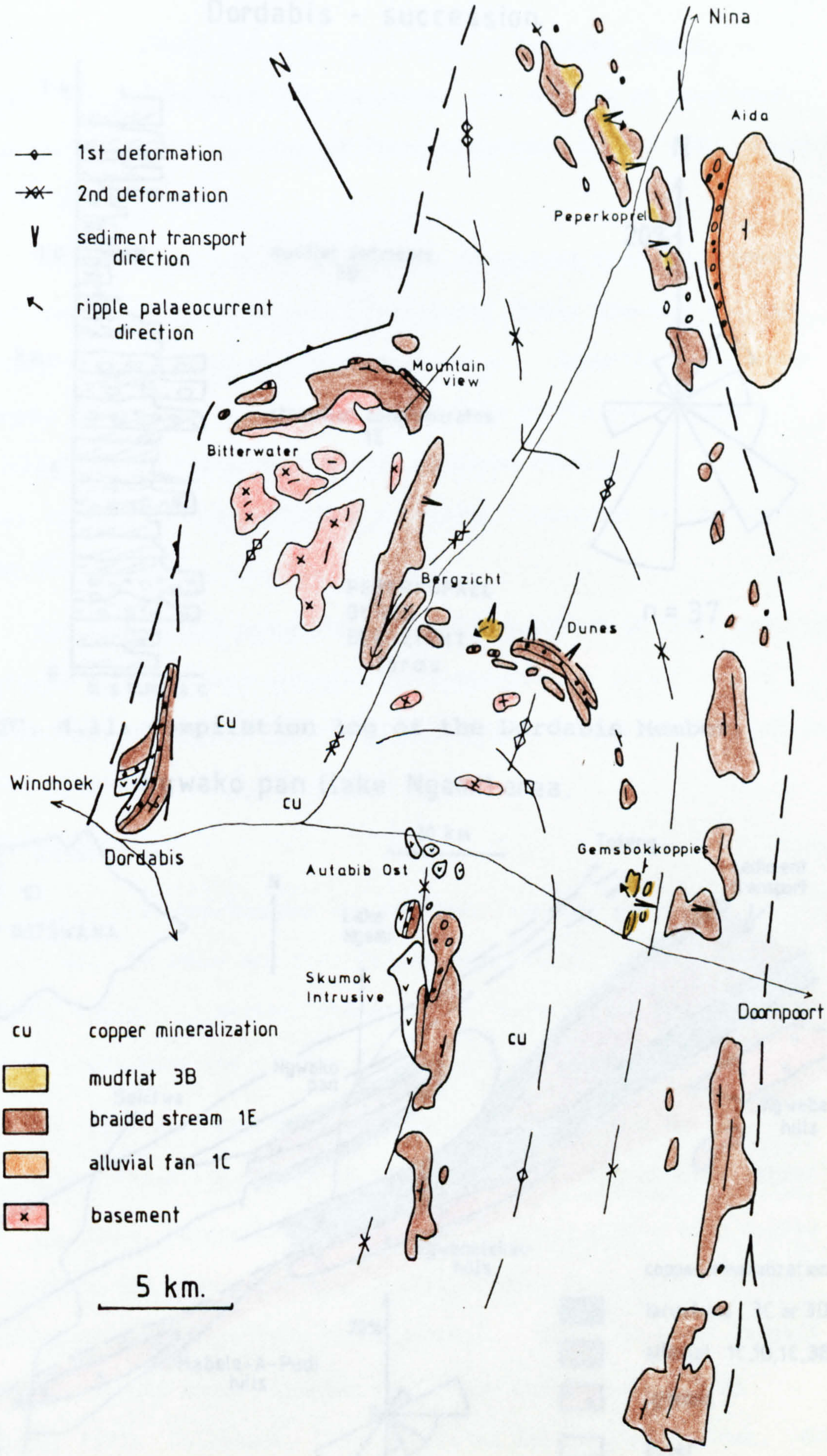


FIG. 4.10: Facies Association C, the DORDABIS MEMBER, containing Facies 1E and 3B (+ 1C). No lacustrine sediments occur in the Dordabis area.

Dordabis - succession.

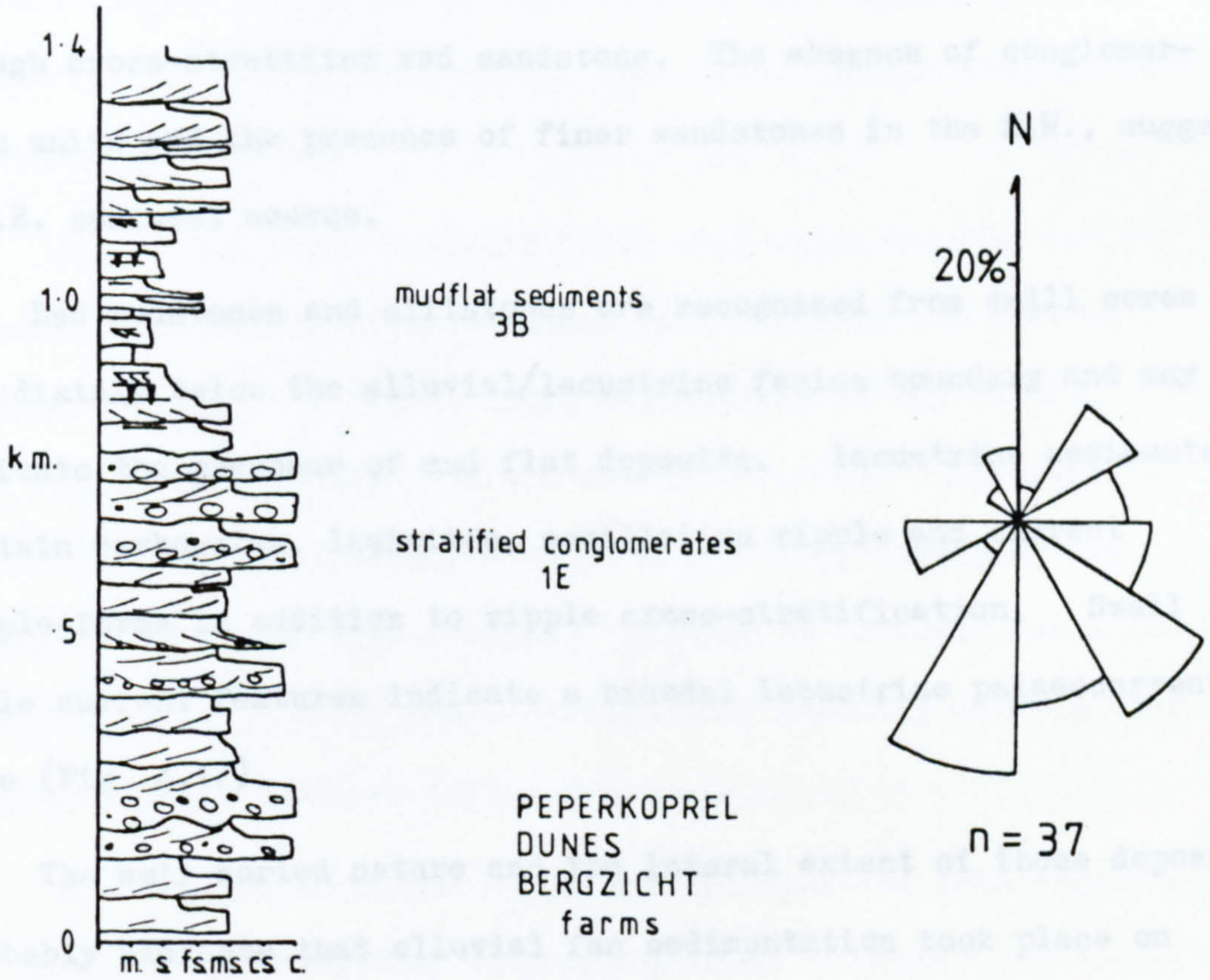


FIG. 4.11: Compilation log of the Dordabis Member.

Ngwako pan (lake Ngami) area.

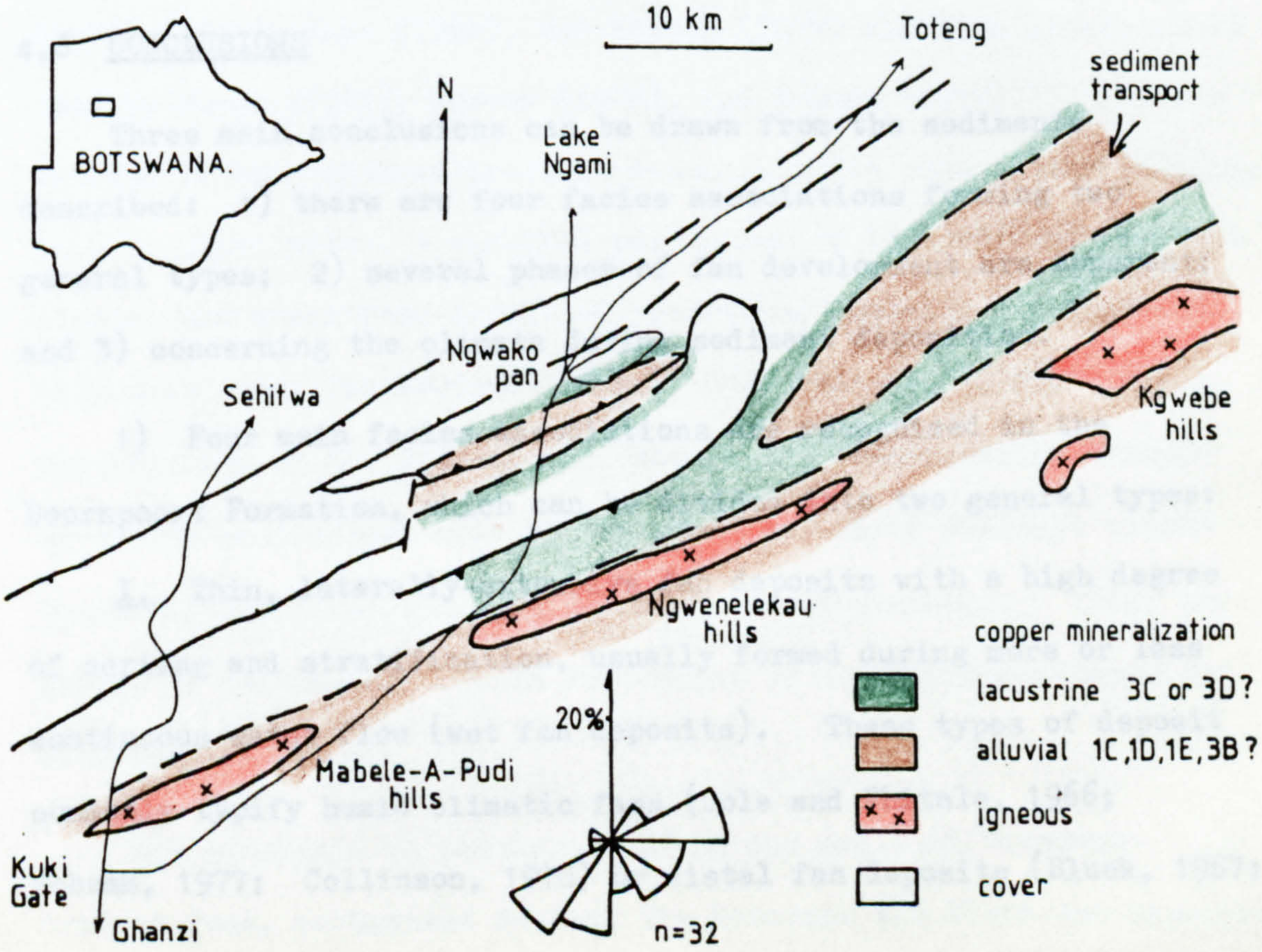


FIG. 4.12: Facies Association D, the LAKE NGAMI MEMBER.

with rounded clasts ($<$ 4 mm. diameter) of basement origin, and trough cross-stratified red sandstone. The absence of conglomeratic units and the presence of finer sandstones in the S.W., suggest a N.E. sediment source.

Red mudstones and siltstones are recognized from drill cores immediately below the alluvial/lacustrine facies boundary and may indicate the presence of mud flat deposits. Lacustrine sediments contain carbonates, laminites, oscillation ripple and current ripple-forms in addition to ripple cross-stratification. Small scale current features indicate a bimodal lacustrine palaeocurrent rose (Fig. 4.12).

The well sorted nature and the lateral extent of these deposits probably indicate that alluvial fan sedimentation took place on broad fans, possibly in the form of braided stream deposits, and in large lakes.

4.6 CONCLUSIONS

Three main conclusions can be drawn from the sediments described: 1) there are four facies associations forming two general types; 2) several phases of fan development are apparent; and 3) concerning the climate during sediment deposition.

1) Four main facies associations are recognized in the Doornpoort Formation, which can be divided into two general types:

I. Thin, laterally-extensive fan deposits with a high degree of sorting and stratification, usually formed during more or less continuous water flow (wet fan deposits). These types of deposit commonly typify humid climatic fans (Cole and Chitale, 1966; Schumm, 1977; Collinson, 1978) or distal fan deposits (Bluck, 1967;

Steel, 1974). Examples of this type of fan complex occur in the Klein Aub, Dordabis and probably Lake Ngami Members (facies associations A, C and D).

II. Thick, conglomeratic zones with rapid lateral facies changes into either finer sediment or lacustrine and aeolian deposits typify the second type, represented by the Witvlei, Okasewa and Nossob fan complexes of the Eskadron Member. Alluvial fan sediments contain debris and mudflow deposits, common on dry, semi-arid/arid climatic fans (Schumm, 1977) or in proximal fan areas (Bluck, 1967). These fan complexes were probably derived from narrow, stable sediment feeder zones.

2) Sedimentary clast-types are incorporated into conglomerates by two processes: either from the erosion of previously-deposited lithified sediment or by fan-head entrenchment and reworking. Entrenchment on modern fans has been described by Bull (1965), Lustig (1965), Ruhe (1964), and Wasson (1977) and from experimental fans by Hooke (1967), Weaver (1976), and Schumm (1977). This reworking of the fan-head produces deposits which show better sorting, smaller clast sizes, a variable percentage of basement and sediment clasts, and which form localized restricted deposits intercalated with more usual fan sediment (Ruhe, 1964; Tanner, 1976). Since the majority of the Witvlei and Okasewa fan conglomerates contain up to 50% sedimentary clasts, the sheer volume of sediment clast-types discounts their origin by fan-head entrenchment. Thus, the source of sedimentary clasts is thought to be previously-deposited alluvial fan rocks.

The existence of basement-derived and sediment/basement-derived fans, recognized in both the Eskadron and Klein Aub Members,

clearly indicates two periods of alluvial fan development. It is possible that the sediment/basement-derived fans were formed as a result of the erosion of the observed earlier basement-derived sediments or that the system was more complex, the earlier fans forming adjacent to local basement highs, whereas the later fans formed part of large fan complexes which prograded over the earlier deposits.

3) In addition to the identification of two separate alluvial fan cycles, these rocks enable speculation about the climatic conditions during deposition. Walker (1967a) suggested that the association of Red Bed alluvial fan sediments, wind-blown deposits and evaporitic minerals indicate a semi-arid/arid depositional climate. All parts of this association are present on the Witvlei fan. Evidence for a semi-arid/arid depositional climate is suggested by the occurrence of debris and mudflows, as well as by the large variety of basement clast-types in conglomerates. Blissenbach (1954) pointed out that alluvial fan conglomerates, formed in a semi-arid/arid climate, should contain virtually all the basement rock-types as clasts, due to the predominance of mechanical over chemical weathering in these conditions.* F.N. Doornpoort conglomerates from the Witvlei fan and Klein Aub Member contain most of the basement rock-types exposed to the North, as clasts, thus supporting the evidence for a semi-arid/arid climate.

4.7 ALLUVIAL FANS OF THE DOORNPOORT FORMATION

4.7.1 General Discussion

Sedimentation on alluvial fans is dominantly tectonically controlled, since uplift affects the rate of erosion and hence the sediment supply (Steel, 1974; Heward, 1978). Climate affects the

* Signs of weathering in basement-derived clasts are limited to the sericitization of feldspars and mechanical breakdown. No weathered rims or copper was found.

type of erosion, mechanical or chemical, the rate of sediment transport from the source to the fan, and the morphology of the fan itself. In semi-arid to arid climates, source rocks are broken off and stored in the source area. During storms, sediment is flushed from the source to the fan in rapid unsorted flows. In humid climates the source rocks are broken down by chemical weathering, forming fine clasts and sediment. Precipitation is more frequent and sediment is transported from the source at more regular intervals. Sediment is then progressively transferred to the deposition zone, usually a broad fan surface, where sediment is stratified and sorted by progressive distributary migration.

Heward (1978) described alluvial fan sediments from Northern Spain in terms of sequences, megasequences, and basin-fill sequences, in an attempt to understand their history. He suggested that sequences (0 to 10's of metres thick) form as a result of sedimentation style, whereas megasequences (10's to 100's of metres) reflect fan progradation, aggradation or entrenchment of the fan-head. Basin-fill sequences (100's to 1000's of metres), composed of sequences and megasequences, he attributed to reflect the tectonic history of the succession. Steel et al (1977), Steel (1978), and Bryhni (1978) used a similar approach to reconstruct the history of the Hornelen Basin of W. Norway. Sequences, megasequences and basin-fill sequences can be recognized in the Doornpoort Formation and prove useful in the classification of sedimentation styles, transgressive and regressive fan movements and the tectonic history during sedimentation.

4.7.2 Recognition of Sedimentary Cycles

Sequences in the Doornpoort Formation are generally defined as between 0 to 20 m., megasequences up to 1000 m. and basin-fill sequences up to 11,000 m.

Sequences: Fining and coarsening upwards sequences are present in alluvial fan, lacustrine, playa and mud flat facies (1C, 1E, 3A, 3B, 3C, 3D). Examples of fining upward sequences occur in:

a) Facies 1C and 1E, where conglomerates fine to sandstones in sheetflood/streamflood (Fig. 3.3A) and braided stream (Fig. 3.7) deposits, respectively.

b) Facies 3C and 3D, in which alluvial sandstones fine upwards to lacustrine siltstones, mudstones and limestones (Figs. 3.17B and 3.19B). These sequences were probably formed on a fluvial-lacustrine delta.

c) Facies 3A and 3B reflecting regressive fan lobe deposition (Figs. 3.10 C,D and 3.13).

Coarsening upward sequences are found in:

a) Facies 3A, in which playa mudstones and siltstones coarsen up to medium-grained sandstones of alluvial fan origin (facies 1C) (Figs. 3.10B and 4.8). This coarsening up is completed by a series of small fining upwards units (1-30 mm. in thickness), which probably represent individual depositional units from one flow. The coarsening sequences represent transgressional fan lobe deposition.

b) Facies 3C and 3D in the form of coarsening upward laminites and cycles from siltstones to sandstones.

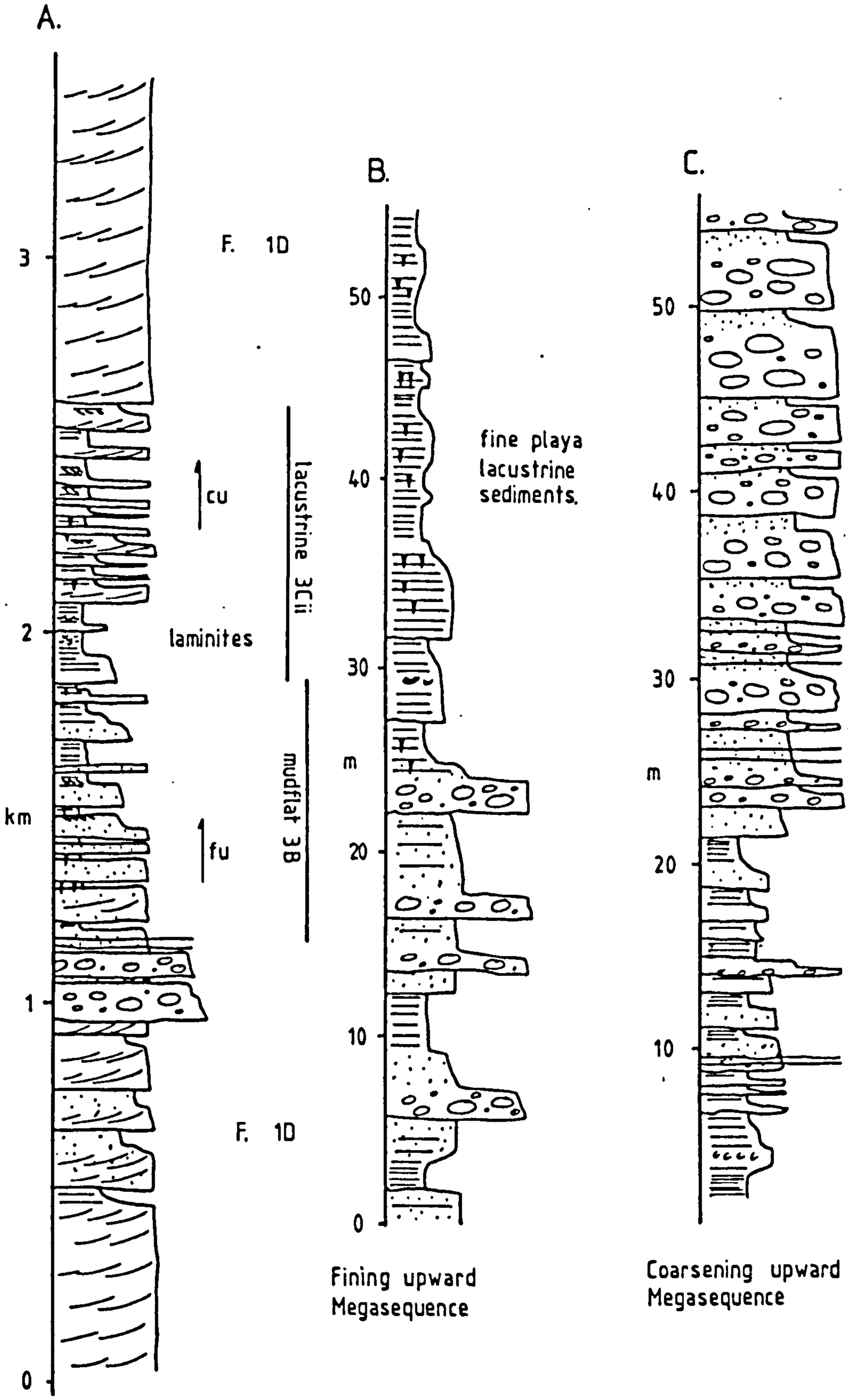
Although rare, these sequences again represent transgressional lobe migration on the adjacent fan surface.

Sequences from the Doornpoort sediments, therefore, appear to reflect depositional processes on the alluvial fan - e.g. lobe abandonment and transgression.

Megasequences: Coarsening upwards megasequences, identified in the Doornpoort facies associations, appear to reflect fan progradation (Fig. 4.13 A,C), whereas fining upwards megasequences indicate fan degradation (Fig. 4.13 A,B). Fan advance and retreat are related to tectonic uplift and scarp retreat due to prolonged erosion (Heward, 1978). Megasequences also form in response to fan-head entrenchment, a process which produces coarsening upward forms (Heward, op. cit.). The type of megasequence and the series of megasequences formed during deposition are dependent, also, on the position on the fan surface. Proximal megasequences may differ in form from distal megasequences, even though they were formed in response to similar uplift. These factors must be considered when fans are correlated using megasequences.

Megasequences, therefore, indicate both tectonic activity and alluvial fan development processes.

Basin-fill Sequences: Basin-fill sequences consist of packets of megasequences and sequences (two examples are shown in Figures 4.4 and 4.13A. Four principal megasequences are recognized in each Doornpoort sedimentary succession, from Klein Aub to Witvlei (Fig. 4.14). They indicate 1) an initial fan degradation; 2) a progradation event leading to the formation of conglomerates; 3) degradation with the transition from alluvial to lacustrine or mud flat sedimentation (in most cases); and 4) fan progradation forming



F. 10

F. 10

FIG. 4. 13: Examples of Megasequences (10's to 100's m) from the Doornpoort Formation; A. Fining and coarsening up megasequences, Karanus River (Fig. 4.2), B. fining up megasequence, Christiodore (CH.11)and C. coarsening up megasequence, Okasewa (OK.41).

alluvial sandstone and conglomeratic deposits. Other megasequences shown on Fig. 4.14 are considered to reflect variations in local fan development. The recognition of the four principal megasequences across the southern margin, implies a correlation of the different successions. This correlation, although it must be considered as tentative and problematical (being dependent on the recognition of principal and minor megasequences) is, however, significant, since alluvial fans of vastly different morphology are found to be laterally-equivalent. This statement refers to the correlation of thick laterally-impersistent fans from the Witvlei Member and thin laterally-extensive fan complexes of the Klein Aub, Dordabis and Lake Ngami Members. The correlation also implies that the different sedimentary successions were derived from a zone of source rocks with a similar tectonic history. This further supports the hypothesis expounded in Chapter II - that the Doornpoort sediments were derived from uplift of the Rehoboth-Irumide Orogenic Belt (1,100 MYR) which strikes E.N.E., parallel to the outcrop zone of the Doornpoort Formation.

4.8 ORIGIN OF FAN COMPLEXES

Four types of alluvial fan complex are recognized corresponding to facies associations A, B, C and D, which can be summarized in two general forms outlined in section 4.6:

I. Thin, laterally-extensive fan deposits of predominantly wet fan sediments, encompassing fan complexes A, C and D. Fan complex A (Klein Aub Member) contains extensive streamflood and braided stream deposits (reconstruction Fig. 4.15A) with clast sizes up to 0.5 m. (Figs. 4.2, 4.3, 4.4 and 3.4), whereas complex C (Dordabis Member) is characterized by well sorted, stratified braided stream deposits and clasts up to 100 mm. in diameter (Figs. 4.10, 4.11 and 3.7).

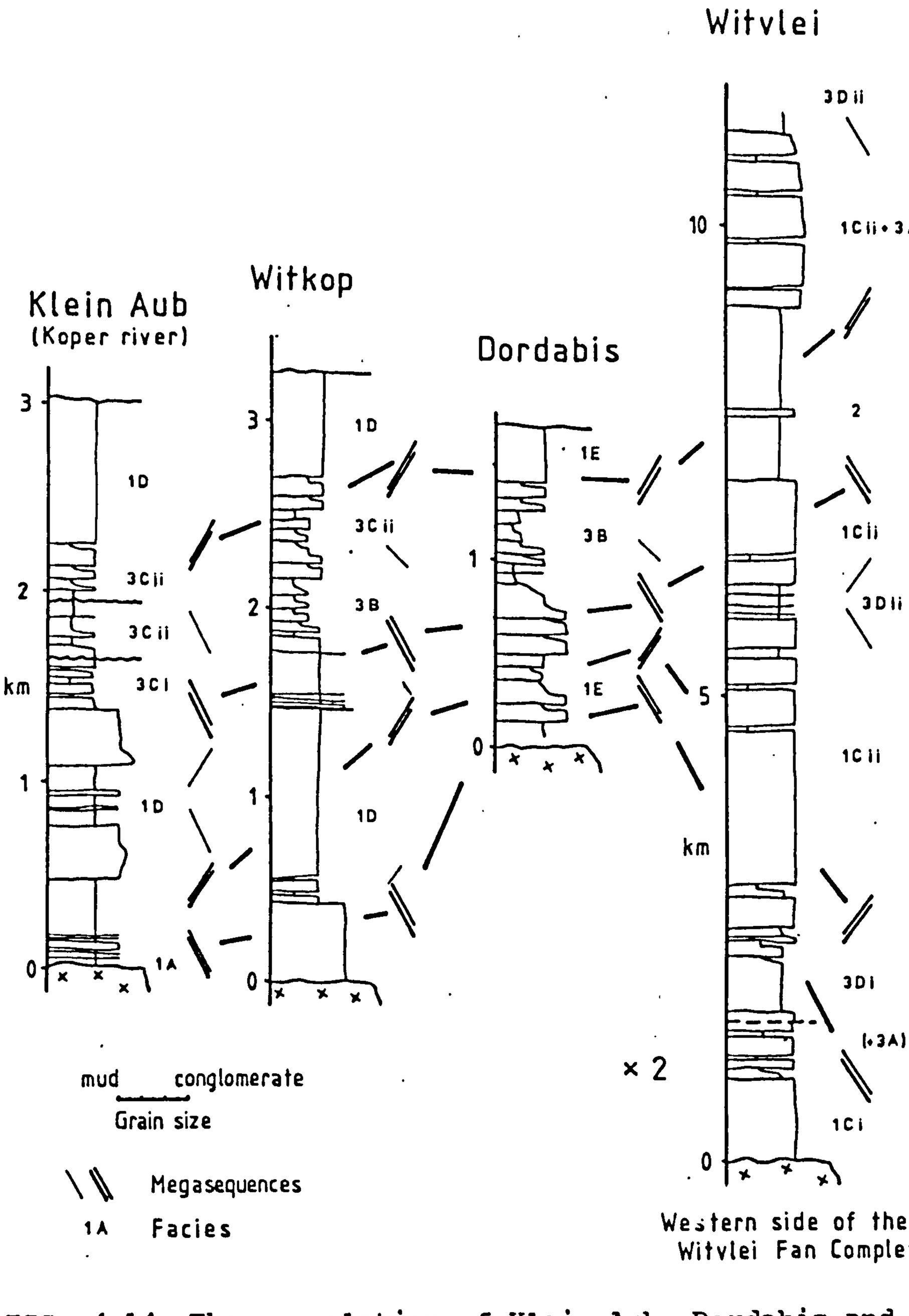


FIG. 4.14: The correlation of Klein Aub, Dordabis and Witvlei Members using coarsening up and fining up megasequences. Note the thickness variations.

II. Thick, laterally impersistent deposits with laterally equivalent lacustrine and aeolian deposits (Fig. 4.6) form Fan complex B (Eskadron Member). 'Dry fan deposits' (debris and mudflows) occur in proximal fan areas, whereas 'wetter fan sediments' (streamflood and possibly braided stream) typify marginal and distal fan positions. Alluvial fan deposits are intercalated with cupriferous playa sediments. (Reconstruction Fig. 4.15B).

Despite the different geographical location of each fan complex (Fig. 4.1) and their varied morphological characteristics, they can be correlated on the grounds of similar nature: relative lack of metamorphism, stratiform copper sulphide ore bodies (see Chapter II), and on their succession of megasequences (Fig. 4.14). Owing to this correlation, it is necessary to seek an explanation for the two morphological forms of fan complex. Three possible reasons spring to mind:

a) Proximal/Distal: One suggestion is to consider fan complexes A, C and D as distal equivalents of B. This follows from the thought that proximal fan sedimentation is typified by thick, impersistent deposits in contrast to the thin, more extensive sediments of distal fan areas. It is further supported by the occurrence of debris and mudflows on fans of complex B, whereas fan complexes A, C and D contain streamflood or braided stream sediments, forming a down-fan zonation of deposits, recognized elsewhere by Bluck (1967) and Steel (1974). This explanation, although attractive, is discounted, since fan complexes of B contain vast quantities of sedimentary clast-types, whereas complexes A, C and D contain few or no sedimentary clasts. If proximal sediments included large amounts of sedimentary clasts, distal equivalents should also.

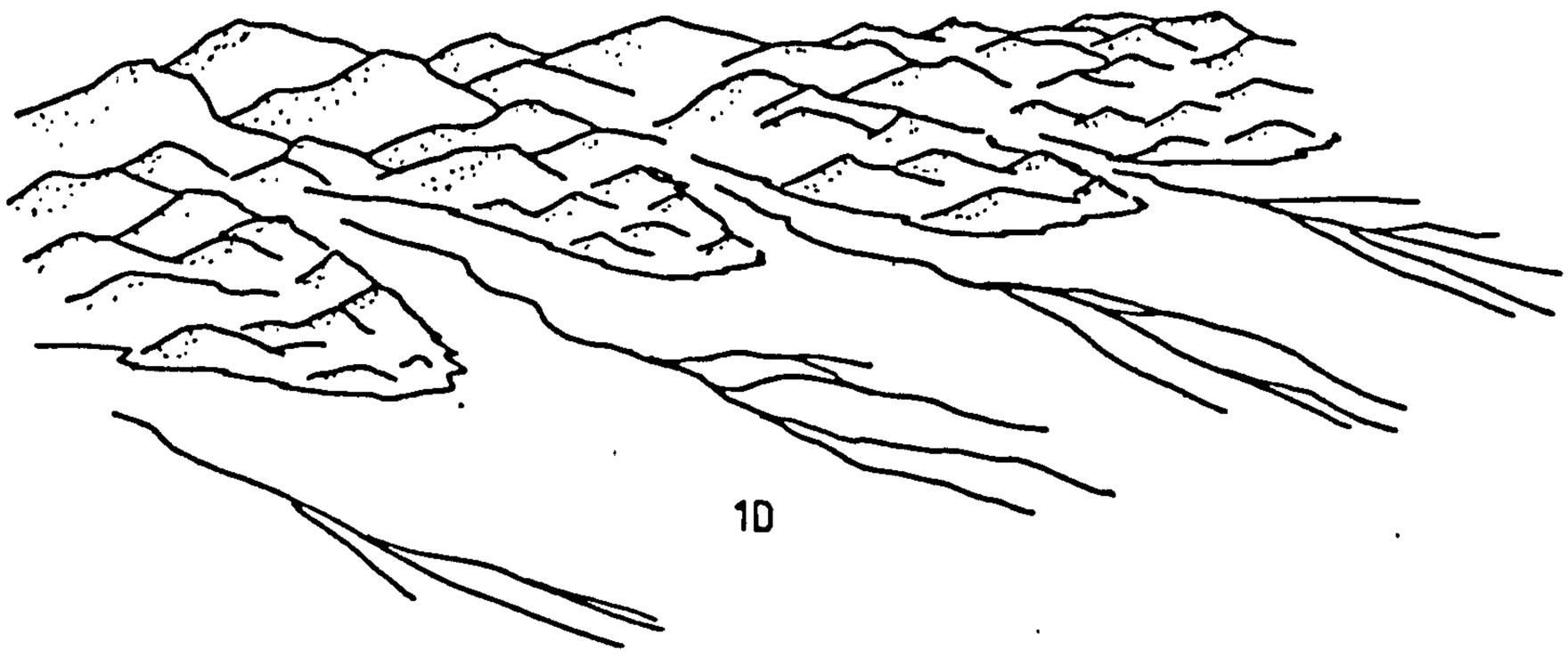


FIG. 4.15: a) Palaeogeographical reconstruction of the Klein Aub area.

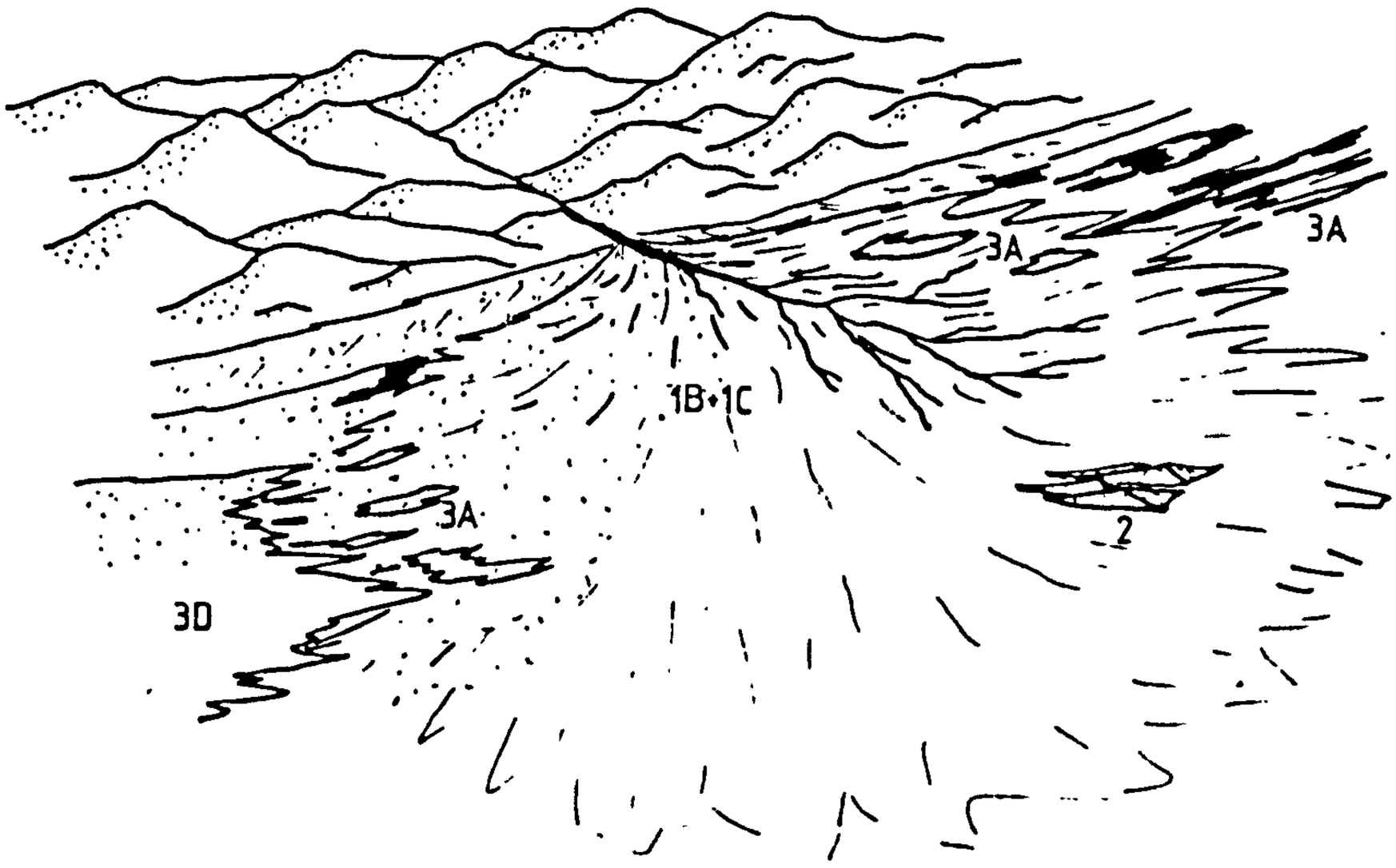


FIG. 4.15: b) Palaeogeographical reconstruction of the Witvlei Fan Complex.

b) Climatic: An alternative explanation involves different climatic regimes. Dry, semi-arid/arid climates result in the formation of thick fans with a preponderance of debris and mudflow deposits, whereas humid climate fans are typified by laterally extensive, thin fan development, formed from streamflood or braided stream deposition. Thus, fan complex B sediments may have been deposited in a drier climate than those of complexes A, C and D. This explanation would require wet climates in the Klein Aub, Dordabis and Lake Ngami areas with a drier climate in between, around Witvlei. If this were the case, the climatic changes must occur over an approximate strike length of 800 km. with an apparent gap of only 60 km. between the wet fan complex C of Dordabis and the dry complex B of Witvlei; it seems improbable.

c) Uplift/Feeder Zone: The final, most plausible explanation involves broad uplift and restricted fan feeder zones. Regional uplift at Klein Aub (fan complex A), for example, led to sedimentation on a broad alluvial plain with no restriction on the lateral migration of distributaries (Fig. 4.15A). In contrast, the Witvlei fan (complex B) was deposited from a narrow fan feeder zone, probably in response to localized uplift, possibly along fault zones. A stable feeder zone led to a great thickness of sediment, forming localized, laterally-variable deposits (Fig. 4.15B).

4.9 SUMMARY

Sediments of the Doornpoort Formation were deposited in a semi-arid to arid climate forming a series of molassic sedimentary successions, composed of alluvial fan, playa, lacustrine, mud flat and aeolian facies. Four laterally equivalent facies associations with distinct geographical settings are recognized, characterized by

two morphological forms: 1) thin, laterally persistent alluvial fan deposits with intercalated lacustrine and mud flat sediments (e.g. Klein Aub fan complex); and 2) thick, alluvial deposits interdigitated with playa, lacustrine and aeolian facies (e.g. Witvlei fan complex). Each alluvial fan complex contains at least two sedimentation cycles indicated by the incorporation of lithified red sandstone clasts (except the Dordabis and Lake Ngami Members). The Witvlei fan complex consists predominantly of reworked alluvial fan sediments and basement rocks, whereas the Klein Aub complex was mainly basement-derived. Thick, narrow fan complexes formed as a result of a stable, restricted channel feeder zone and localized uplift, whereas broad, thin fans were produced by regional uplift and deposition on wide alluvial plains.

CHAPTER V

DIAGENESIS OF THE DOORNPOORT SEDIMENTS

This chapter describes the diagenesis of metamorphosed and deformed, Late Proterozoic, red and non-red sediments of the Doornpoort Formation, using modern and ancient analogues. It includes a discussion of modern and ancient red sediments, a detailed description of post-diagenetic and diagenetic features of the Doornpoort sediments and speculations about the chemistry of the diagenetic fluids.

5.1 RED BED DIAGENESIS

All sedimentary facies, defined in Chapter III, contain red sediments - in fact, over 80% of the Doornpoort rocks are red. Their red colour is derived from ferric iron in the form of haematite, present as clots (usually after magnetite), grain cutans, authigenic growths and matrix disseminations. Recognizable diagenetic features include dissolution and replacement of detrital grains and authigenic mineral growths. A paragenetic sequence of authigenic minerals is evident in the aeolian sandstones (facies 2) of the Witvlei fan complex and partially established in other Doornpoort Red Beds.

The minerals and textures of these red sediments are complex, a result of the prolonged diagenetic, metamorphic and tectonic history of the rocks (Fig. 5.1). Each stage of their history can be recognized by the minerals and textures produced, and since the effects of deformation and metamorphism are variable across the southern foreland, the diagenesis of these sediments can be studied.

HISTORY OF THE DOORNPOORT RED BEDS

DEPOSITION - Facies Environment
Sorting - Porosity

DIAGENESIS - Dissolution
Replacement/Conversion
Authigenic Minerals (Paragenetic Sequence)

DEEP BURIAL - Calcite Replacement
Pressure Solution
Clays → Micas + Illite (Burial Metamorphism)

DEFORMATION - Two phases - Cleavage
Sub-grain development
Pressure Solution

METAMORPHISM - Lower Greenschist Facies
- Growth of - Epidote
- Micas
- Talc

FIG. 5.1: A brief outline of the history of Red Bed development, resulting in complex textures.

5.1.1 Continental Red Beds

Red Beds occur in a variety of geological environments and settings (Turner, 1980) and in both humid and semi-arid/arid climates (Walker, 1967 a,b, 1974). The red colour is generally considered to be of post-depositional origin, formed by the conversion of particulate goethite and other iron hydroxides to haematite (Walker, 1967a, 1976; Berner, 1969b; Langmuir, 1971), and precipitation of iron oxy-hydroxides from interstitial solutions, which then "age" to haematite (Walker, 1967a, 1976; Hubert and Reed, 1978; Walker et al, 1978). Two sources of iron have been suggested: firstly, detrital goethite and iron oxy-hydroxides, present within the silt and clay fractions of the sediment plus detrital opaque oxides, such as magnetite, titaniferous-magnetite and ilmenite (Van Houten, 1961, 1964, 1968; Walker, 1976; Ixer, Turner and Waugh, 1979); secondly, from in situ alteration of ferromagnesian silicates (Walker, 1967a, 1974, 1976; Walker et al, 1978; Hubert and Reed, 1978). A controversy over which source of iron is predominant has arisen (Van Houten, 1968; Walker et al, 1978). However, it has been suggested by Folk (1976) and Turner (1980) that detrital iron accounts for the colouration of fine sediment, whereas in situ alteration is probably the dominant source of iron in the coarser sediments.

Seemingly, ancient Red Beds are characterized by a lack of ferromagnesian minerals, the presence of 'clay ball' pseudomorphs after plagioclase feldspars and authigenic minerals - predominantly as over-growths on detrital grains (e.g. Waugh, 1970, 1978; Walker, 1976; Kessler, 1978). In contrast, Recent and Cenozoic Red Beds

contain partially dissolved or replaced ferromagnesian minerals and small authigenic mineral phases forming in pore spaces and dissolution voids (Walker, 1967 a,b; Walker et al, 1978). Walker et al (1978) outlined a model illustrating the stages of early diagenesis in 1st cycle desert alluvium (Fig. 5.2). Three stages were identified: 1) an initial post-depositional detrital clay infiltration; 2) alteration of amphiboles, pyroxenes and Ca-plagioclase; and finally, 3) the onset of K-feldspar and quartz alteration, plus the growth of authigenic minerals - principally, haematite, zeolites, clay minerals, quartz, K-feldspar and calcite. Walker (1976) suggested that the removal and replacement of ferromagnesian minerals and the dissolution and recrystallization of early authigenic minerals, account for the mineralogical maturity and authigenic minerals and overgrowths in ancient Red Beds.

After the removal of the effects of deformation, metamorphism and deep burial, the diagenetic features of the Doornpoort red sediments are similar to ancient Red Beds.

5.1.2 Doornpoort Red Beds

a) Post-diagenetic features

Since metamorphism is associated with deformation and that their effects are variable across the southern foreland, diagenetic, deep burial, metamorphic and deformational minerals and textures can be recognized. Sediments from the Klein Aub/Witkop region and the Lake Ngami area have been effected by penetrative deformation and metamorphism, whereas rocks of the Witvlei and Dordabis areas are less deformed. Thus, diagenetic studies have been centred on the Witvlei area and the effects of deformation and metamorphism are best described from the Klein Aub area.

DIAGENESIS IN FIRST-CYCLE DESERT ALLUVIUM, UNITED STATES AND MEXICO

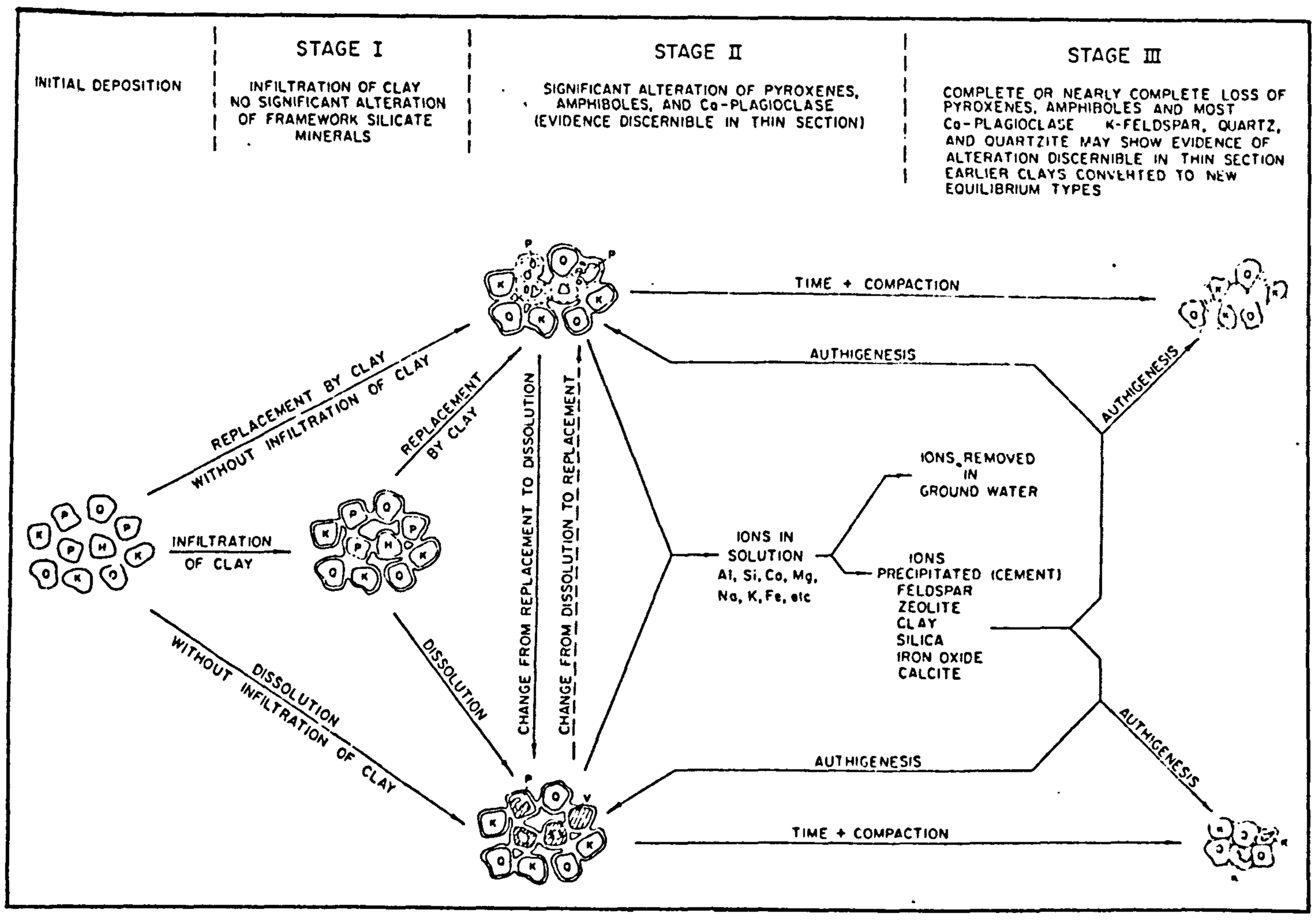


FIG. 5.2: The diagenesis of Recent to Cenozoic alluvial fan Red Beds from the Soronan Desert, United States and Mexico ; taken from Walker et. al. (1978). Alteration and the formation of authigenic minerals are the two essential processes.

Figure 5.3 illustrates the mineralogical and textural complexities developed in the Red Beds following a long tectono-thermal history (Fig. 5.1). Metamorphic chlorite, muscovite and epidote form in the cleavage and epidote also surrounds diagenetic pseudomorphs, of mainly sericite.

Deformation: This section describes the detailed effects of deformation; the more regional aspects have been covered in Chapter II. Three main textures are recognizable in the Klein Aub Mine area: a) a strong cleavage, most intense in fold hinges, forming zones of broken grains (Fig. 5.3); b) the development of sub-grains which form in response to pressure. Large grains unstable during deformation recrystallize to form smaller equivalents (Hobbs, Means and Williams, 1976, pp. 73-135; White, 1976). Sub-grain formation is restricted to intense zones of deformation and is recognized in sandstones from Witvlei and Klein Aub; c) pressure solution effects, illustrated by stylolite formation and sutured grain boundaries (Fig. 5.13).

Metamorphism: Deformation is associated with lower green-schist facies metamorphism, indicated by the growth of muscovite, chlorite and epidote (Fig. 5.3). Epidote also forms at the boundaries of diagenetic pseudomorphs and detrital grains.

Deep Burial: Deep burial effects include pressure solution and the conversion of clay minerals to micas and illite. Pressure solution resulted in stylolite formation and the development of sutured grain boundaries. Deep burial and deformational pressure solution are inseparable effects and are only distinguished since they are more common in deformed areas. Clay mineral conversion resulted in the formation of illite, chlorite and muscovite - a

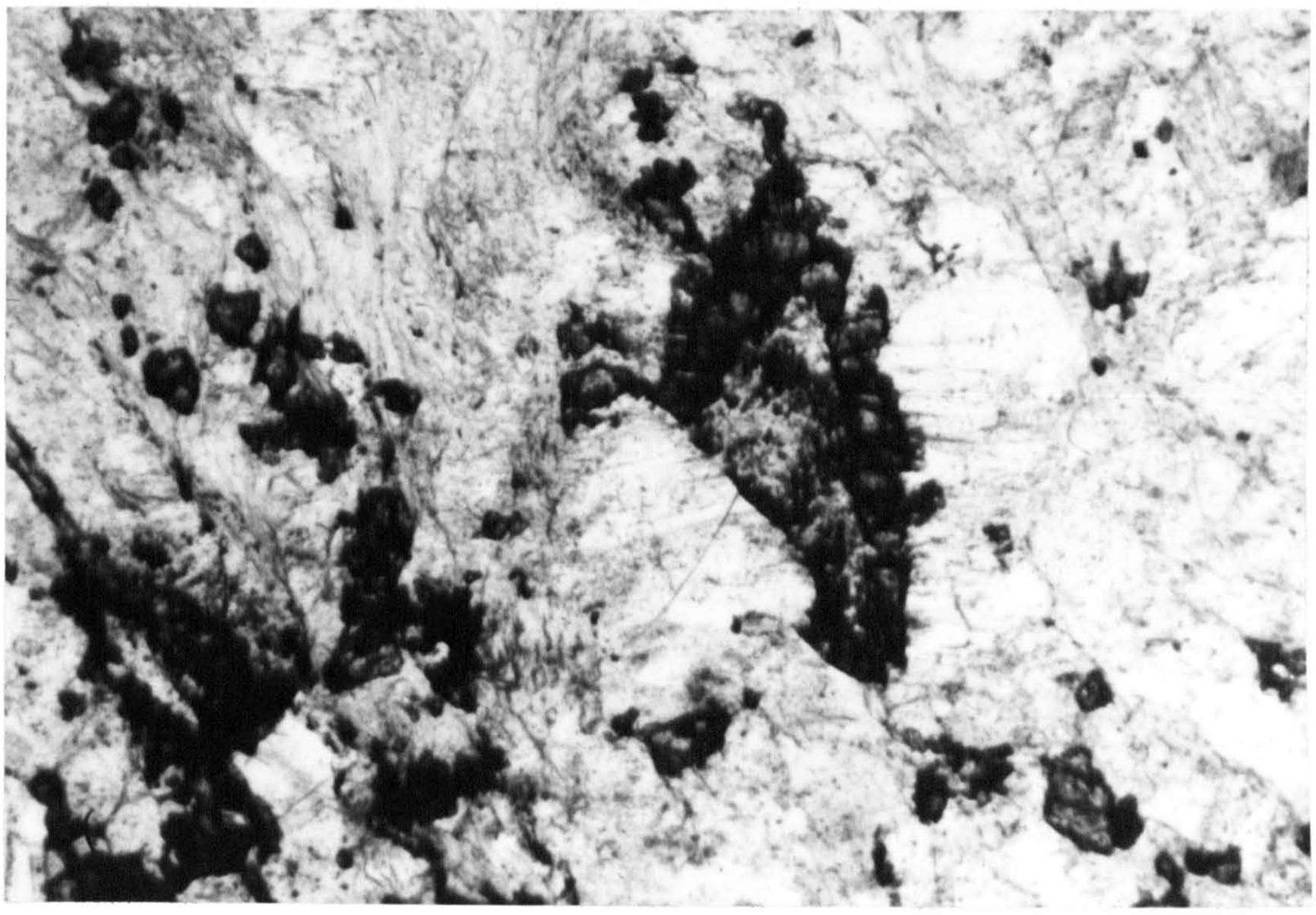


FIG. 5.3: Photograph (ppl.) and sketch indicating the mineralogical and textural complexity of the Doornpoort Red Beds (rock from Klein Aub, TS. 41027.). Metamorphic chlorite, muscovite and epidote form in the cleavage of the rock, which shatters detrital grains. Metamorphic epidote also surrounds diagenetic pseudomorphs - containing mainly sericite.

reaction which occurs on the boundary between deep burial diagenesis and burial metamorphism (see Miyashiro, 1973, p.37; Blatt et al, 1980, p.361). Micas formed by burial metamorphism are randomly orientated (Fig. 5.13) and may occur within grains, whereas those formed during lower greenschist facies metamorphism are aligned along cleavage directions. The effects of deep burial are most easily recognized in the least deformed areas.

b) Diagenetic features

This section contains detailed descriptions of diagenetic features present within the Doornpoort Red Beds, predominantly from the Witvlei fan complex.

Dissolution and Replacement - Mineralogical Maturity: A striking feature of the Doornpoort Red Beds is the maturity of the detrital mineral assemblage. It consists, dominantly, of quartz, feldspars and opaque iron oxides, with minor amounts of epidote, mica, sphene, hornblende, zircon and rutile. This is in sharp contrast to the wide variety of minerals in the provenance rocks. Minerals, such as olivine, pyroxene, hornblende and epidote, are much more common in provenance areas and rare in the sediments. This is surprising, since during mechanical weathering (such as predominates in semi-arid/arid climates), these minerals have a high survival potential and thus should form important constituents of the sediments. It is assumed that they have been removed during diagenesis.

Walker (1967a) and Walker et al (1978), in their description of the diagenesis of first cycle alluvial fan sediments of the Soronan Desert of Western U.S.A., clearly outlined the age-dependent removal of ferromagnesian minerals, by processes of dissolution and

replacement. Walker (1976) indicated that this process probably accounted for the mineralogical maturity of all ancient Red Beds. Many examples of mineralogically-mature Red Beds are cited in the literature (e.g. Waugh, 1970, 1978; Hancock, 1978; Kessler, 1978).

Evidence supporting the early diagenetic removal of unstable detrital minerals from the Doornpoort red sediments is indicated by dissolution and replacement textures:

1) In the fluvial sandstones of the Witvlei fan complex (facies 1C(ii)), epidote and micas have undergone diagenetic alteration, releasing iron (Fig. 5.4) - now present as haematite halos around the altering grains. Walker (1976, pp. 275-7) describes similar textures.

2) The replacement of plagioclase by clay minerals and micas is a feature found in all the Doornpoort Red Beds, indicating the breakdown of detrital feldspar in unstable conditions. Various stages of this breakdown are preserved, leading to the production of 'clay balls' (Figs. 5.5 and 5.12). These textures were also described by Walker (1976), although the principle alteration mineral was kaolinite, which was probably metamorphosed in the Doornpoort sediments to yield illite* and muscovite (sericite).

3) Finally, the occurrence of dissolution voids in feldspars and quartz, recognized using Scanning Electron Microscopy (Fig. 5.6). It is not 100% certain that these are diagenetic features.

The mineralogical maturity of the Doornpoort Red Beds, together with evidence provided by dissolution and replacement textures observed in the sediments, indicate that early destructive diagenetic reactions probably removed detrital phases.

* F.N. Varified using the Electron-Microprobe.

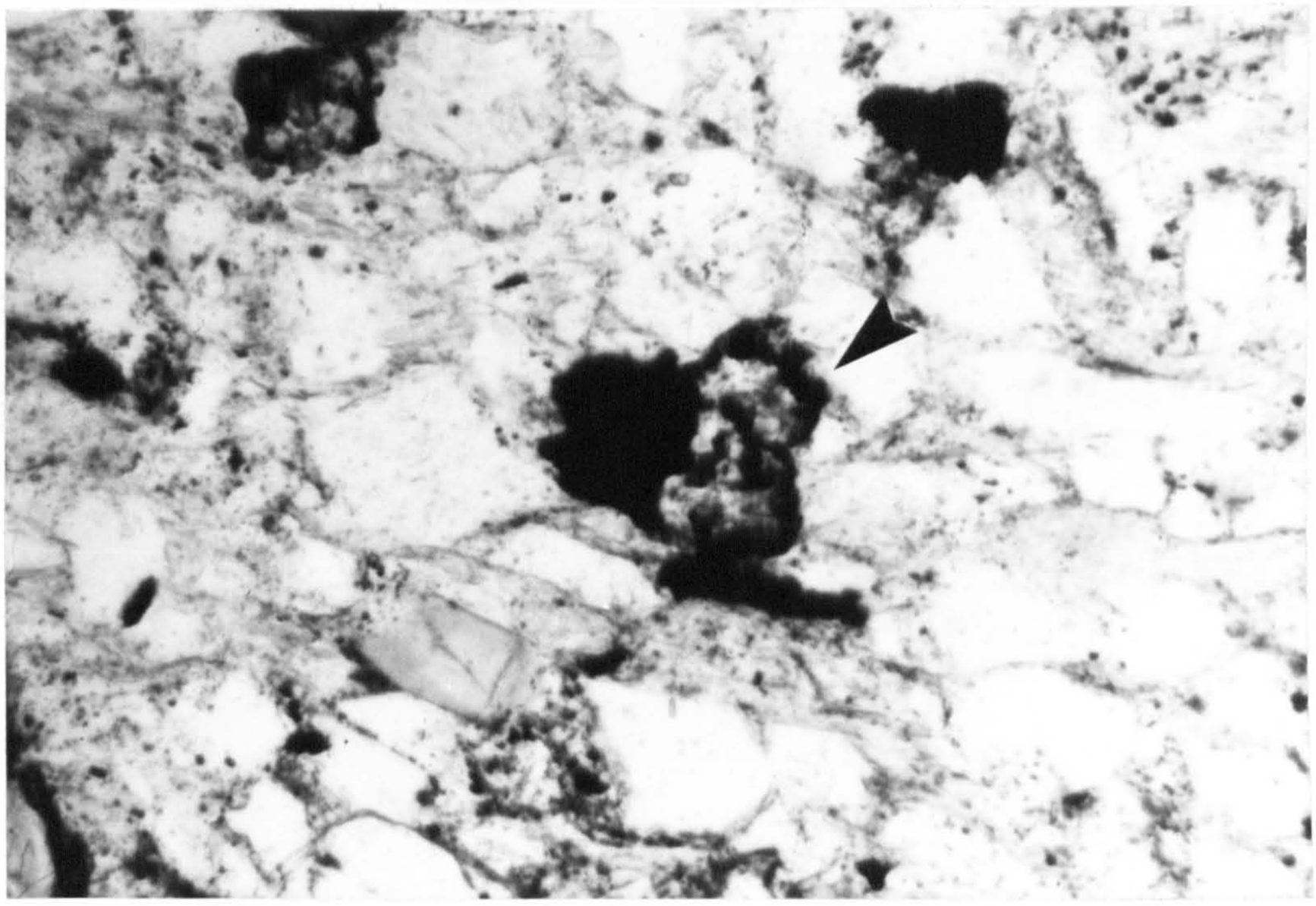


FIG. 5.4: a) Photomicrograph showing an alteration halo of haematite around detrital epidote (TS. 41027, Klein Aub, ppl.).

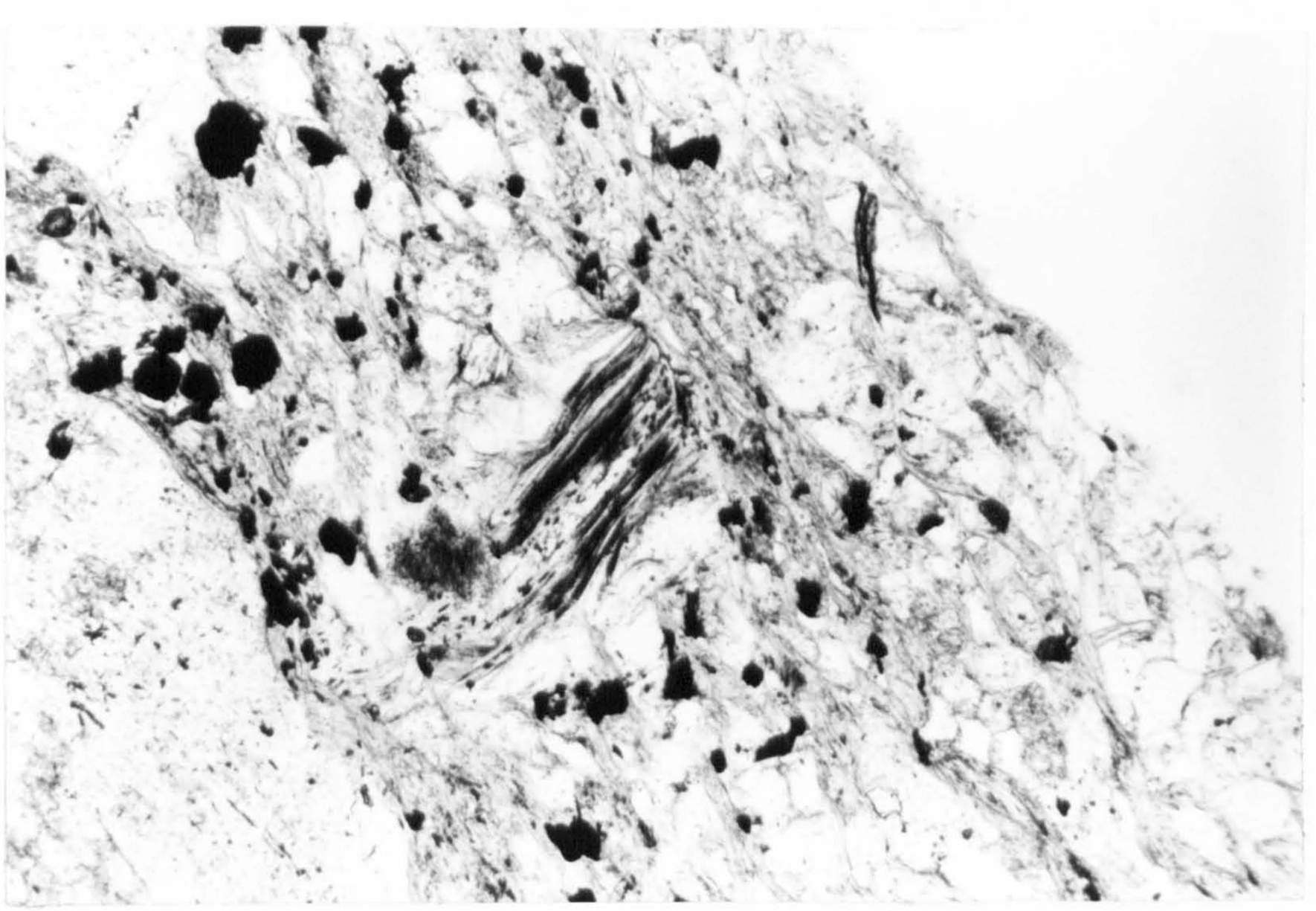


FIG. 5.4: b) Haematite halos around detrital mica ; altered micas lie oblique to the cleavage direction, SE.- NW. on this photomicrograph (TS. 41027, ppl.).

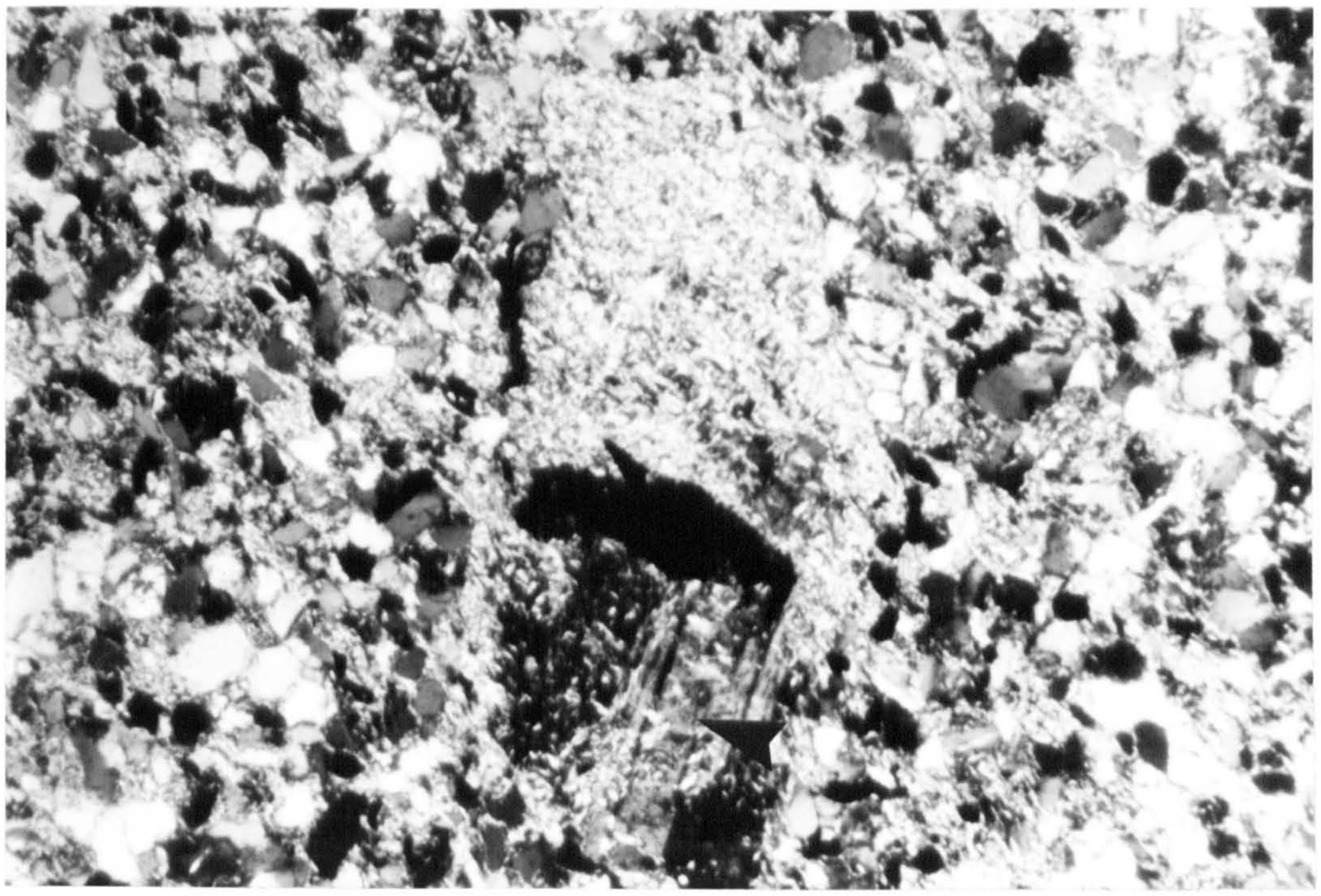


FIG. 5.5: a) Partial replacement of a detrital plagioclase grain(twinned) by sericite and illite (TS.41051, ppl.).

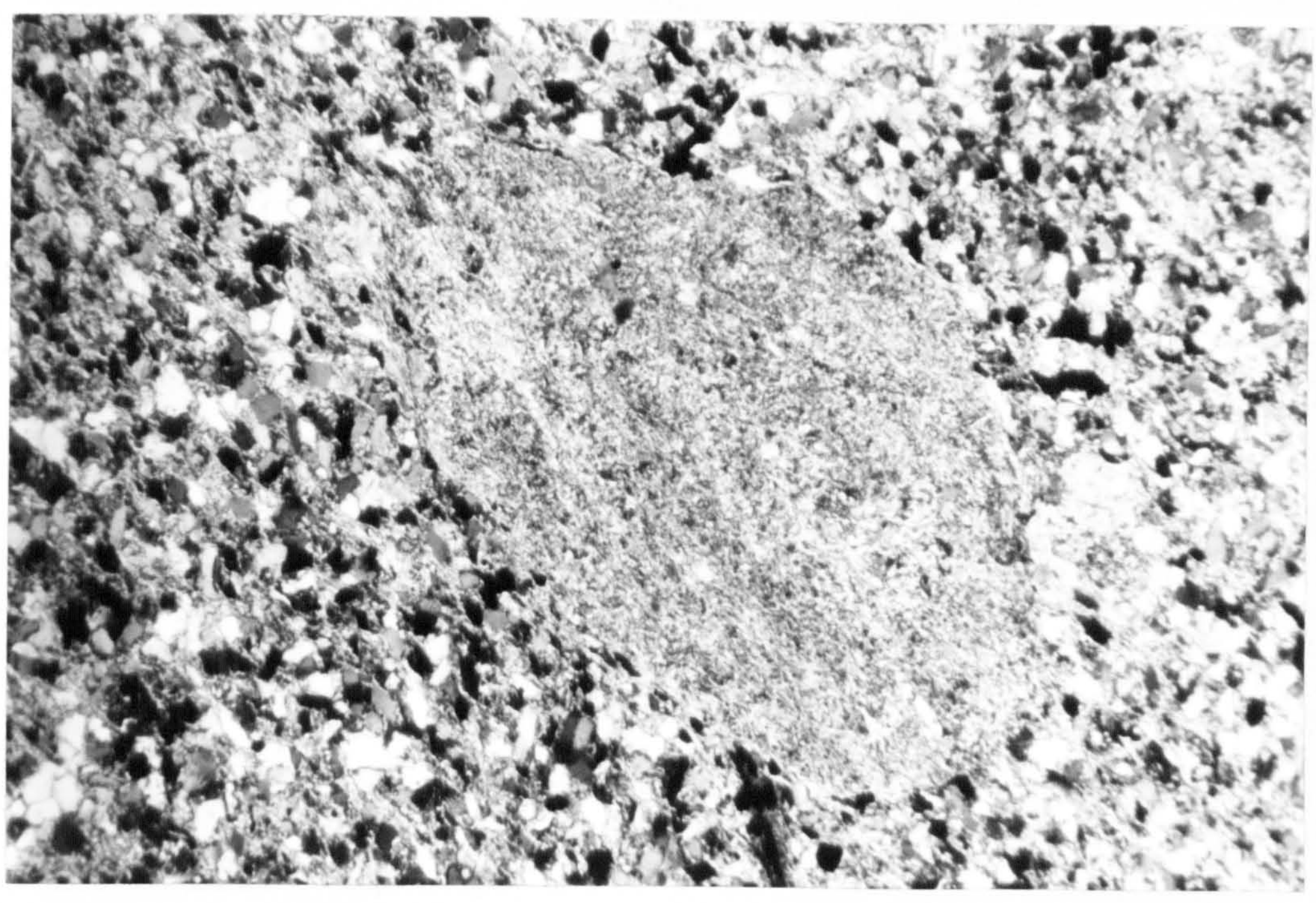


FIG.5.5: b) Total replacement of plagioclase by sericite forming a "clay ball" pseudomorph (TS. 41051, Klein Aub, ppl.).

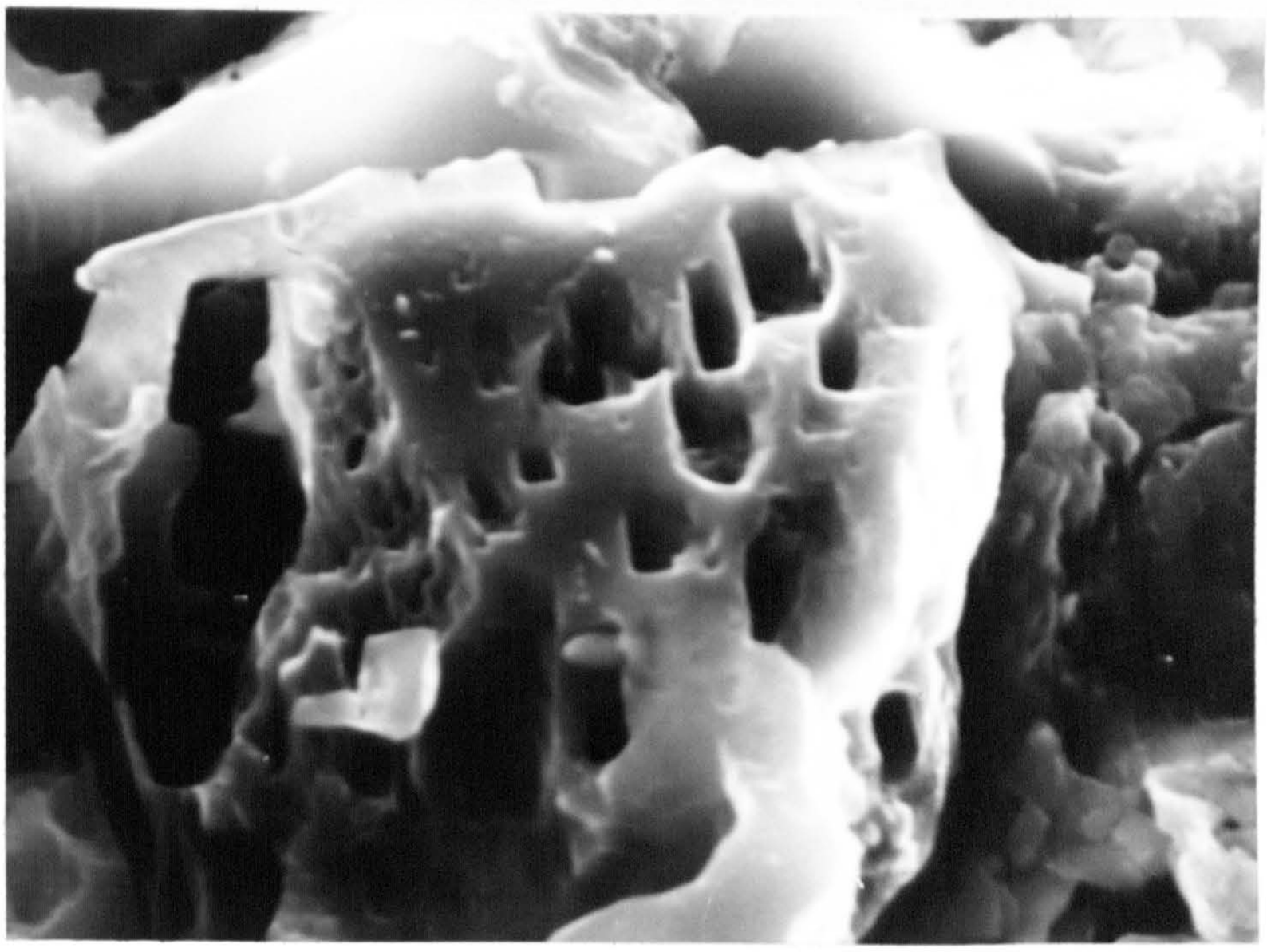


FIG. 5.6: a) Scanning Electron-Microprobe (SEM) photograph of small dissolution voids in detrital feldspar (rock of TS. 41041, Klein Aub).

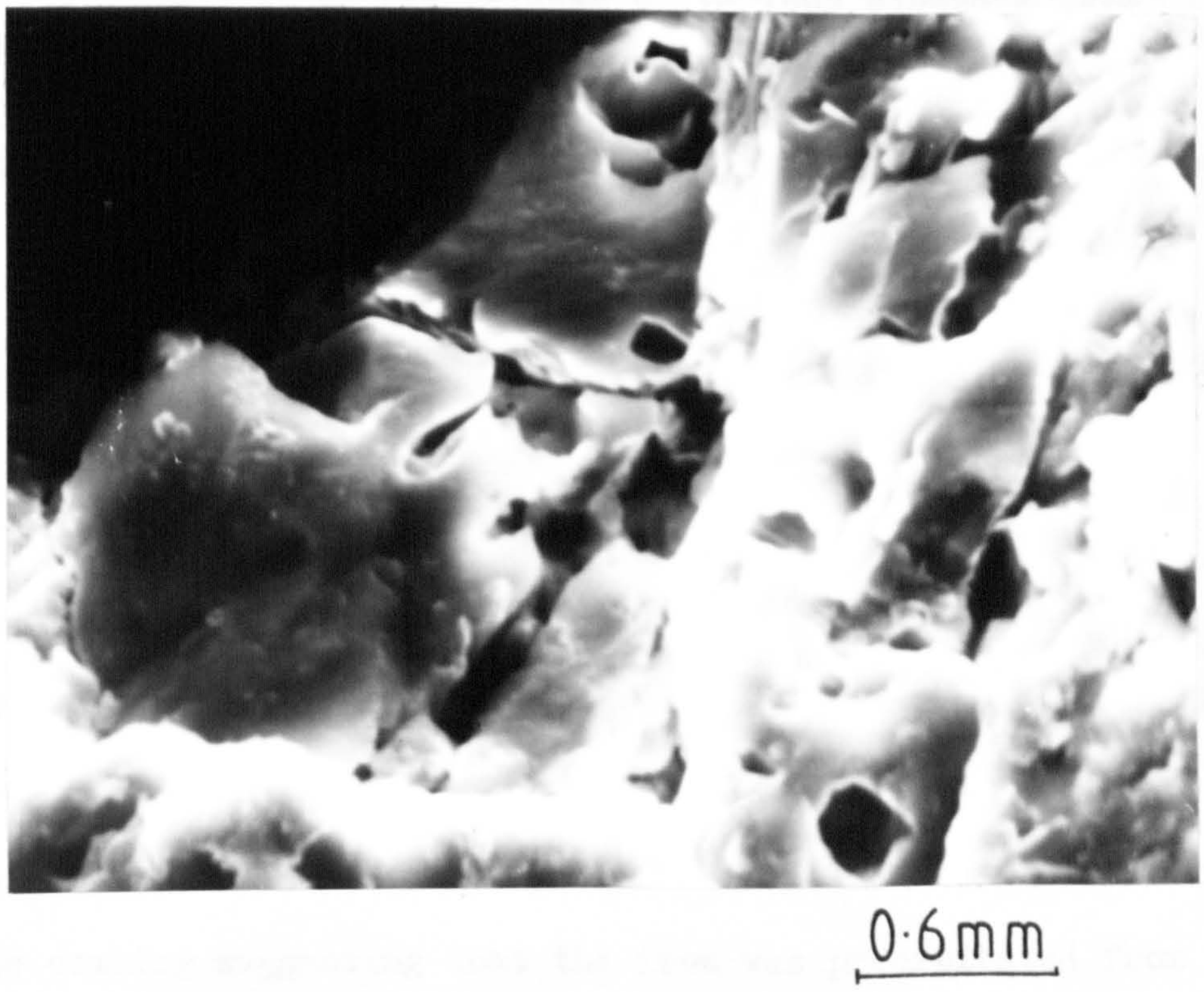


FIG. 5.6: b) S.E.M. photograph of quartz dissolution, possibly formed during diagenesis (sample Dordabis 20 Red Bed).

Opaque Oxides: Iron oxide clots and grains in the red Doornpoort sediments are dominantly haematite and titaniferous haematite, some of which contain martitization textures, indicating alteration from magnetite and titaniferous magnetite (Van Houten, 1968; Ramdohr, 1969, p.906). The alteration of magnetites and ilmenite to haematites is common in ancient Red Beds and progressive with age and depth of burial (Van Houten, 1968; Ixer et al, 1979).

Doornpoort red sediments also contain rock fragments of haematite and plagioclase laths, which were probably magnetite/feldspar lava clasts (Fig. 5.7). Turner (1980, p.234, Fig. 4.42A) recognized similar features, attributing them to alteration of rock fragments.

Authigenic Minerals: In situ dissolution and replacement of detrital grains result in the release of various elements into interstitial groundwaters. Movement of these ions and changing diagenetic conditions led to the formation of authigenic minerals:

i) Haematite

The first authigenic mineral to form during the diagenesis of the Doornpoort sediments was haematite, coating detrital grains (Fig. 5.13), filling pore spaces (Fig. 5.8) and penetrating fractures and cleavage of detrital feldspars (Fig. 5.13). The pigmentation of the sediment is derived mainly from this haematite (also see Van Houten, 1961, 1964, 1968; Walker, 1967a). Sand grains in Aeolian sandstones of the Witvlei fan complex (facies 2) contain a uniform haematite coating suggesting that the iron was precipitated from solution in the form of oxy-hydroxides, which then aged to haematite. Adjacent alluvial fan red sediments have a more irregular haematite distribution which probably reflects the limited

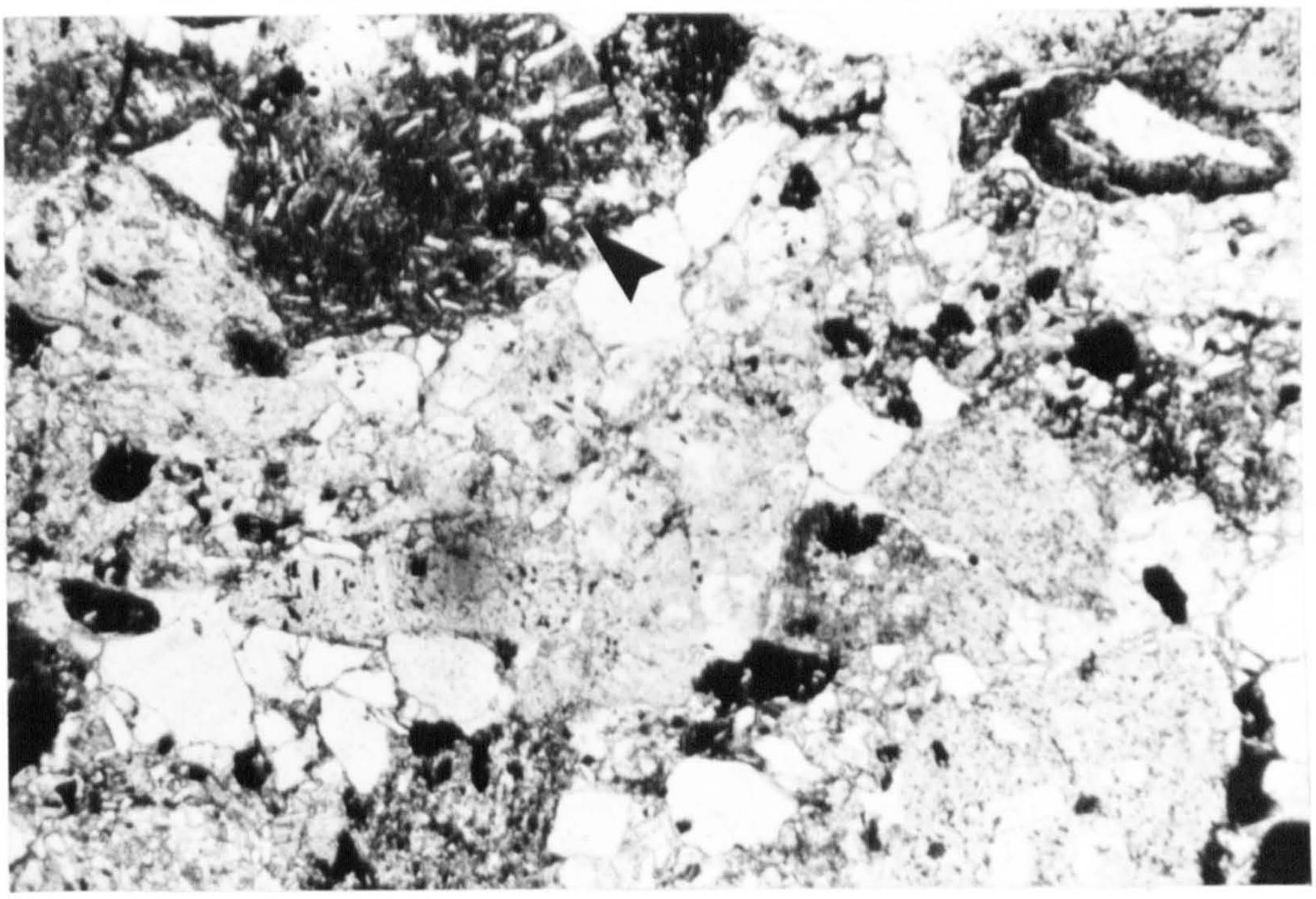


FIG. 5.7: Photomicrograph showinga clast of haematite and plagioclase laths (top left), haematite probably replacive after magnetite - clast possibly of volcanic origin (PT.4364, Witvlei farm Okajirute West, ppl.).

glass

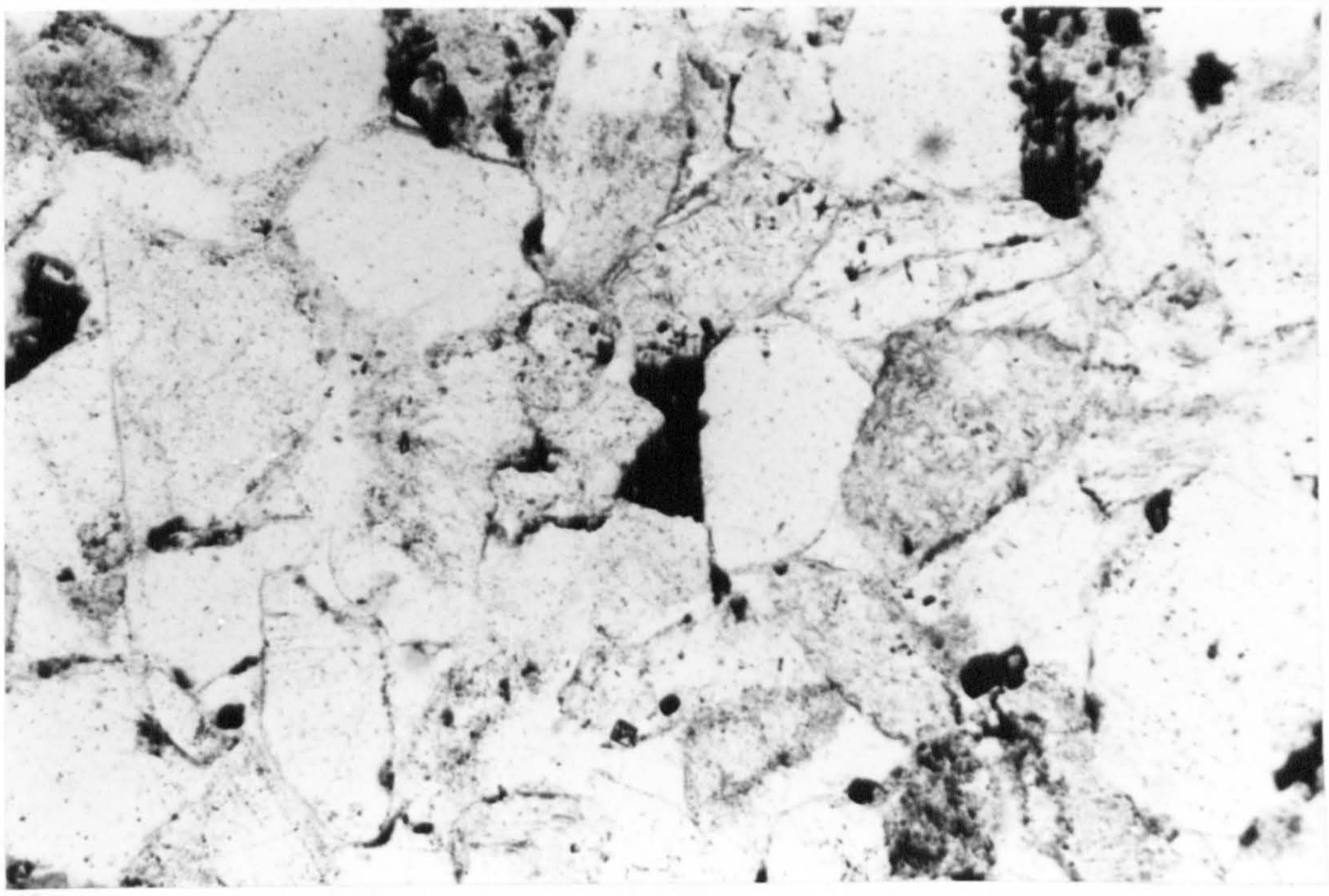


FIG. 5.8: Haematite filling pore spaces (TS.40764, Aeolian sandstone, Witvlei, ppl.).

movement of interstitial fluids, and hence iron, in poorly sorted, low porosity sediments.

ii) Titaniferous haematite/Titanium oxides

Titaniferous haematite occurs as overgrowths on haematite grains (Fig. 5.9) and is often closely associated with titanium oxide phases - probably rutile (Fig. 5.10). The distribution of titanium is not homogeneous. This close association of iron and titanium supports earlier suggestions that many of the opaque oxide phases are alteration products of ilmenite and titaniferous magnetite. Ixer et al (1979) presented similar observations from the St.Bees sandstone of Northern England.

iii) Anatase (TiO_2)

Distinct from the association of iron and titanium are the euhedral tetragonal grains of anatase which occur as clusters in pore spaces, or as single grains along grain boundaries (Figs. 5.11, 5.13). The anatase probably formed from titanium released during the martitization of titaniferous magnetite and ilmenite by haematite (Miller and Folk, 1955; Ixer et al, 1979). Anatase is present in the majority of Doornpoort Red Beds and abundant in the aeolian sandstones.

iv) Feldspars

Two types of authigenic feldspar exist: Microcline and plagioclase. Microcline forms optically-continuous overgrowths (Fig. 5.12) which are rare, found only in the aeolian sandstones. Authigenic plagioclase is far more common, present either as optically-continuous overgrowths or non-optically-continuous grain cements (Fig. 5.13). Optically-continuous overgrowths are the

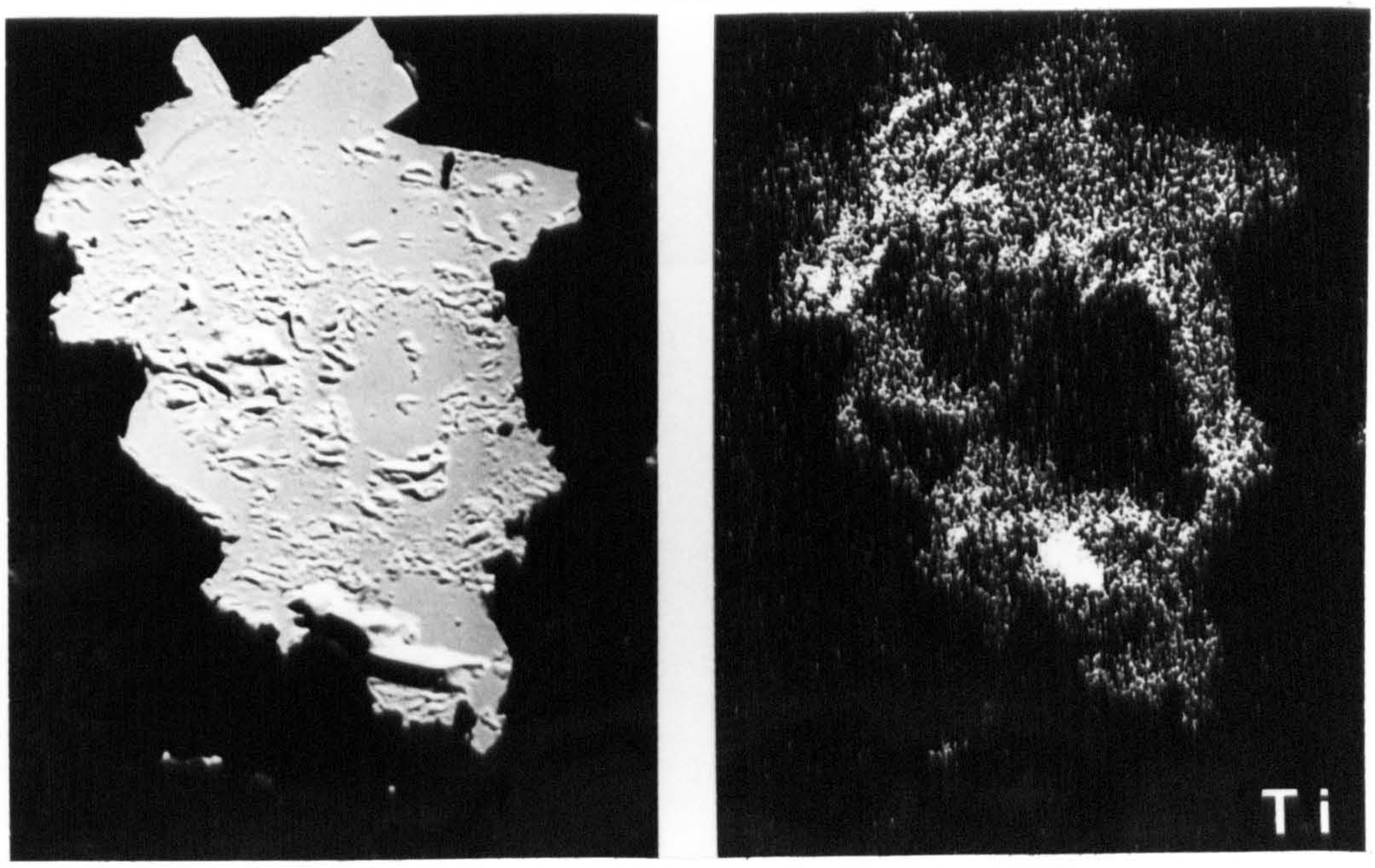


FIG. 5.9: An Electron Back-Scatter Image (EBSI.) and titanium element scan of an opaque grain from the aeolian sandstones of the Witvlei Fan, showing a haematite core surrounded by euhedral titaniferous haematite overgrowths (PT. 4565).

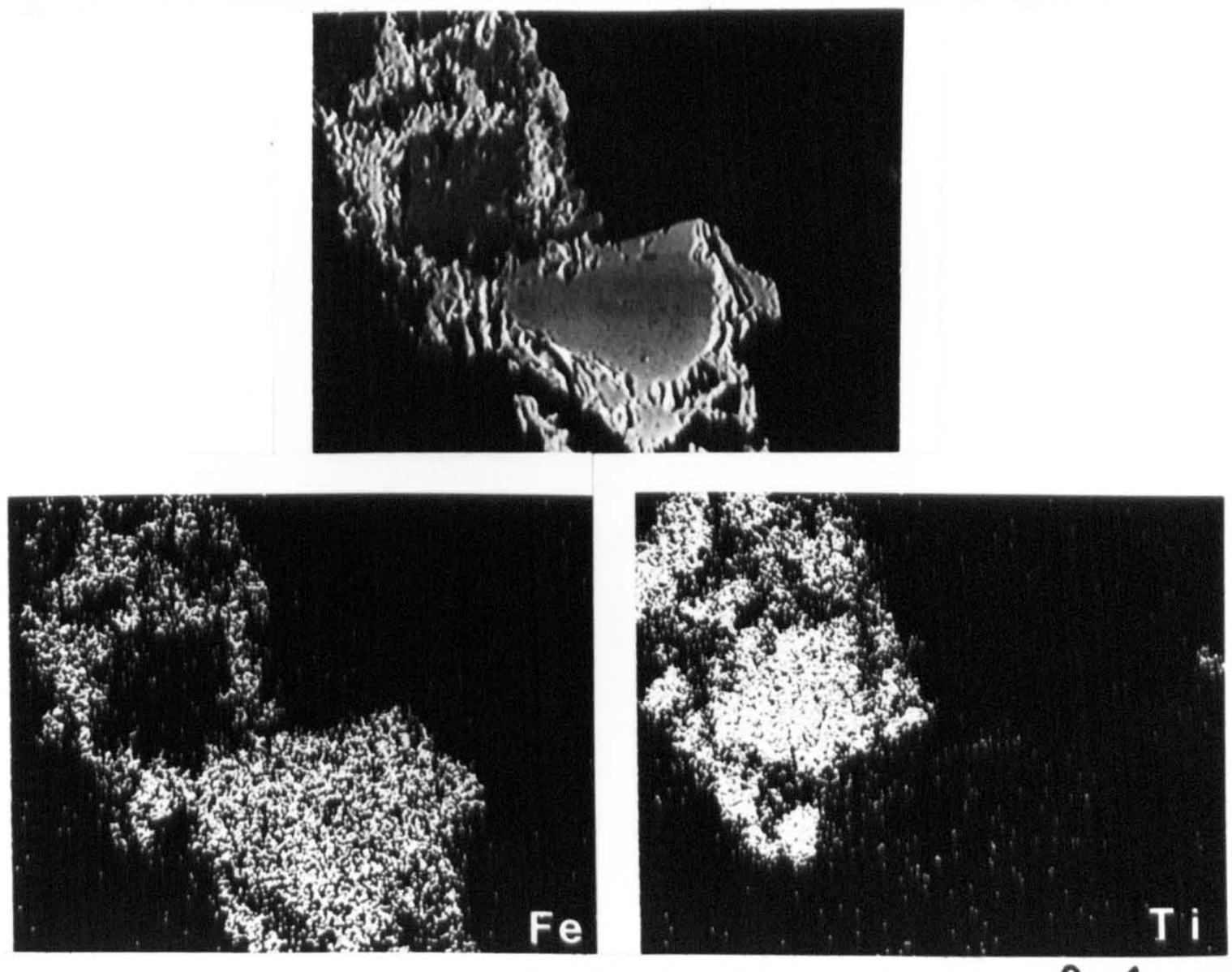


FIG. 5. 10: An EBSI. and iron plus titanium scans, illustrating the close association of authigenic anatase/rutile (TiO2) and haematite in the aeolian sandstones of the Witvlei Fan (PT.4565).

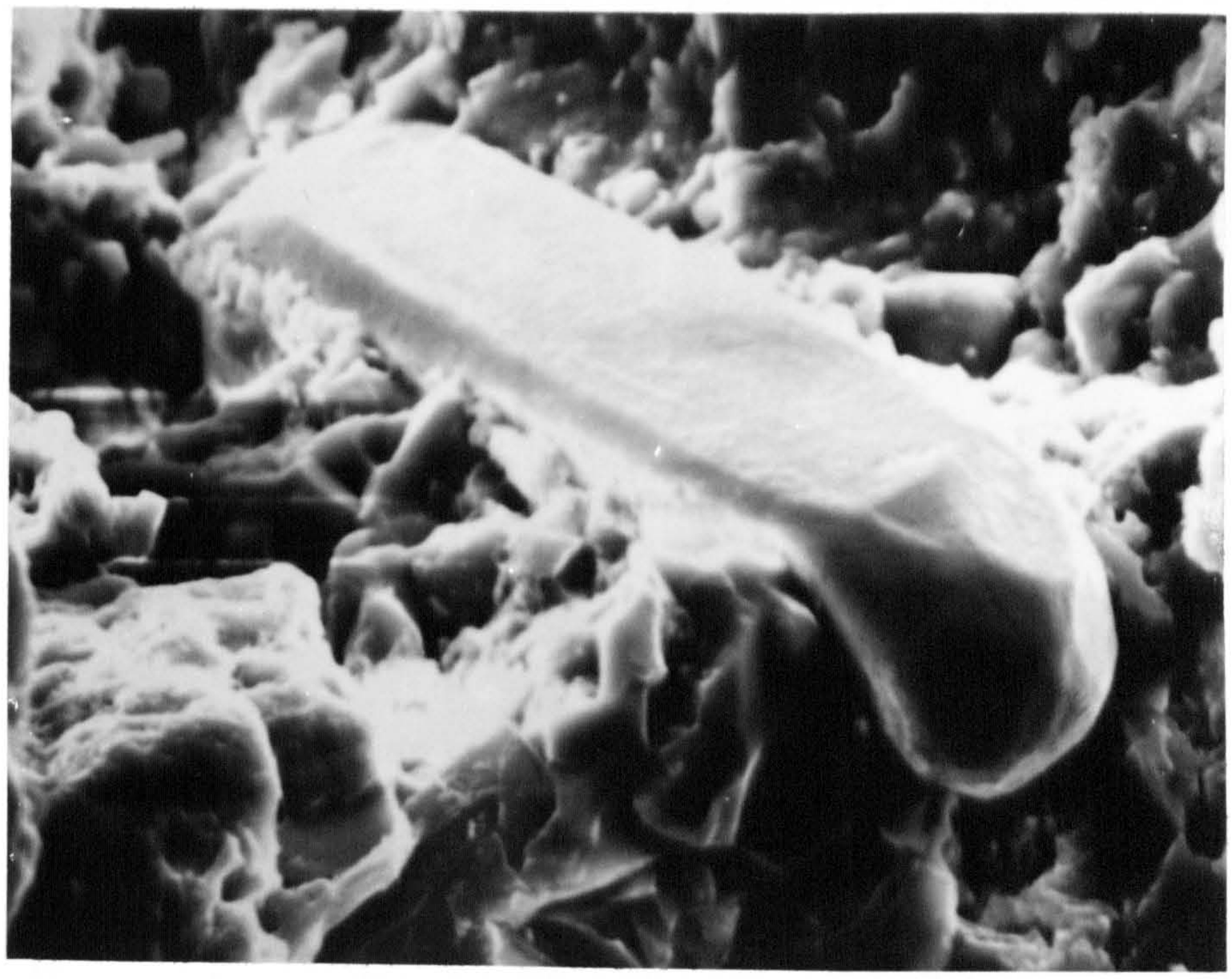


FIG. 5.11: A Scanning Electron microscope photograph of an isolate, euhedral (tetragonal) anatase grain from the Red Beds of the Klein Aub area (rock of TS.41044).

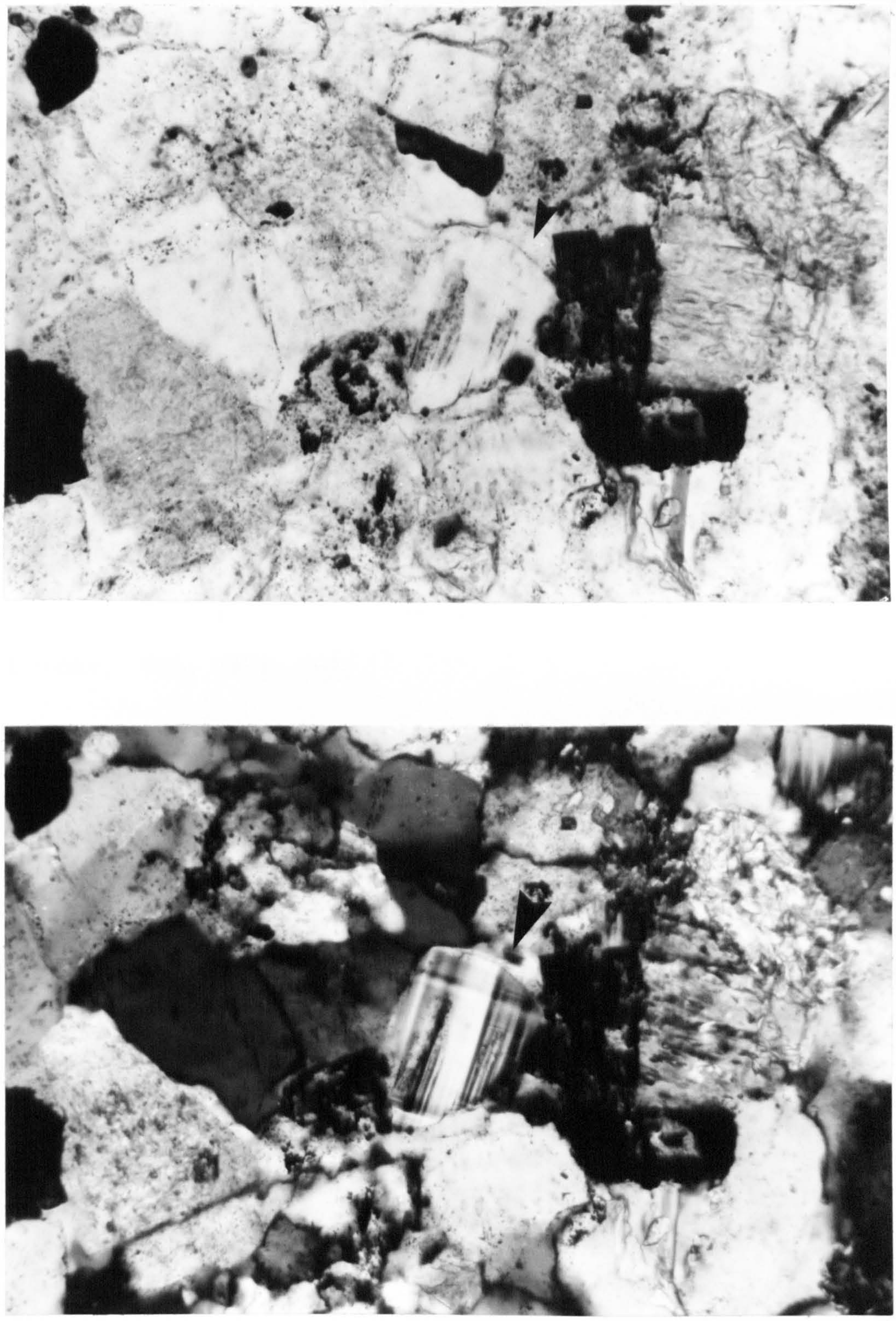


FIG. 5.12: Detrital microcline with a microcline overgrowth (arrowed), from the aeolian sandstones of the Witvlei Fan (TS.40764. ppl and x nicols).

commonest form, recognized by their similar twinning to the host grain, which may not always match exactly (Fig. 5.13). These overgrowths are separated from their detrital hosts by a haematite coat, and are themselves clear in contrast to the cloudy, altered nature of the feldspar host. They fill pore spaces and cement authigenic anatase (Fig. 5.13).

Non-optically-continuous plagioclase usually forms overgrowths on detrital feldspars (Fig. 5.13) but may occur as pore cements (Fig. 5.4). In contrast to optically-continuous forms they display broad albite twins and rare 'chequer-board' twinning (see Hancock, 1978, Plate 1B).

Textural relationships between the two optical forms of authigenic plagioclase described (recognized in the aeolian sandstones), indicate that non-optically-continuous forms formed after the optically-continuous overgrowths (this is clearly illustrated in Figure 5.13). Despite their optical and time differences, both authigenic forms consist of pure albite (Fig. 5.15). The reason why early optically-continuous albite formed, followed by non-optically-continuous plagioclase of the same composition is not known. It may be due to a change in conditions during diagenesis, affecting the rate of feldspar growth and hence the ordering of the mineral lattice.

In the alluvial fan sediments of the Witvlei fan complex (facies 1C(ii)), authigenic albite is associated with a calcite cement (Fig. 5.16). A similar association is recognized in the adjacent reduced playa sediments (facies 3A) and is of particular significance, since chalcopyrite is an additional mineral in the assemblage (Figs. 5.23 and 5.24).

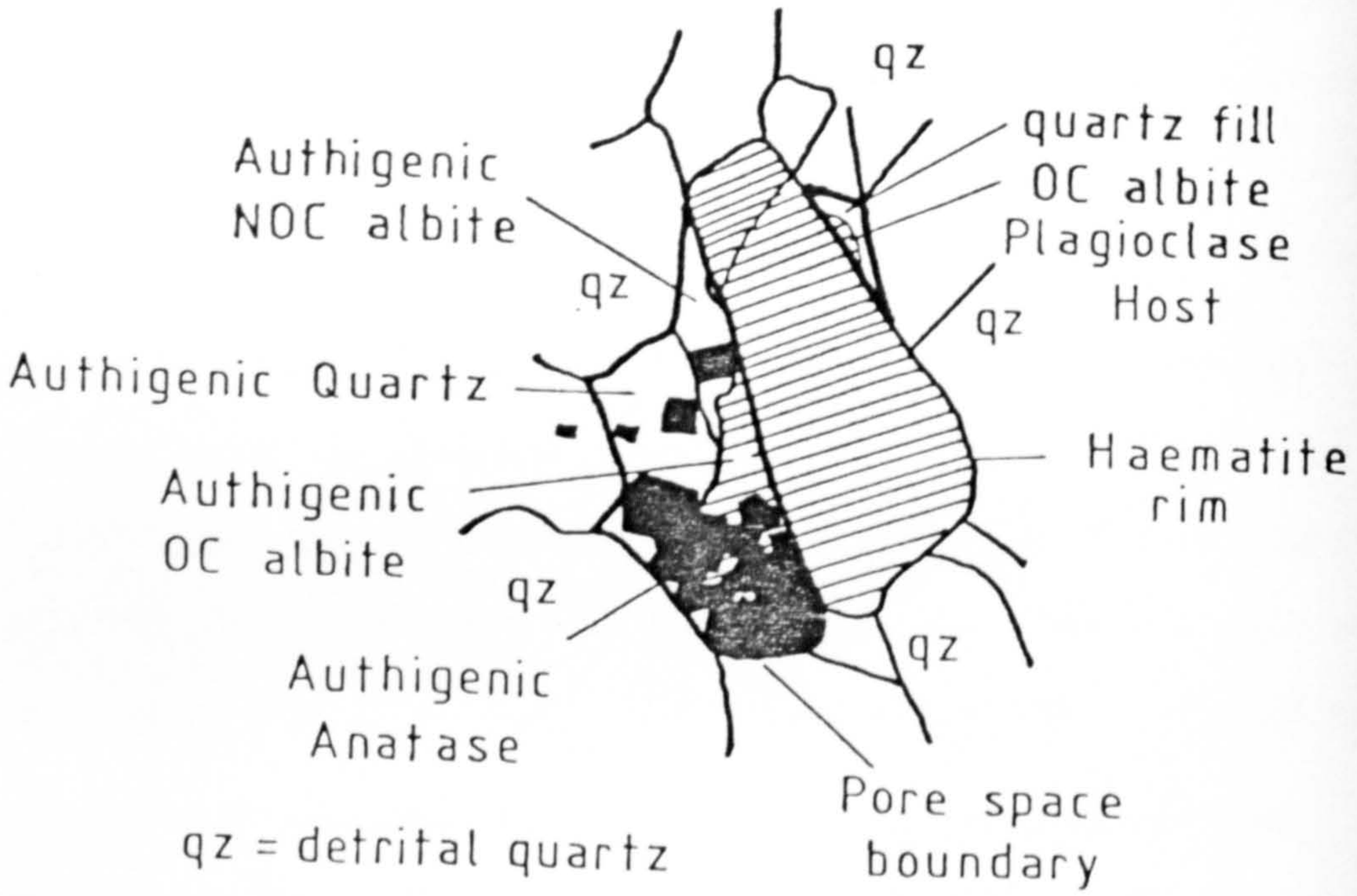
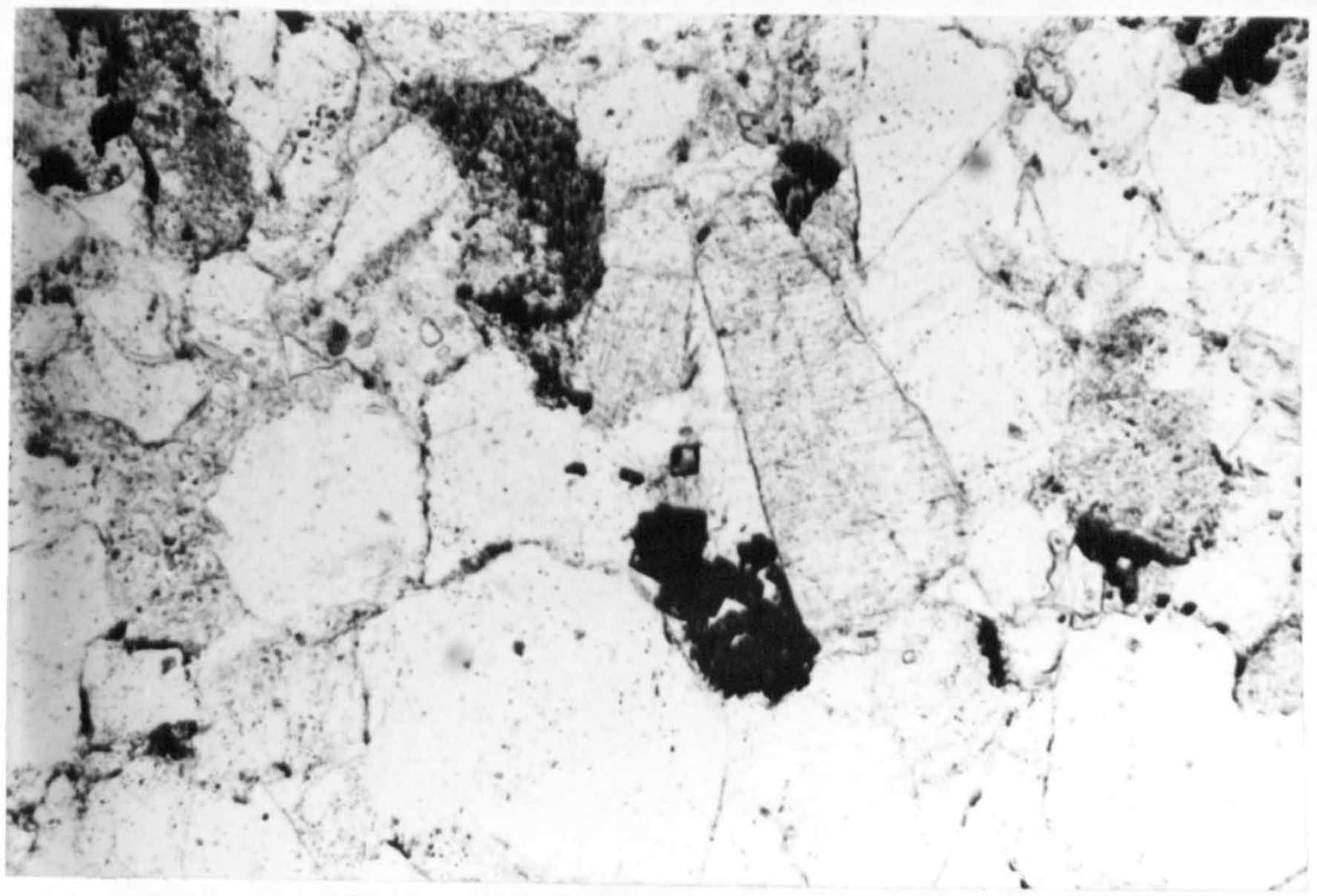
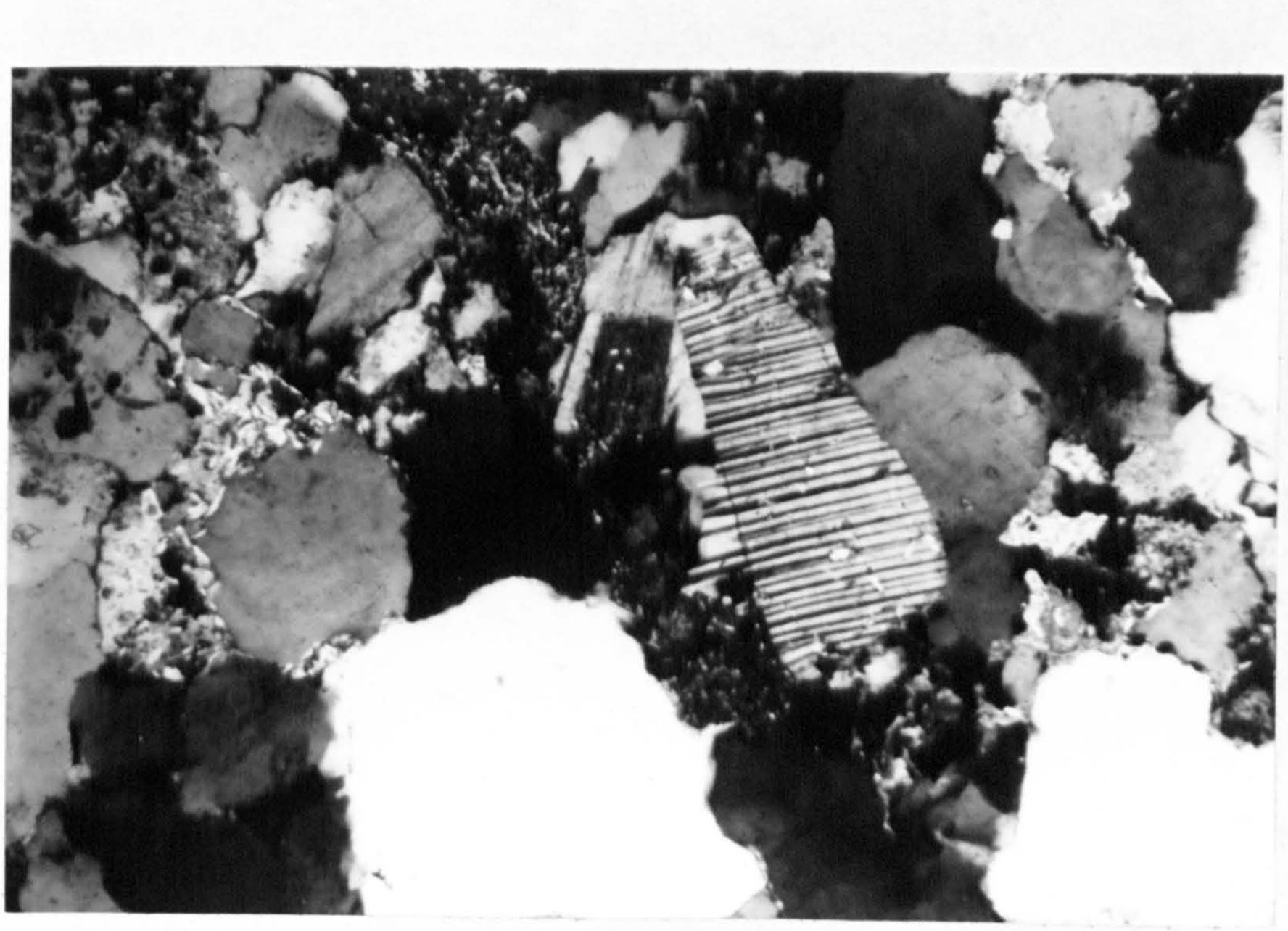


FIG. 5.13: Photomicrographs and a sketch of diagenetic minerals from the aeolian sandstones of the Witvlei Fan, illustrating a paragenetic sequence of authigenic minerals 1). Haematite - coating detrital grains and impregnating detrital feldspars, 2). Authigenic anatase (TiO_2) - euhedral growths in pore spaces, 3). Optically-continuous albite (OC), 4). A later Non-optically-continuous albite (NOC) phase, and 5). A quartz cement.

Note the sericitization of detrital feldspar grains (left) and sutured grain boundaries (right), formed by alteration and pressure solution effects, respectively. (PT.40764, ppl and x nicols).





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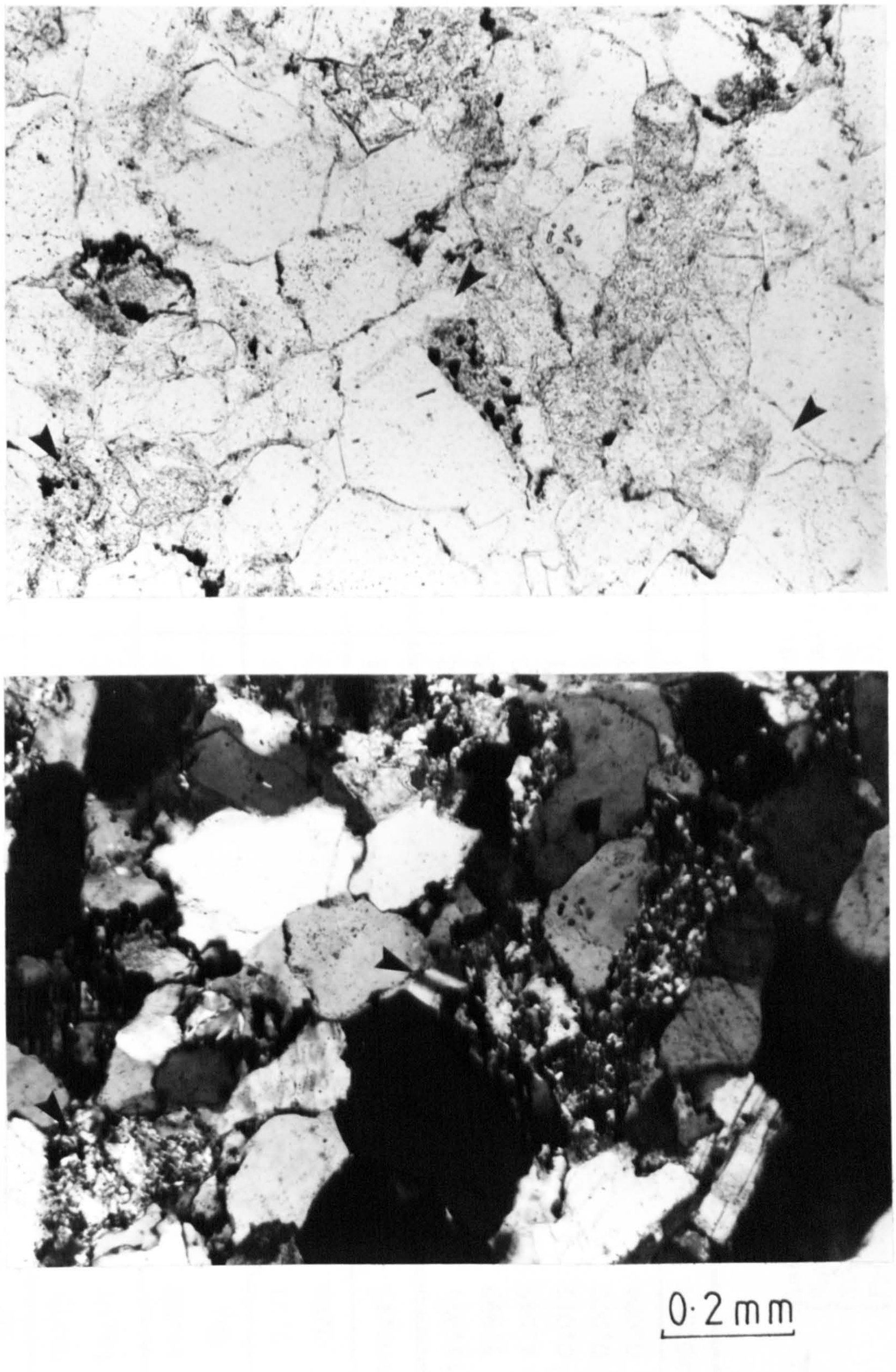

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FIG. 5.14: Authigenic albite cement (centre, arrowed and twinned) from the aeolian sandstones of the Witvlei Fan. Note the numerous optically-continuous quartz overgrowths (right, arrowed) and the complex diagenetic pseudomorphs of haematite and sericite/illite (left, arrowed). (TS. 40764, ppl and x nicols).

ELEMENT	HOST	OV.1 OC	OV.2 NOC	HOST	OV.1 OC	HOST	OV.1 OC	HOST	OV.1 OC/NOC	OV NOC	OV OC
SiO_2	68.46	68.75	67.93	67.60	68.62	67.73	68.60	68.07	67.70	68.15	68.04
Al_2O_3	19.59	19.48	19.66	19.80	19.10	19.52	19.49	19.09	19.56	19.43	19.60
NaO	11.96	11.99	11.91	11.47	11.83	11.81	11.69	12.05	11.76	11.71	11.51
CaO	0.23	0.10	0.23	0.93	0.00	0.41	0.09	0.16	0.22	0.00	0.01
FeO	0.06	0.03	0.02	0.09	0.00	0.02	0.06	0.02	0.04	0.06	0.28
K_2O	0.04	0.10	0.11	0.16	0.01	0.06	0.10	0.06	0.09	0.07	0.13
TOTAL:	100.34	100.45	99.86	100.05	99.56	99.55	100.03	99.45	99.37	99.42	99.57
Si	11.940	11.971	11.912	11.853	12.031	11.933	11.982	11.981	11.922	11.975	11.949
Al	4.028	3.999	4.063	4.093	3.948	4.053	4.013	3.960	4.060	4.025	4.057
Na	4.044	4.049	4.048	3.899	4.029	4.034	3.958	4.113	4.017	3.991	3.918
Ca	0.043	0.019	0.043	0.175	0.001	0,027	0.017	0.031	0.041	0.001	0.002
Fe	0.009	0.002	0.003	0.013	0.002	0.003	0.009	0.003	0.006	0.008	0.041
K	0.009	0.004	0.024	0.035	0.000	0.013	0.022	0.041	0.021	0.017	0.029
TOTAL:	20.073	20.044	20.093	20.068	20.011	20.063	20.001	20.129	20.067	20.017	19.996

FIG. 5.15: Electro-microprobe analyses of detrital plagioclase feldspars (Host) and optically-continuous (OC), non-optically-continuous (NOC) albite overgrowths. Note the purity of all overgrowths. (From one section PT 4565, of aeolian facies (2), Witvlei fan complex).

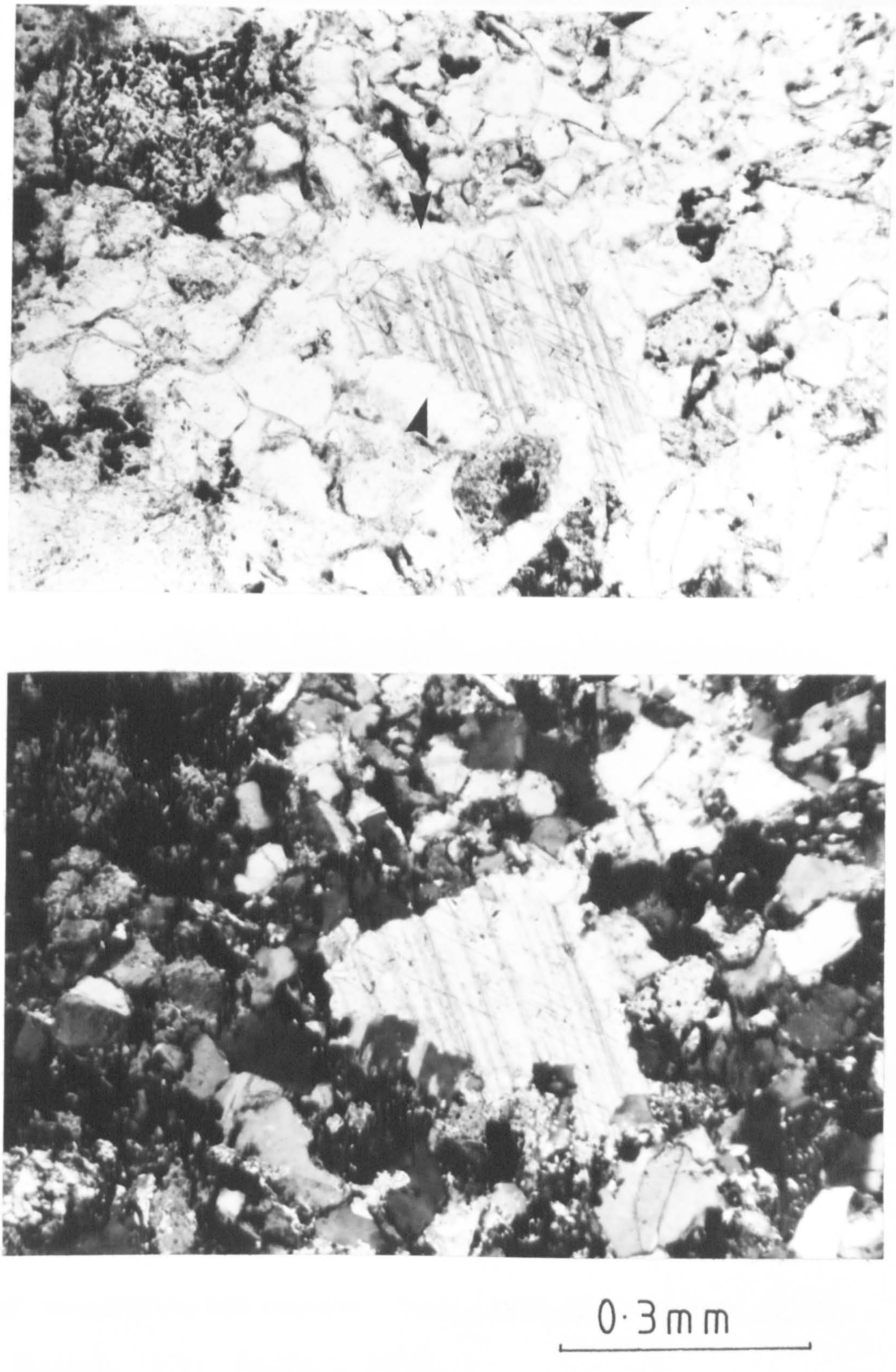


FIG. 5.16: This photomicrograph illustrates the association of authigenic albite (clear, arrowed) and calcite (centre, twinned) from the Red Bed conglomerates of the Witvlei Fan Complex (facies 1C(ii)). A similar association is recognized in the adjacent marginal playa sediments, Fig. 5.23, 5.24. (PT. 4635, Okatjirute West, ppl and x nicols).

In the Permo-Triassic, Penrith sandstones of Northern England, potash feldspar overgrowths on detrital orthoclase and microcline are described by Waugh (1970) and from the Middle Jurassic of the North Sea by Blanche and Whitaker (1978) and Hancock (1978). However, in the Doornpoort sediments and in the Rotliegendes sandstones of Western Germany (Hancock, 1978), authigenic potash feldspar is rare with albite overgrowths most common. Kastner (1971) suggested that the growth of authigenic feldspars, within carbonate-rich rocks, is dependent on the K/(K+Na) ratio of the groundwaters. If potassium is more abundant than sodium in groundwaters, potassium feldspar forms. If this can be applied to clastic sediments then the K/(K+Na) ratio must have been low during the diagenesis of the Doornpoort sediments and the Rotliegendes sandstones of W. Germany.

v) Quartz

Quartz is the most abundant mineral, forming over 50% of diagenetic mineral growth, occurring as either optically-continuous overgrowths on detrital quartz grains, or as a cement (Fig. 5.17). Euhedral quartz overgrowths are recognized using the Scanning Electron Microscope (Fig. 5.18).

Quartz is a common authigenic mineral in Red Beds as both euhedral overgrowths and cements (Waugh, 1970 a,b; Glennie et al, 1978; Hancock, 1978; Kessler, 1978).

vi) Calcite

Two forms of authigenic calcite exist. Firstly, small rhombs in pore spaces and replacing detrital grains (Fig. 5.19), common in alluvial fan sandstones (facies 1C(ii)) and in aeolian deposits

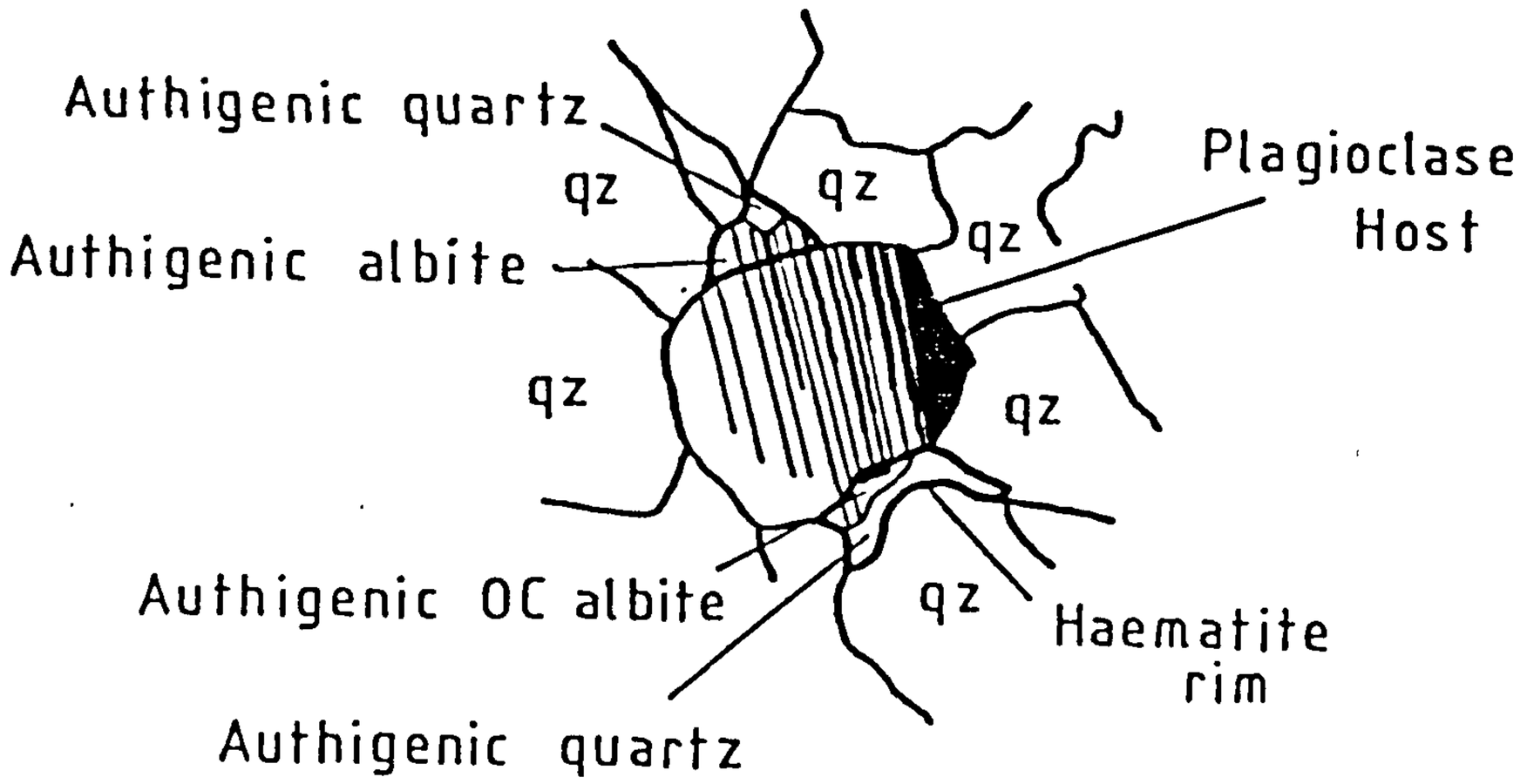
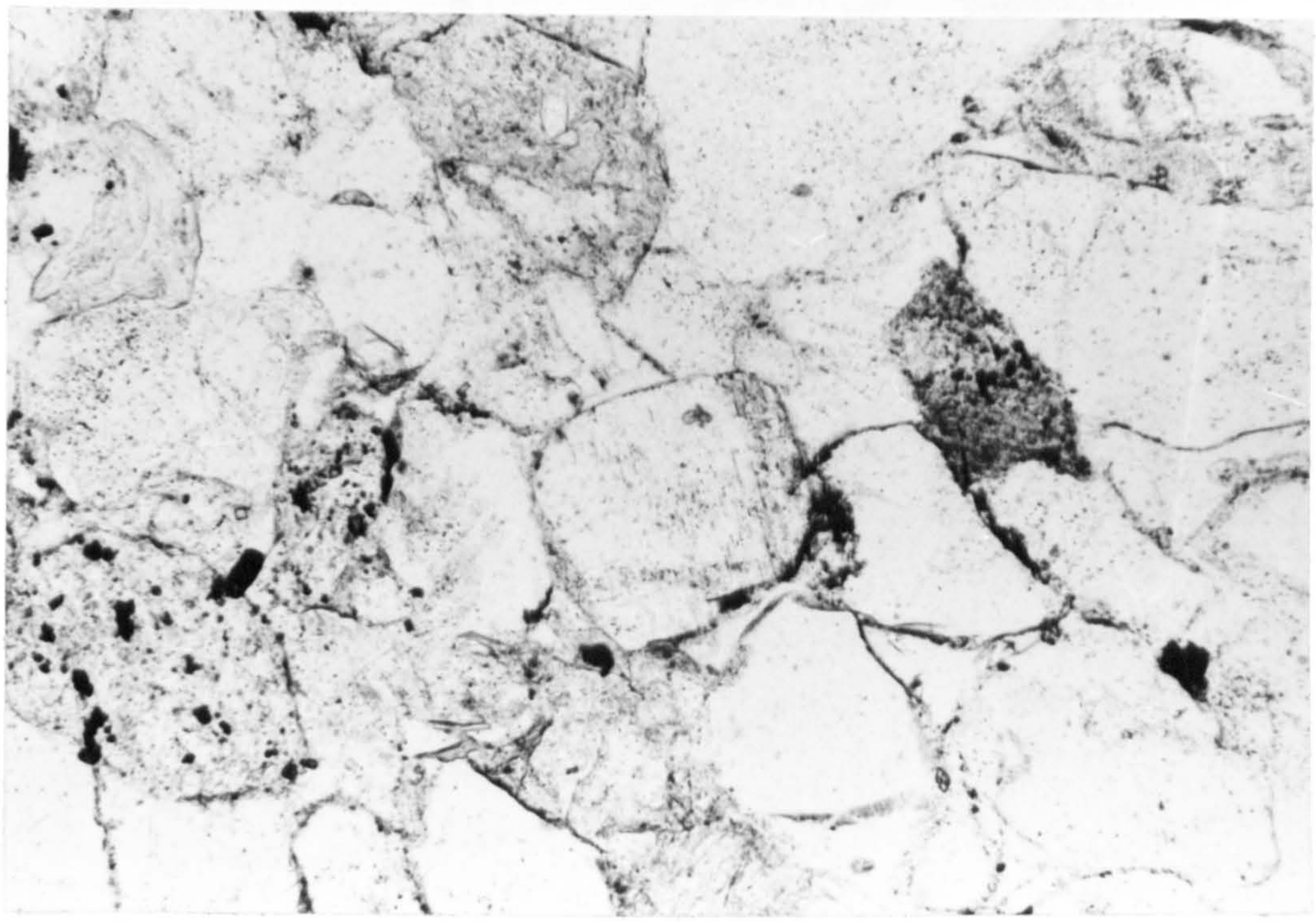


FIG. 5.17: A photomicrograph and sketch showing the relationship between authigenic Optically-continuous (OC) albite and authigenic quartz from the aeolian sandstones of the Witvlei Fan. Quartz appears to cement the remaining pore space. Note the sutured pressure solution grain boundaries (top left, and bottom right)and the complex diagenetic pseudomorph of haematite and sericite (left). (TS. 40764, ppl and x nicols).



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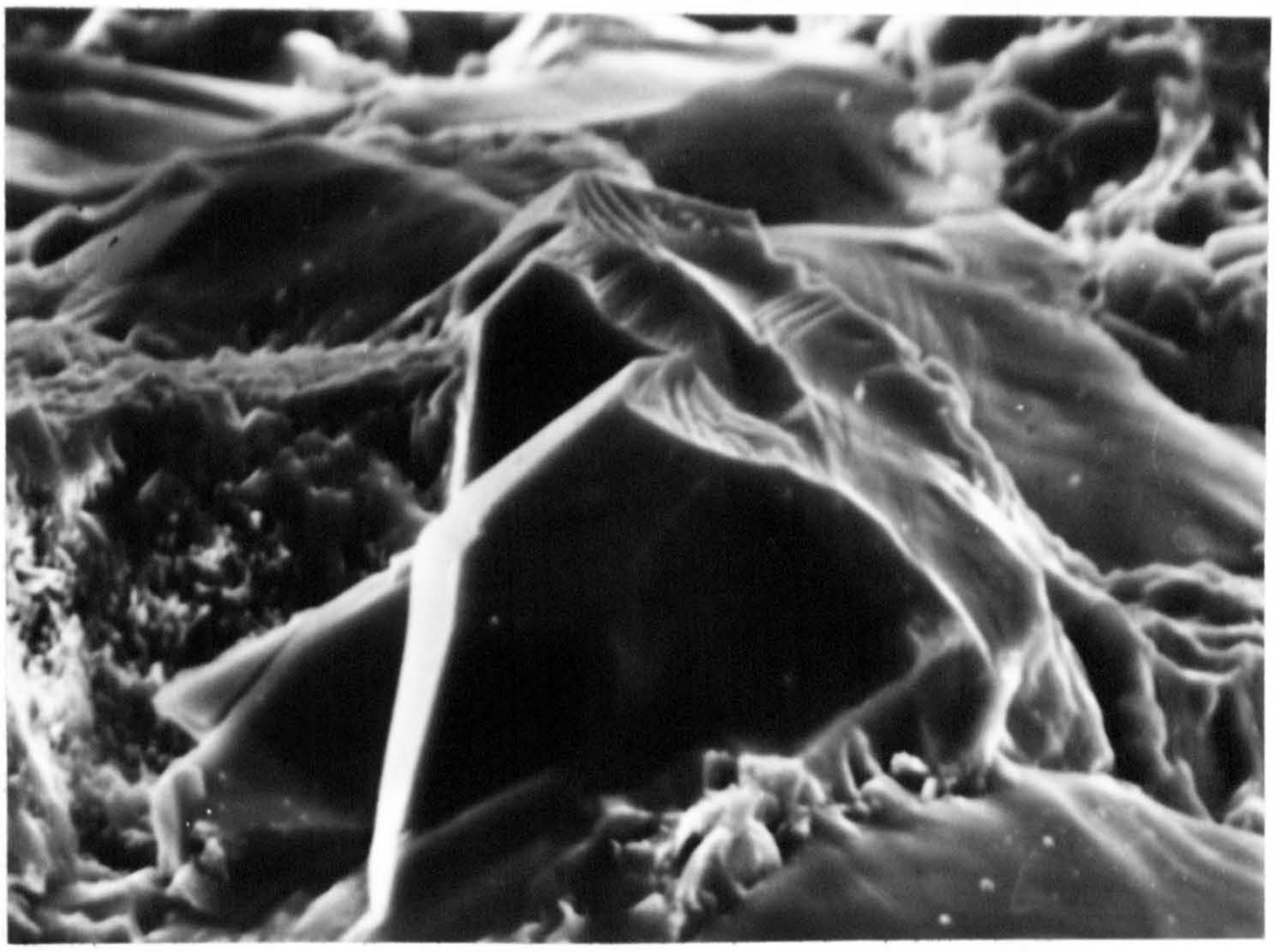


FIG. 5. 18: S.E.M. photograph of euhedral, authigenic quartz , note the conchoidal fracture. (rock of TS. 40764, Aeolian sandstones of the Witvlei Fan).

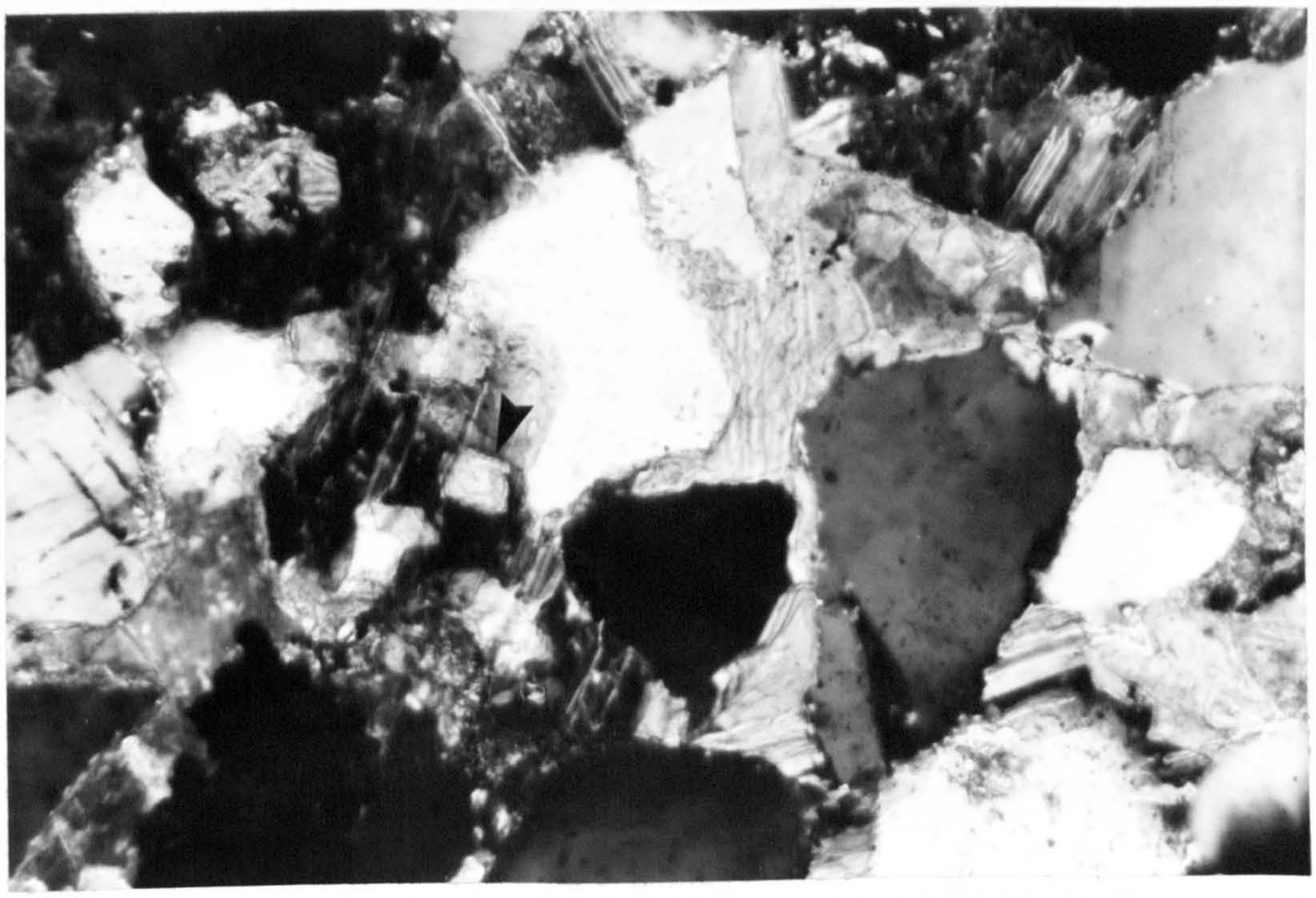


FIG. 5.19: Replacive and pore filling calcite. Note the euhedral rhombs (arrowed), possibly a calcite replacement after dolomite. (PT. 4564, Aeolian sandstones of Witvlei, ppl or x nicols).

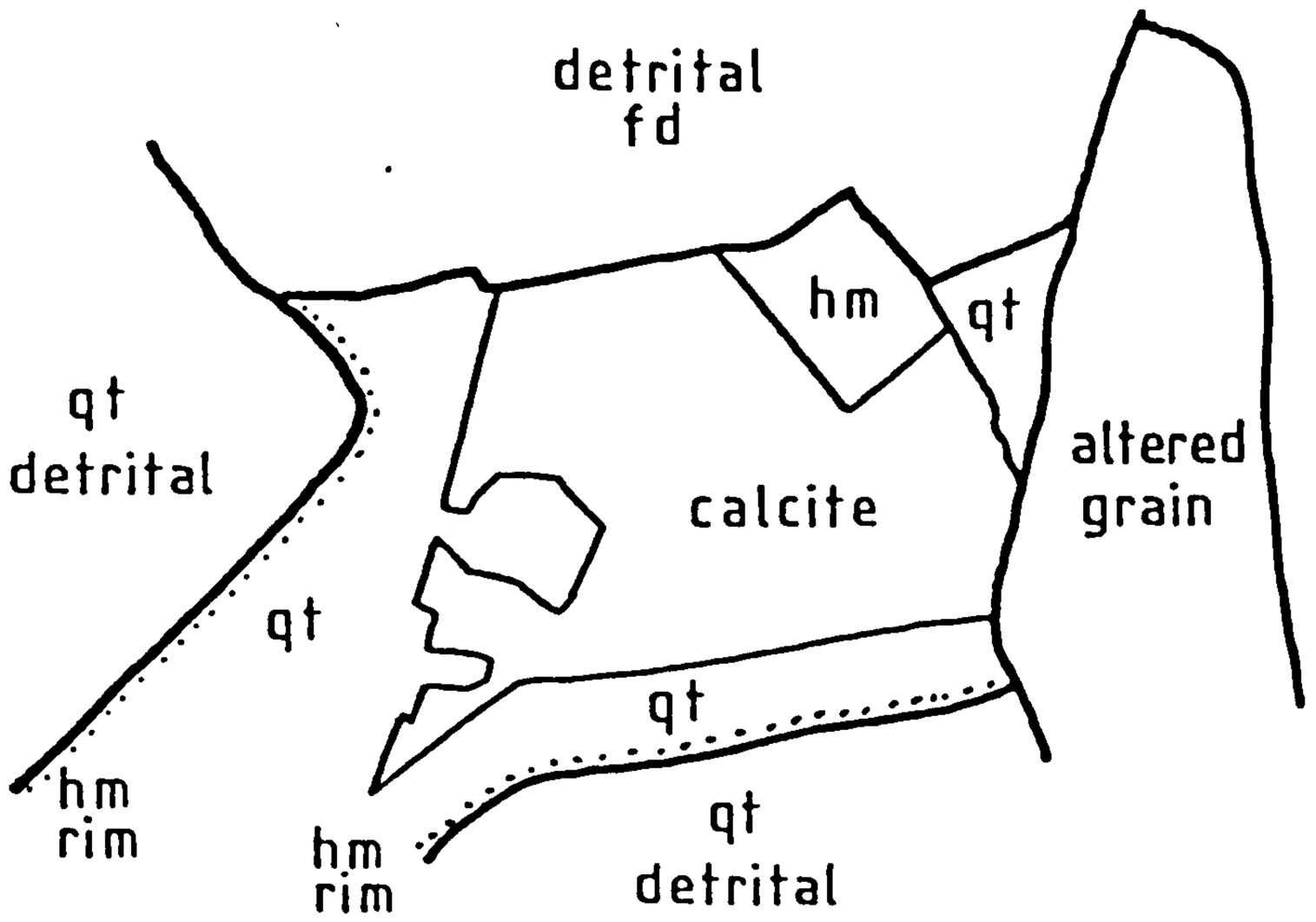


FIG. 5.20: A thin section sketch illustrating the relationship between authigenic haematite (hm), quartz (qt) and calcite (cc) with detrital grains (qt = quartz and fd = feldspar). Calcite is the final pore filling cement after authigenic quartz and haematite. (TS. 40764).

(facies 2). These rhombs may be replacive after dolomite, which is a common late diagenetic mineral (Glennie et al, 1978). Secondly, calcite cements remaining pore spaces (Fig. 5.20) and replaces detrital and authigenic minerals. This form is particularly evident around playa sediments. Late diagenetic calcite has been recognized in other ancient Red Beds by Glennie et al (1978), Hancock (1978), Kessler (1978) and Waugh (1978 a,b).

Paragenetic Sequence: A paragenetic sequence of authigenic minerals is recognized in the aeolian sandstones of the Witvlei fan complex. The first authigenic phase is represented by haematite coatings and overgrowths and provides a unique diagenetic time marker which enables the recognition of authigenic overgrowths. Figure 5.13 illustrates the first four minerals of the sequence: early haematite, which surrounds and impregnates a detrital plagioclase grain, followed by euhedral anatase forming in pore spaces, which is cemented by firstly, optically-continuous albite and secondly, non-optically-continuous plagioclase, and the pore space is finally infilled by quartz. The relationship between authigenic albite and quartz can be seen more clearly in Figure 5.17 where a small overgrowth of optically-continuous albite is surrounded by a later quartz cement. The final mineral of the sequence is calcite, which occurs as small rhombs, pore cements or as a replacive phase after diagenetic and detrital minerals (Fig. 5.20).

Figure 5.21 summarises the paragenetic sequence of minerals and their textural occurrence. It is, however, the 'ideal' or most complete sequence recognizable in parts of the aeolian sandstones, whereas incomplete sequences can be found in alluvial fan

A PARAGENETIC SEQUENCE OF DIAGENETIC MINERALS

1. HAEMATITE:
   - Coats grains
   - Inpregnates feldspars
   - Fills pore spaces
   - Associated with titanium oxides

2. TITANIFEROUS HAEMATITE:
   - Euhedral overgrowths
   - Fills pores

3. ANATASE: (TiO_2)
   - Euhedral minerals - clusters in pores and isolated grains

4. FELDSPARS:
   - Microcline overgrowths
   - Albite overgrowths - optically-continuous
     - non-optically-continuous
     - cements pores

5. QUARTZ:
   - Euhedral overgrowths
   - Fills pores - cement

6. CALCITE:
   - Isolated rhombs (after dolomite)
   - Fills pores
   - Replacement mineral

FIG. 5.21: A paragenetic mineral sequence recognised in the aeolian sandstones of the Witvlei Fan.

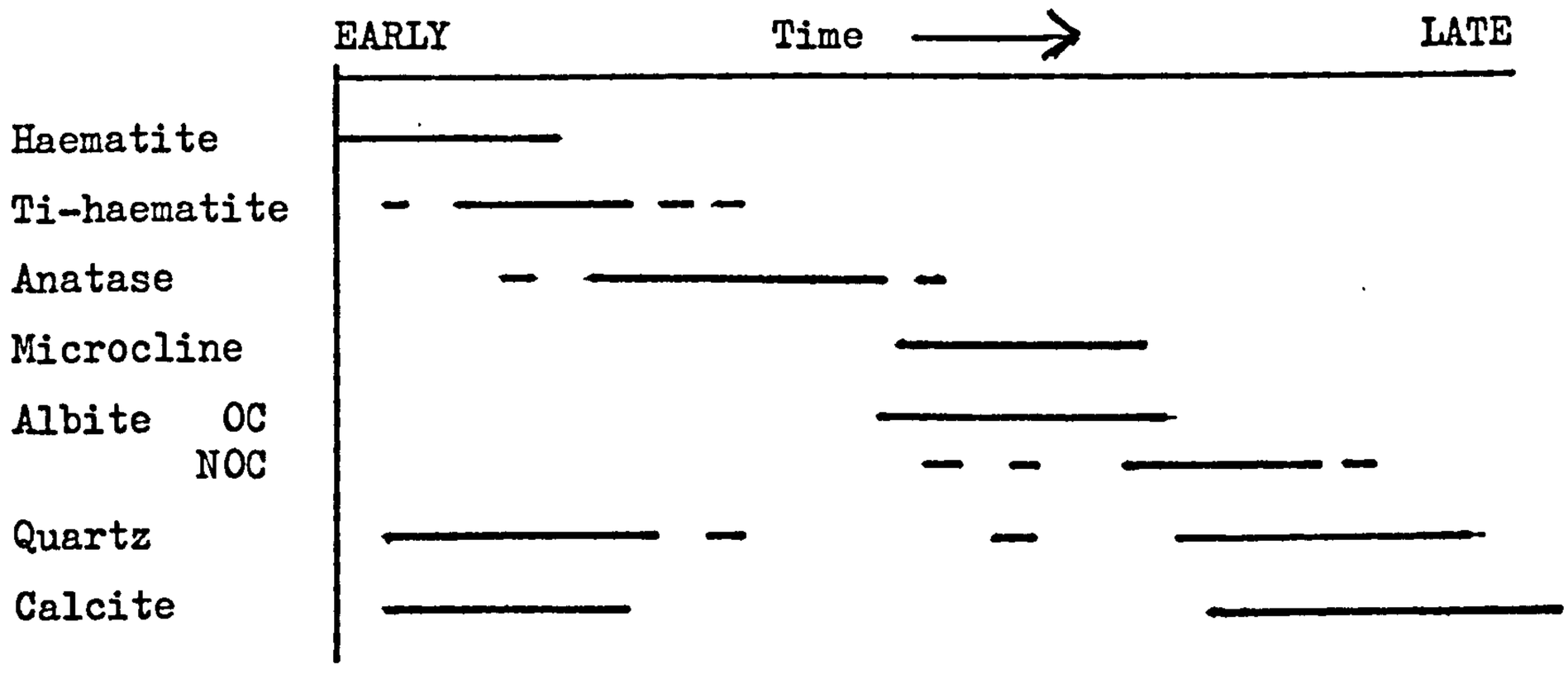


FIG. 5.22: The distribution of authigenic phases through time, in the Witvlei fan Red Beds.

sediments from Witvlei and Klein Aub. Figure 5.22 illustrates the general pattern of development of authigenic minerals through time. It is realised that on the data base used, the paragenetic sequence described may only be of limited use in attempting to deduce the nature of changes in groundwater chemistry but it is, however, an advance on merely describing and documenting authigenic phases. The sequence may be of particular value in understanding the ore deposits in adjacent sediments.

5.2 NON-RED SEDIMENT DIAGENESIS

Red and non-red sediments of the Doornpoort Formation are closely associated and their colouration is considered to be of diagenetic origin. Colouration in the sediments is predominantly due to the valency state of iron and extensive thin section studies have led to the conclusion that green sediments owe their colour to chlorite and illite, black to organic matter, grey to organic matter and iron oxides plus sulphides, and brown and yellow rocks to iron oxides and micas. Reduction of the sediments led to the removal or conversion of iron from the ferric to the ferrous state. This is immediately evident, since green sediments contain far fewer magnetite and haematite clots and grains, than the surrounding Red Beds.

Reduction occurred during the diagenetic breakdown of organic matter. Ample evidence for organic activity is indicated by the abundance of algal mat laminations and structures in the playa sediments of the Witvlei fan (and Okasewa fan) (Figs. 3.12, 5.23) and by carbonaceous laminae in the lacustrine rocks of the Klein Aub fan complex (Fig. 6.10). Reduced conditions led to the formation of sulphides, by the bacteriogenic decay of organic matter releasing

H_2S which was converted to copper and iron sulphides (see Berner, 1969).

Additional authigenic minerals include chlorite and micas which probably represent the deep burial and metamorphic equivalents of early diagenetic sheet silicates and clay minerals. Calcite is common, predominantly as a replacive phase after diagenetic and detrital minerals, plus possibly gypsum or anhydrite (Chapter 3.4). Adjacent to coarse-grained alluvial sediments of facies 1C(ii) on the Witvlei fan, playa sediments of facies 3A contain authigenic albite associated with diagenetic carbonate nodules (Fig. 5.23); albite forms around the edges of the carbonate nodules, which disrupt and break up algal laminations. These textures are of significance, since chalcopyrite may form between the calcite and albite, and may be intergrown with the latter (Fig. 5.24). Chemical analysis of these authigenic albites and those associated with calcite in the adjacent Red Beds (Fig. 5.16), indicate that they are both pure albite in composition (Fig. 5.25). The evidence suggests that the association of albite and calcite within both the Red Beds and the playa sediments is diagenetic and therefore produces crucial evidence that the copper/iron sulphides are also of diagenetic origin.

Events considered to have taken place during the diagenesis of red and green sediments are summarized in Figure 5.26. An early oxidation period for all sediments is envisaged; a process which continues in Red Bed formation but is halted by the decay of organic matter in reduced sediment formation. This initial oxidation probably removed unstable minerals, such as olivine,

FIG. 5.23: A green algal-bound playa siltstone from the Witvlei Fan, containing copper sulphides (black) and stratiform diagenetic nodules of calcite (high relief) with authigenic albite (clear, arrowed) at their margins. The diagenetic association of calcite and albite was recognized in the adjacent Red Beds also, Fig. 5.16. (TS. 40765, OKW. 5, core, Witvlei, ppl).

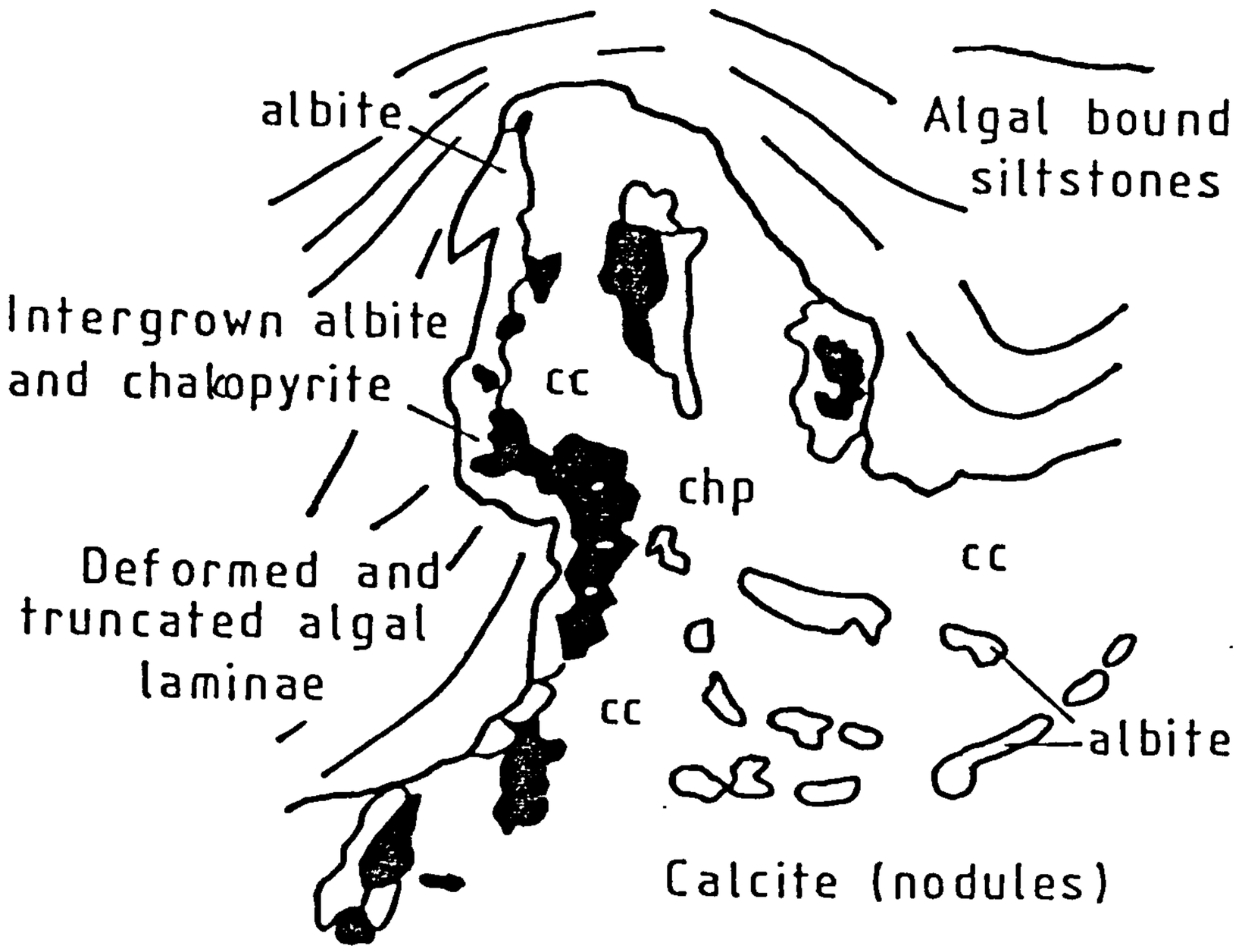
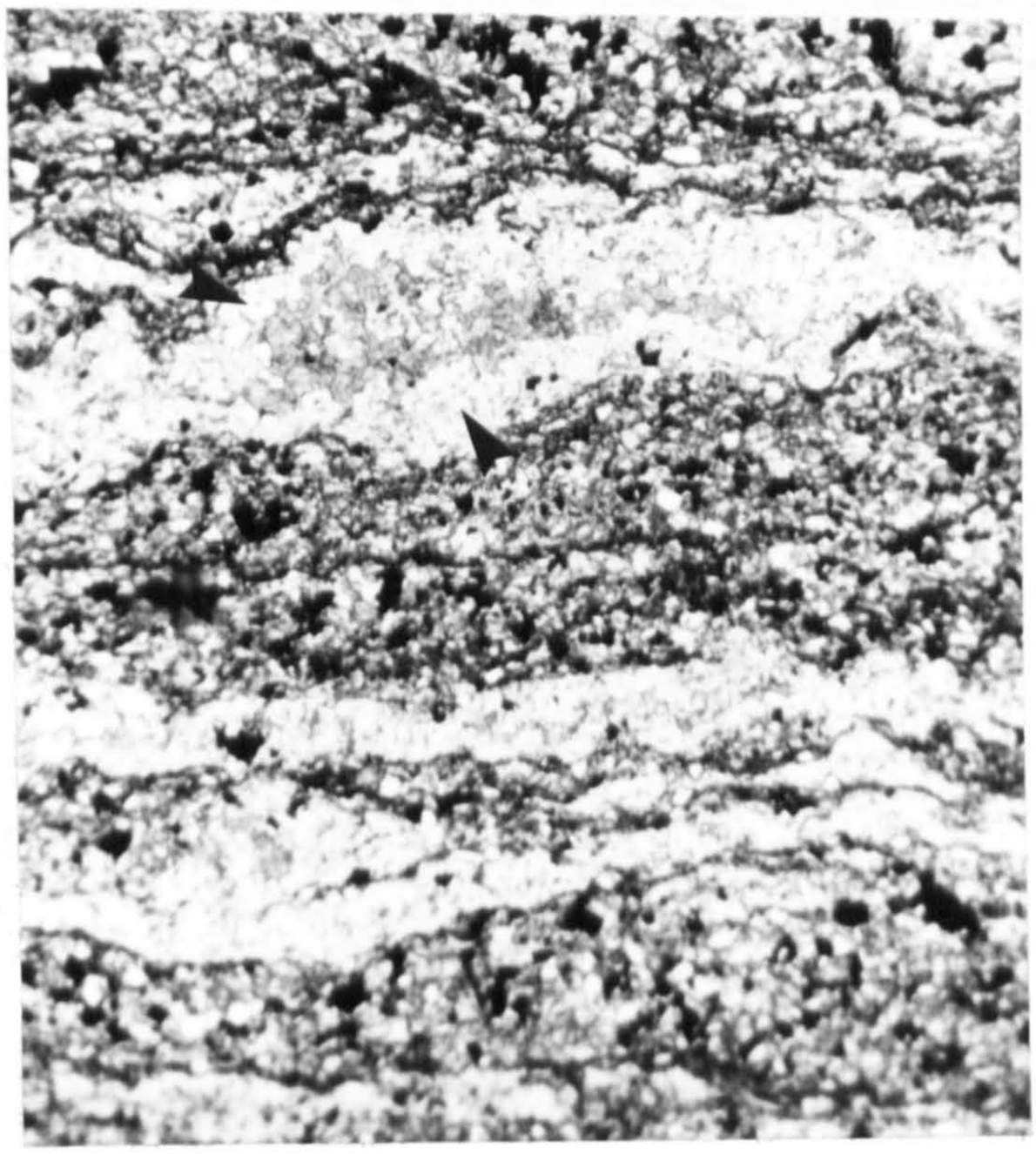


FIG. 5.24: A photomicrograph and sketch from the same slide as Fig. 5.23. showing the margin of a diagenetic calcite nodule. It clearly indicates 1). the diagenetic nature of these nodules - deforming and truncating algal laminae, 2). the association of calcite, albite(analyses-Fig. 5.25) and chalcopyrite - albite and chalcopyrite are intergrown. Thus suggesting a DIAGENETIC origin for the COPPER SULPHIDES.

Several different morphological calcite are present in the nodules - all Low - Magnesium calcite. (TS. 40765, OKW. 5 core, Witvlei Fan, ppl).



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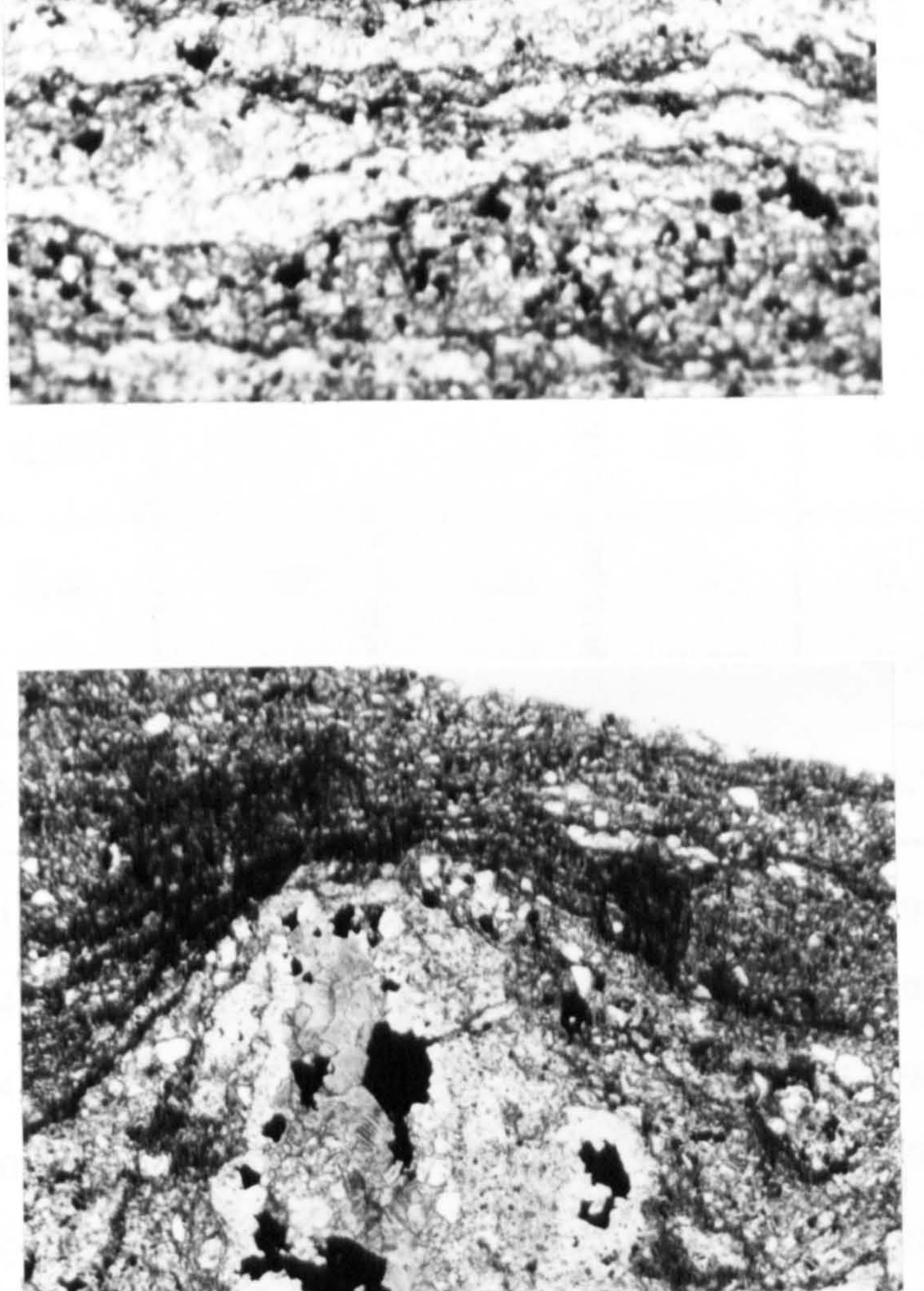

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AUTHIGENIC FELDSPAR ANALYSES (ALBITE/CALCITE ASSOCIATION)

ELEMENT	RED BED ALBITE			PLAYA ALBITE		
	1	2	3	1	2	3
SiO_2	67.94	68.17	68.36	68.27	68.33	68.15
Al_2O_3	19.47	19.74	19.64	19.27	19.29	19.57
NaO	11.76	11.60	11.14	11.55	11.75	11.64
CaO	0.04	0.07	0.18	0.04	0.04	0.03
FeO	0.00	0.02	0.02	0.25	0.25	0.14
K_2O	0.02	0.06	0.08	0.07	0.07	0.07
TOTAL:	99.23	99.46	99.42	99.45	99.73	99.60
Si	11.960	11.947	11.986	11.997	11.985	11.957
Al	4.041	4.077	4.058	3.991	3.988	4.048
Na	4.016	3.940	3.788	3.935	3.996	3.960
Ca	0.008	0.012	0.034	0.008	0.008	0.006
Fe	0.000	0.003	0.003	0.036	0.036	0.021
K	0.005	0.013	0.017	0.016	0.016	0.015
TOTAL:	20.030	19.992	19.886	19.983	20.029	20.007

FIG. 5.25: Electron microprobe analyses of authigenic albite associated with calcite in Red Bed and playa sediments of the Witvlei fan complex.

Note the similarity and purity of the authigenic albite.

DOORNPOORT SEDIMENT DIAGENESIS

MECHANICAL WEATHERING

↓

DEPOSITION

DISSOLUTION - Hb, Px, Ol.

PARTIAL CONVERSION - ILM + Mt

RED BED DIAGENESIS

OXIDATION

DISSOLUTION - Hb, epid, sph, Fd, Qtz.

REPLACEMENT - Plagioclase

CONVERSION - Mt + Ilm → Hm

AUTHIGENIC MINERALS

Haematite
Ti-haematite
Feldspars
Quartz
Calcite

GREEN BED DIAGENESIS

REDUCTION

RETENTION OF Sph, epid, Hb, Mt.

DISSOLUTION OF OPAQUE OXIDES

$Fe^{3+} \rightarrow Fe^{2+}$ (Soluble)

AUTHIGENIC MINERALS

Chlorite
Clays (Micas)
Sulphides
Albite - Witvlei
Specularite - Klein Aub
Calcite

FIG. 5.26: Summary of the various stages of diagenesis leading to the formation of Red and Green Beds of the Doornpoort Formation. (Hb - hornblende, Px = pyroxene, Ol = Olivine, Ilm = Ilmenite, Hm = Haematite, sph = sphere, Qtz = quartz, epid = epidote, Fd = feldspar).

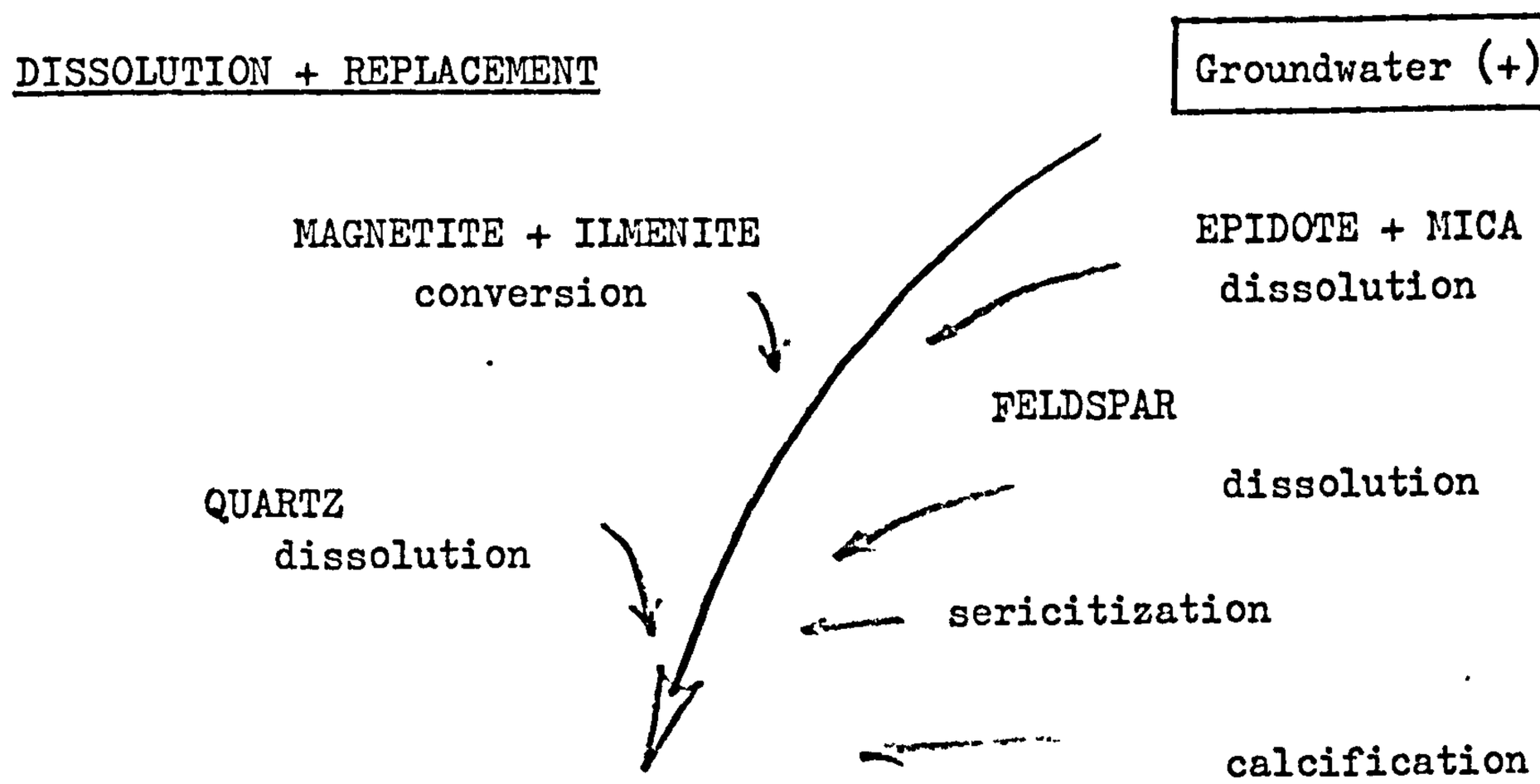
pyroxene and hornblende and partially oxidised detrital opaque oxides in all sediments. Oxidation was stopped in green sediments, leading to the retention of the more resistant ferromagnesian minerals - epidote, sphene, rutile - and magnetite. This observation that green sediments contain more heavy minerals than associated Red Beds was also recognized by Hubert and Reed (1978) from the East Berlin Formation, Connecticut Valley, U.S.A.

5.3 GROUND WATER CHEMISTRY

The alteration of detrital minerals takes place during diagenesis, since minerals are only stable in the environment in which they form (Keller, 1969; Walker, 1976). A collection of minerals derived from a variety of igneous and metamorphic rocks under a semi-arid/arid climate will undergo alteration during early diagenesis. Conditions present during diagenesis are dependent on both groundwater and freshwater chemistry as rain and riverwater percolate into the recently-deposited sediment. Many of the detrital minerals are unstable and are rapidly removed and replaced, releasing ions into solution. Water is the only reagent necessary for the alteration of unstable ferromagnesian minerals in these conditions (Krauskopf, 1967, pp. 113-6; Walker, 1976). Ions released into aqueous solution may then recombine to form new authigenic minerals, depending on the chemical and physical conditions of the groundwater solutions.

In the Doornpoort Red Beds, in situ dissolution and replacement of detrital minerals led to the release of the following elements into interstitial waters: Si, Al, Ca, Na, Fe, K, Ti and Mg (Fig. 5.27). These elements were derived from the conversion of ilmenite, titaniferous magnetite and magnetite to haematite, Ti + Fe;

DOORNPOORT RED BED DIAGENESIS



AUTHIGENIC MINERALS

HAEMATITE	Fe
TITANIFEROUS HAEMATITE	Fe + Ti
ANATASE	Ti
FELDSPARS - Albite	Na + Al + Si
- Microcline	K + Al + Si
QUARTZ	Si
CALCITE	Ca + HCO_3^-

FIG. 5.27: Ions released during the dissolution and replacement of detrital grains recombine to form authigenic minerals. All textures occur in the Doornpoort Red Beds.

dissolution and replacement of feldspars, Al, Si, Ca, Na, K; alteration of micas and epidote, Al, Si, Fe, Ca, K, Mg; and the dissolution of quartz, Si. Highly unstable ferromagnesian minerals towards the top of the Moh stability sequence (Goldrich, 1938), namely, olivine, pyroxenes and hornblende, were probably removed during early diagenesis, releasing Si, Mg, Fe, Ca and Al, into interstitial waters. Migration of these solutions in an open system resulted in the distribution of ions and nucleation forming overgrowths, coatings and pore cements.

The porosity and permeability of the sediments during early diagenesis may have controlled the amount of alteration and authigenic mineral growth. Porous, well sorted sediments (e.g. Aeolian sandstones of Witvlei) enabled the migration of diagenetic groundwaters and the growth of numerous overgrowths and authigenic phases, which either nucleated on detrital host grains or in pore spaces. Low porosity sediments (e.g. poorly sorted alluvial fan sediments) probably had more restricted groundwater circulation, leading to a reduction of the alteration effects and a relative lack of authigenic minerals, due to the paupacy of the correct ions at individual nucleation sites. The transport and circulation of ions to the correct nucleation sites is an important consideration during diagenesis - e.g. the formation of authigenic overgrowths of albite is dependent on the availability of Na, Al and Si at the detrital host grain.

Evidence from the Doornpoort sediments indicates the importance of groundwater circulation on diagenesis. The well sorted aeolian sandstones contain many authigenic minerals and an even distribution of iron staining. Poorly sorted alluvial sediments, however, have

an irregular iron distribution and show a general lack of authigenic phases.

A paragenetic sequence of authigenic minerals is recognized in the aeolian sandstones of the Witvlei fan complex, which reflects the changing groundwater chemistry in these sediments (Fig. 5.21). Initially, the groundwaters were depleted with respect to Fe and Ti, indicated by the formation of Fe cutans, titaniferous haematite overgrowths and euhedral anatase grains. Subsequently, the formation of feldspars, namely, microcline and albite, further removed K, Na, Al and Si. Depletion in silica denoted by abundant quartz overgrowths and cements, followed by removal of Ca^{2+} and HCO_3^- ions during calcification of detrital and early authigenic phases, and the production of calcite cements.

Interstitial conditions during Red Bed formation are considered oxidizing and alkaline (Van Houten, 1973; Walker and Waugh, 1973; Walker, 1976; Hubert and Reed, 1978; Walker et al, 1978; Waugh, 1978; Turner, 1980). Since haematite is stable, red sediments must plot within the haematite stability field on an Eh-pH diagram and must therefore be oxidizing (Fig. 5.28). Inferences that the conditions are alkaline are based on work by Krauskopf (1959) on silica and alumina solubility in aqueous solutions. Both alumina and silica are soluble in interstitial solutions during Red Bed formation, since authigenic minerals containing both SiO_2 and Al_2O_3 form from groundwater solutions (e.g. albite, microcline and quartz). From Krauskopf's work, silica and alumina are only soluble in aqueous solutions in conditions with pH values of between 9-10 or greater (Fig. 5.29). Thus, within the Doornpoort Red Beds, conditions must have been alkaline ($pH > 9.5$), since

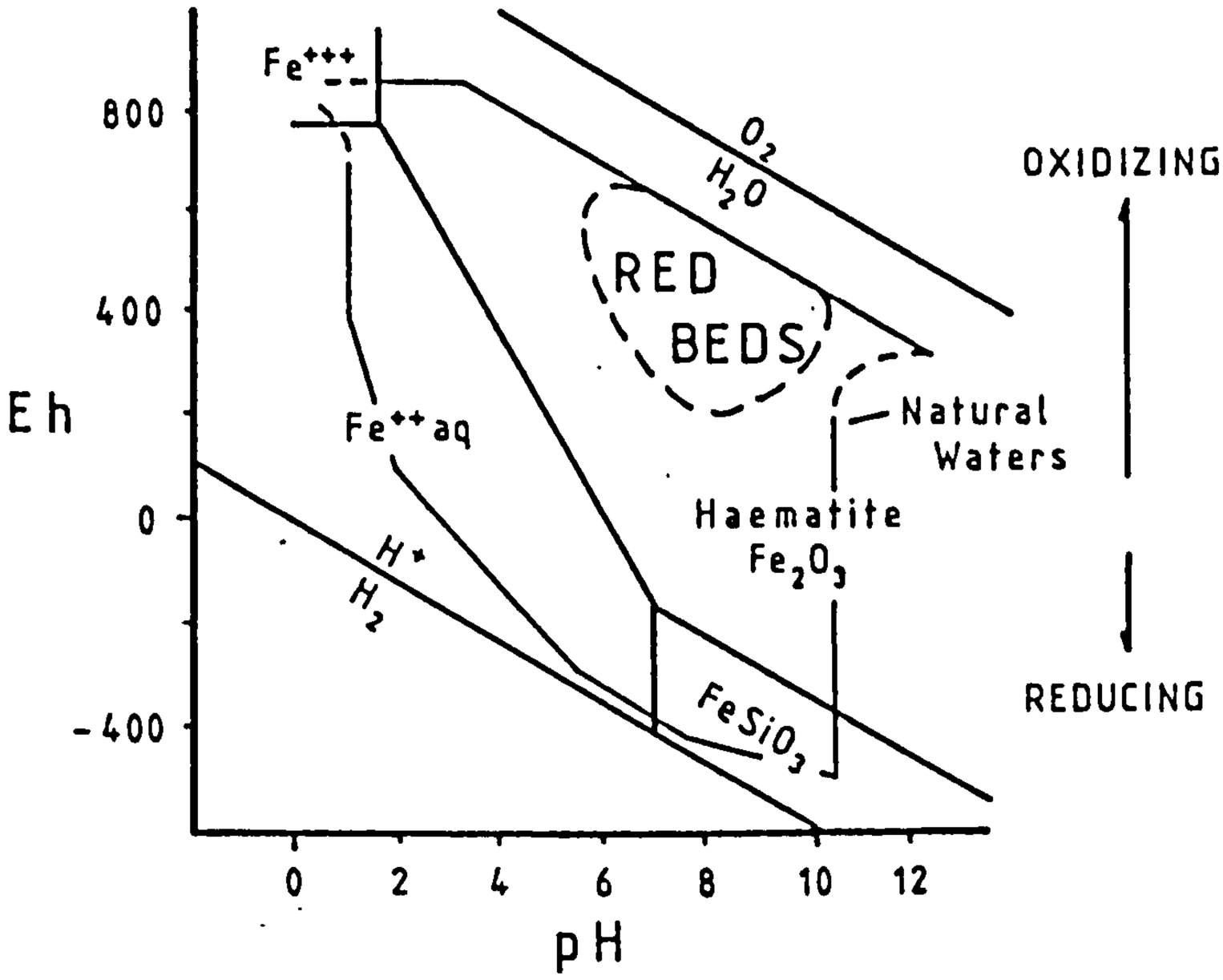


FIG. 5.28: An Eh-pH diagram illustrating the approximate field in which the Doornpoort Red Beds probably formed. The field plots within the limit of natural waters (Baas-Beck ing et. al.,1960) and in the stability field of haematite at 25°C and 1 atmosphere (Garrels and Christ, 1965).

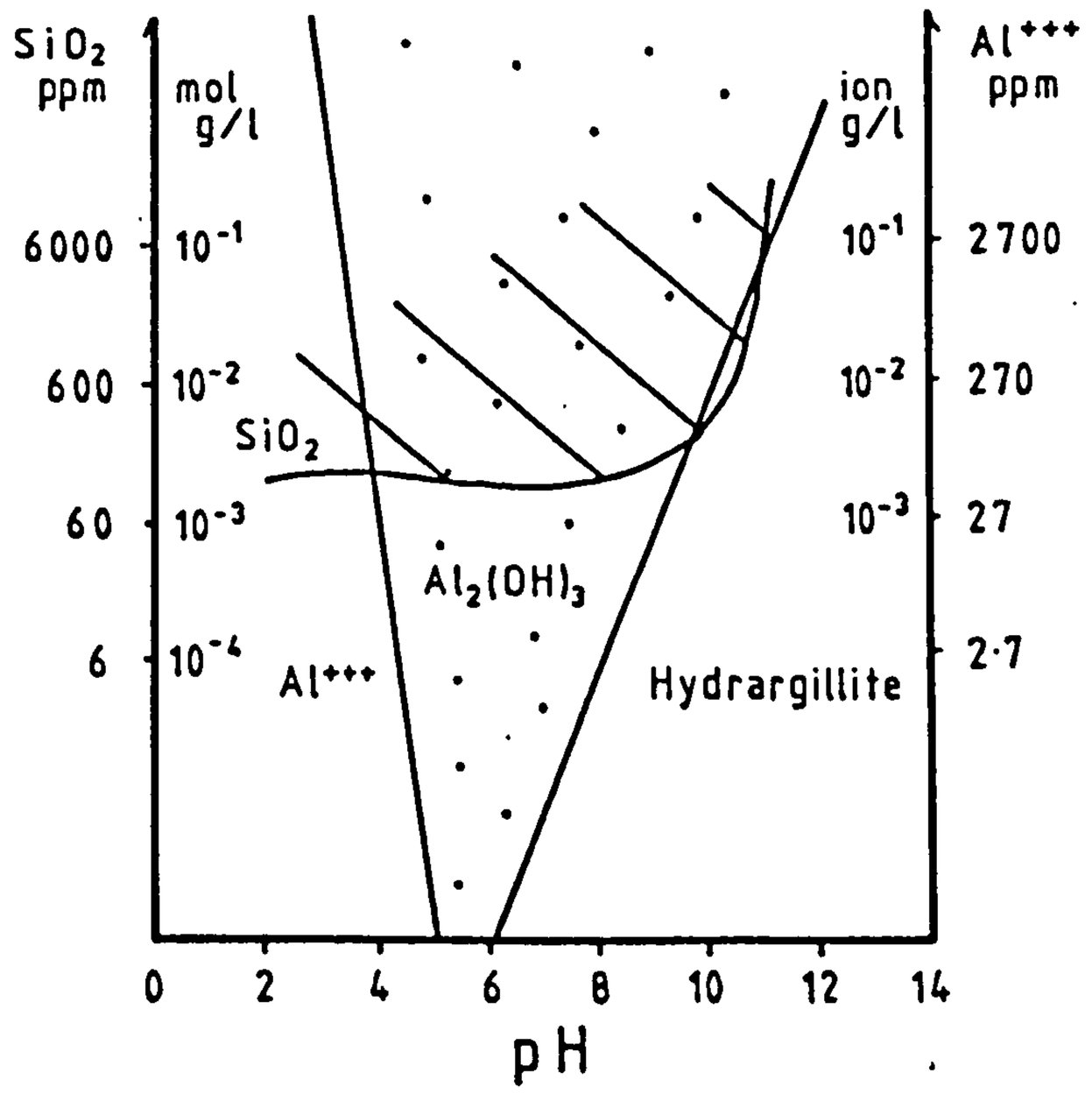


FIG. 5.29: Two superimposed curves indicating the solubility of silica (SiO2) and of aluminium(Al+++) as functions of pH, Al^{3+} and SiO2 soluble in unshaded areas.(After Millot, 1970. - from Krauskopf, 1957. and Wey, 1962). Al and SiO2 are only soluble together at pH's of 9-10 or above (ie. alkaline conditions). (25°C and 1 atmosphere)

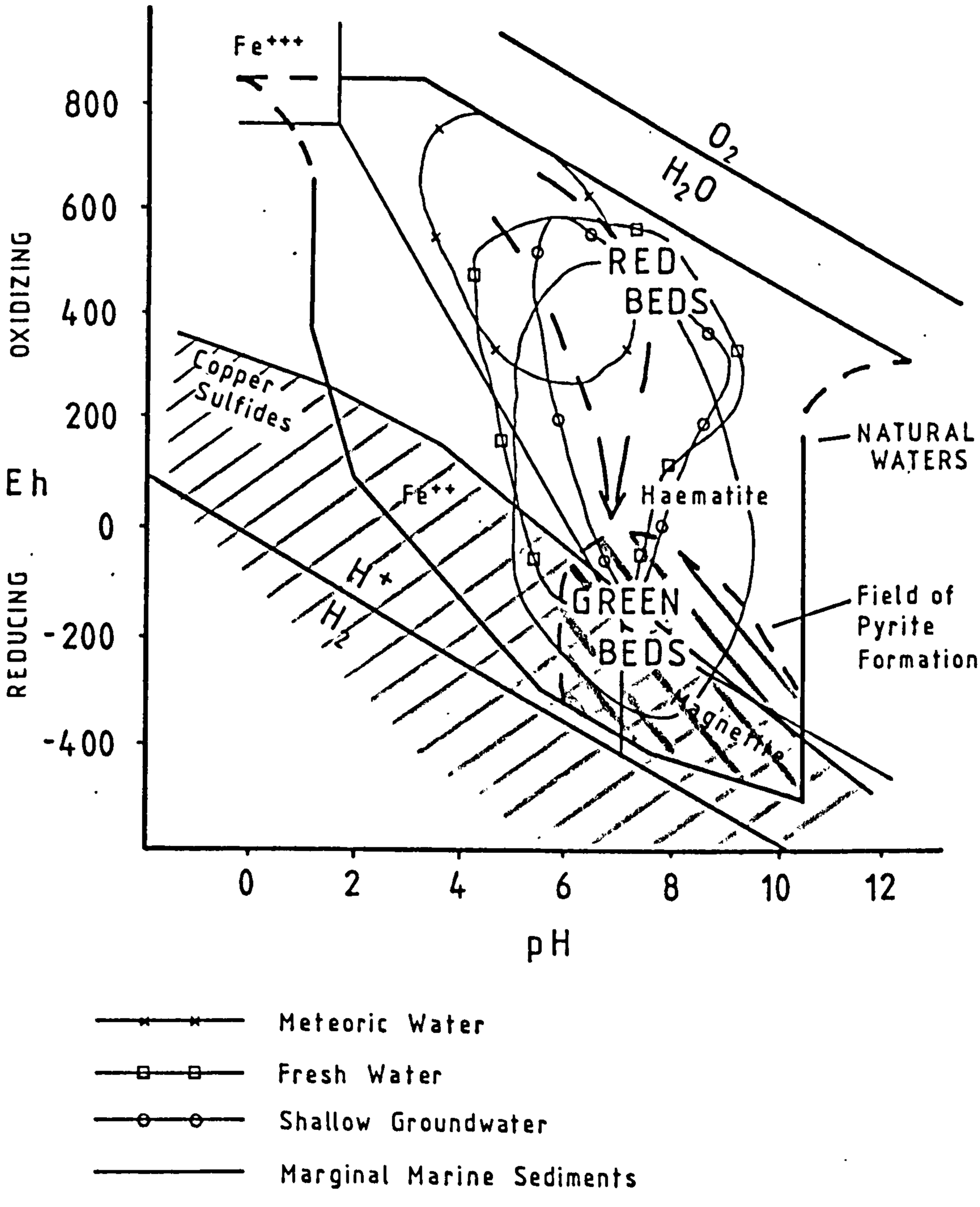


FIG. 5.30: A summary Eh-pH diagram illustrating the relative positions of Red and Green Doornpoort sediments during diagenesis. The stability fields of meteoric water, fresh water, shallow ground-water and marginal marine sediments are shown within the field of natural waters (Baas-Beck ing et.al. 1960). Red Beds plot in the stability field of haematite and in oxidizing, alkaline conditions whereas Green Sediments form in the stability fields of haematite, magnetite, Fe++aqueous, pyrite (\\) and copper sulphides (//). (see Garrels and Christ, 1965). The arrow indicates the proposed path of evolution of diagenetic, plus surface and ground-waters in the Witvlei Fan Complex. (25°C and 1 atmosphere)

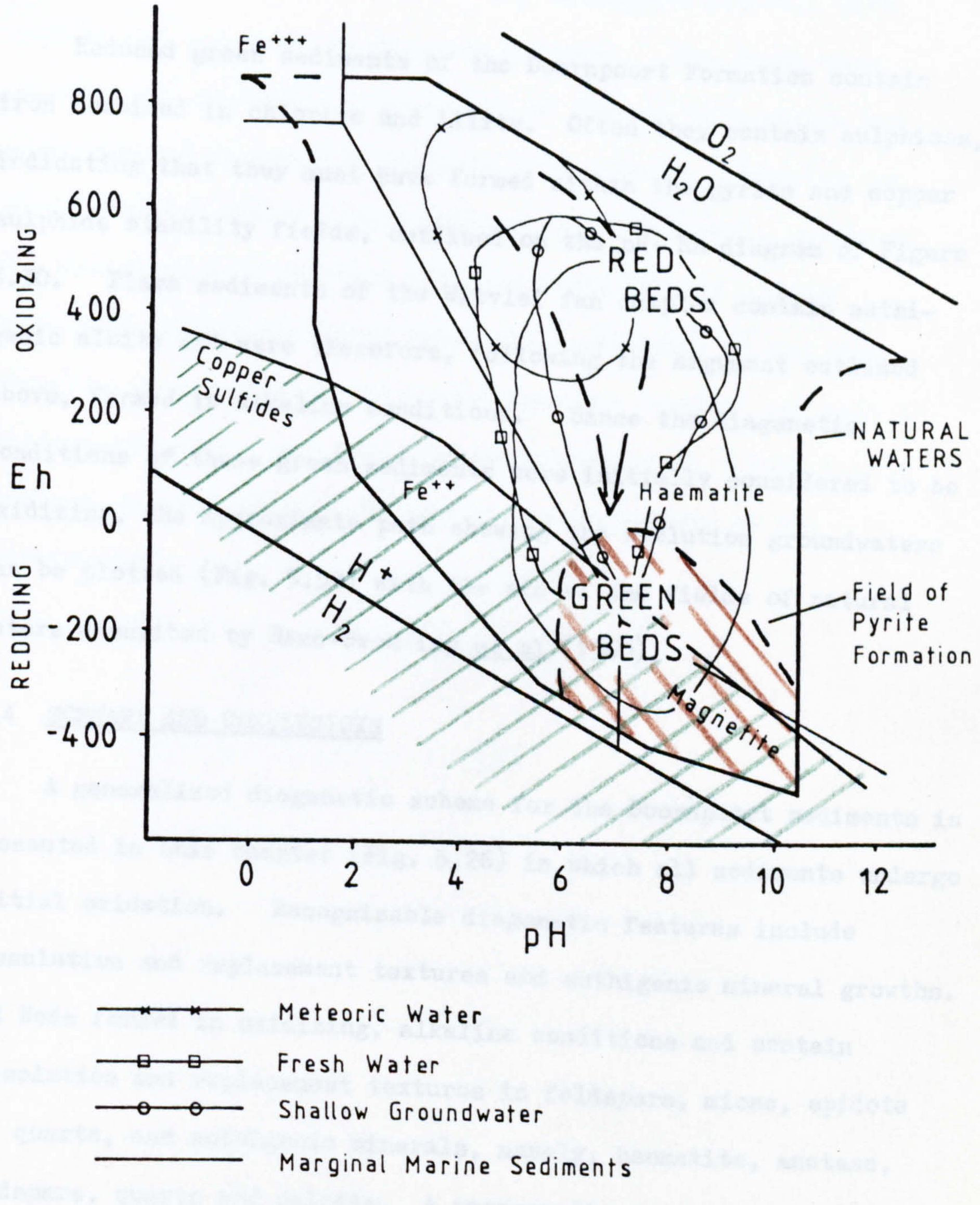


FIG. 5.30: A summary Eh-pH diagram illustrating the relative positions of Red and Green Doornpoort sediments during diagenesis. The stability fields of meteoric water, fresh water, shallow ground-water and marginal marine sediments are shown within the field of natural waters (Baas-Beck ing et.al. 1960). Red Beds plot in the stability field of haematite and in oxidizing, alkaline conditions whereas Green Sediments form in the stability fields of haematite, magnetite, Fe++aqueous, pyrite (\\) and copper sulphides (//). (see Garrels and Christ, 1965). The arrow indicates the proposed path of evolution of diagenetic, plus surface and ground-waters in the Witvlei Fan Complex. (25°C and 1 atmosphere)

authigenic albite and quartz are relatively common phases (Summary, Fig. 5.28).

Reduced green sediments of the Doornpoort Formation contain iron combined in chlorite and illite. Often they contain sulphides, indicating that they must have formed within the pyrite and copper sulphide stability fields, outlined on the pH-Eh diagram of Figure 5.30. Playa sediments of the Witvlei fan complex contain authigenic albite and were therefore, following the argument outlined above, formed in alkaline conditions. Since the diagenetic conditions of these green sediments were initially considered to be oxidizing, the approximate path showing the evolution groundwaters can be plotted (Fig. 5.30) with the aid of the fields of natural waters described by Baas-Beck ing et al (1960).

5.4 SUMMARY AND CONCLUSIONS

A generalized diagenetic scheme for the Doornpoort sediments is presented in this chapter (Fig. 5.26) in which all sediments undergo initial oxidation. Recognizable diagenetic features include dissolution and replacement textures and authigenic mineral growths. Red Beds formed in oxidizing, alkaline conditions and contain dissolution and replacement textures in feldspars, micas, epidote and quartz, and authigenic minerals, namely, haematite, anatase, feldspars, quartz and calcite. A paragenetic sequence of authigenic minerals is recognized in the aeolian sandstones of the Witvlei fan complex. Green sediments contain authigenic chlorite, sulphides and clays (now micas), in addition to albite in the playa sediments of Witvlei. After the initial oxidation period, the sediments were reduced by the decay of organic matter and are considered to have been formed under alkaline, reducing conditions.

Progressive burial of the sediments resulted in the replacement of clays by micas, detrital and authigenic minerals with calcite and the onset of pressure solution. The rocks were subsequently deformed in two stages of Damaran deformation and metamorphosed to lower greenschist facies grade. Despite the effects of deformation, metamorphism and deep burial, involving the destruction of original and diagenetic fabrics and the conversion of diagenetic to metamorphic minerals, it has been possible to see through the post-diagenetic 'veneer' and gain an insight into early and late diagenetic processes. This insight has proved invaluable in interpreting many aspects of the mineralization.

CHAPTER VI

ORE GENESIS

INTRODUCTION

Low grade stratiform copper/silver ore deposits occur in reduced playa and marginal lacustrine sediments, closely associated with Red Bed sandstones and conglomerates. The ores consist of zoned copper and iron sulphide deposits, predominantly concentrated in clastic sediments. No volcanics are associated with the mineralized horizons.

This chapter describes the major controls on the copper mineralization, presents sulphur, lead, carbon and oxygen isotopic data, outlines a model for ore genesis and concludes with a discussion of this model and its relationship to the genesis of other stratiform Red Bed ore deposits.

6.1 DOORNPOORT COPPER MINERALIZATION

6.1.1 Sedimentology and Mineralization

Copper and silver mineralization is widespread in the Doornpoort sediments occurring in playa horizons at Witvlei, Okasewa, Hamis and Kojeka and in marginal lacustrine deposits at Klein Aub, Kagas Noord and Lake Ngami (Fig. 6.1). The ores are stratiform and concentrated in the first reduced horizons of each succession (Figs. 6.2, 6.3, 4.5). They rest above, or alongside, alluvial fan red sediments which lie unconformably on a mineralized basement.

The most obvious sedimentary control on all the ore deposits is the association of coarse alluvial fan sediments and mineralization. Mineralized horizons occur above, or adjacent to, alluvial fan conglomerates (Figs. 6.2, 6.3, 4.5, 4.9). This is particularly evident in the Witvlei, Klein Aub and Lake Ngami areas. At Kagas

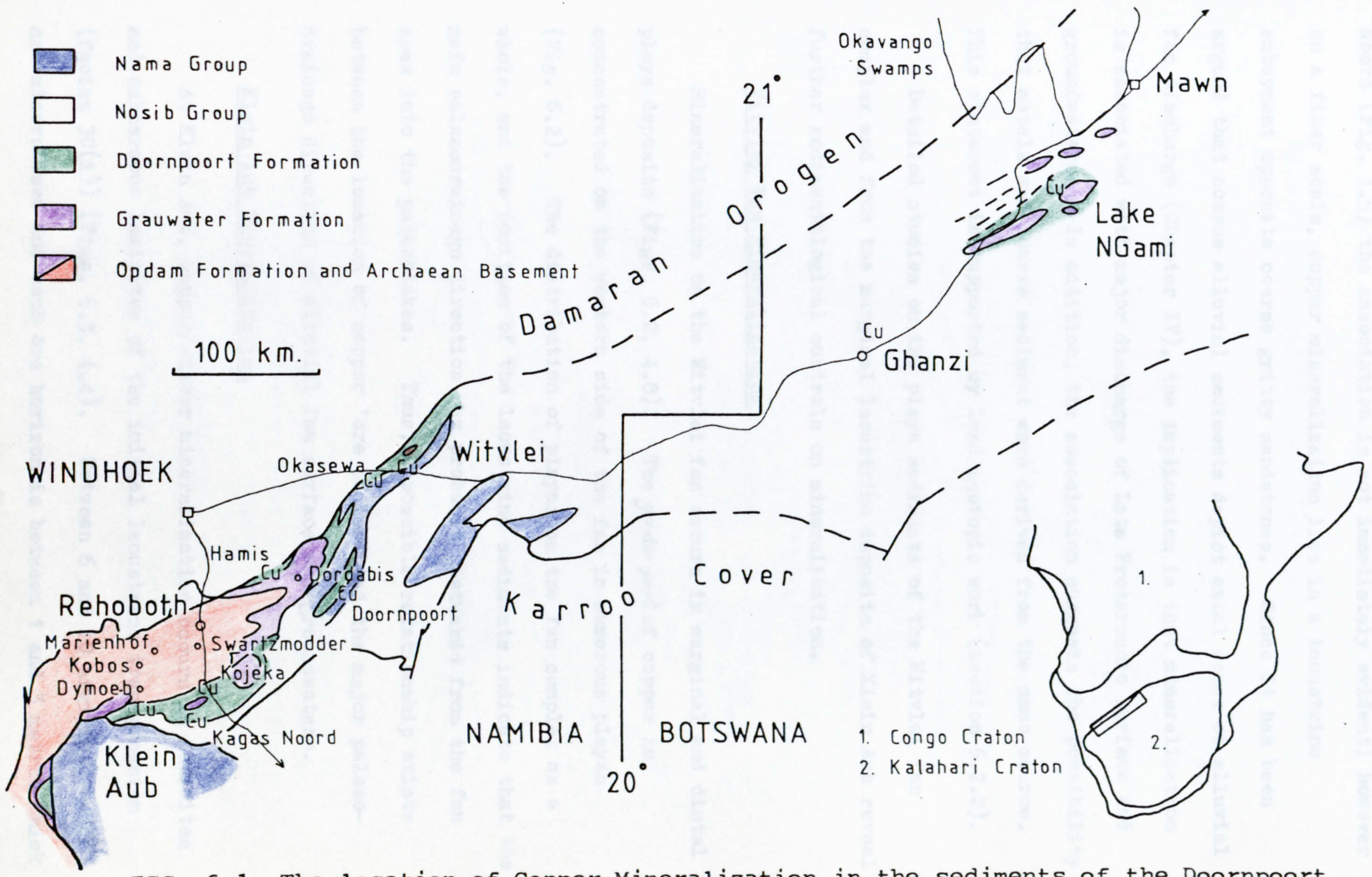


FIG. 6.1: The location of Copper Mineralization in the sediments of the Doornpoort Formation, Namibia and Botswana. (Cu = copper mineralization)

Noord (Fig. 4.5) the association is not immediately evident; however on a finer scale, copper mineralization lies in a lacustrine embayment opposite coarse gritty sandstones. Since it has been argued that coarse alluvial sediments depict axial zones of alluvial fan discharge (Chapter IV), the implication is that mineralization is associated with major discharge of Late Proterozoic surface and groundwaters. In addition, the association suggests the possibility that metals and coarse sediment were derived from the same source. This statement is supported by lead isotopic work (section 6.2.2).

Detailed studies on the playa sediments of the Witvlei fan complex and from the marginal lacustrine deposits of Klein Aub reveal further sedimentological controls on mineralization.

Witvlei Fan Mineralization

Mineralization on the Witvlei fan occurs in marginal and distal playa deposits (Figs. 6.2, 4.8). The greater part of copper is concentrated on the western side of the fan in numerous playas (Fig. 6.2). The distribution of playas on the fan complex as a whole, and the position of the lacustrine sediments indicate that the main palaeodrainage direction was probably westwards from the fan apex into the palaeolakes. Thus, a possible relationship exists between the location of copper 'ore bodies' and the major palaeodrainage direction of alluvial fan surface and groundwaters.

Klein Aub Mineralization

At Klein Aub, copper/silver mineralization occurs in laminites and calcareous laminites of the initial lacustrine transgression (facies 3C(i)) (Figs. 6.3, 4.4). Between 6 and 10 argillite bands are mineralized and each ore horizon is between 1 and 3 metres thick

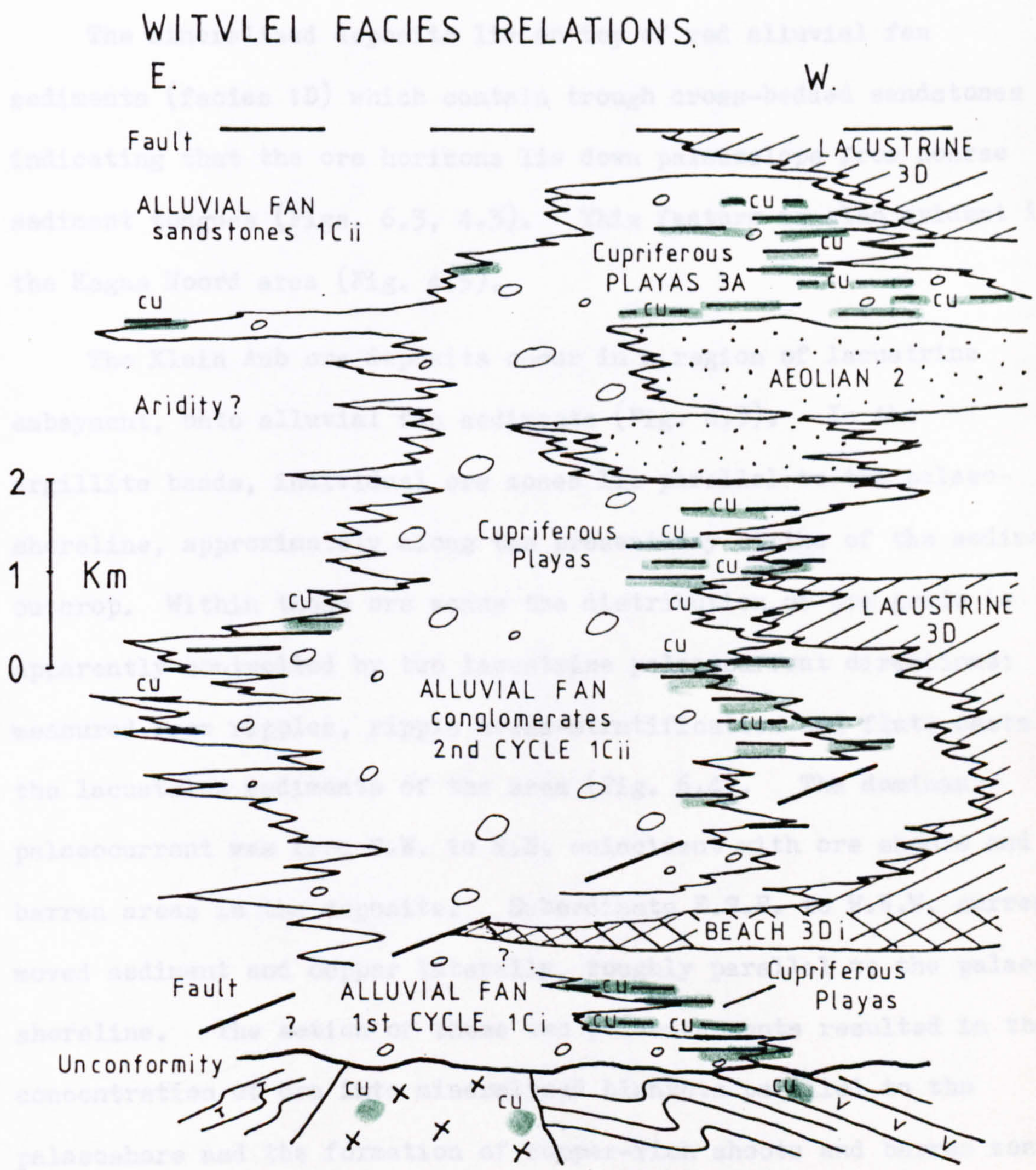


FIG. 6.2: A vertical sedimentological section of the Witvlei Fan Complex showing rapid lateral facies variations. Note the concentration of playa sediments and copper mineralization on the Western side of the Fan and the position of lacustrine sediments of Facies 3D. The evidence suggests that palaeodrainage was from central fan areas to the West. Also note the thickness of the succession and the mineralized basement.

extending for up to 2 km. along strike.

The mineralized deposits lie on top of red alluvial fan sediments (facies 1D) which contain trough cross-bedded sandstones indicating that the ore horizons lie down palaeoslope from coarse sediment tongues (Figs. 6.3, 4.3). This feature is also evident in the Kagas Noord area (Fig. 4.5).

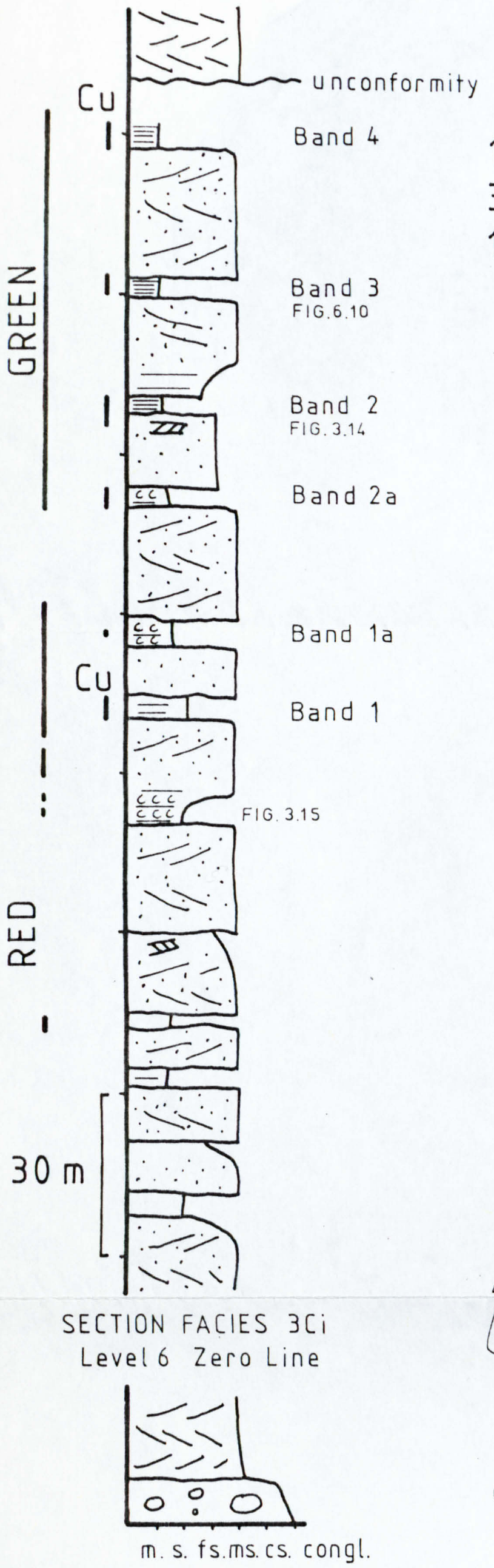
The Klein Aub ore deposits occur in a region of lacustrine embayment, onto alluvial fan sediments (Fig. 6.3). In the argillite bands, individual ore zones lie parallel to the palaeo-shoreline, approximately along the present-day strike of the sediment outcrop. Within these ore zones the distribution of ore grade is apparently controlled by two lacustrine palaeocurrent directions; measured from ripples, ripple cross-stratification and flute casts in the lacustrine sediments of the area (Fig. 6.4). The dominant palaeocurrent was from S.W. to N.E. coincident with ore shoots and barren areas in the deposits. Subordinate E.S.E. to W.N.W. currents moved sediment and copper laterally, roughly parallel to the palaeo-shoreline. The action of these two palaeocurrents resulted in the concentration of ore into mineralized blankets parallel to the palaeoshore and the formation of copper-rich shoots and barren zones, within these blankets (see Page 195). * F.N.

This palaeocurrent control on ore grade not only implies a syngenetic origin but also suggests that copper was introduced in particulate form during sedimentation (see Page 195).

6.1.2 Ore Horizons and Copper/Iron Sulphides

In the Doornpoort sediments, copper and silver occur in reduced green and black fine sediments. Mineralized horizons consist of zoned copper and copper/iron sulphide bodies with an average grade

* Both mineralized and unmineralized fine, reduced laminites are found in the Klein Aub Ore horizons.



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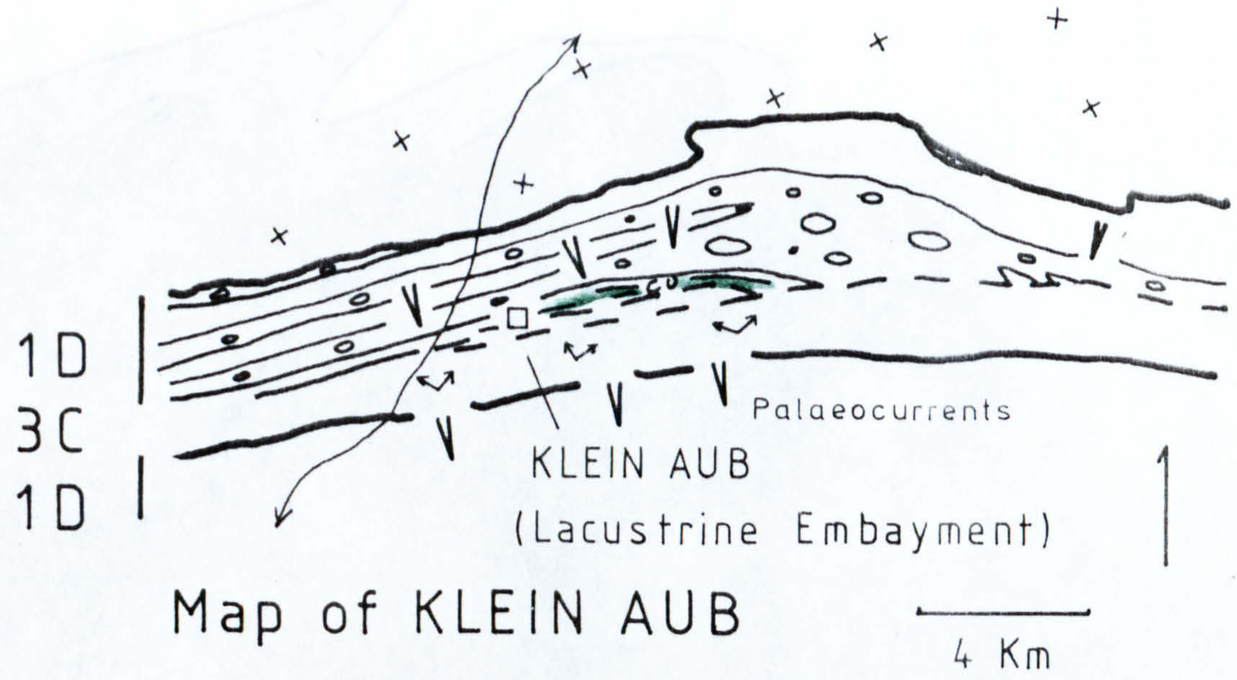
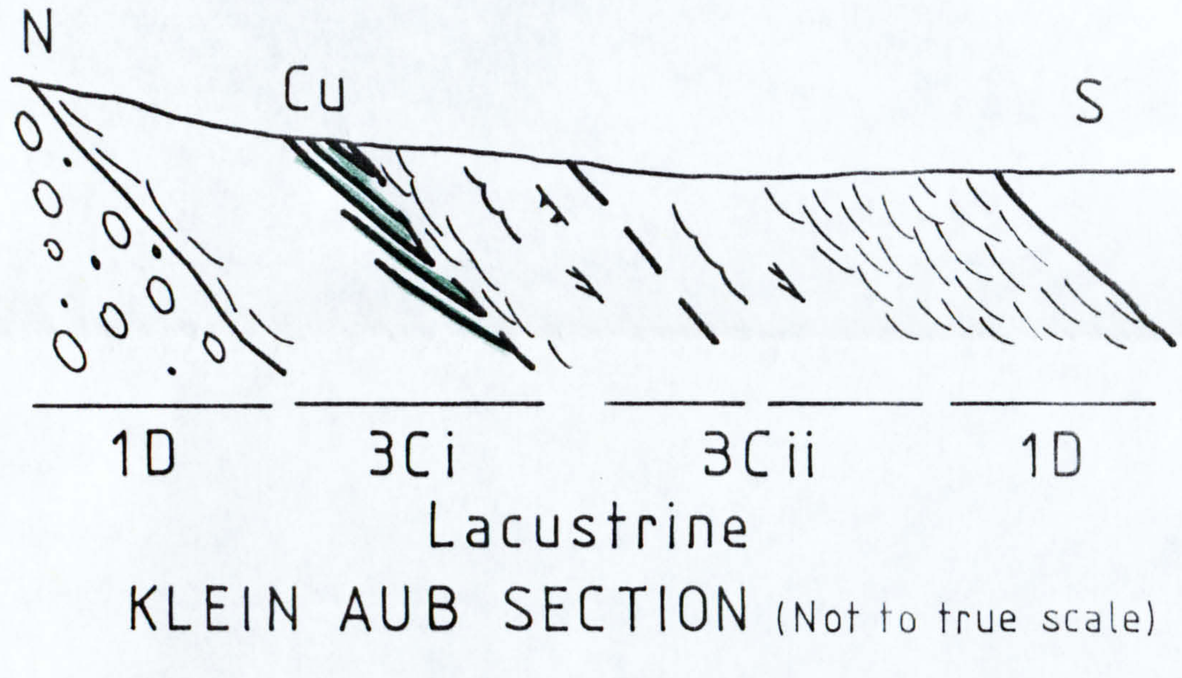


Map of KLEIN AUB

4 Km



KLEIN AUB SECTION (Not to true scale)

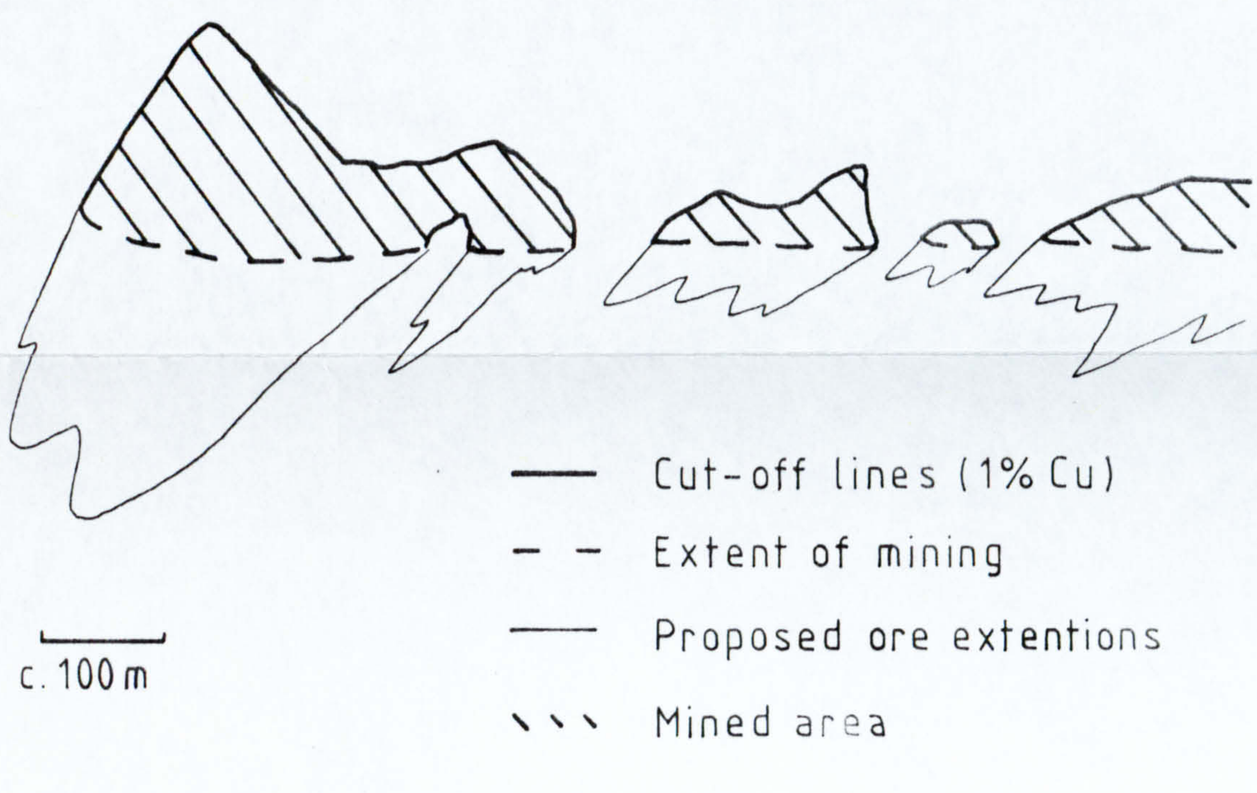


FIG. 6.3: The KLEIN AUB ORE DEPOSITS : 1). an underground log of the copper-bearing Facies 3C(i) sediments, 2). a facies map of the Klein Aub area illustrating the Lacustrine Embayment and alluvial plus lacustrine palaeocurrents, 3). a cross section showing the position of the mineralized bands, and 4). a plan view of Band 4, indicating the position of the Ore Blanket with mined areas and proposed ore extentions indicated.

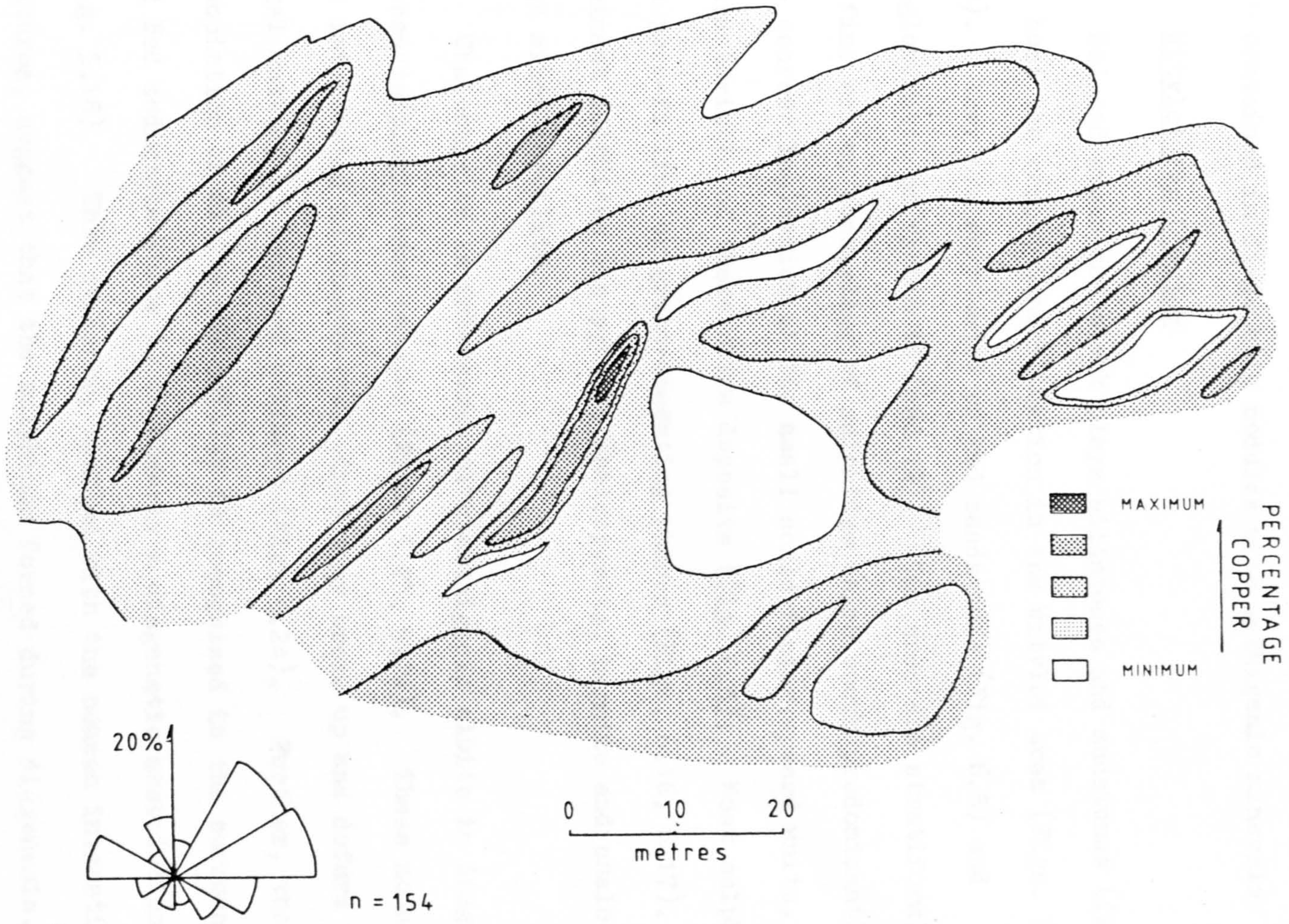


FIG. 6.4: Contours of copper % (related to ore thickness) from Band 3 of the Klein Aub ore deposit. Copper rich ore shoots and barren areas appear coincident with lacustrine palaeocurrent directions. (Band 3, Levels 5 and 6, Klein Aub Mine, stope E1140).

of 2% copper (Toens, 1975) and minor quantities of silver. Silver occurs in the copper and iron sulphides and has a variable distribution along the southern foreland.

Sulphides fill pore spaces and cement detrital grains and are also contained in diagenetic nodules with authigenic minerals.

Witvlei Fan Complex

Reduced green and black playa siltstones and mudstones (facies 3A) host the copper mineralization in the Witvlei area (Figs. 6.5, 4.8). They are surrounded by red sandstones (Fig. 6.5) and conglomerates of facies 1C (and 1B). The ores are stratiform, even on fine scales consisting of sulphides which occur predominantly in the coarser lamination of the small scale fining upward units, characteristic of these playa deposits (Fig. 6.5). Most sulphides are pore-filling or grain-cementing phases (Figs. 6.16, 6.17). The dominant sulphides are pyrite, chalcopyrite, bornite and chalcocite with minor covellite.

Chalcopyrite is intergrown with authigenic albite in diagenetic carbonate/plagioclase nodules (Figs. 5.23, 5.24). These nodules are interpreted as diagenetic, since they break up and deform the algal matting of the host sediment (Fig. 5.24). Further, the association of albite and calcite is recognized in the surrounding Red Bed sediments where it is clearly a diagenetic association (Fig. 5.16). This evidence, coupled with the common interstitial textures, suggest that the sulphides formed during diagenesis.

Several other textural forms of sulphide occur. Pyrite may cement detrital grains at the base of coarse sediment fractions (Fig. 6.6), clearly indicating that this pyrite formed from solution during diagenesis. This is supported by the fact that compaction

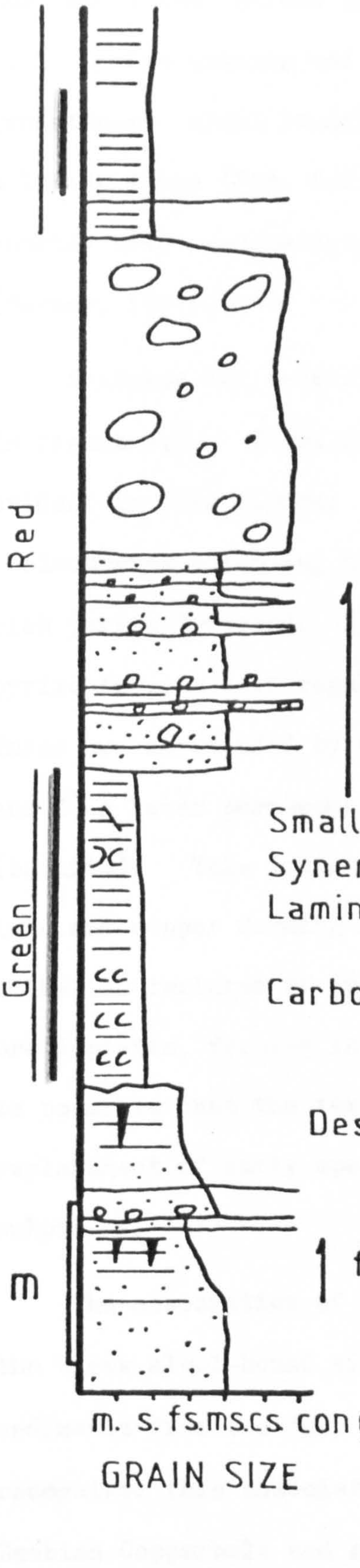
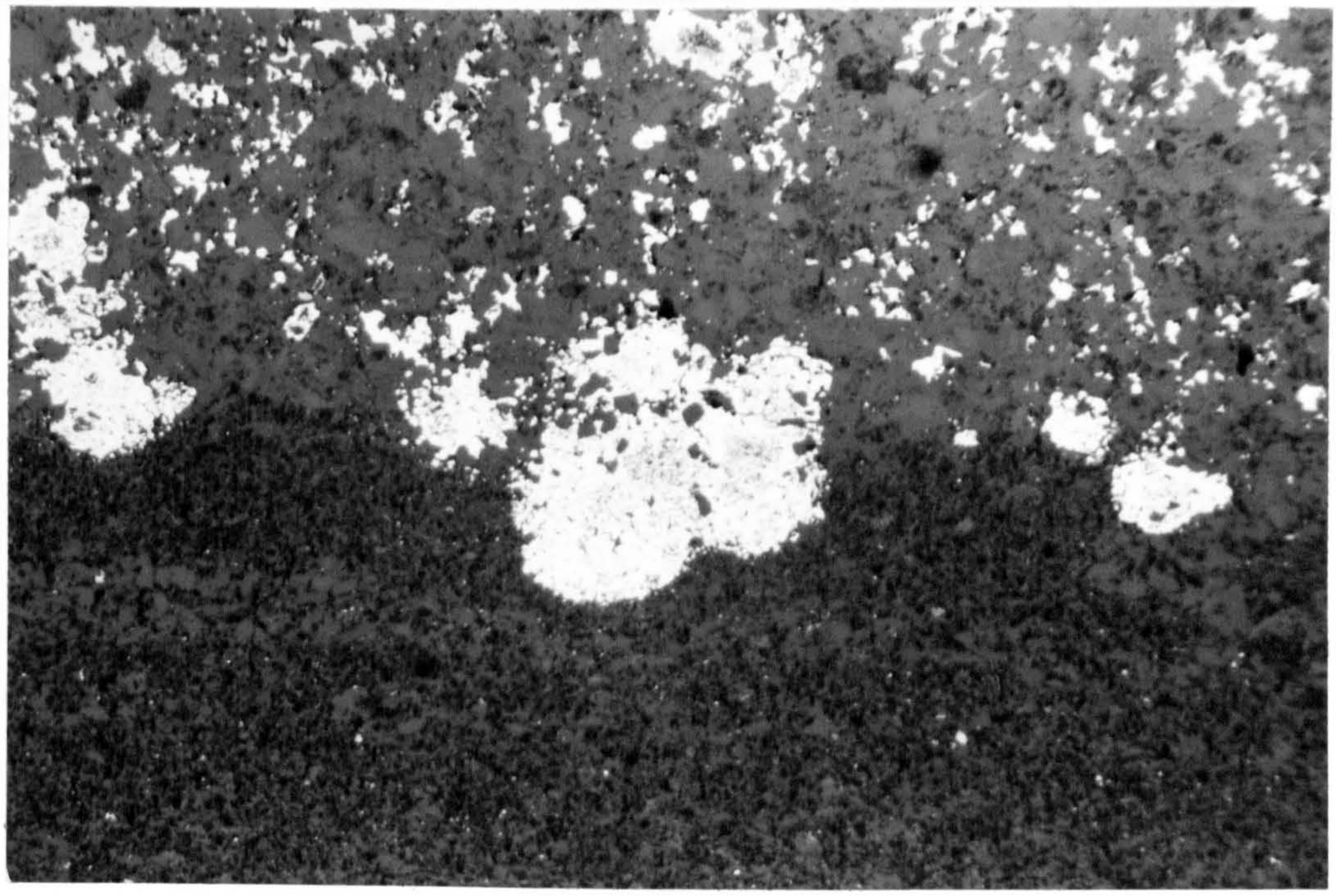


FIG. 6.5: Marginal Fan copper-bearing playa sediments of the Witvlei Fan Complex. Note the close association of alluvial and playa sediments. (Drill core section OKW.5).

has forced the 'porous pyrite' grain into the finer sediment below. Small pyrite spheres and rings of spheres occur in finer sediment (mudstones - algal bound) and are interpreted as early framboidal sulphide forms (Fig. 6.7). Framboidal pyrite generally forms shortly after sedimentation due to the breakdown of organic matter (Berner, 1971).

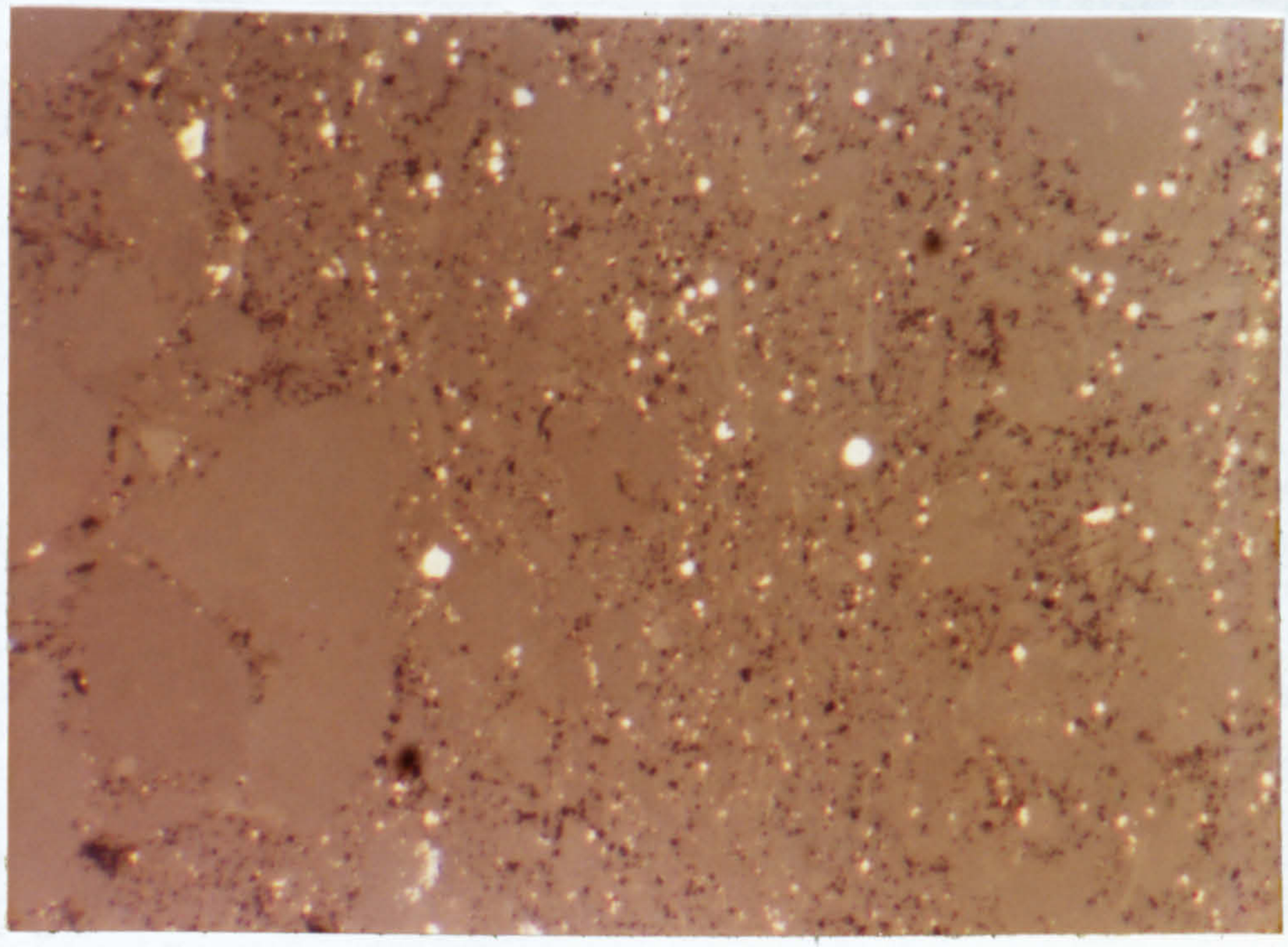
Evidence for several generations of sulphides is illustrated in figure 6.8. Three generations of sulphide formation are evident in this figure: 1) an early rounded grain of pyrite/chalcopyrite which may be a detrital sulphide or an early copper-rich pyrite framboid; 2) authigenic overgrowths of non-cupriferous pyrite forming both regular and irregular sword-like projections. These are surrounded by an iron oxide phase, probably haematite; and 3) a later pore-cementing phase of copper and iron sulphide (bornite). This latter phase contains irregular distributions of iron and copper forming broadly lath-shaped structures. Similar lath-like textures of specular haematite are found in the Klein Aub ore deposits, forming in veins and within the sediment bands. It is possible that the textures shown in figure 6.8 indicate the replacement of early specular haematite by copper and iron sulphides.

The association of chalcopyrite and quartz is recognized in the black algal-bound siltstones and mudstones of the distal playa sediments from the farm Daheim (Fig. 6.9). Clemmey (1976, p.304) recognized this association in sediments from Chibuluma on the Zambian Copperbelt and suggested that it indicated a replacement texture after chrysocolla ($CuSiO_3H_2O$). He postulated that chrysocolla formed a detrital particle which became unstable during



0·9 mm

FIG. 6.6: A photomicrograph of pyrite cementing a coarse siltstone of Facies 3A. The pyrite probably formed during early diagenesis, indicated by the position of the Porous Pyrite grains which have been pressed into the finer sediments below, probably during compaction of the sediment. (PT. 4563, Daheim, core D1, Reflected light (rl.)).



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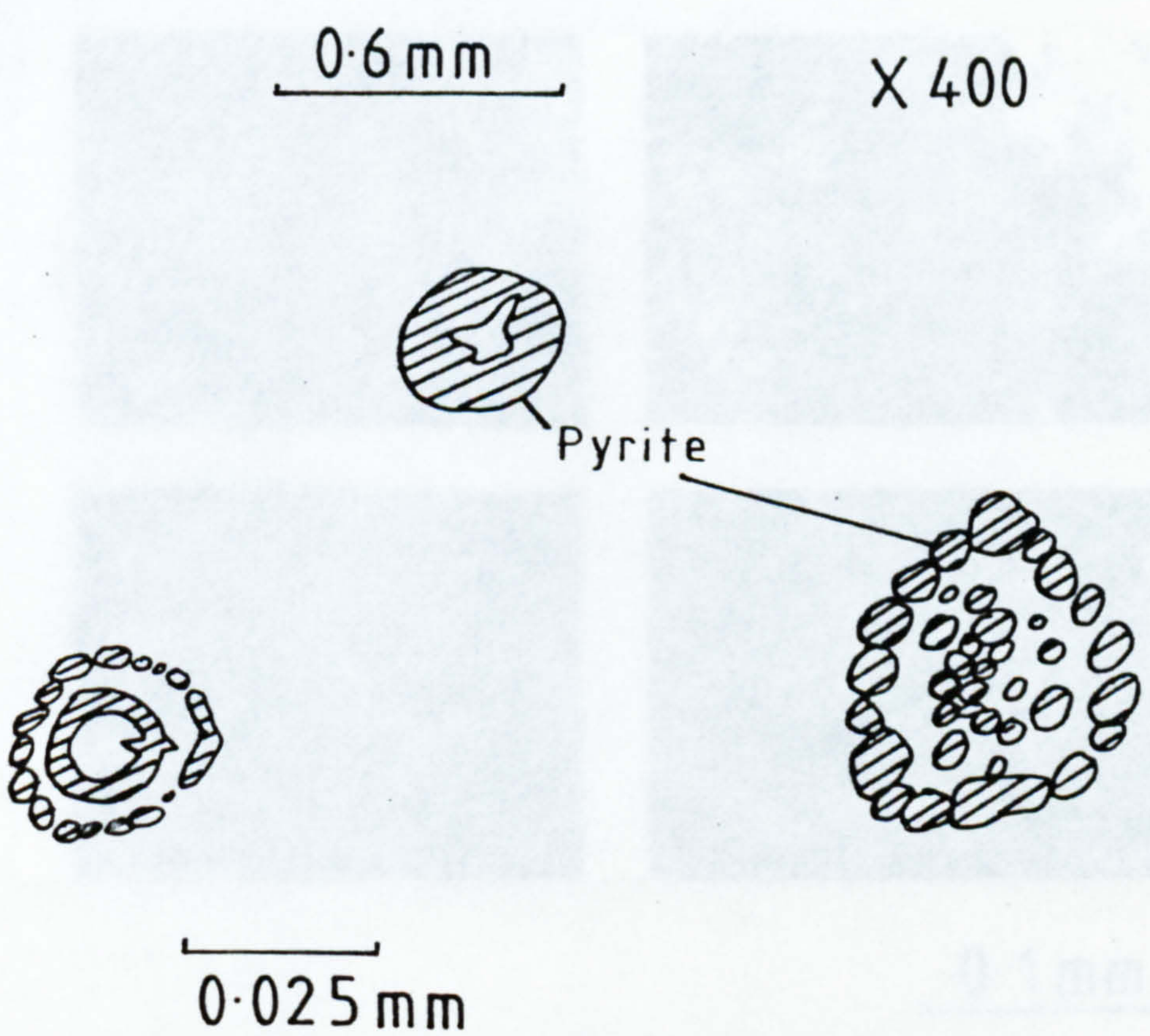
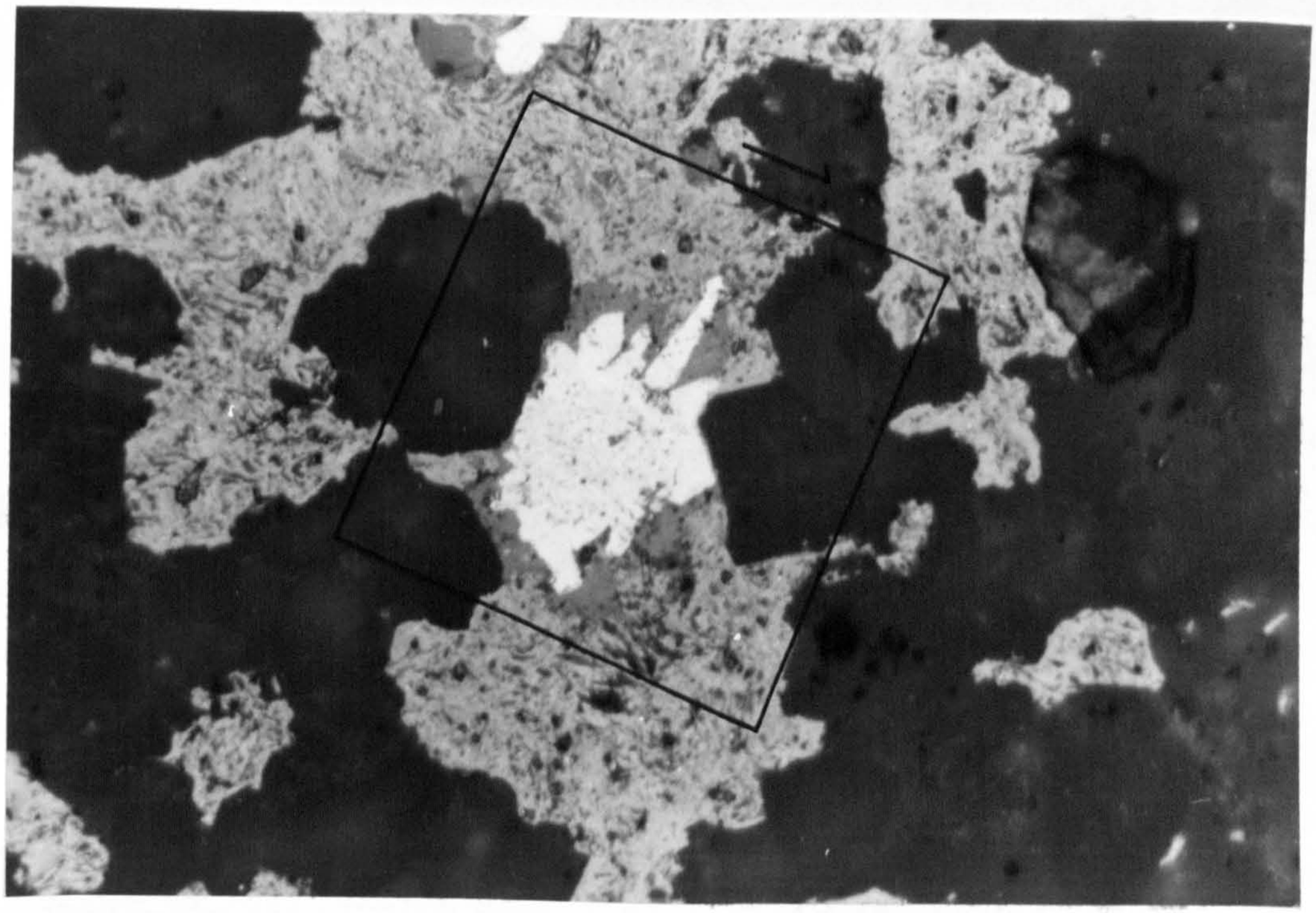


FIG. 6.7: Photomicrograph of fine algal bound siltstones ofthe distal playa sediments of the Witvlei Fan, containing small framboidal pyrite forms illustrating the textures sketched. (PT. 4562, Daheim, core D1, r1.).

(A)



(B).

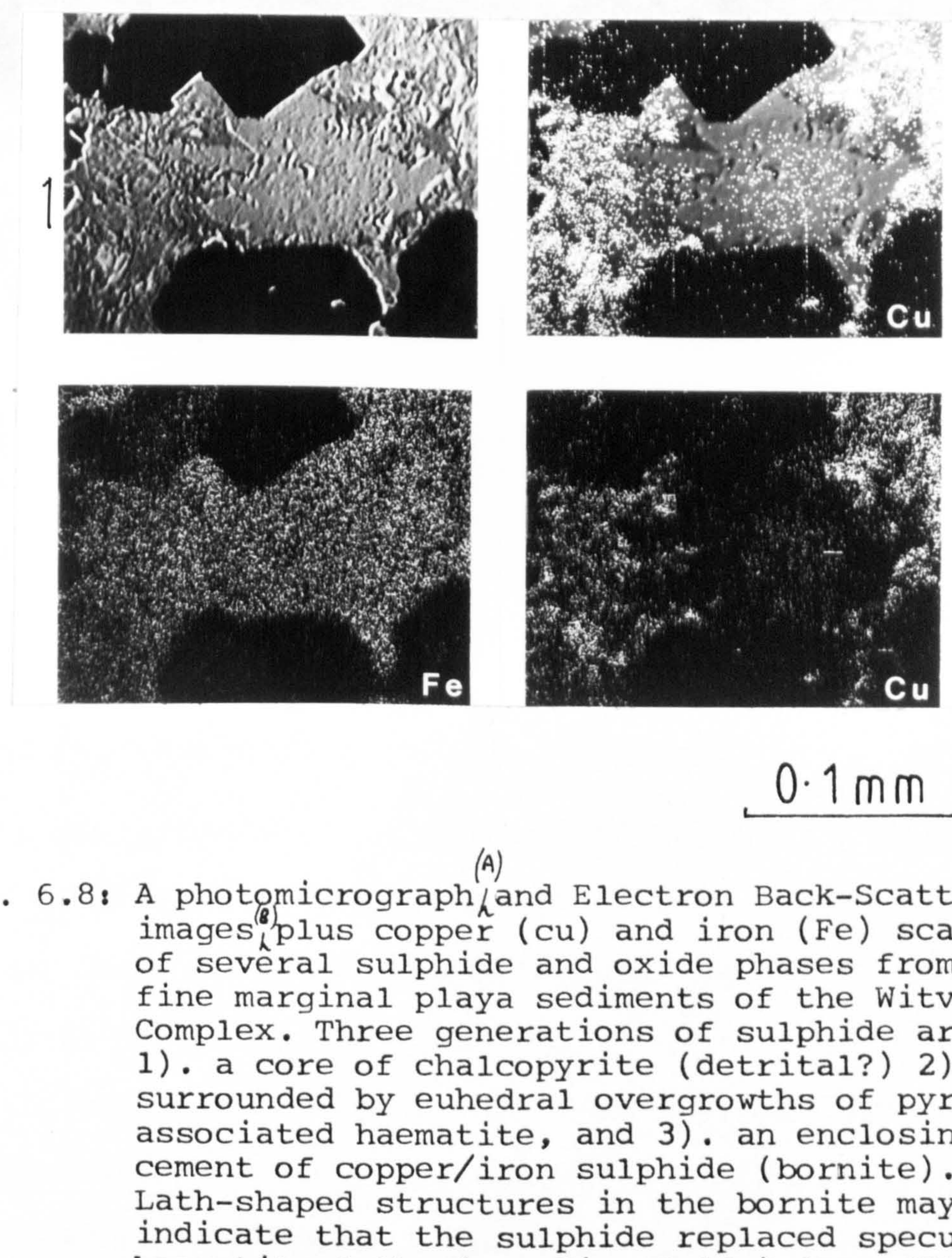


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FIG. 6.8: A photomicrograph (A) and Electron Back-Scatter images (B) plus copper (cu) and iron (Fe) scans of several sulphide and oxide phases from the fine marginal playa sediments of the Witvlei Fan Complex. Three generations of sulphide are evident 1). a core of chalcopyrite (detrital?) 2). surrounded by euhedral overgrowths of pyrite with associated haematite, and 3). an enclosing cement of copper/iron sulphide (bornite). Lath-shaped structures in the bornite may indicate that the sulphide replaced specular haematite laths.(see Fig. 6.12.) (PT. 4560, core OKW.5, r1.).

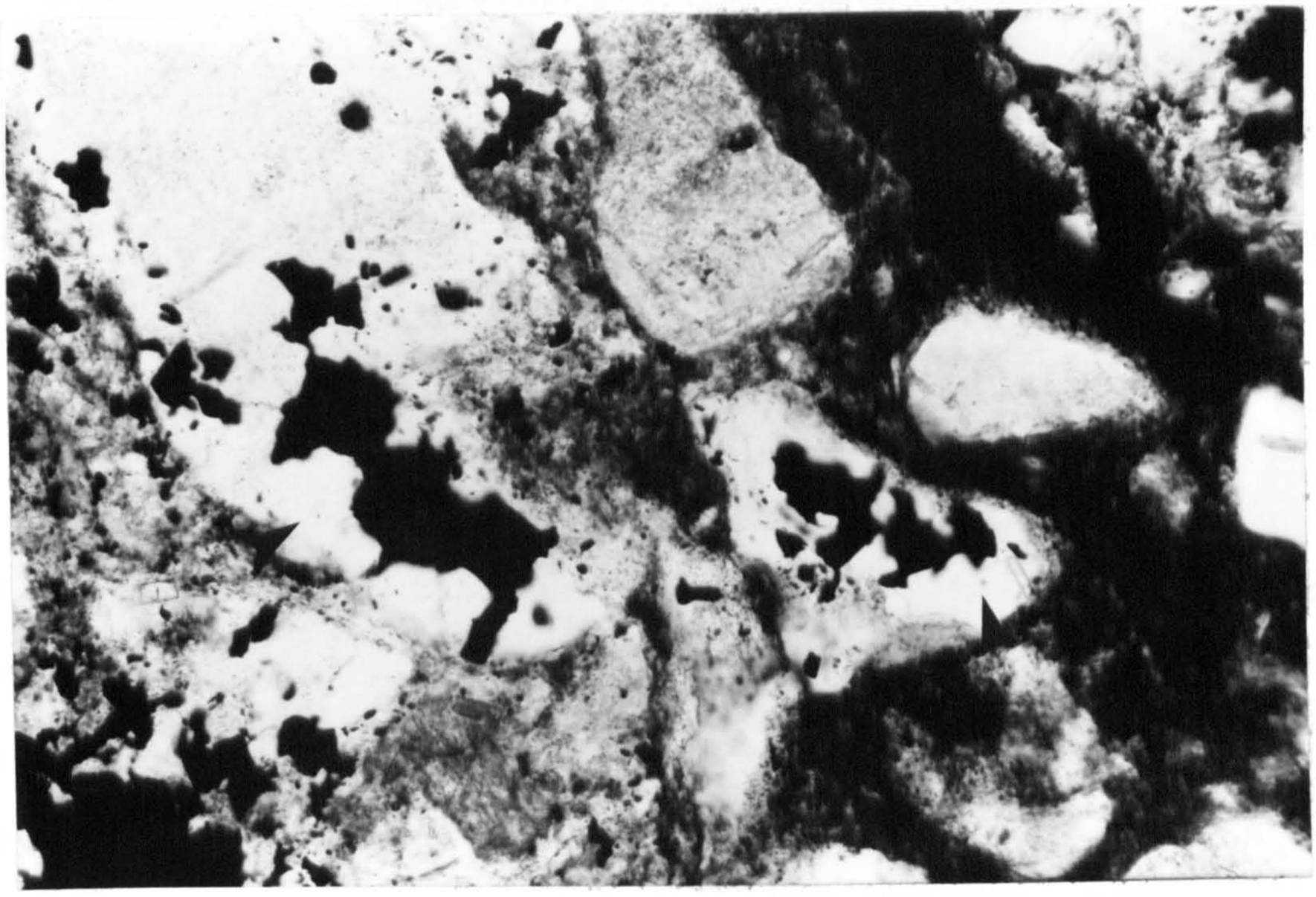


FIG. 6.9: A photomicrograph showing the close association of chalcopyrite (black) and quartz (arrowed), in the distal playa sediments of the Witvlei Fan Complex. (PT. 4562, Daheim, core D1, ppl.).

diagenesis leading to the formation of copper sulphides and authigenic quartz. Woodward et al (1974) reported chrysocolla from mature fluvial sediments, indicating that it may occur as a detrital particle. However, in the Doornpoort sediments, the association of quartz and chalcopyrite is rare, indicating perhaps, that detrital chrysocolla was not an important copper phase during sedimentation.

In addition, copper sulphides occur in stratiform and cross-cutting veinlets. These veinlets are normally only copper-bearing in copper-rich sediments and are thought to have formed during late diagenetic remobilization of copper and also calcite and quartz, during compaction and deep burial.

Klein Aub Fan

Copper mineralization at Klein Aub occurs in laminites and calcareous laminites within the lacustrine argillite bands, themselves contained within alluvial fan red/green sandstones (facies 3C(i), Chapter III). The ores are stratiform on large (Fig. 6.3) and on fine (Fig. 6.10) scales, and consist predominantly of chalcocite and bornite with minor chalcopyrite, pyrite and covellite. As in the case of the Witvlei deposits, sulphides fill pore spaces, cement detrital grains and are preferentially located in the coarser sediment fractions of the laminations (Fig. 6.13).

The association of copper sulphides and haematite is a common feature of the Klein Aub ores (Figs. 6.11, 6.12). Usually, the mixture of haematite and sulphide is irregular (Fig. 6.11), replacing and cementing detrital grains and forming in the axes of small scale pinch and swell folds. However, copper sulphides may occur between randomly orientated laths of specularite (Fig. 6.12) in both coarse and fine sediment laminations. Specularite may also form in large

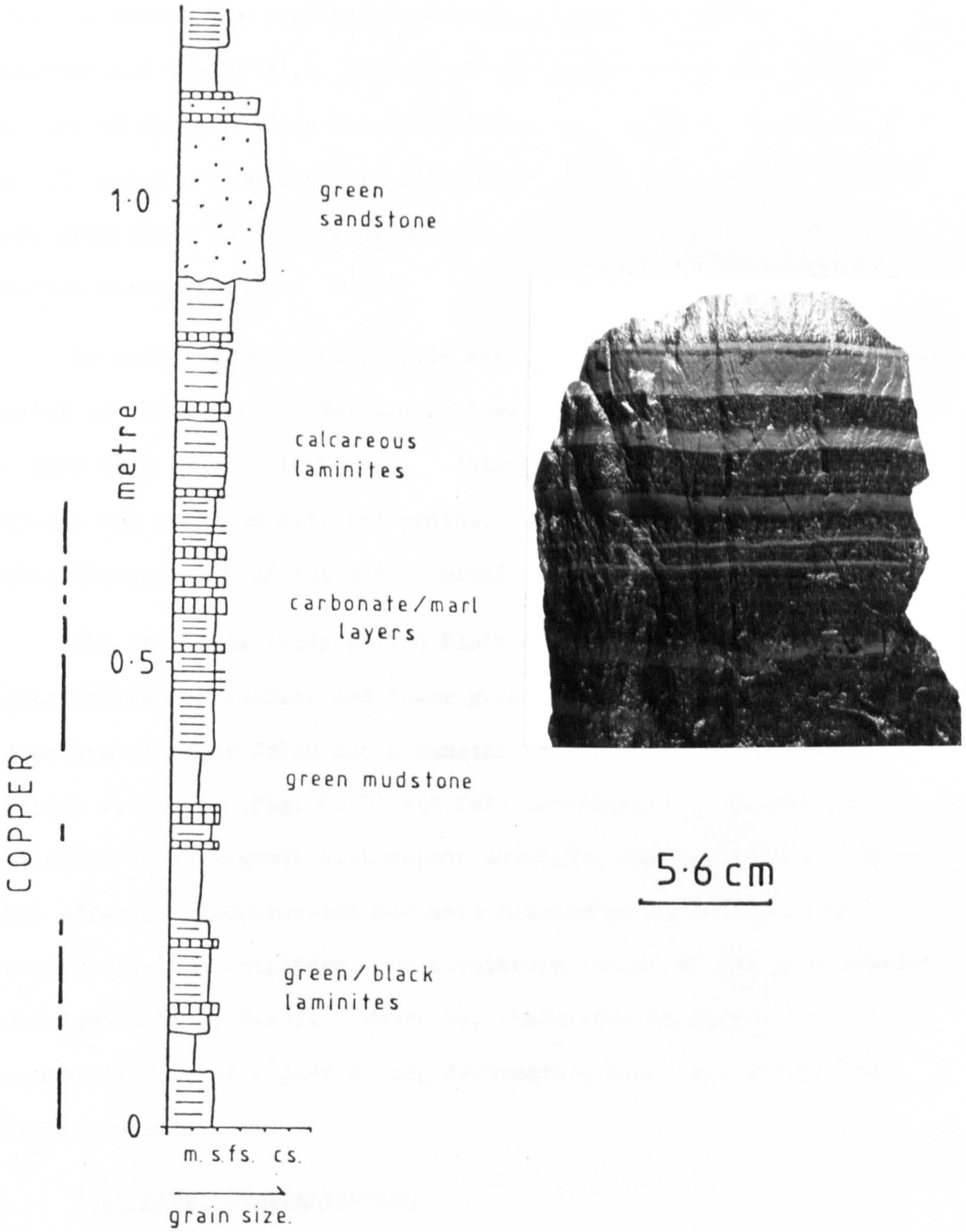


FIG. 6.10: Log and photograph of a lacustrine argillite band (Band 3) from the Klein Aub Mine. The log illustrates the association of fine clastic laminites with high ore grade - copper-bearing laminites shown in the photograph. Note the highly stratiform nature of the copper sulphides (concentrated in the black layers).

veins or 'quartz blows' with quartz, chlorite and calcite. These veins crosscut the argillite ore-bearing bands and may be mineralized (bornite). Because of the replacive (or displacive) nature of the haematite and specularite, its random or irregular habit, and its occurrence in often quite large veins, these features are considered to be late diagenetic, formed during deep burial and burial metamorphism.

An antipathy between calcite and copper sulphides appears to exist in these ores. Calcareous laminites tend to contain less copper than clastic laminites. Authigenic calcite fills pore spaces and replaces detrital grains. The antipathy may indicate that the majority of sulphides formed after this calcite cement.

The argillite bands of the Klein Aub area have been effected by penetrative deformation and lower greenschist facies metamorphism. A series of minor folds and a penetrative cleavage reorientate copper sulphides (Fig. 6.13) and fold laminations. Metamorphic chlorite is intergrown with copper sulphides and haematite. Despite the effects of deformation and metamorphism in remobilizing the copper and iron sulphides, the stratiform nature of the ores remains detectable (Fig. 6.13). There is, therefore, no major remobilization of copper during deformation and lower greenschist facies metamorphism.

Lake Ngami Mineralization

Copper and iron sulphides of the Lake Ngami area of N.W. Botswana are commonly associated with nodules containing quartz, calcite, chlorite and perhaps barites (Fig. 6.14). These nodules are considered to be of diagenetic origin, since they deform surrounding laminations. However, their precise origin is uncertain.

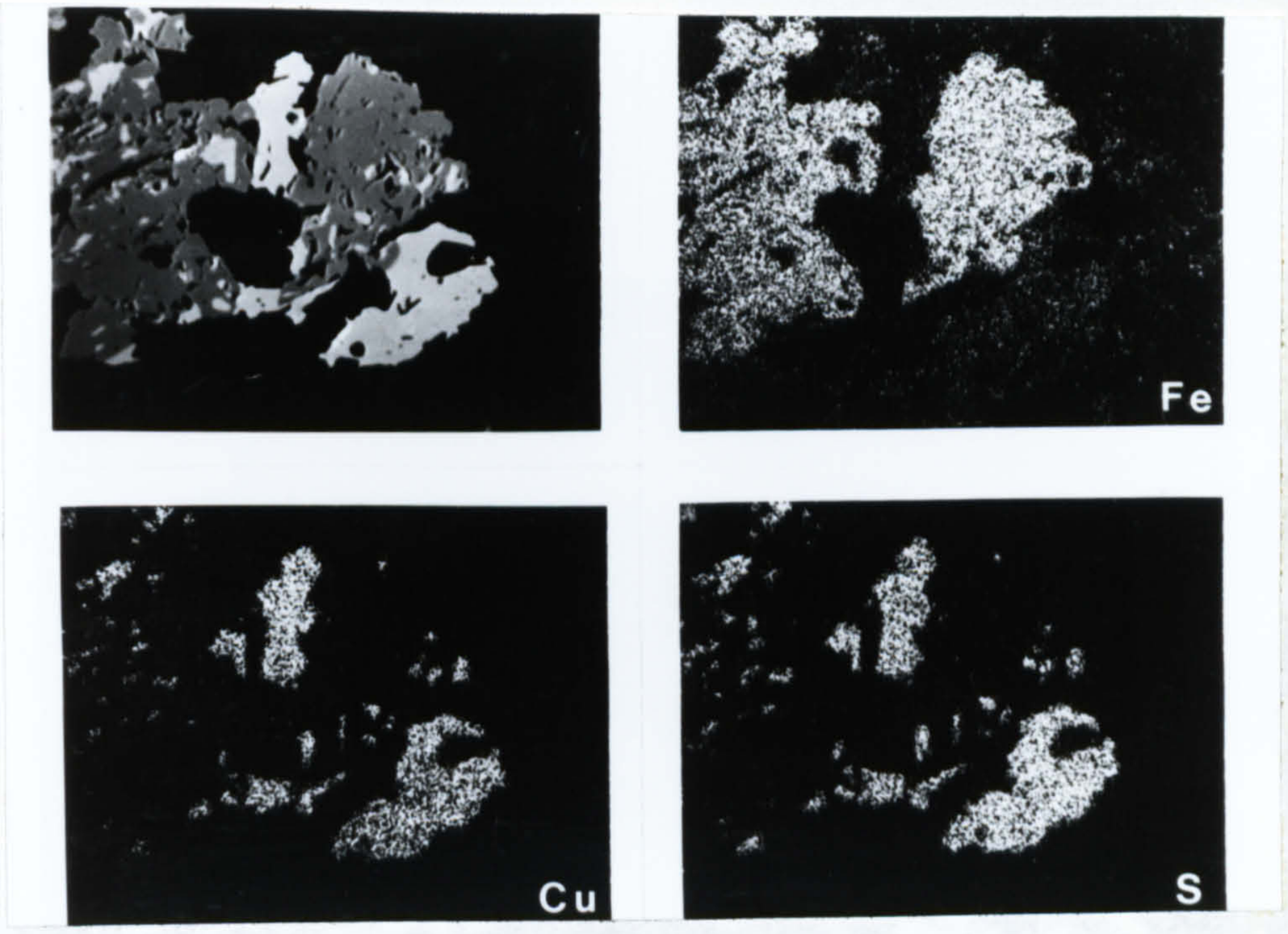


FIG. 6.11: Electron Back-Scatter Image plus iron (Fe), copper (Cu) and sulphur (S) scans indicating the irregular association of copper and copper/iron sulphides, with haematite, in the Klein Aub Ores. (PT. 4568 B, Band 2).

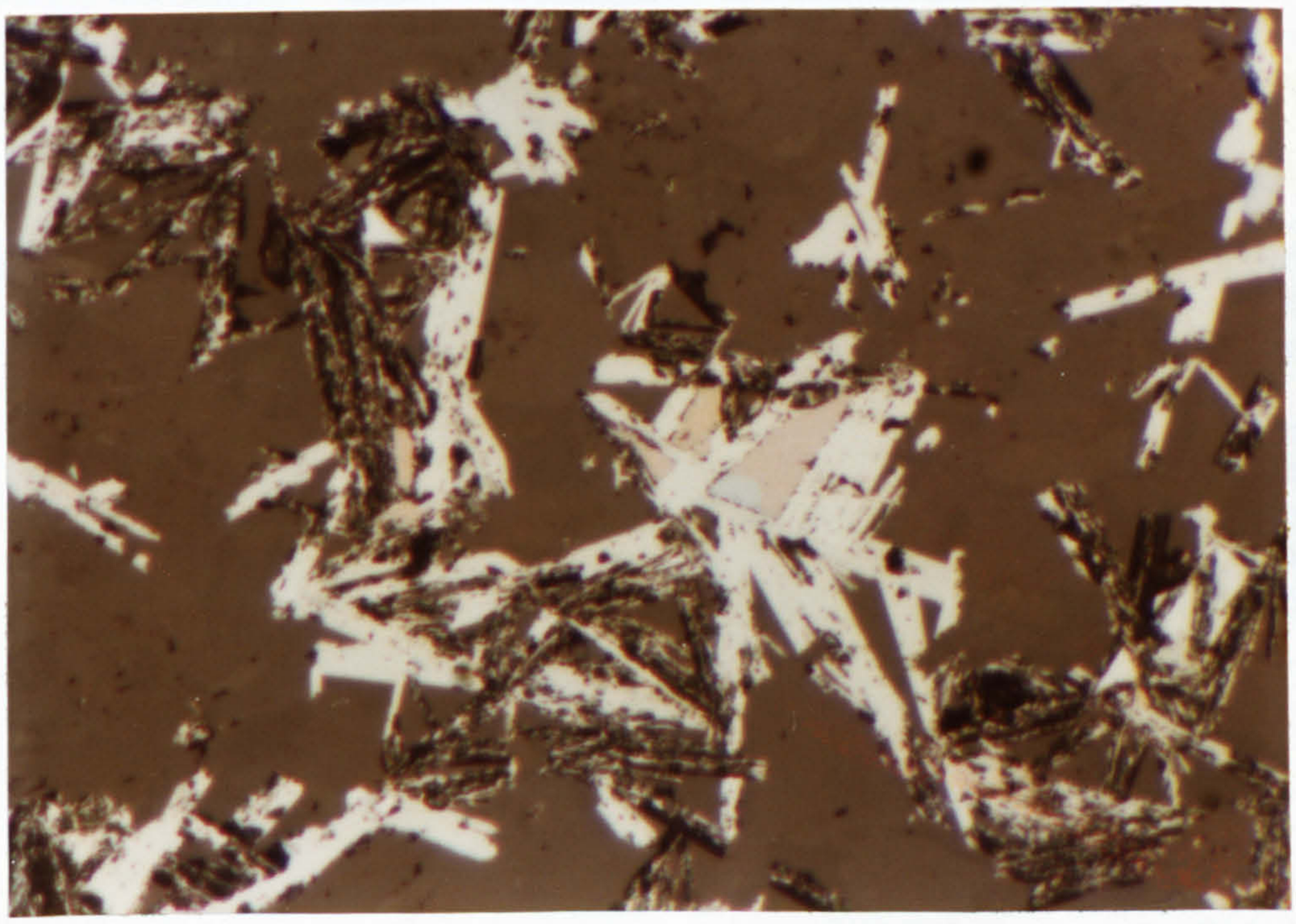


FIG. 6.12: Randomly orientated specular haematite laths (white) with interstitial bornite (pink) and chalcocite (blue), a photomicrograph from the Klein Aub Mine. (PT. 4562, Band 2, E.1040, r1.).

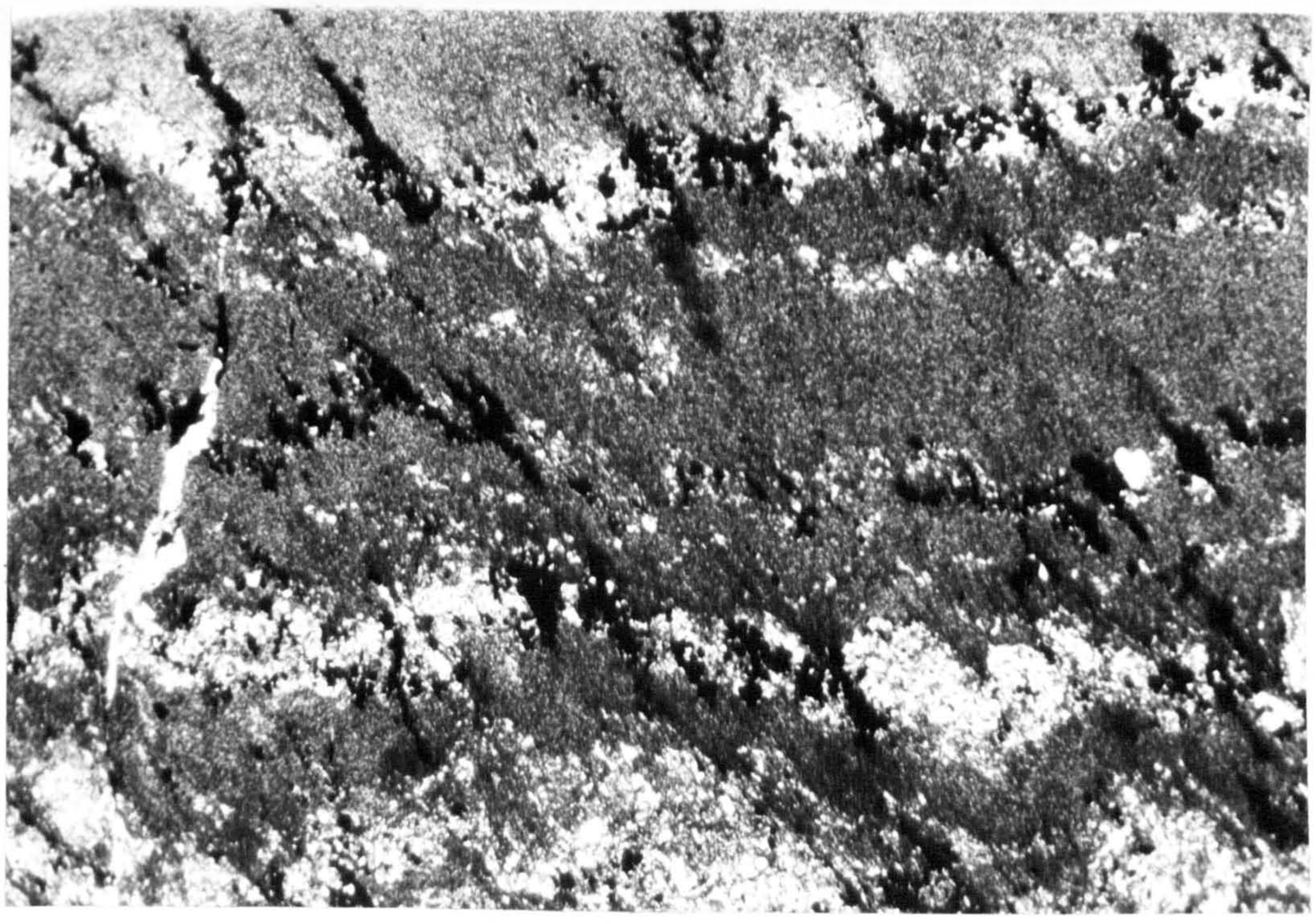
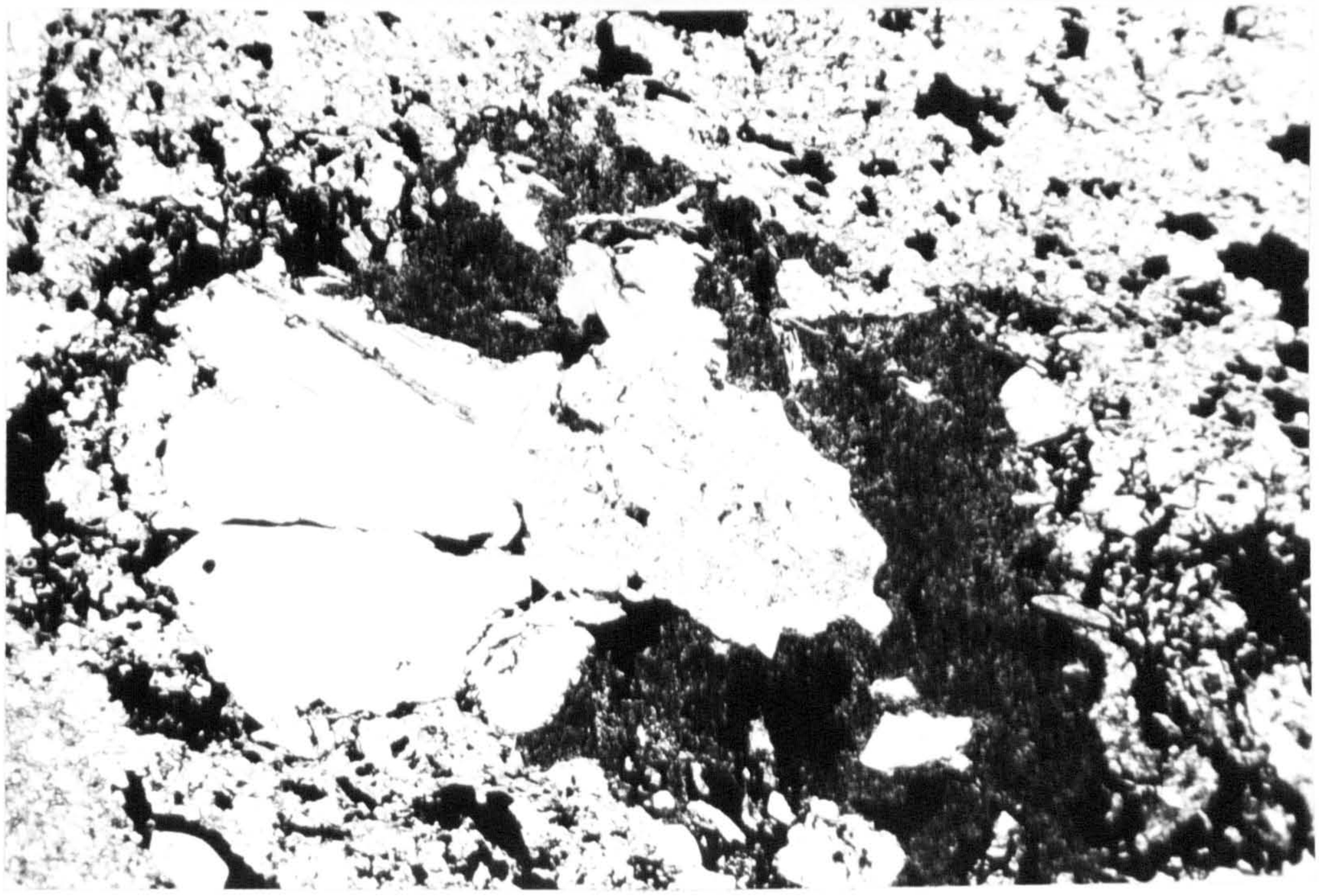


FIG. 6.13: A photomicrograph of the fine copper- bearing laminites of the Klein Aub Ores. The rock is highly cleaved (cleavage trace from bottom right to top left). Note that the copper sulphides (black) are alined in the cleavage but are concentrated in the coarser sediment laminations and hence stratiform. Also note the sulphide-bearing quartz / calcite vein (left). (TS. 40980, Band 1, sample for S and Pb isotopic studies, ppl.).



x 30

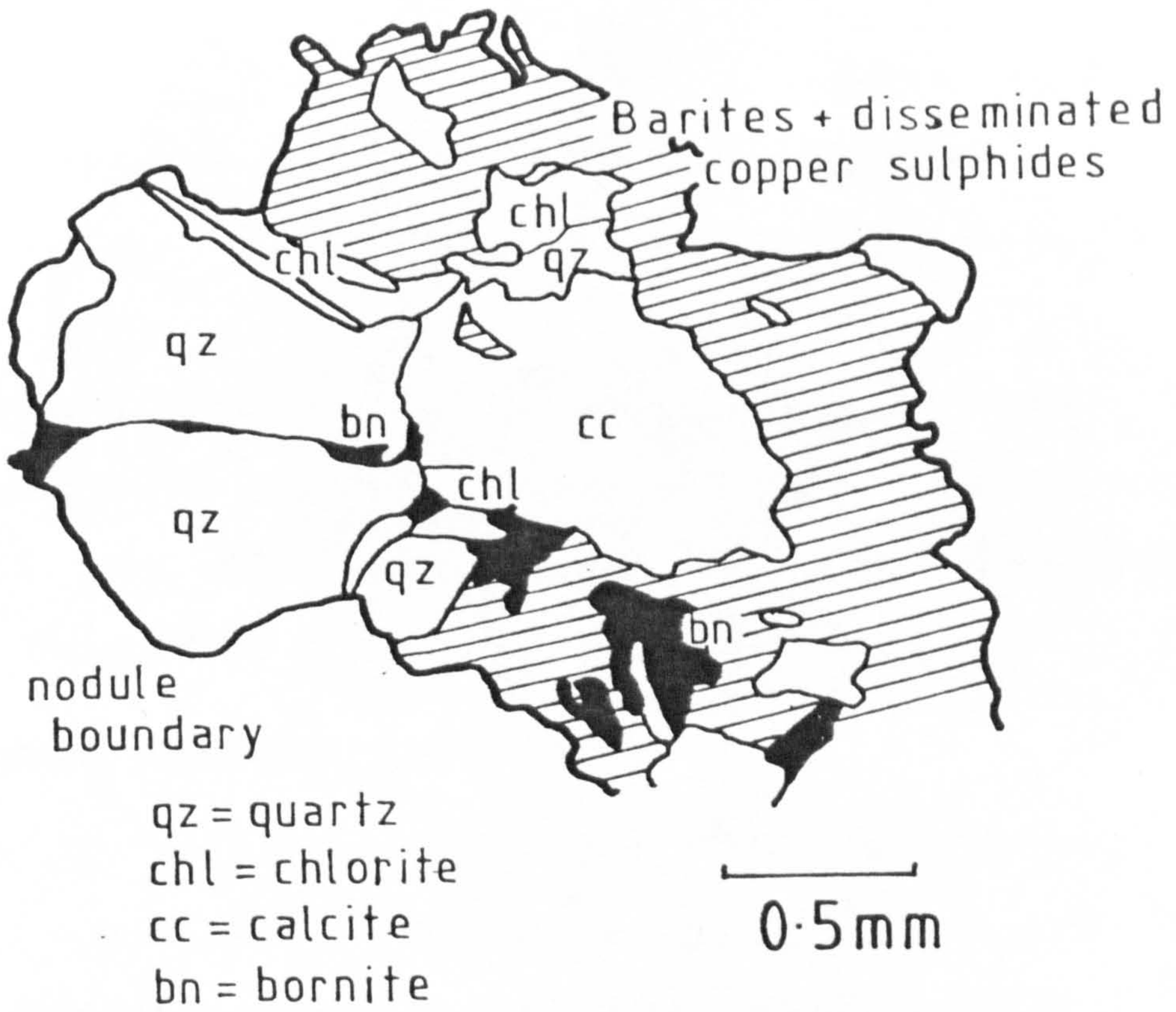


FIG. 6.14: Photomicrograph and sketch of a diagenetic nodule from the Lake Ngami area (Zeta Concession). The nodule contains authigenic quartz, calcite, chlorite, barites (with finely disseminated copper sulphides) and bornite. (PT. 4365, core ZP.2, ppl.).

6.1.3 Mineral Zonation

All mineralized horizons of the Doornpoort Formation are zoned, generally from copper-depleted sulphides at the margins to copper-rich sulphides in the centre (3-d). The zonation generally produces a mineral sequence from pyrite → chalcopyrite → bornite → chalcocite (→ covellite). However, mineral zonation is often irregular (Fig. 6.15), includes a variety of textures and may be a function of diagenetic change in Eh and pH conditions (Vink, 1972).

Playa Deposits

Within playa sediments of the Witvlei fan complex, mineral zonation is highly irregular and appears to reflect copper distribution. Variations in mineral phase occur over a few millimetres. These mineral changes are usually conformable to bedding and are apparently unrelated to the grain size of the host sediment and hence its porosity. Replacement textures are often complex and highly irregular (Figs. 6.15, 6.16, 6.17). In addition to the classic progressive enrichment of copper in sulphide phases, copper depletion may also occur, involving the replacement of chalcopyrite by pyrite, for example.

Lacustrine Deposits

Mineral zonation in the mineralized argillite bands of Klein Aub is more regular than that of Witvlei (Fig. 6.15). The ore deposits, dominantly chalcocite and bornite, are surrounded by pyrite cubes (3-d). These cubes may be replaced by copper, leading to the development of a copper sulphide cube with a haematite halo. Cubes may also contain veins of copper sulphide and overgrowths formed in pressure shadows, developed during cube rotation (Fig. 6.18).

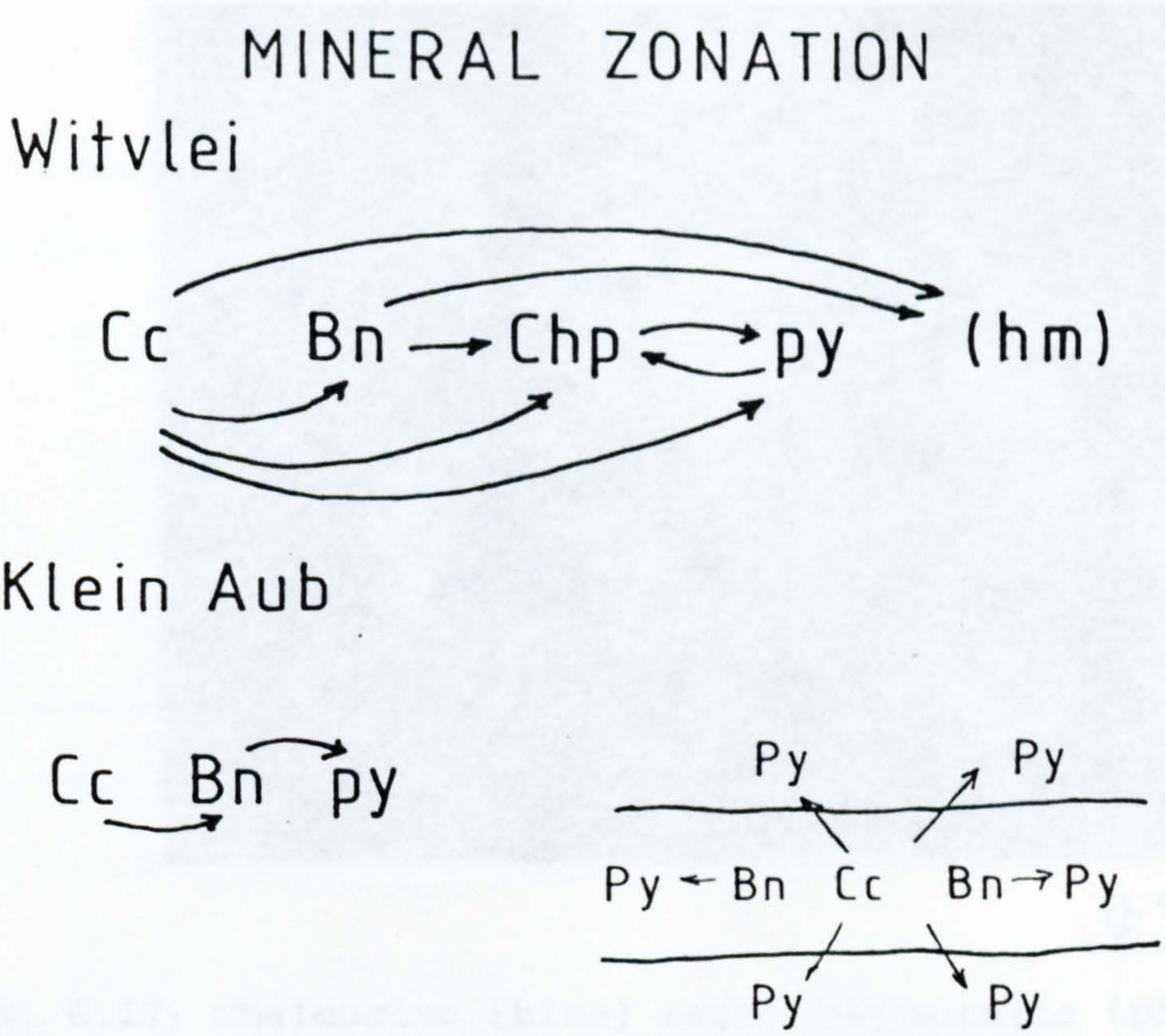


FIG. 6.15: Mineral zonation of copper and iron sulphides from the Witvlei and Klein Aub mineral deposits. Zonation at Witvlei is highly complex and irregular in comparison to the more uniform zoned ores of Klein Aub.

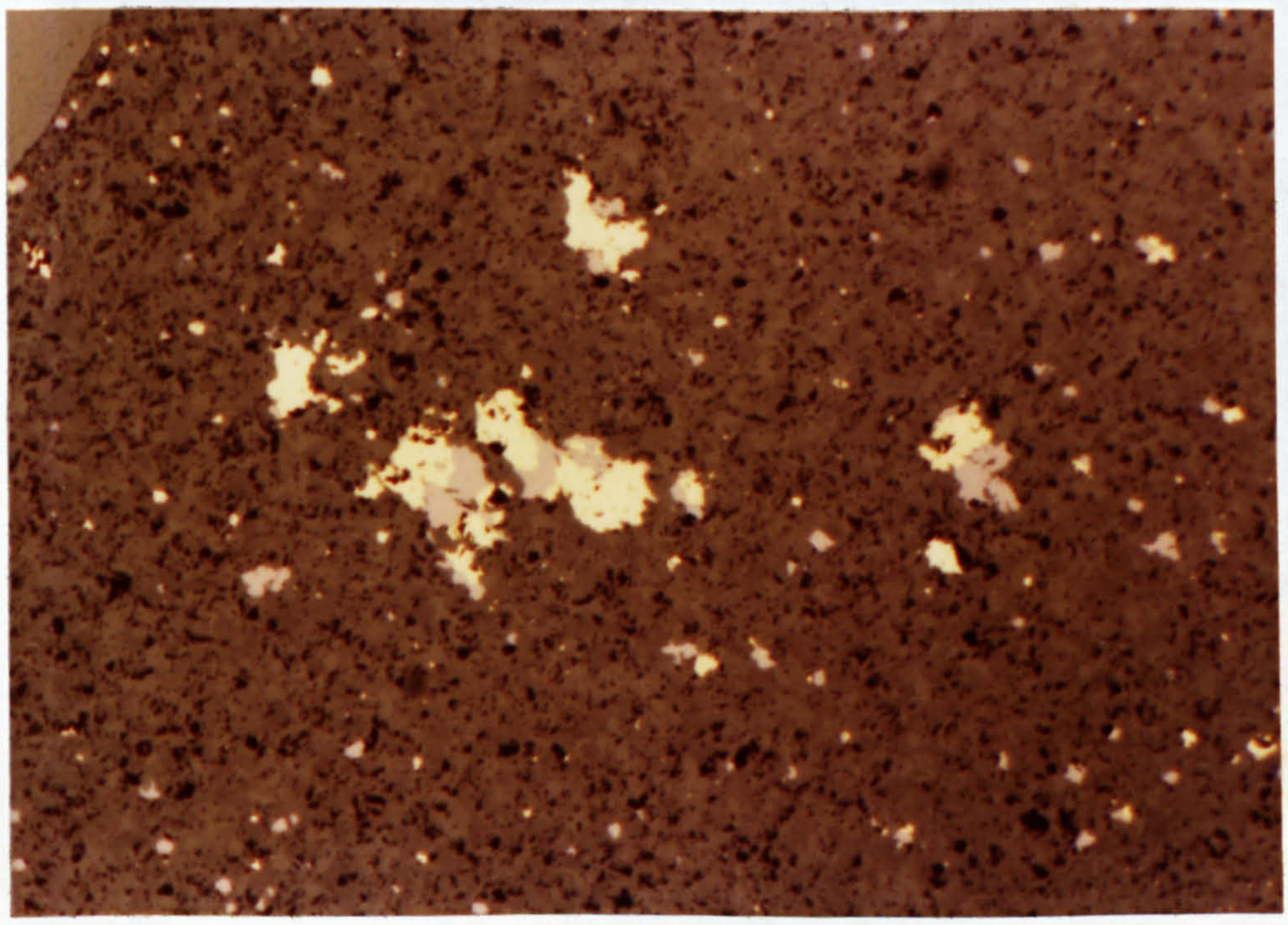


FIG. 6.16: Bornite (pink) replacing chalcopyrite (bright yellow) in playa sediments of the 1st Alluvial Fan cycle (Facies 1C(i)) of the Witvlei Fan Complex. (PT. 4564, Eskadron, ESK. 60, r1.).

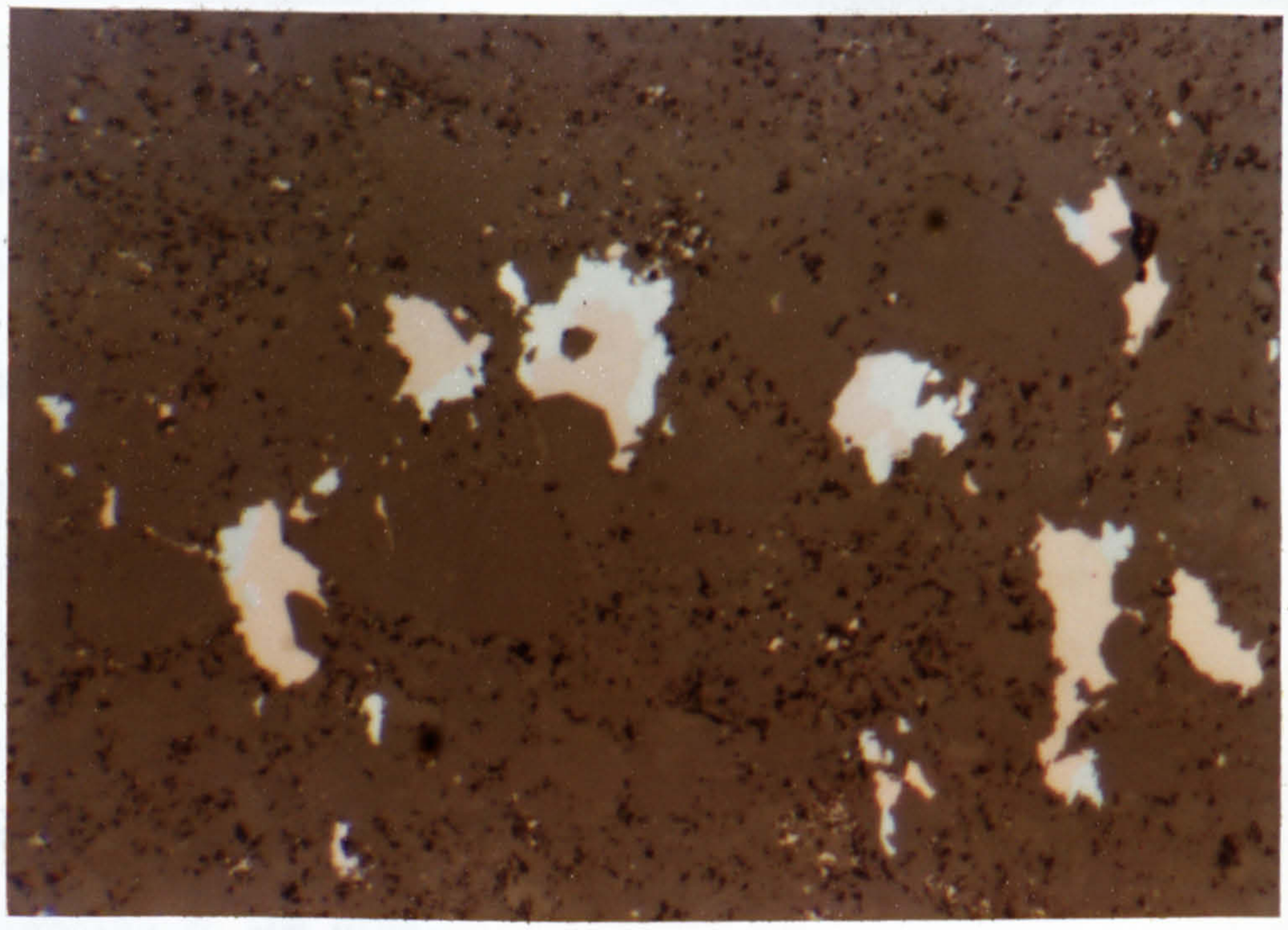


FIG. 6.17: Chalcocite (blue) replacing bornite (pink) in the playa sediments of the 1st Alluvial Fan cycle (Facies 1C(i)), Witvlei Fan. Note the interstitial (pore filling) nature of the sulphides and euhedral outlines of authigenic, diagenetic silcate minerals. (PT. 4561, Eskadron, ESK. 36, core, r1.).

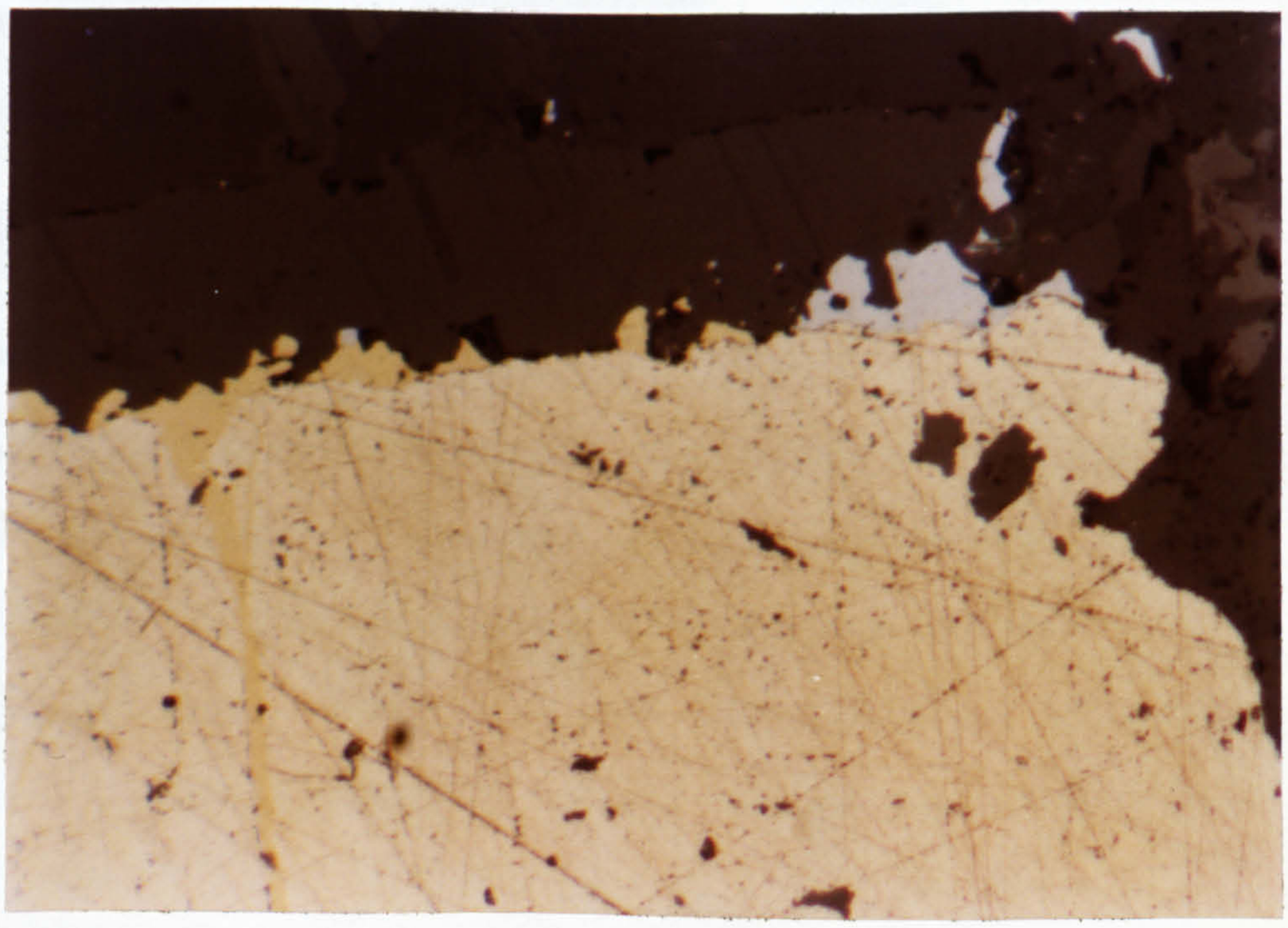


FIG. 6.18: The corner of a pyrite cube found immediately below Band 1 of the Klein Aub Mine. Chalcopyrite (yellow) fills fractures and along with chalcocite (blue), forms sulphide overgrowths which fill a pressure shadow (also with quartz, calcite, and chlorite), formed during cube rotation in either compaction or deformation. (PB. 4024, from TS. 40984,r1.).

Occasionally, copper horizons may zone upwards directly from chalcocite and bornite to pyrite, with no 3-d zonation.

Summary

Sedimentological evidence suggests that the Doornpoort metals were derived from the same source as the coarse alluvial fan sediments and were introduced shortly after or during sedimentation in alluvial fan surface and groundwaters. Major palaeodrainage conduits and lacustrine palaeocurrents had a role in the location and concentration of the ores.

Copper occurs in playa and lacustrine sediments in the form of zoned copper/iron ore bodies. The sulphides are stratiform and were probably formed during diagenesis. The diagenetic history of the sediments and ores is complex, involving *at least* three generations of sulphide formation. Evidence suggests that copper was mobile at several stages during diagenesis.

6.2 ISOTOPIC EVIDENCE

Introduction

Sedimentological studies suggest that the stratiform copper deposits of the Doornpoort Formation were probably derived from basement rocks. To test this hypothesis, sulphur and lead isotopic studies were undertaken on both sedimentary and basement samples, in order to establish the source of lead and sulphur, the mode of sulphur fixation and possibly, the age of the deposits themselves. In addition, carbon and oxygen isotopes were studied in an attempt to determine the source of sedimentary carbonates and their relationship to sulphide formation.

The work involved sulphur isotopic studies on sulphides, carbon and oxygen isotopes on carbonates and uranium-lead isotopes on trace lead in sulphides and whole rock samples. Sedimentary samples were selected to ensure the widest possible range of sulphides in terms of sedimentary facies and mineralogy.

To aid the interpretation of the sulphur isotopic results, samples from the stratiform copper deposits and groundwater precipitates around Chuquicamata, Exotica and Caleta Coloso, Chile, were analysed.

Sample locations, extraction and analytical methods are outlined in Appendix III.

6.2.1 Sulphur Isotopes

Eighteen sulphur isotopic analyses from basement and sedimentary mineralized rocks were studied; taken from throughout the southern foreland (Figs. 6.1, 6.21 and Appendix III). Eight Chilean samples were analysed: six from Chuquicamata and Exotica and two from Caleta Coloso (Figs. 6.23, 6.24 and Appendix III).

This section involves a brief résumé of sulphur isotopic systematics, their significance in geological terms and a discussion of the results obtained. A rudimentary grasp of sulphur isotope systematics is essential to the understanding of the results obtained in this study.

Systematics

There are four natural isotopes of sulphur, with atomic masses 32, 33, 34 and 36 and approximate natural abundances of 94.9%, 0.75%, 4.3% and 0.2% respectively. Fractionation effects cause small changes in the relative abundance of these isotopes. Sulphur

isotopic variations are defined using the $^{34}S/^{32}S$ isotopic ratio and express in del ^{34}S values according to the following equation:

$$\delta^{34}S\ (‰) = \frac{\left(^{34}S/^{32}S\right)_{SAMPLE} - \left(^{34}S/^{32}S\right)_{STANDARD}}{\left(^{34}S/^{32}S\right)_{STANDARD}} \times 1000$$

: the reference standard used is the Cañon Diablo *Troilite* (C.D.T.) which by definition has a $\delta^{34}S$ value of 0‰. Fractionation of isotopes in natural systems produces a range of $\delta^{34}S$ values, commonly between + 25 ‰ (the value for present-day seawater (Holster and Kaplan, 1966)) and - 40 ‰. Two types of fractionation affect both carbon and sulphur isotopes; Equilibrium (see Coleman, 1977) and Kinetic fractionation. Both forms rely on the fact that the light isotope forms a weaker chemical bond than the heavier one and therefore tends to react more easily.

Kinetic fractionation relies on the greater rate at which the lighter isotope reacts (whereas Equilibrium fractionation is a consequence of the different bond strength between light and heavy isotopes). In the early stages of a reaction the light isotope, forming a weaker bond, tends to react more quickly and is therefore concentrated preferentially in the reaction products (Fig. 6.19, stage 1). As the reaction progresses the reservoir of sulphur in the reactants diminishes and the amount of heavier isotope reacting to form products increases (Fig. 6.19, stage 2). When the reaction is complete, the isotopic composition of the products is identical to *that of* the reactants (Fig. 6.19, stage 4).

Kinetic fractionation occurs in 'open' and 'closed' systems, giving different isotopic results. 'Open system' fractionation results in products enriched in ^{32}S, the reaction does not go to

ISOTOPIC FRACTIONATION

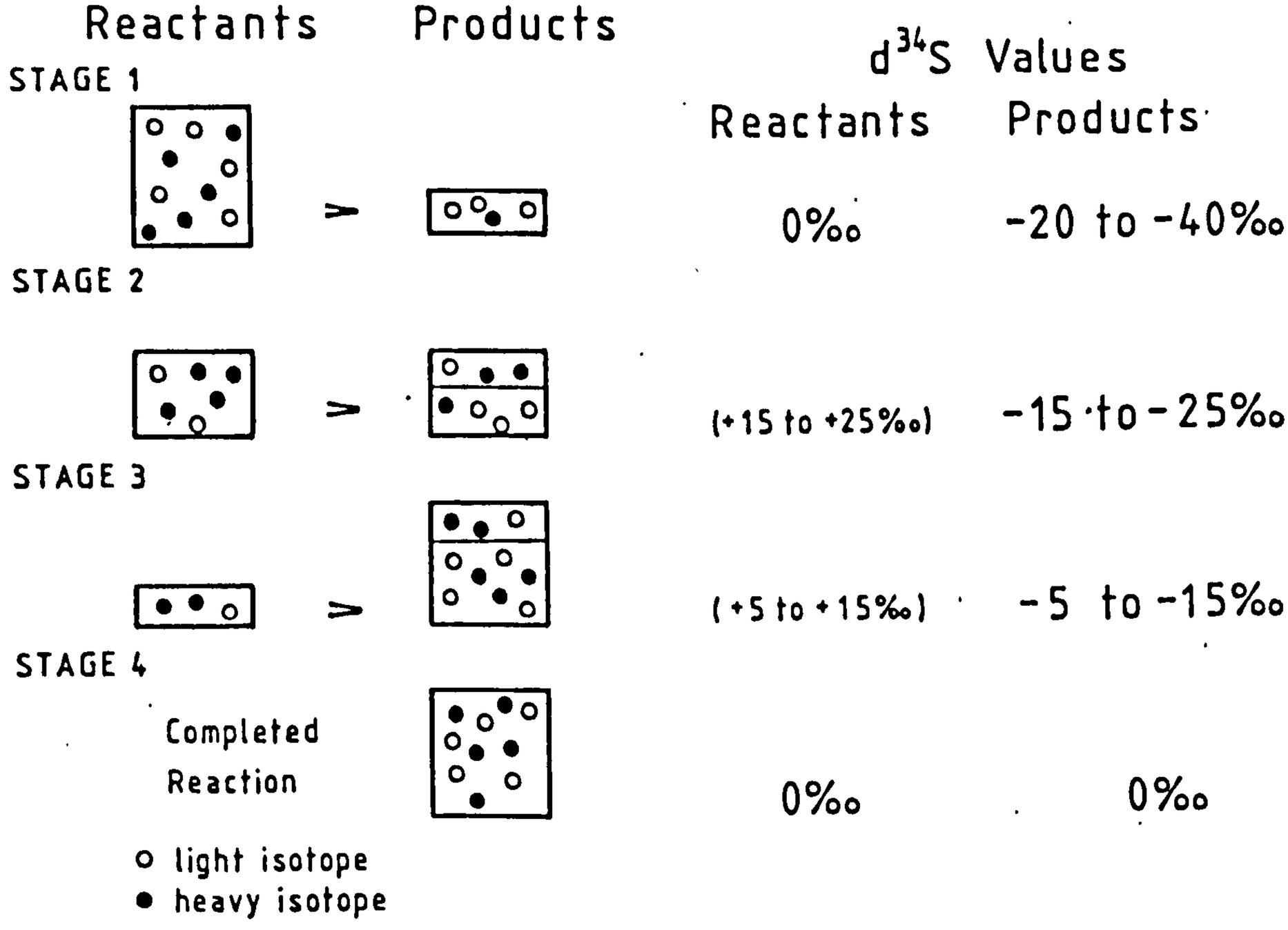


FIG. 6.19: Sulphur Isotopes : KINETIC FRACTIONATION.

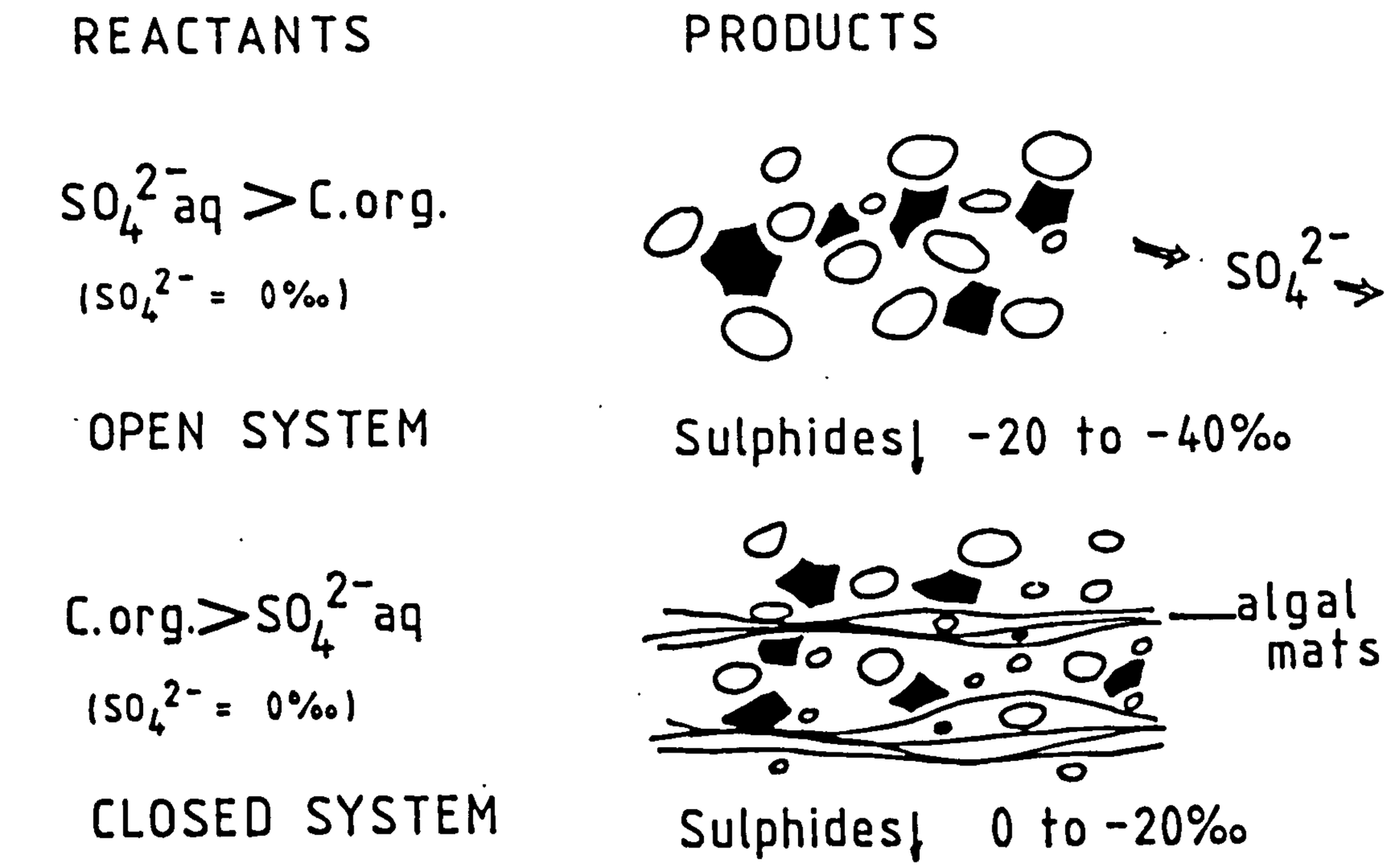


FIG. 6.20: The Kinetic Fractionation of sulphur isotopes by the bacterial (C.org.) reduction of sulphate (SO4 aq.) in OPEN and CLOSED SYSTEMS. The two examples represent the end members of a reaction series.

completion (stage 1). Isotopically-light products are formed. In a 'closed system' the reaction may either go to completion, resulting in no isotopic change from reactants to products (stage 4), or if some of the products are separated from the reaction mixture at different stages during the reaction, a spread of isotopic values may result. This range of results will lie between the original sulphur isotope value and that produced by fractionation in an open system.

In natural systems the oxidation of sulphide to sulphate produces no isotopic fractionation (Kaplan and Rafter, 1958; Nakai and Jensen, 1964), whereas the reduction of sulphate to sulphide involves fractionation to lighter isotopic values (Thode, Kleenekoper and McElcheran, 1951; Feely and Kulp, 1957; Harrison and Thode, 1958; Nakai and Jensen, 1964). This reduction process may involve bacteria, principally Desulphovibro desulphuricans. In laboratory experiments, Harrison and Thode (1957) used this bacterium in the reduction process and discovered a fractionation of -22 °/oo from reactants to products. In natural systems, Nakai and Jenson (1964) recorded a similar fractionation value, whereas Rees (1973) obtained values of up to -50 °/oo. 'Normal' bacterial fractionation of sulphur isotopes in open systems involves a change of -20 °/oo to -40 °/oo (Coleman, pers. comm.).

In practice, the isotopic values given by bacterial reduction of sulphate to sulphide depend upon the relative amounts of bacteria and sulphate available (Rees, 1973). If the reservoir of sulphate exceeds the amount of organic material, then sulphides enriched in ^{32}S will form. This is 'open system' fractionation and values of -20 °/oo to -40 °/oo, from the original isotopic value, can be expected (Fig.

6.20). If the quantity of organic matter exceeds the sulphate reservoir, a 'closed system' operates and the reaction gives a range of isotopic values from the original to those produced by open system fractionation (Fig. 6.20).

A more comprehensive and rigorous treatment of sulphur isotope systematics is presented in Coleman (1977).

Discussion of Results

Sulphur isotopic results from Namibian and Botswanan sulphides are presented in figure 6.21 and the Chilean samples in figure 6.23. These results are discussed below and in an Unpublished Report for the Institute of Geological Sciences, enclosed in the back pocket of this thesis.

a) DOORNPOORT RESULTS

Basement Sulphides

Pyrite from the volcanogenic massive sulphide ores of the Kobos mine, galena from quartz veins on the farm Marienhof and copper sulphides from sheared metasedimentary rocks on Swartzmodder farm (Chapter II, Appendix III), give isotopic values around 0°/oo. Isotopic values of 0°/oo are often indicative of magmatic sources. Both samples, Kobos and Galena are considered to be of magmatic origin, whereas the source of the Swartzmodder ores is uncertain.

Klein Aub Sulphides

Seven samples were analysed from the Klein Aub lacustrine sediments (facies 3C(i) and 3C(ii)), five mineralized samples - three stratiform chalcocite/bornite ores (B2. Hm. M; B3. TS. M, 40980): one chalcopyrite vein sample (4051) and one sample of bornite replacing a pyrite cube on the edge of a mineralized band -

BASEMENT

No.	Sample	Description	$\delta^{34}S$ CDT °/oo
B1	Kobos	Volcanogenic pyrite	+ 0.2 °/oo
B2	Galena	Vein Galena	- 0.8 °/oo
S	Swart.	Metasedimentary chalcopyrite	+ 5.3 °/oo

KLEIN AUB

No.	Sample	Description	$\delta^{34}S$ CDT °/oo
KAI	B2 HM M	Chalcocite/Green silt	- 35.2 °/oo
KA2	B3 TS M	Chalcocite/Green sandstone	- 34.5 °/oo
KA3	40980	Chalcocite/Green silt	- 21.4 °/oo
KA4	4051	Chalcopyrite/vein	- 28.9 °/oo
KA5	Bn	Bornite/replace pyrite cubes	- 20.9 °/oo
KA6	B4 Py	Pyrite/cubes	- 30.4 °/oo
KA7	A. UN. Py	Pyrite/cubes	- 27.4 °/oo

WITVLEI

No.	Sample	Description	$\delta^{34}S$ CDT °/oo
W1	Esk 9	Bornite/disseminated	- 22.2 °/oo
W2	Esk 54	Bornite/chalcocite/green silt	- 11.8 °/oo
W3	OKWS	Chalcopyrite/red + green lam.	- 8.9 °/oo
W4	ESK 60	Chalcopyrite/vein	- 17.4 °/oo
WS	Gypsum	Gypsum/nodular (secondary)	- 16.0 °/oo

OTHER

No.	Sample	Description	$\delta^{34}S$ CDT °/oo
KN	K.N.	Pyrite cubes Kagas Noord	- 20.3 °/oo
LN1	ZP21	Bornite/strataform vein	- 25.5 °/oo
LN2	ZP31	Chalcopyrite/strataform vein	- 37.9 °/oo

(All values ± 0.5 °/oo)

Figure 6.21: NAMIBIAN AND BOTSWANAN SULPHUR ISOTOPIC RESULTS

and two pyrite samples: 1) pyrite cubes from below band 4 (B4. Py), and 2) from facies 3C(ii) of the second lacustrine transgression (A. Un. Py). (Figs. 6.21 and 6.22).

All samples have $\delta^{34}S$ values of between -20 °/oo and -40 °/oo. Two explanations for these results can be supported. Firstly, that these sulphides were formed by the bacterial reduction of sulphate with a value of 0 °/oo, in an open system, producing a fractionation of -20 °/oo to -40 °/oo. Secondly, from isotopic fractionation in a closed system with a source value of -20 °/oo, producing the range of values between -20 °/oo and -40 °/oo. Since no source value of -20 °/oo was detected, the former explanation is proposed.

There are two possible sources of sulphate with a $\delta^{34}S$ value of around 0 °/oo - either a primary magmatic source or from the erosion of basement sulphides. Both basement samples analysed from North of Klein Aub (Kobos and Galena) give $\delta^{34}S$ values close to 0 °/oo and since there is no isotopic fractionation during the oxidation of sulphide to sulphate, they provide a potential sulphur source.

Claypool et al (1980) suggested that the $\delta^{34}S$ value of Late Proterozoic sea-water was +30 °/oo. Bacterial fractionation in an open system of this sulphur source would produce values of between +10 °/oo and -10 °/oo in the sedimentary sulphides. Since these values do not occur, any influence of sea-water sulphate is rejected.

Sedimentological data indicate that the Klein Aub ores were concentrated by lacustrine palaeocurrents and that the copper was probably particulate, therefore, during sedimentation. However, because basement sulphides give $\delta^{34}S$ values of 0 °/oo and no such values are recognized in the Klein Aub sediments, the introduction

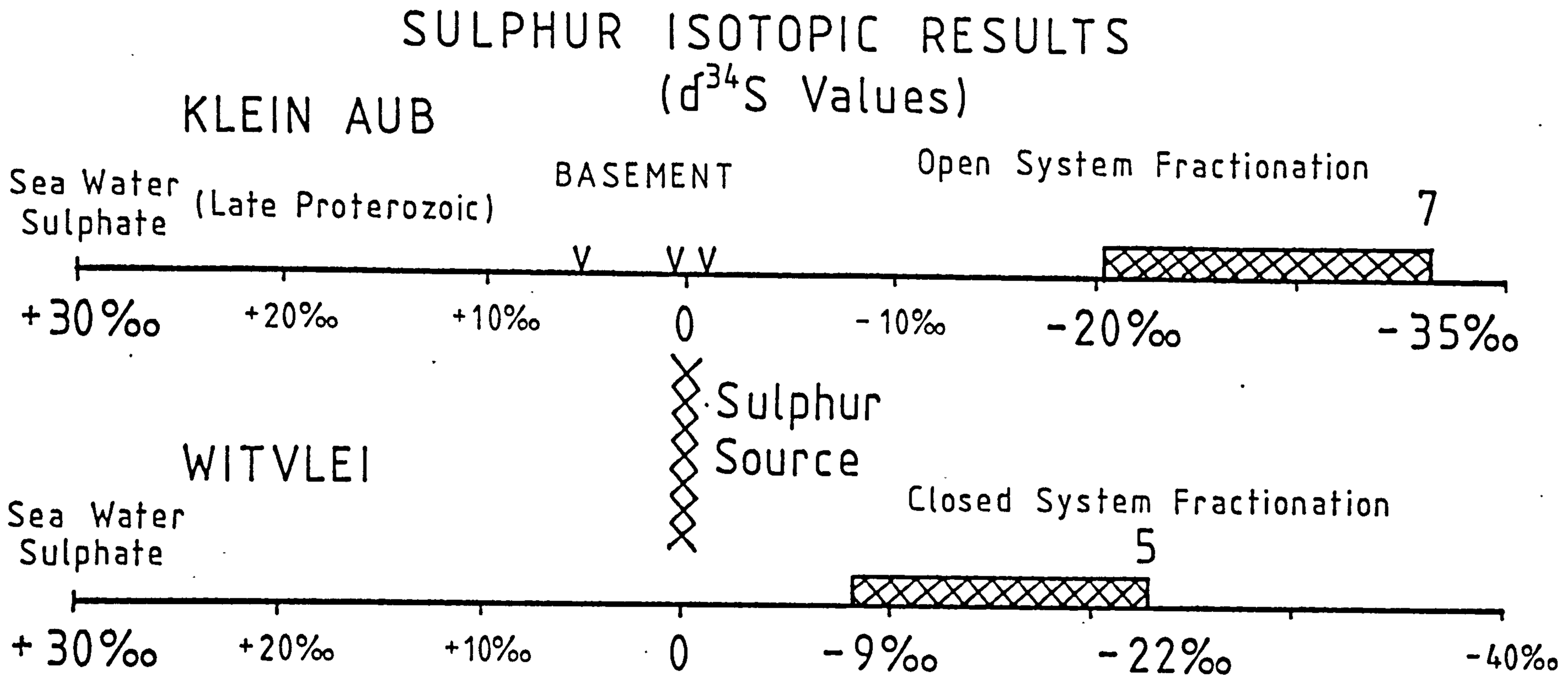


FIG. 6.22: Sulphur Isotopic results and interpretation from the Witvlei and Klein Aub areas, Namibia. Sulphides formed from the bacterial reduction of 0 ‰ sulphate, in Open and Closed Fractionation systems.

of copper as a particulate sulphide phase is therefore improbable. Textural evidence supports this finding, since the copper minerals are interstitial and not rounded.

Witvlei Sulphides

Four sulphide and one gypsum samples were analysed from the Witvlei playa sediments. Samples ESK.9 and ESK.60 were taken from the centre of playa deposits and ESK.54 and OKWS from playa margins. $\delta^{34}S$ values of these samples range between -8.9 °/oo and -22.2 °/oo (Figs. 6.21 and 6.22). These sulphides formed by the bacterial reduction of sulphate and two explanations are possible to account for their origin. Firstly, reduction in an open system from original $\delta^{34}S$ values of +10 °/oo or secondly, by fractionation in a closed system from values close to 0 °/oo.

The lack of sulphide samples from the adjacent basement, hinders the interpretation of these results. However, a source material of about +10 °/oo could only be derived by a mixture of sea-water and magmatic sulphate (+30 °/oo and 0 °/oo) or by prior fractionation of sea-water sulphate. Since the playa sediments are enclosed by continental alluvial fan deposits (Figs. 6.2, 4.7), a sulphur source of +10 °/oo is unlikely. These sulphides are therefore considered to have formed by bacterial reduction of sulphate with a value of 0 °/oo in a closed system (Fig. 6.22), resulting in a spread of values between 0 °/oo and about -20 °/oo. The sulphate source can be considered either as magmatic or of basement sulphur origin.

The sulphur isotopic results are compatible with geological observations. Open system fractionation involves a large reservoir

of sulphate relative to bacteria and organic matter. The Klein Aub sediments were deposited at the margins of large permanent lakes which probably contained large quantities of sulphate, derived principally from the weathering of basement rocks. Bacterial reduction of a large sulphate reservoir leads to fractionation of the lighter sulphur isotopes into sulphides and the depletion of organic carbon and bacterial, long before the sulphate.

The playa sediments of the Witvlei fan complex were, on the other hand, formed in temporary lakes on the alluvial fan surface, deposited by spasmodic influx of water and sediment. In these conditions, the supply of sulphate was probably highly variable. The irregular distribution of algal mat material in the playas, reflects the variability in the amount of organic matter. Therefore, with variable quantities of reactants, sulphate reduction would have led to a range of $\delta^{34}S$ values, with both open and closed systems operating.

Other Sulphide Results

Isotopic results from Lake Ngami (Zp 21, Zp 31) and Kagas Noord (K.N.) give negative $\delta^{34}S$ values of less than -20 °/oo (Fig. 6.21). These samples are taken from lacustrine sediments and probably reflect isotopic fractionation in an open system from a sulphur source of about 0 °/oo.

b) CHILEAN RESULTS

Weathering of primary copper porphyry sulphides* F.N. at Chuquicamata (Fig. 6.23) and the downward perculation of the resultant fluids, led to the development of a supergene sulphide blanket, immediately below the water table, within the porphyry (Fig. 6.23). Draining surface waters contain precipitates of iron, aluminium and also

* No 1° Chuquicamata sulphide available at the time of analysis.

gypsum and copper sulphate (Robinson, 1978). Subsurface movement of large volumes of supergene fluids has led to the development of large deposits of copper oxide-cemented gravels and mineralized bedrock (Robinson, 1978; Mũnoz, 1975; Clemmey, pers. comm.). At Exotica the resultant cements and precipitates from the draining supergene fluids of Chuquicamata, have formed an economic ore body (Clemmey, pers. comm.).

Caleta Coloso copper deposits consist of oxide and sulphide cemented Red Bed gravels, which may represent equivalent Cretaceous deposits to the Upper Tertiary deposits of Exotica (Andrew, 1980).

Two samples of chalcocite were analysed from the supergene blanket of Chuquicamata (CPs), one copper sulphate and one gypsum samples from the groundwater precipitates (CS), two gypsum and copper sulphate samples from the Exotica gravel cements (Cos) and two sulphide samples (chalcocite) from the Caleta Coloso gravels (CGc) (Fig. 6.23). The isotopic results are presented in figure 6.24.

The isotopic results fell between +1.3 °/oo and -7.5 °/oo and therefore show little isotopic variation. This is not unexpected, however, from the samples associated with the Chuquicamata porphyry. Little isotopic fractionation occurs during the oxidation of sulphides to sulphates (Nakai and Jensen, 1964), nor a significant amount during the chemical precipitation of sulphates from solution (Thode et al., 1961). However, during the reduction of sulphate to sulphide, bacterial reduction must have occurred, involving isotopic fractionation. The values of these sulphides (-7.5 °/oo and -3.6 °/oo) indicate that fractionation must have taken place in a closed system, with the reaction nearing completion.

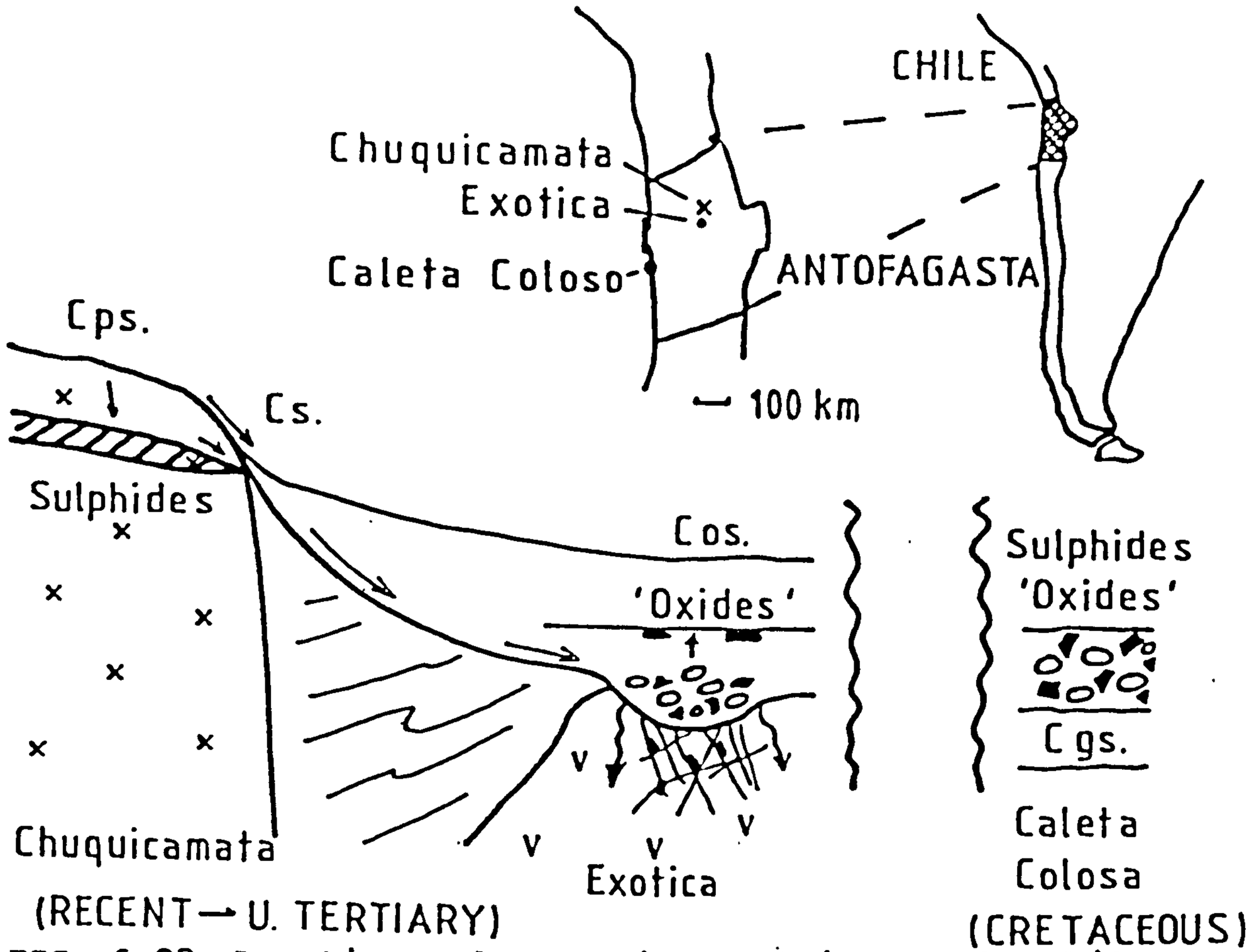


FIG. 6.23: Location and geological setting of the Chilean Sulphur Isotopic samples.

Sample		Description	$\delta^{34}S$ °/oo
CHUQUICAMATA			
C (Ps)	(3)	Supergene chalcocite	+ 1.3 °/oo
C (Ps)	(4)	Supergene chalcocite/Primary? pyrite and chalcopyrite	- 6.8 °/oo
CS	(5)	Copper Sulphate precipitate	- 3.6 °/oo
Cs	(6)	Gypsum precipitate	- 0.6 °/oo
EXOTICA			
Cos	(1)	Gypsum cemented gravel	- 2.5 °/oo
Cos	(7)	Gypsum plus Copper Sulphate cement from oriented gravel	- 3.5 °/oo
CALETA COLOSO			
C Gc	(2)	Sulphide from cemented gravel	- 7.5 °/oo
C Gc	(8)	Sulphide from cemented gravel	- 3.6 °/oo

Figure 6.24: CHILEAN ISOTOPIC RESULTS

The Caleta Coloso sulphides occur in small pockets within copper oxide cemented gravels; little or no organic matter is present for the reduction. A model is therefore proposed, involving the migration of reducing groundwater fluids from adjacent playa sediments within the sequence. These fluids encountered pockets of sulphate which were totally reduced, forming sulphides of copper and iron with $\delta^{34}S$ values equivalent to those of the original sulphate.

Sulphur Isotopic Zonation in Red Beds and Playa Deposits

The copper sulphides of the Red Bed gravels at Caleta Coloso and the Witvlei playa sediments are related.

On alluvial fans, ground and surface waters drain into topographically-low areas in which playa sediments form and salts plus organic matter concentrate. Organic growth and remains tend to concentrate in the centre of these playas but may have a variable distribution depending on the micro-environments present. In central playa areas, where the concentration of sulphate is highest and generally in excess of organic matter, open system isotopic fractionation may result, leading to the formation of isotopically-light sulphides. Towards the edge of the playa sediments the amount of organic matter is likely to exceed that of sulphate and lead to closed system fractionation, resulting in less depleted $\delta^{34}S$ values (Fig. 6.25). Therefore, ideally there should be a zonation of $\delta^{34}S$ values from central playa areas towards their margins. Reducing fluids migrating into adjacent Red Bed sandstones and conglomerates from these playa sediments will totally reduce pockets of sulphate to sulphide producing the same isotopic value (Fig. 6.25).

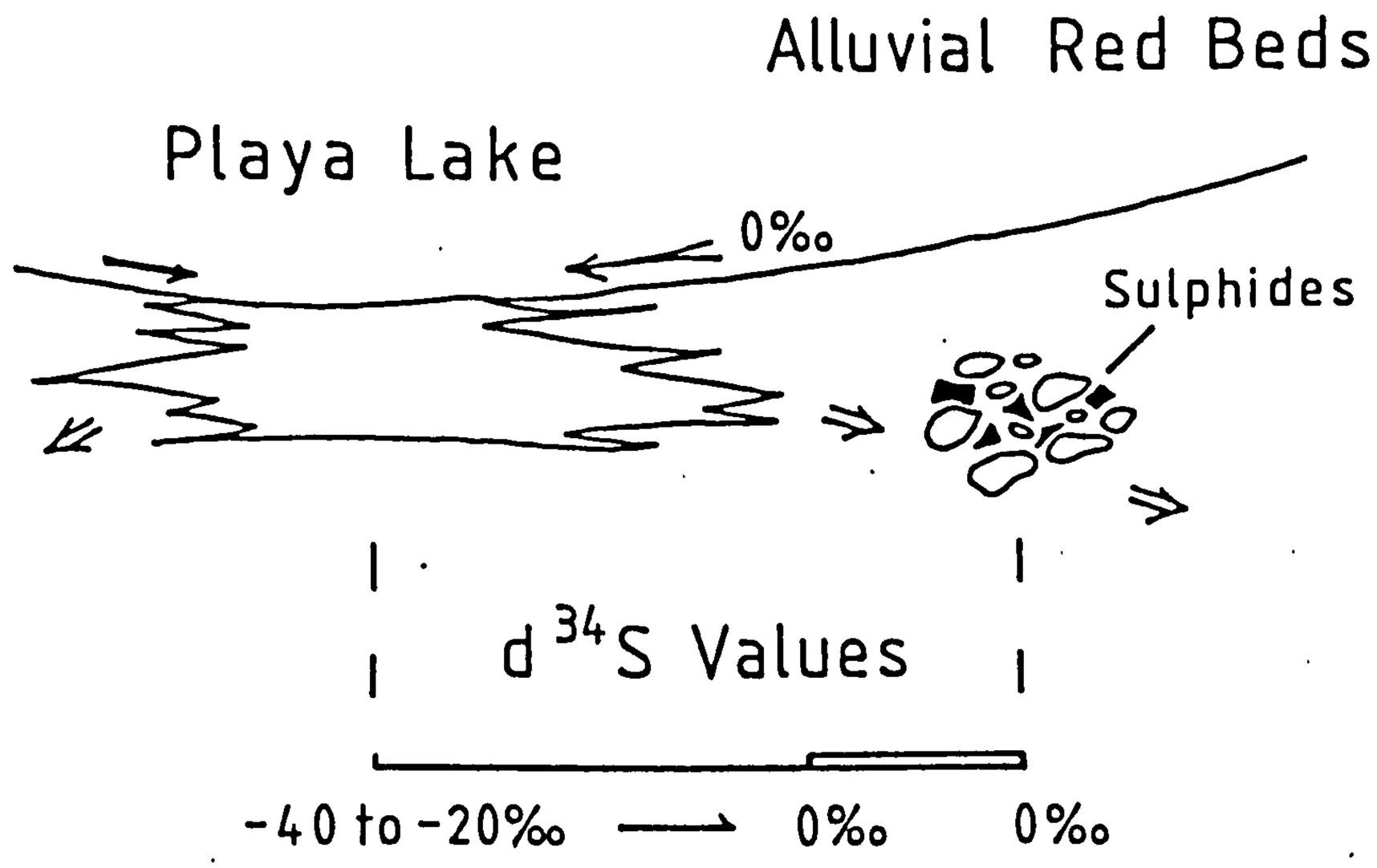


FIG. 6.25: A model for the Sulphur Isotopic zonation of Sulphides within playa and Red Bed alluvial fan sediments. (Broad arrows indicate the movement of reducing ground-waters).

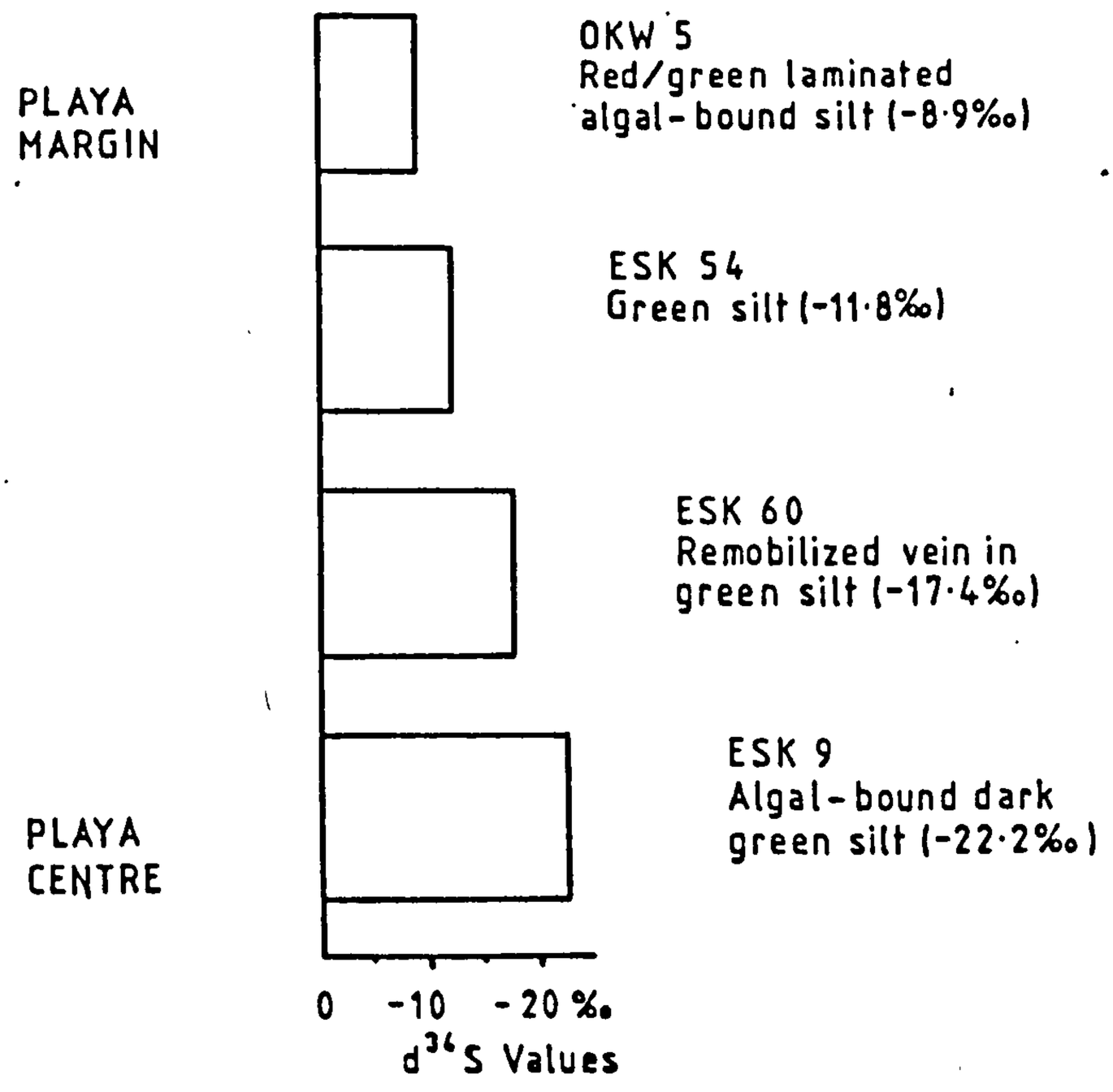


FIG. 6.26: Indication of the Sulphur Isotopic zonation of playa sediments in the Witvlei Fan Complex.

Observed isotopic results from both Witvlei and Caleta Coloso tentatively support this model. Samples analysed from the Witvlei playas show this zonation of $\delta^{34}S$ values from depleted to un-depleted towards the playa margins (Fig. 6.26). The Caleta Coloso samples represent the Red Bed pockets of sulphate totally reduced to sulphide by passing reducing fluids and yielding no change in their isotopic values (Fig. 6.24).

6.2.2 Lead Isotopes

This section presents lead isotopic data on trace lead in sulphides and whole rock lead from basement and sedimentary mineral deposits in the Klein Aub area, Namibia. Three sulphide samples from basement mineral occurrences: volcanogenic massive sulphide deposits of Kobos, galena veins from the farm Marienhof and chalco-pyrite in shear metasediments on the farm Dymoeb (AK.10); three unmineralized whole rock sedimentary samples from within the ore horizons (B1. UM. T.; B2. UM. and B2. CUME); and seven sediment samples with varying amounts of one or a combination of pyrite, chalcopyrite, bornite and chalcocite, were analysed. Seven of the samples were also analysed for their sulphur isotopic values. The results are shown in figure 6.27 and the localities of the specimens indicated in Appendix III.

The relevance of Lead Isotopes

The lead isotopic results are plotted on a lead : lead plot (Fig. 6.28) against the two-stage 'growth curve' of Stacey and Kramers (1975), representing the evolution of terrestrial lead. The two-stage curve represents the line of 'best fit' through the lead ratios of galena from stratabound massive sulphide deposits around

BASEMENT

Sample	206/204	207/204	208/204	
KOBOS	15.466 ± 0.008	15.275 ± 0.007	35.13 ± 0.01	†
AK 10	16.55 ± 0.01	15.533 ± 0.01	36.668 ± 0.02	
GALENA	16.514 ± 0.004	15.473 ± 0.003	36.288 ± 0.006	†

SEDIMENTARY

Sample	206/204	207/204	208/204	
40996	18.621 ± 0.014	15.676 ± 0.007	38.15 ± 0.02	
B4 Py	18.682 ± 0.014	15.688 ± 0.007	38.222 ± 0.016	†
B2 CUM E	18.739 ± 0.006	15.712 ± 0.004	38.161 ± 0.011	*
40980	22.461 ± 0.016	15.900 ± 0.008	39.99 ± 0.021	†
B3 M TS	22.719 ± 0.01	15.952 ± 0.004	40.697 ± 0.01	†
4051	23.011 ± 0.018	15.924 ± 0.013	38.752 ± 0.04	†
B2 M HM	26.249 ± 0.02	16.141 ± 0.008	40.015 ± 0.023	†
B2 M1	27.586 ± 0.019	16.217 ± 0.003	41.565 ± 0.019	
B1 UM T	36.095 ± 0.03	16.622 ± 0.008	45.728 ± 0.02	*
B2 UM 8	38.930 ± 0.02	16.894 ± 0.006	45.254 ± 0.016	*

STANDARDS

Sample	206/204	207/204	208/204
SRM 981 A	16.896 ± 0.001	15.441 ± 0.001	36.568 ± 0.00
SRM 981 B	16.914 ± 0.012	15.463 ± 0.00	36.608 ± 0.00

Lead isotopic data from the Klein Aub area, Namibia. (* Unmineralized whole rock samples, † samples also analysed for sulphur isotopes. B1 = Argillite band number 1, py = pyrite).

Figure 6.27: LEAD ISOTOPIC RESULTS

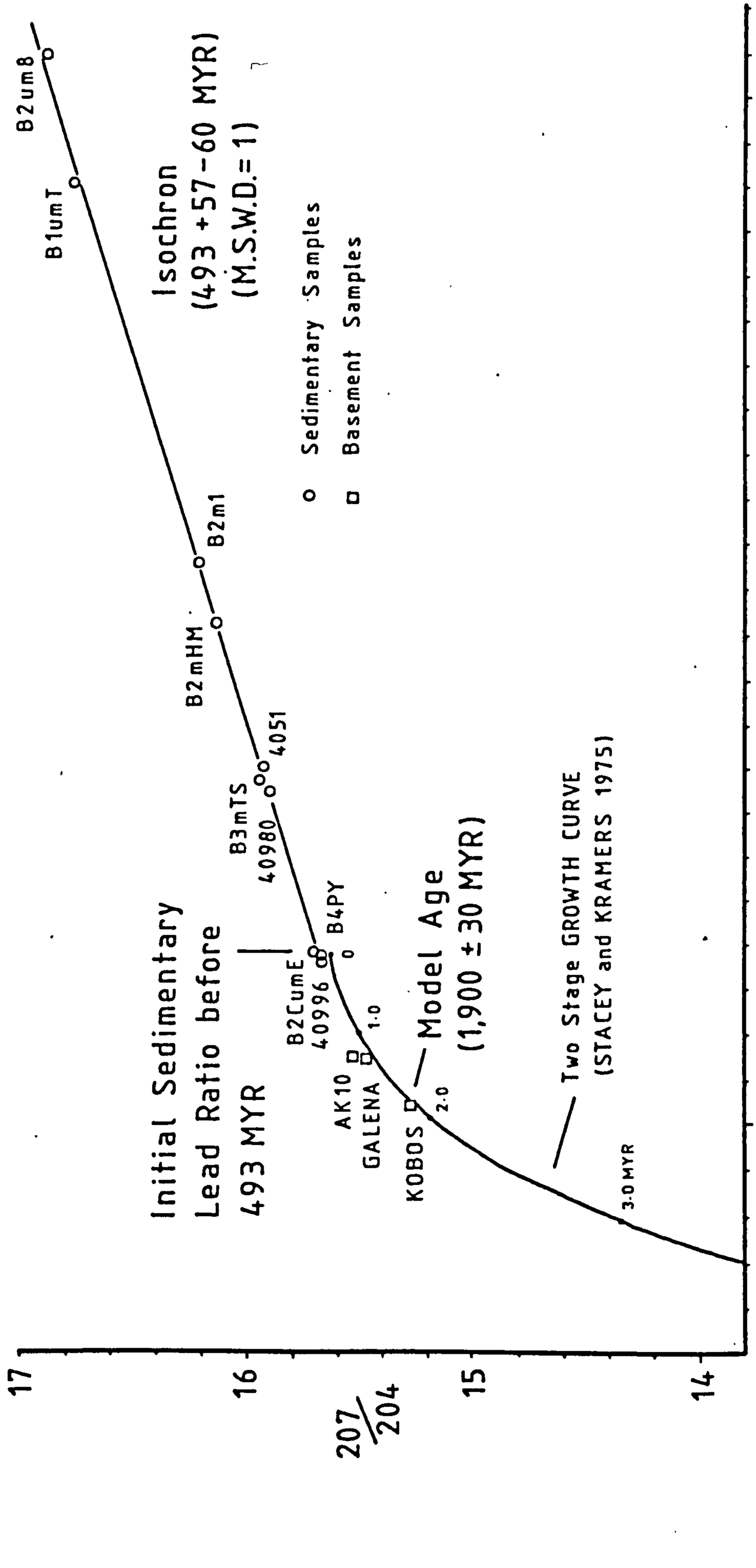


FIG. 6.28: Lead isotopic results from the study of basement and sedimentary rock samples in the Klein Aub area - plotted on a Lead:Lead plot.

the world. Cummings and Richards (1975) suggest a continuously-changing curve, rather than two distinct stages. However, the curve defines the increase in the terrestrial lead ratios 207/204 and 206/204 through time, in response to the radioactive decay of uranium. Uranium 238 decays to lead 206, Uranium 235 to lead 207 and lead 204 is non-radiogenic. Points on the curve have age significance and are called "Model ages". The sample Kobos lies close to the growth curve and is interpreted as having age significance - a model age of 1,900 ($\pm$ 30) MYR (from Stacey and Stern tables, 1972). This is one of the oldest ages from the Damaran basement of Namibia and indicates that these basement rocks were effected by the Eburnian Orogeny (2000 $\pm$ 200 MYR's) (Chapter II).

The two-stage model for the evolution of terrestrial lead, proposes an increase in the uranium concentration within part of the earth (probably the Upper Mantle) at about 3,700 MYR. An increase in the uranium concentration in any lead system will result in the generation of additional radiogenic lead and evolution along a higher trajectory on the lead : lead plot (higher μ value).

The two other basement samples, AK.10 and Galena, plot above the growth curve and to the left of the present-day terrestrial lead value. In addition, four samples of trace lead in sulphides from basement rocks further North in the Damara Orogenic Belt, plot above the curve (Fig. 6.29) but are less primitive (Marlow, 1981). Since these points lie above the growth curve there must have been an increase in the uranium concentration in the source region at some previous time. The point of intersection of a line, drawn tangentially to the growth curve passing through the point with the highest 207/204 and lowest 206/204 ratio (the most primitive: AK.10) of the

basement cloud gives an approximate minimum age for this increase in uranium in the source region (Line X, Fig. 6.29). The age indicated is approximately 2,000 MYR; the Eburnian orogeny.

Sedimentary leads are highly radiogenic, lying on a line above and to the right of the growth curve; they are anomalous leads (Fig. 6.28). This line represents an isochron and gives an age of 493 +57/-60 MYR (M.S.W.D. = 1). Three points - one copper sulphide, one iron sulphide and a whole rock sample - cluster at the base of this secondary isochron. This point is interpreted as the initial ratio of 207/204 and 206/204 lead in the sediments at 493 MYR. The initial ratio plots within the 'cloud' of basement samples on the lead: lead plot (Fig. 6.29), which strongly suggests that the source of sedimentary lead was from basement rocks!

The anomalous lead line produced from the sedimentary leads indicates a metamorphic age of 493 MYR, which corresponds to the age of emplacement of the Naukluft Nappes, 30 km. West of Klein Aub (Ahrendt et al, 1978) (see Chapter II). This interpretation is geologically reasonable, since deformation and metamorphism were intense enough to remobilize copper/iron sulphides (Fig. 6.13) and therefore, trace and whole rock lead. The evolution of the sedimentary lead line implies the introduction of uranium during this 493 MYR metamorphic event.

Summary

The sedimentary lead results can most easily be described using a four-stage evolutionary model. The lead was initially derived from the Upper Mantle which evolved according to the two-stage model of Stacey and Kramers (1975). Prior to 2000 MYR, an increase in the uranium concentration in the source region resulted in the departure

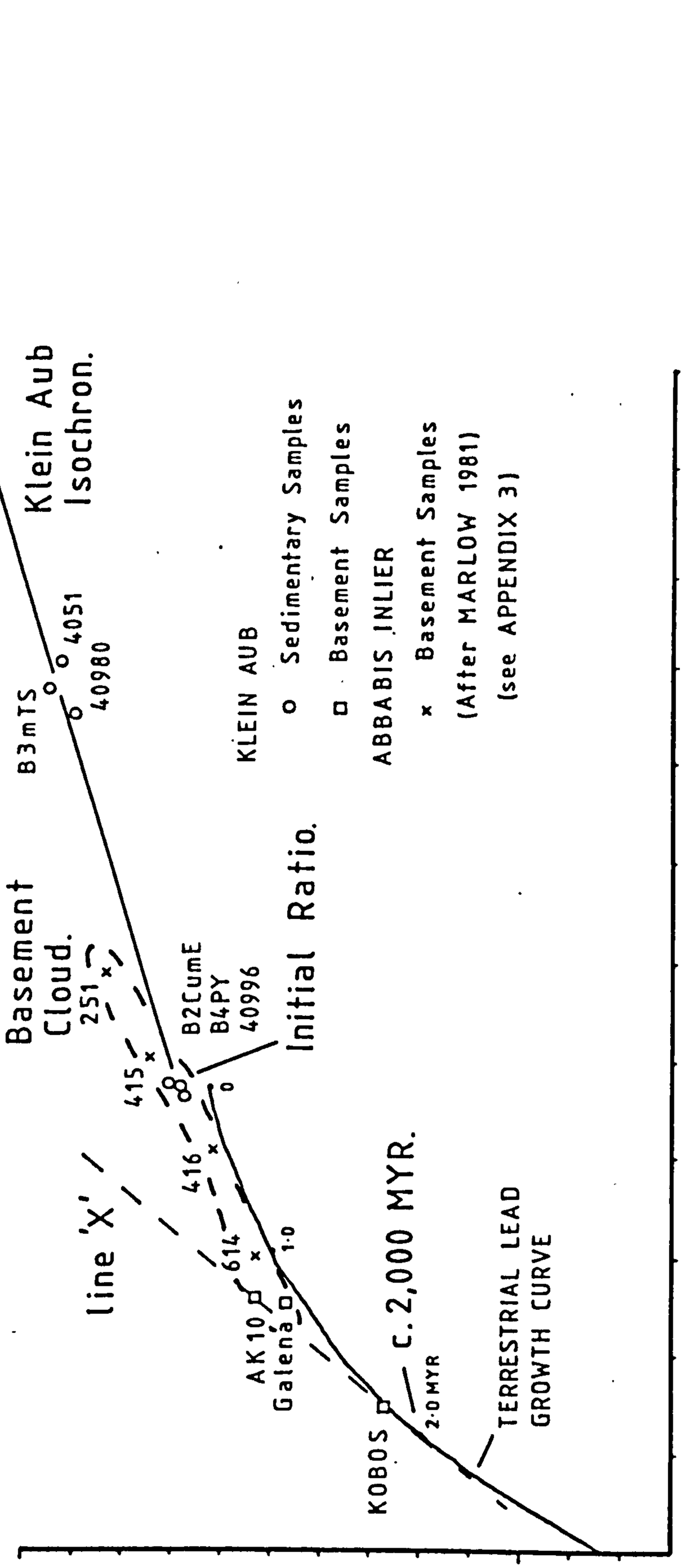


FIG. 6.29: A Lead isotopic plot of sedimentary and basement lead results from the Klein Aub area and Abbabis Inlier, S. of Usakos (Appendix III, from Marlow, 1981). The Initial Ratio of the sedimentary lead of Klein Aub plots within a Basement Cloud. The line 'X' is drawn through the most primative of the basement lead values tangentially to the Growth Curve - an age of 2,000 MYR is indicated.(see text).

of lead evolution from the growth curve (stage 3). This system evolved, probably in a very complex way, giving rise to a cloud of basement values lying above the growth curve. The sedimentary rocks formed between 1,100 MYR and 850 MYR as a result of uplift and erosion of basement rocks. Basement lead was transported from the provenance area into the sediments. The addition of uranium and the remobilization of sedimentary trace lead in sulphides and whole rock lead during a 493 +56/-60 MYR event, led to the formation of an anomalous lead line (stage 4).

Lead and Ore Genesis

This lead isotopic data *are* important to the formulation of a model of copper ore genesis of the Klein Aub deposits, since it provides evidence that the sedimentary lead was derived from base-ment rocks. If the lead has a magmatic source the initial ratio of the sedimentary lead isochron should lie close to the growth curve, indicating direct separation of the ore-bearing fluid from mantle-derived rocks. The initial ratio, however, lies above the growth curve within a zone of basement lead values and clearly indicates a complex evolution.

Detailed consideration of lead isotope systematics is covered in Doe (1970), Stanton (1972) and York and Farquhar (1972).

6.2.3 Carbon and Oxygen Isotopes

Six carbon and oxygen isotopic measurements were made: three from Klein Aub, two from Witvlei and one from Kagas Noord. Two of the samples were associated with sulphides which were analysed for their sulphur isotopic values (KC2 (40524) and KN1 (KN)). The systematics of carbon and oxygen isotopes are similar to those of

sulphur and not covered here (Hudson, 1977). Little is known about Late Proterozoic carbon and oxygen isotopic values, placing the usefulness of such a study in doubt.

Discussion of Results

The results are tabulated in figure 6.30 and plotted on a carbon versus oxygen isotope plot in figure 6.31, against the fields of Phanerozoic Carbonates (Hudson, 1977). The Doornpoort results plot to the left, having highly-negative $\delta^{18}O$ values, in common with either Precambrian Carbonates (Schidlowski et al, 1975). Playa carbonates from Witvlei give slightly high $\delta^{13}C$ and $\delta^{18}O$ values than the lacustrine carbonates of Klein Aub and Kagas Noord. They are interpreted as evaporitic forms in contrast to the early diagenetic lacustrine carbonates. These interpretations are probably incorrect owing to our poor knowledge of Precambrian Carbonate isotopic values, but the important point is that they are not organic-derived when compared with Phanerozoic equivalents. This is in contrast to the bacteriogenic origin of the associated sulphides.

Textural evidence suggests that the carbonates are replacive with early and late diagenetic origins.

* *

Summary of the Isotopic Evidence

Sulphur isotopic studies indicate that sedimentary sulphides formed by the bacterial reduction of either basement-derived or magmatic sulphate, in an open (Klein Aub) and closed (Witvlei) system during diagenesis. Studies of sulphur on analogous sulphides and sulphates from Chile, when compared with the playa sulphide results from Witvlei, indicate a zonation of $\delta^{34}S$ values from

No.	Sample		$\delta^{13}C$ P.D.B:	$\delta^{18}O$ P.D.B.
		KLEIN AUB		
KC1	S.R.H.	Carbonate nodules in a possible sabkha replaced horizon.	-1.4°/oo	-19.35°/oo
KC2	40524	Carbonate cement - replacive associated with sulphides.	-2.0°/oo	-19.18°/oo
KC3	Vein	Vein Carbonate associated with haematite and feldspares.	-1.98°/oo	-18.43
		KAGAS NOORD		
KN1	Pyrite	Carbonate associated with pyrite (KN)	-2.1°/oo	-18.97
		WITVLEI		
WC	ESK	Pink carbonate from playa lake.	+1.9°/oo	-16.47
WC2	MAT	Replaced gypsum-mat carbonate.	+1.2°/oo	-15.67°/oo

(All values ± 0.05 °/oo)

Figure 6.30: CARBON/OXYGEN ISOTOPIC RESULTS

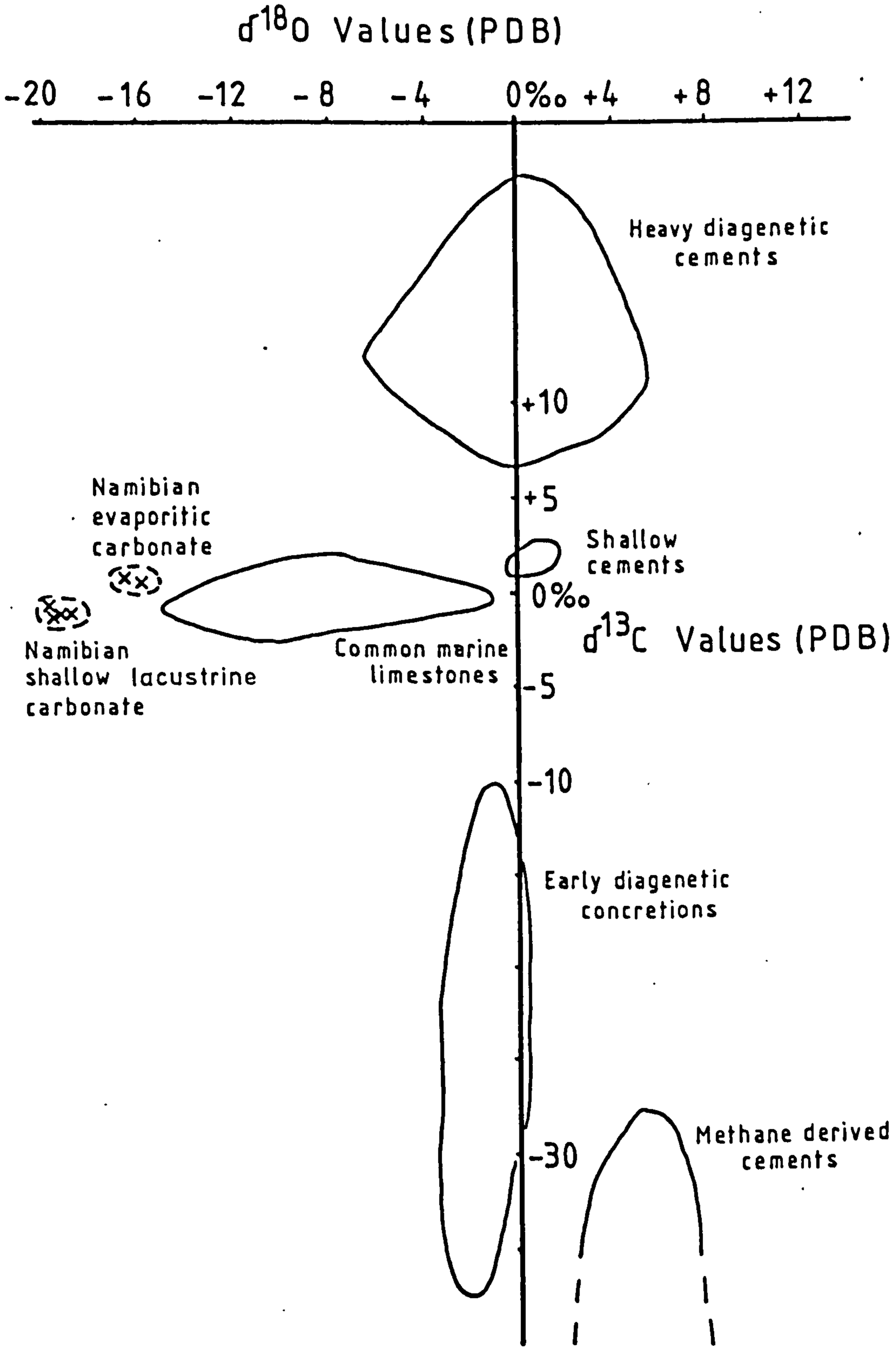


FIG. 6.31: A diagram featuring Carbon and Oxygen isotopic data of Namibian Evaporitic (Witvlei samples) and shallow lacustrine (Klein Aub/Kagas Noord samples) carbonates, plotted against the fields for Phanerozoic carbonates (see Hudson, 1977).

depleted to original values in playas and surrounding Red Beds. This zonation is considered to be a function of the relative distribution of organic matter and sulphate within the sediments.

Studies of lead isotopes of the Klein Aub area suggest that all sedimentary lead, and hence probably copper and silver also, was basement-derived. An Eburnian age of 1,900 ± 30 MYR's was obtained from the Kobos mine and an age of 493 +56/-60 MYR's from the sedimentary sulphides, indicating a metamorphic event.

Carbon and oxygen isotopic data *are* somewhat ambiguous.

6.3 MODEL FOR ORE GENESIS

6.3.1 Salient Features of the Doornpoort Copper Deposits

Copper deposits of the Doornpoort Formation are both stratabound and stratiform. They occur in fine-grained reduced playa and marginal lacustrine sediments which formed in topographically-low areas on, or adjacent to, Late Proterozoic alluvial fans. Mineralization is found in the first reduced horizons of the sedimentary successions, adjacent to coarse fluviatile red sediments. Copper occurs in sulphides which fill pore spaces and cement detrital grains.

A syngenetic model is proposed for the Doornpoort copper deposits. Lead isotopic evidence indicates that the copper was probably derived from the weathering of mineralized basement rocks. Sedimentological studies indicate that the distribution of copper was probably controlled by the palaeodrainage of alluvial fan surface and groundwaters and that at Klein Aub, the ores were concentrated by lacustrine palaeocurrents. Metals were apparently introduced during or shortly after sedimentation, in solution and/or particulate form by surface and groundwater solutions. Bacterial reduction of

groundwater sulphate, forming sulphides, fixed and concentrated the copper in the sediments during diagenesis.

6.3.2 Stratiform Copper/Red Bed Association

The association of stratiform copper and red sediments is a common feature, recognized in the Kupferschiefer deposits of Europe (Rentzsch, 1974), the Zambian Copperbelt (Garlick, 1972; Clemmey, 1976), the White Pine deposits of Canada (Brown, 1974), the Adelaidean ores of Australia (Rowlands, 1974), and the lesser known Oamities deposit of Namibia (Lee and Glenister, 1976), amongst others. The dominant controls on stratiform ore deposits of this association are considered to be low latitude arid to semi-arid weathering and sedimentation (Strakov, 1970; Clemmey, 1976; Badham, 1981). Semi-arid to arid weathering both releases and concentrates copper in low grade mineral deposits. This primary concentration of copper appears essential to the formation of stratiform copper deposits within the surrounding sediments (Badham, 1981).

Arid weathering of low grade copper deposits has been in progress for a long period of geological time in Chile. This process has involved the release of copper and the supergene enrichment of primary copper and iron sulphides within copper porphyry deposits (Gustafson and Hunt, 1975). Oxidation of primary sulphides above the water table leads to the release of copper and iron which percolate downwards and enrich primary sulphides just below the water table to form a supergene copper sulphide blanket. Water table fluctuations effect the size of this sulphide blanket.

Groundwater solutions draining from these Chilean copper porphyries are highly acidic and may contain significant concentrations

of copper, up to several hundred ppm. at Chuquicamata (Jarrel, 1944). Copper tends to precipitate around these porphyry coppers forming large deposits of Chrysocolla ($CuSiO_3.H_2O$) and copper sulphates plus carbonate (Newberg, 1967; Mûnoz, 1975). Mûnoz (1975) estimated that large stratiform ore bodies of an average of 1-2 million tons at 2 to 5% copper are common around weathering copper porphyry deposits in the Antofagasta area of Chile. The Exotica ore body, for example, derived from the weathering of the Chuquicamata porphyry, contains 160 million tons of c.1.86% copper (Mûnoz, 1975; Robinson, 1978).

Thus associated with the weathering of low grade copper porphyry deposits in Chile, large concentrations of secondary copper occur. Uplift and erosion of these deposits, associated with periodic sediment flushing - a characteristic of semi-arid to arid sedimentation (see Chapter III) - would lead to the substantial movement of copper from the provenance to the sedimentary basin. Such an event with additional concentration during sedimentation and/or diagenesis, may lead to the formation of distal stratiform economic ore bodies.

6.3.3 Copper Transport in Aqueous Solutions

Several methods of copper transport in aqueous solution have been proposed involving 1) the formation of organic complexes, 2) complexes with iron hydroxide, 3) ion exchange on clay particles, 4) as a grain coating; or in particulate form (Fig. 6.32).

Studies by Gibbs (1973) and Ashry (1973) on the mode of transport of trace metals in rivers (Gibbs from the Amazon and Yukon rivers and Ashry from the Egyptian Nile) concluded that copper is carried dominantly in particulate form (Fig. 6.32). Further

COPPER TRANSPORT.

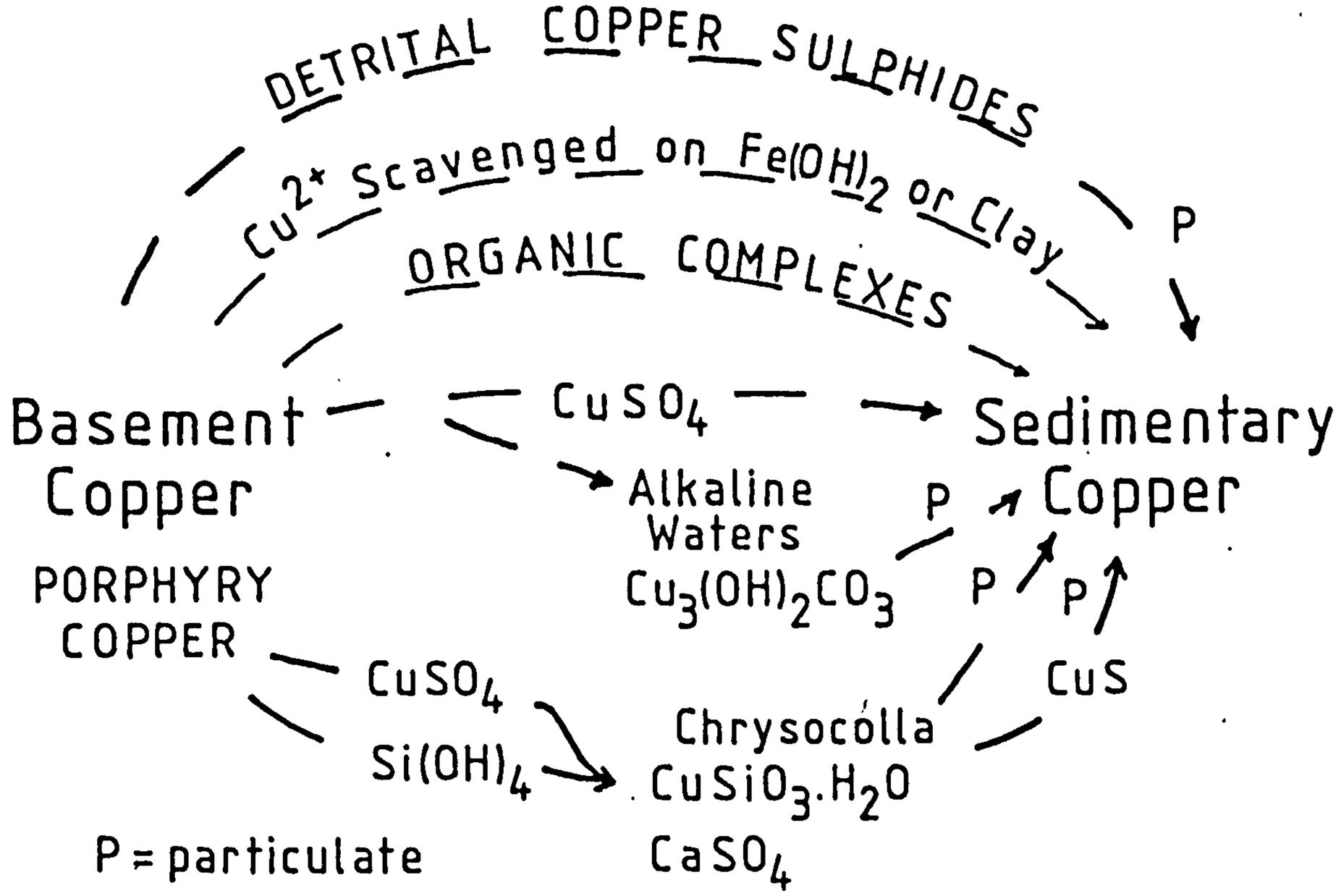


FIG. 6.32: Possible methods of copper transport in natural waters.

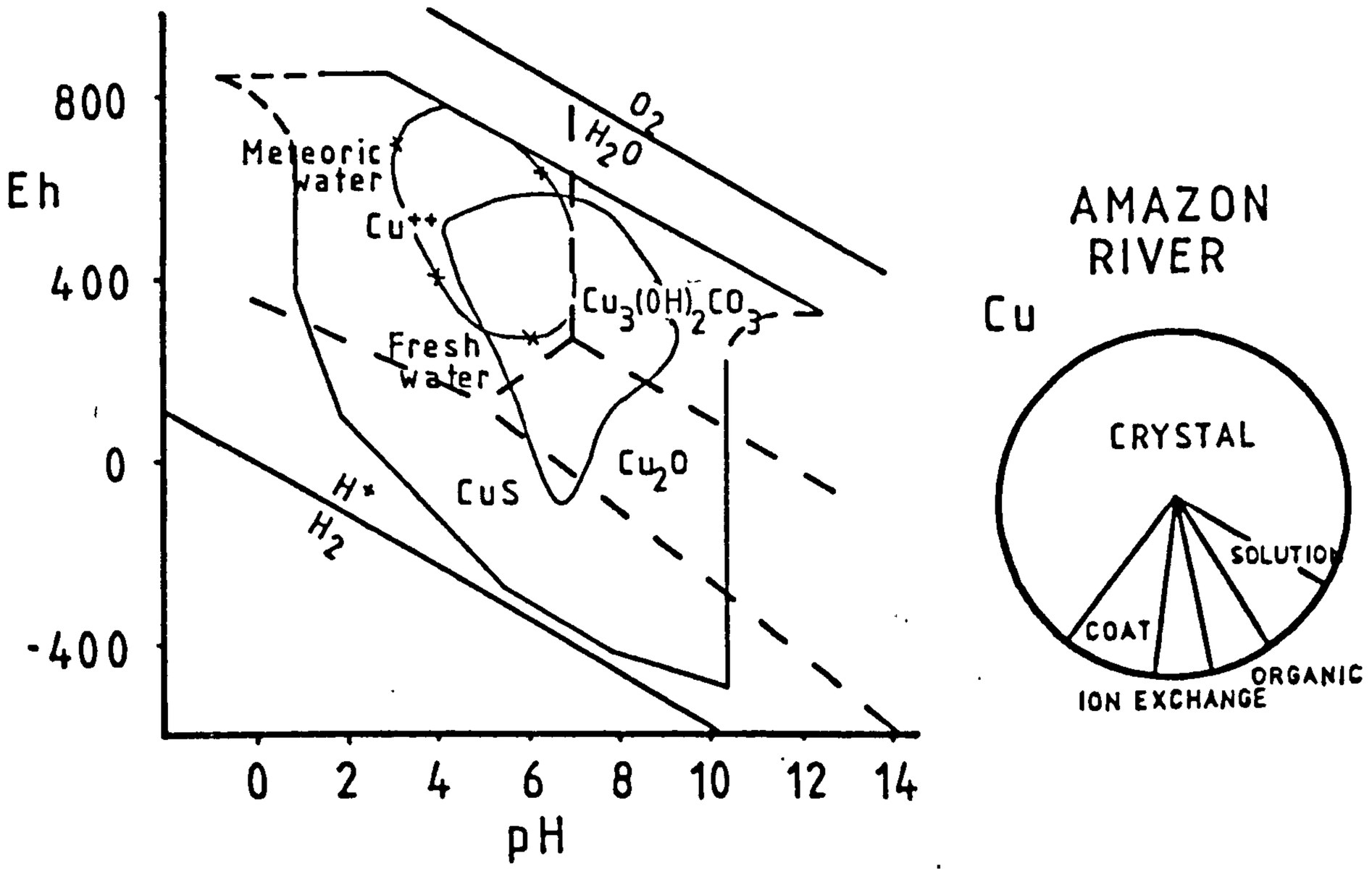


FIG. 6.33: An Eh-pH diagram (left) illustrating the limits of natural waters, stability fields of Cu++, MALACHITE, Cu2O and Copper sulphides (CuS), plus the fields of Meteoric and Fresh Waters. And a pie diagram (after Gibbs, 1973) indicating the principle method of copper transport in the Amazon River.

support for this finding is suggested by the chemistry of copper in aqueous solution.

Copper is transported from the weathering horizon, predominantly, in the form of copper sulphate, in acidic solutions (Newberg, 1967; Strakov, 1970). However, if the pH of the solution rises above 5.3 (>5.3, Huff, 1962) or 6.6 (>6.6, Strakov, 1970), copper sulphate becomes unstable and copper is converted to the carbonate form ($Cu_3(OH)_2CO_3$), which is insoluble (Fig. 6.33) (Huff, 1962; Temple, 1964; Strakov, 1970; Levinson, 1974; Richards, 1974). The basic copper carbonate (malachite) is carried in particulate form within the suspended sediment load (Strakov, 1970, III, pp. 71-2; Rickard, 1974). Since malachite has a specific gravity of between 4.0 and 3.6, Strakov (1970) suggested that in "long rivers" it precipitates out into alluvial sediments and in "short rivers" is carried to the margins of large lakes or shallow seas.

However, copper may also be transported in rivers as particulate copper sulphide but is relatively unstable (Stendal, 1979), although copper sulphides have been reported 145 km. from their source in the Atacama Desert of Chile (Clemmey, 1978).

6.3.4 Origin of the Doornpoort Copper Deposits

Copper mineralization of the Doornpoort Formation is broadly similar to other Red Bed/stratiform ore deposits. Stratiform copper is hosted within green carbonaceous siltstone and mudstones associated with red sediments. The association of Red Beds, aeolian sandstones and possible evaporitic minerals suggests deposition in a semi-arid to arid climate. Palaeomagnetic data from Southern Africa indicates that the region was in low latitudes during sedimentation (Fig. 6.34). Conditions are therefore

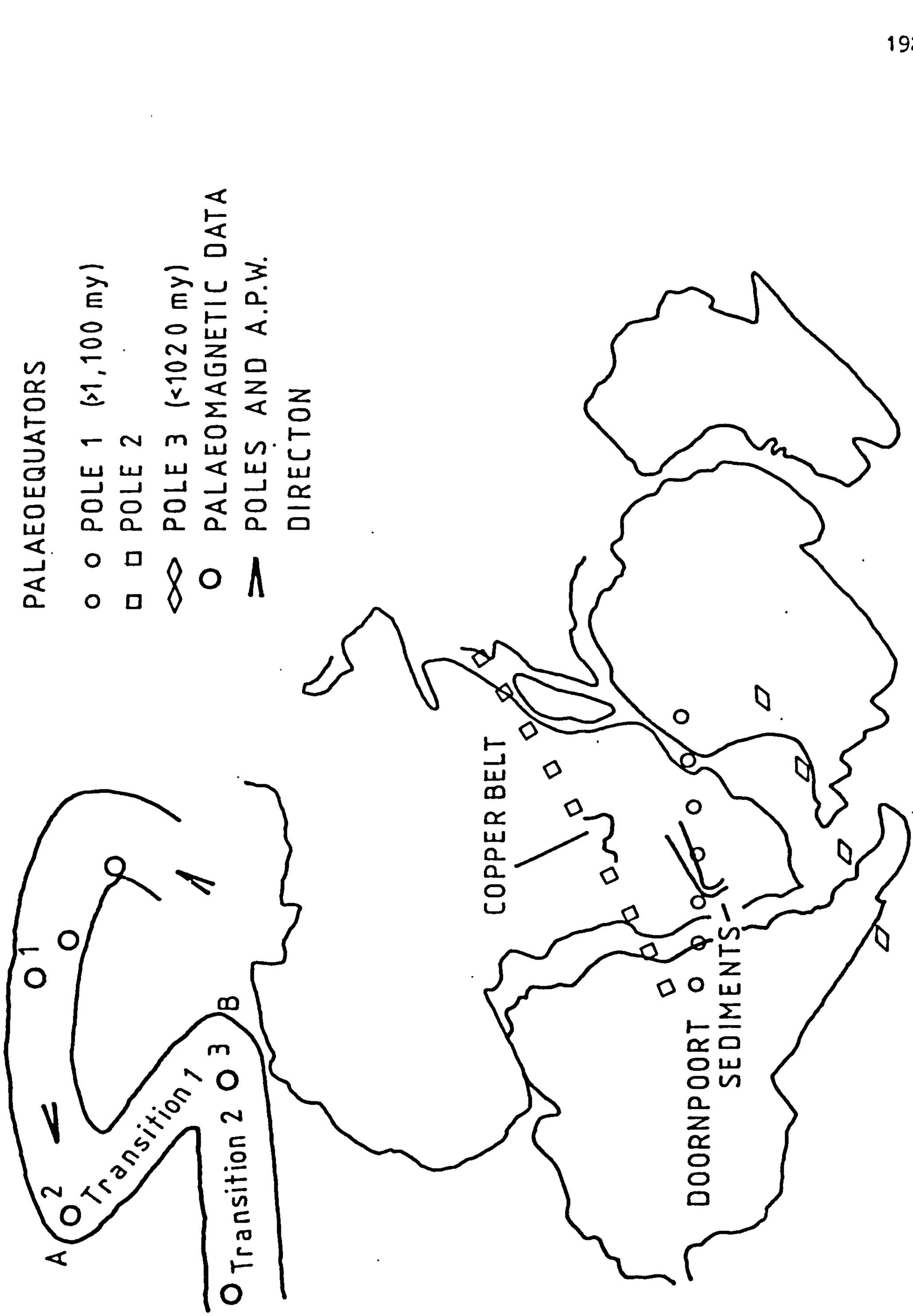


FIG. 6.34: Apparent polar wander path and corresponding palaeoEquators covering the period of initial Doornpoort and Roan (Zambian Copperbelt) sedimentation (adapted from Clemmey, 1976; after Piper (1974) and McElhinney and McWilliams (1977).

FIG. 6.35: A photograph of a copper sulphide and chrysocolla (green) bearing Granodiorite from Basement rocks of the Witvlei area (farm Okatjepuiko). A copper porphyry?

satisfied for the weathering of low grade basement copper deposits.

Basement rocks beneath the Doornpoort Formation contain many mineralized deposits (Chapter II). The most interesting deposit is a copper sulphide and oxide-bearing granodiorite from the Witvlei basement (Fig. 6.35). Large areas of this granodiorite are mineralized, containing malachite and chrysocolla, as well as bornite/chalcocite, possibly indicating copper release during weathering. This may be the remanence of an eroded copper porphyry, and several mining companies convinced of this, are at present exploring large areas of basement North of Klein Aub for similar deposits.

It is postulated that weathering of basement mineralized rocks in a semi-arid to arid climate released and concentrated copper in the provenance area of the Doornpoort sediments. Periodic flushing and storage events are envisaged, contributing to the concentration and distribution of copper. Subsequent erosion of the primary and satellite ore deposits, formed within the provenance area, led to further transport of copper into the sedimentary basin.

Copper Transport

Copper was transported from the basement to the sediment in streams and rivers and concentrated in topographically low areas. In the Witvlei area, copper is concentrated on the western side in the proposed maximum drainage path of alluvial fan ground and surface waters. Localized uplift and deposition in the Witvlei area (see Chapter IV) possibly resulted in a relatively short distance of copper transport despite the preponderance of second cycle alluvial fan sediments. The form of introduced copper is not clear; however, evidence for detrital chrysocolla (Fig. 6.9) and

possibly detrital chalcopyrite (Fig. 6.8) occurs. The majority of copper was probably introduced as copper sulphate which collected and concentrated in reduced playa sediments before and during diagenesis.

At Klein Aub, evidence indicates that the copper was introduced in particulate form, which was probably not a sulphide phase. Copper probably settled from suspension as malachite, within the other suspension deposits, and was concentrated by gentle lacustrine palaeocurrents. Since malachite has a specific gravity of 4.0 in contrast to quartz, 2.6 and feldspar, c.2.5, it was probably concentrated as a placer mineral. The deposits are, however, not placer accumulations (sensu. stricto); firstly, due to the origin of the copper minerals and secondly, because of the absence of associated heavy minerals. The term 'suspension-placer' is tentatively suggested for these deposits.

The occurrence of malachite, as opposed to copper sulphate, is probably a consequence of distance from source and sedimentation style. Regional uplift and deposition on broad alluvial plains in the Klein Aub area suggest deposition in large rivers with the concentration of copper some way from its source. The mixing of acidic weathering solutions and the more alkaline waters of the alluvial fan, probably raised the pH of the river water sufficiently for malachite to form.

Copper Diagenesis

Copper was fixed within the reduced sediments, in sulphides, formed by the bacterial reduction of groundwater sulphate, during diagenesis. Sulphide formation is dependent on the availability of organic matter and sulphate. Variations in the amount of reaction

materials led to the development of sulphides containing variable $\delta^{34}S$ values.

Textural evidence suggests that sulphides in all the Doornpoort deposits were initially iron-rich and progressively enriched by copper during diagenesis. This is supported by the common occurrence of haematite halos around enriched minerals and the association of copper and specularite in copper-rich zones of the Klein Aub ore deposits. Progressive replacement of iron by copper in the sulphide phases, reflects the greater affinity of copper for the sulphide ion during diagenesis.

Mineralized deposits of the Witvlei fan complex probably concentrated copper in sulphides during the progressive influx of copper sulphate from alluvial fan surface and groundwaters. This copper enrichment stage, also recognized by Anhaeusser and Button (1973), probably post-dated the sulphur isotopic zonation of the playa sediments.

At Klein Aub, diagenesis probably involved the conversion of malachite to copper sulphide * F.N. - a reaction which according to Strakov (1970) is "universal and complete". Since the solubility of copper sulphides is hundredths or thousandths that of basic carbonates, copper was converted from its least stable to its most stable form. Where copper was concentrated in the oxide form, it remains concentrated in the sulphide, because of the greater affinity of copper (over iron) for the sulphide ions. Replacement of initial iron sulphides by copper at Klein Aub probably gave rise to the association of specular haematite and sulphides, which is such a common feature of these ore deposits (Figs. 6.11, 6.12).

* Conversion of malachite to copper sulphide releases carbonate.

$Cu_3(OH)_2CO_3 + S^{2-} \Rightarrow (CuS) + CO_3^{2-} + H_2O.$

Calcite is a common diagenetic mineral in the Klein Aub ore horizons.

Mineral zonation is therefore considered to reflect the greater affinity of copper for sulphide ions during diagenesis and essentially reflects the original copper distribution of the sediments or major copper traps during diagenesis.

6.4 MINERALIZATION IN RED BED/STRATIFORM ORE DEPOSITS

Red Bed/stratiform ore deposits are generally considered to have formed in low latitude arid to semi-arid climates and are situated in sediments of marine and lacustrine transgressions, adjacent to weathered basement rocks and alluvial fan red sediments. This type of ore deposit has recently been reviewed by Badham (1981), who concluded that a polyphase model for their origin is generally accepted, usually involving the early diagenetic fixation of copper from metalliferous groundwater solutions.

In considering the genesis of these deposits two fundamental points must be discussed. Firstly, the source of metals and secondly, their mode of fixation and concentration in the host sediments.

Source

Two possible sources of metals have been proposed. Firstly, a volcanogenic or magmatic origin suggested by White (1971) and Brown (1971, 1978) for the White Pine copper deposits of Michigan and by Annels (1979 (b)) for the metals of the Mufulira ores of the Zambian Copperbelt. Annels suggested that the metals were introduced by volcanic exhalation, whereas Brown proposed the migration of magmatic fluids, containing copper in the form of chloride complexes.

Secondly, a basement source has been proposed involving the release of base metals from mineralized basement rocks during semi-arid to arid weathering (outlined in section 6.3.2). Wakefield (1978) has provided evidence of copper-porphyry type mineralization and supergene weathering of granodioritic rocks, in the Samba area of the Zambian Copperbelt. He suggests that this copper release was probably the source for some of the Lower Roan stratiform mineralization. Garlick (1961), Van Eden (1974), Binda (1975) and Clemmey (1976) also proposed a basement origin for the Copperbelt metals, and Rentzsch (1974) suggested a similar origin for the Kupferschiefer mineralization.

Copper Introduction and Fixation

Binda (1975) and Clemmey (1976) suggested that copper was introduced into the Lower Roan sediments of the Copperbelt in particulate form as either copper sulphides or chrysocolla (Clemmey, p.306).

Van Eden (1974) proposed that copper was introduced in solution and fixed in sulphides during diagenesis. Several variations on this theme have been developed. Renfro (1974) suggested that stratiform copper, lead and zinc deposits (which are associated with Red Beds and overlain by thick evaporitic sequences) were concentrated in algal-bound fine sediments by evaporitic processes. Metals derived from terrestrial rocks are envisaged to have been transported in chloride complexes (see Rose, 1976) and concentrated in carbonaceous sulphide-bearing fine sediments, by the upward migration of groundwaters, during evaporation on a sabkha flat, forming above the host horizons.

In explaining the origin of the Kupferschiefer ore deposits, Rentzsch (1974) proposed that metal-bearing terrestrial groundwaters mixed with marine solutions and that the bacterial reduction of sea-water sulphate formed sulphides, at the margins of the Rote Fäule red facies. These Kupferschiefer deposits clearly cross-cut stratigraphic units and probably represent roll-front deposits in which copper was carried in solution in red sediments and deposited as sulphides on contact with reduced deposits.

Annels (1974, 1979(b)), however, suggested that the metals of the Mufulira ore bodies were formed by the migration of carbonaceous and copper-chloride solutions into structural highs and deposited in receptive host sediments.

Summary

In general conclusion, stratiform ore deposits of this association were probably formed during early diagenesis and the metals introduced either in groundwaters, or during sedimentation in particulate form. The metals were derived from basement or magmatic/volcanogenic sources. Concentration of the ores possibly took place initially in the source area and subsequently during sedimentation and diagenesis.

6.5 DOORNPOORT COPPER MINERALIZATION - CONCLUSIONS

Copper mineralization in the Doornpoort sediments can be classified under the Red Bed - Copper association. Copper and silver were derived from the weathering of mineralized basement rocks in a semi-arid to arid climate, as suggested by lead and possibly sulphur isotopic work. The formation of enriched primary and satellite deposits probably enhanced copper concentration in the provenance area. Release of

copper during weathering and the subsequent erosion of primary enriched and satellite mineral deposits, resulted in the removal of copper from the provenance area into the sedimentary basin (Summary, Fig. 6.36).

Copper was transported in alluvial fan surface and groundwaters, either in solution as copper sulphate, or in particulate form, predominantly as malachite, with perhaps chrysocolla and chalcopyrite. Mineralized ground and surface waters concentrated in topographic low areas on, or adjacent to, alluvial fan sediments. Malachite fell out of suspension in the marginal lacustrine deposits at Klein Aub and was reworked as a placer mineral, by lacustrine palaeocurrents.

The metals were fixed as sulphides during diagenesis, formed by the bacterial reduction of groundwater sulphate. Bacterial fractionation and variations in the relative proportions of organic matter and sulphate in the playa sediments of the Witvlei fan complex, led to a possible sulphur isotopic zonation of the ore horizons. Replacement of early iron sulphides by copper, in turn, led to the copper zonation of all the deposits.

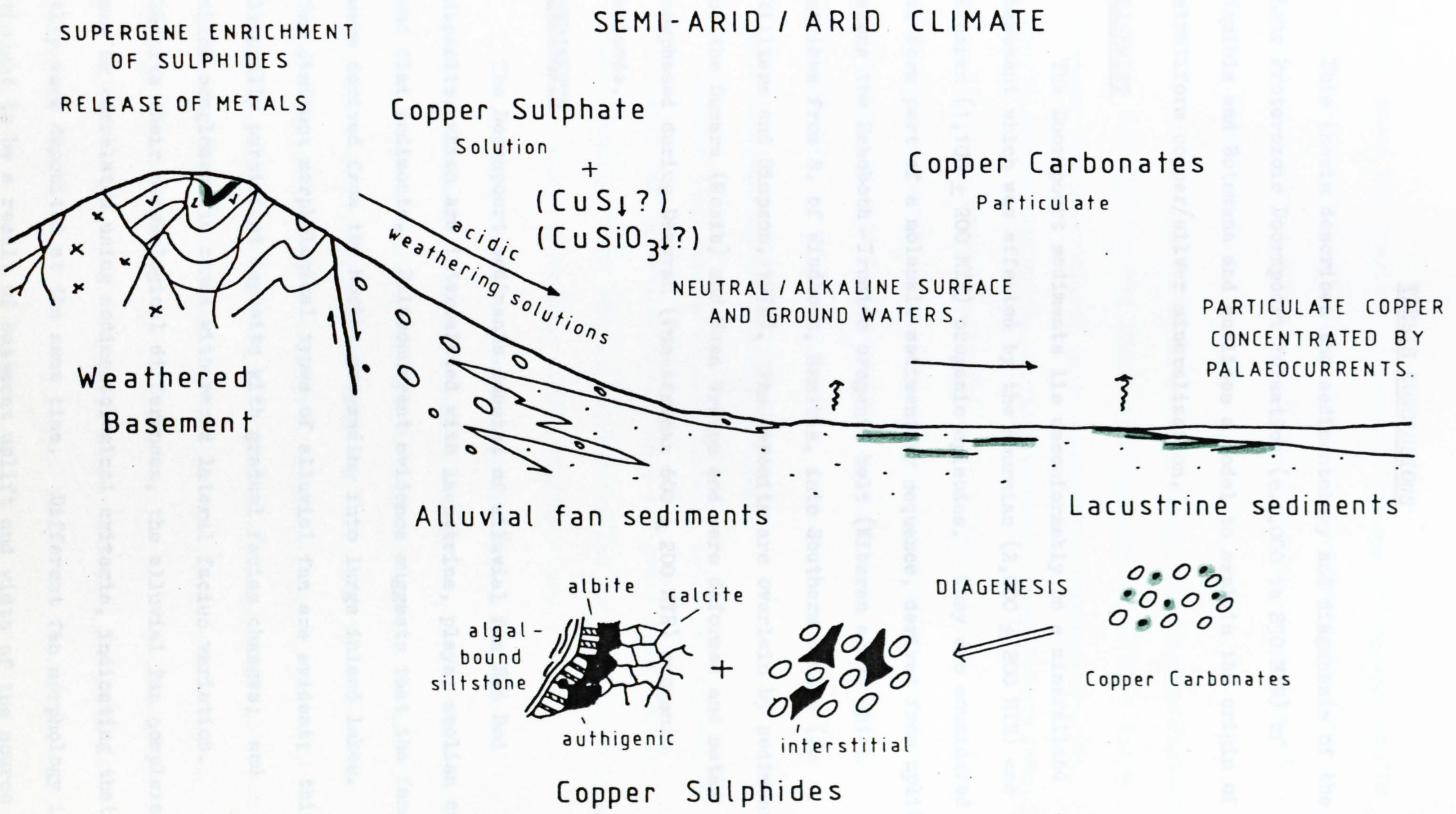


FIG. 6.36: A summary of the model proposed for the ORE GENESIS of copper mineralization in the DOORNPOORT FORMATION sediments.

THESIS CONCLUSIONS

This thesis describes the sedimentology and diagenesis of the Late Proterozoic Doornpoort Formation (c.1,000 to 850 MYR) of Namibia and Botswana and outlines a model to explain the origin of stratiform copper/silver mineralization.

BASEMENT

The Doornpoort sediments lie unconformably on a mineralized basement which was affected by the Eburnian (2,000 ± 200 MYR) and Kibaran (1,100 ± 200 MYR) orogenic episodes. They are considered to form part of a molassic sedimentary sequence, derived from uplift along the Rehoboth-Irumide orogenic belt (Kibaran age), which strikes from S. of Windhoek, Namibia, into Southern Zambia (De Villiers and Simpson, 1974). The deposits are overlain by sediments of the Damara (Nosib) and Nama Groups and were deformed and metamorphosed during Damaran (Pan-African 600 ± 200 MYR) orogenic episode.

SEDIMENTS

The Doornpoort sediments consist of alluvial fan Red Bed deposits, which are intercalated with lacustrine, playa, aeolian and mud flat sediments. Palaeocurrent evidence suggests that the fans were derived from the North, prograding into large inland lakes. Two distinct morphological types of alluvial fan are evident; thin, laterally persistent deposits with gradual facies changes; and thick conglomeratic zones with rapid lateral facies variation. Despite their morphological differences, the alluvial fan complexes may be correlated using sedimentological criteria, indicating that they were deposited at the same time. Different fan morphology is thought to be a result of basement uplift and width of the source

zone; broad fan complexes formed in response to regional uplift and unrestricted distributary migration, whereas narrow fans developed due to localized uplift and deposition from a narrow, stable feeder zone.

Lacustrine sediments were predominantly deposited on fluvial deltas, but also contain beach and suspension deposits. Playa sediments are intercalated with alluvial fan conglomerates and sandstones, forming mainly on thick laterally impersistent fans.

The association of alluvial fan Red Beds, aeolian sandstones and possible evaporitic minerals, found in playa and lacustrine sediments, indicate that deposition took place in a semi-arid/arid climate.

DIAGENESIS AND RED BED/COPPER ASSOCIATION

Reduced playa and marginal lacustrine sediments, surrounded by alluvial fan Red Bed deposits, host low grade copper/silver mineralization. The ores are stratiform and are considered to have been emplaced during, or shortly after, sedimentation.

Evidence presented suggests that the metals were derived from mineralized basement rocks, released during Late Proterozoic semi-arid to arid weathering, and transported - initially as copper sulphate - onto the alluvial fans. On contact with neutral or weakly-alkaline aqueous solutions, copper sulphates were probably converted to insoluble basic carbonates ($Cu_3(OH)_2CO_3$) and carried in suspension. Metalliferous waters concentrated in topographic low areas; in playas or at the margins of inland lakes. Particulate basic carbonates were deposited with the suspended sediment load and perhaps reworked by lacustrine palaeocurrents,

forming placer deposits. The metals were fixed during diagenesis as sulphides, formed by the bacterial reduction of basement-derived groundwater sulphate. In the playa sediments of the Witvlei fan complex, copper minerals form part of a paragenetic sequence of diagenetic minerals - namely, albite and calcite. The association of albite and calcite is recognized in surrounding Red Bed sediments and forms part of a larger paragenetic mineral sequence. Conditions during diagenesis are considered alkaline and oxidizing in Red Beds and alkaline and reducing in green playa sediments.

Perhaps the most significant advance made in this thesis, is the recognition of the importance of sedimentological and textural studies on the interpretation of isotopic data, in this type of research. The knowledge of what sedimentary facies each sample is contained in, its relationship with surrounding samples and facies, and the textural form of the sample itself, is believed crucial to any understanding and interpretation of isotopic results.

A P P E N D I C E S

APPENDIX I

STRATIGRAPHY AND NOMENCLATURE

Lithostratigraphic correlation on the southern foreland of the Damaran Orogenic Belt is highly complex due to the large number of volcano-clastic cycles and intrusives, and their often localized extent. In addition, the southern margin of the Damaran belt represents a very large area (over 120,000 sq. km.).

The author has erected a generalized succession encompassing most of the major rock groups present, spanning 2,000 MYR. This succession (Table 1) is derived mainly from the stratigraphic sub-divisions of the South African Geological Survey's Committee for Stratigraphy (1979), and from personal communications with Dr. K. Schalk of the Namibian Geological Survey.

Pre-Doornpoort stratigraphy is shown in Tables 2 and 3, and post-Doornpoort classification in Tables 3 and 4. Tables 3 and 4 also outline the history of the stratigraphic development taken from Schalk (1970) (Table 3) and Toens (1975) (Table 4).

Tables 5 and 6 give more detailed (and recent) divisions, concerning the Doornpoort and Klein Aub Formations, from the areas West of Rehoboth (Klein Aub), around Dordabis, near Maltahöhe and around Witvlei. These are taken from the Geological Survey Stratigraphic Committee (1979).

Table 7 introduces the subdivisions made in this thesis for the Doornpoort, Klein Aub and Ghanzi Formations, based on sedimentological analysis and recognition of sedimentary facies changes. This new classification considers the Klein Aub and Ghanzi Formations to be part of the Doornpoort Formation, which itself has four members divided in terms of geographical position and sedimentary facies:

APPENDIX I (Contd)

1) KLEIN AUB MEMBER

Klein Aub, Witkop, Kagas Noord areas (W. and S. of Rehoboth).

2) DORDABIS MEMBER

East of Dordabis and around the farm Doornpoort.

3) ESKADRON MEMBER

Okasewa, Witvlei and Black Nossob (Kehoro farm) areas.

4) LAKE NGAMI MEMBER

Lake Ngami, Ghanzi and adjoining areas.

Detailed description of the sedimentary facies involved are included in Chapter IV (and III).

APPENDIX I (Contd)

STRATIGRAPHY OF THE SOUTHERN MARGIN OF THE DAMARAN OROGENIC BELT (GENERALIZED)

		MYR		
PAN-AFRICAN OROGENY (600 ± 200 MYR)	NAMA GROUP		(unconformity)	COVER
		c530		
		c750		
	DAMARAN GROUP		BLAUBECKER FORMATION	
			NOSIB FORMATION	
		c850		
	DORDABIS (NUWEDAM) GROUP		KLEIN AUB FORMATION	REHOBOTH MACMATIC ARC
			DOORNPOORT FORMATION	
		c1000		
KIBARAN OROGENY (1100 ± 200 MYR)			GRAUWATER FORMATION	
			UBIB OR NÜCKOPF FORMATION	
	REHOBOTH GROUP	?1600	BILLSTEIN FORMATION	BASEMENT
			DORDABIS FORMATION	
			GAUB VALLEY FORMATION	
			MARIENHOF FORMATION	
EBURNIAN OROGENY (2000 ± 200 MYR)		c1900	ELIM FORMATION	
			CHAMASIS FORMATION	

TABLE 1: APPENDIX I;

Fig. 2.2: A generalized stratigraphic sequence for the Southern Margin of the Damaran Orogenic Belt taken from Schalk (1970) and the South African Committee for Stratigraphy (Geological Survey, 1979). See Appendix I for further details.

APPENDIX I (contd)

LITHOSTRATIGRAPHIC SUBDIVISION OF THE REHOBOTH GROUP, SOUTH WEST AFRICA

Subgroup	Formation	Intrusive Complexes		Lithology
-	-	Kobos granitoid succession (Kobos, Gamsberg, Ganeib, Abendrube granites)	950-1150 MYR	Reddish or greyish granite, occasionally porphyritic, coarse-grained
-	-	Biesiepoort granite	MYR	Greyish, slightly gneissic granite
-	-	Koichas, Tierkolkies, Uitdraai, Neuras, Swartskaap, Koepel, Korabie granites		Reddish or grey, fine-grained granitic rocks, partly granophyric
-	Nauzerus	-	1010 - 1132 MYR.	Acid volcanic rocks and pyroclasts prevailing; interculated quartzite, conglomerate and basic lava
-	Billstein	-		Various types of quartzite, phyllite conglomerate, basic metalava; quartz porphyry
DOORNLEIS	Protea	-		Basic to intermediate lava and pyroclasts prevailing, intercalated quartzite, shale and conglomerate
	Idaberg	-		Reddish and grey quartzite, shale, lenses of limestone; basic to intermediate lava, subordinate acid lava and pyroclasts. Local conglomerate.
-	-	Pikoteel granodiorite and related intrusions	1076 - 1476 MYR	Grey to greenish granodiorite, grading into granite and diorite. Large portions are very coarsely porphyritic.
		Weener tonalite		Fine to coarse-grained tonalite
		Alberta Complex and related intrusions		Basic and ultrabasic intrusions of varying size; basic dykes
	Gaub Valley	-		Quartzite, conglomerate, sericitic phyllite and quartzite, basic and acid metalava
MARIENHOP	Koedoekop	-		Acid volcanic rocks, intercalated basic and intermediate lava, amphibole schist and prominent white quartzite
	Langberg	-	1070-1090 MYRS	Acid volcanic rocks with interbedded basic lava, quartzite and phyllite
	Vetkop	-		White quartzite, sericitic phyllite and quartzite, basic amygdaloidal lava, subordinate acid lava; coarse boulder conglomerate
	Swartmodder	-	1237 MYR	Phyllite, sericite schist, sericitic quartzite, amphibole schist, minor acid volcanic rocks. Prominent succession of acid volcani rocks at base
	Elim	-		Basic lavas, generally altered to grenschist or amphibolite; various types of quartzite, phyllite, magnet quartzite, crystalline limestone which is widely altered to calc-silicate rock; altogether subordinate acid volcanic rocks.

TABLE 2: Stratigraphy of pre-Doornpoort rocks (from Committee for Stratigraphy Geological Survey South Africa.

Table I.—SUBDIVISIONS OF THE "TSUMIS FORMATION"

De Kock (1934)	Gevers (1934)	Geol. Map of S.W.A. (1963)	Martin (1965) Schalk (1961)	Handley (1965)	Present paper
	Not mentioned		Buschmannsklippe tillite	Upper Conglomerate and Quartzite Stage	Blaubeker Formation
Basal Beds of Nama System (The "Duruchaus Series" as developed to the north of Rehoboth was correlated with the "Marienhof Series" of the "Basement Complex")	Upper Dordabis Series (Locally also Quartzite Series of the Damara System)	Kamtsas and Duruchaus Formations in north. Tsumis Formation in south and east	Nosib Formation, including the Kamtsas, Witkoei and Duruchaus Members in north. Tsumis Formation in south and east	Calcareous Quartzite Stage	Nosib Formation, developed in the Kamtsas and the Duruchaus Facies Dikdoorn Beds
				Calcareous Shale Stage	Kagas Beds
				Lower Quartzite and Conglomerate Stage	Eindpaal Beds Leeuberg Beds
	(The Lower Dordabis Series corresponding to the Opdam Formation of Martins' "Dordabis System" was never included in the Tsumis Formation)	Doornpoort Formation, Skumok Formation	Doornpoort Formation, Skumok Formation of the "Dordabis System"		Doornpoort Formation (including "Skumok" porphyry)
Nückopf porphyry				Skumok Formation	Grauwater Formation (including "Nuckopf" porphyry)

Tsumis Formation

Klein Aub Formation

TABLE 3: Taken from Schalk (1970), indicating the complex nomenclature of the Southern Foreland.

Table 1. Details of nomenclature as used in the Klein Aub, Witvlei and Lake N'Gami areas.

NOMENCLATURE USED IN PREVIOUS PUBLICATIONS FOR THE KLEIN AUB AREA														NOMENCLATURE USED IN PRESENT PUBLICATION													
HAUGHEY (1966)			METRES	MARTIN (1965)			METRES	SCHALK (1970)			METRES	KLEIN AUB			METRES	WITVLEI			METRES	BOTSWANA			
NAMA SYSTEM				NAMA SYSTEM				NAMA SYSTEM				NAMA GROUP				NAMA GROUP							
Nama Formation	Upper Quartzite and Conglomerate Stage		900 - 2 800	Tsumis Formation (equivalent of Nosib)				Unnamed Group	Blaubeker Formation		1 000	Nosib GROUP	Tsumis Formation		1 000 - 2 600	GROUP	Tsumis Formation		4 000 +	Group	Upper Ghanzi Formation		---?
	Calcareous Quartzite Stage		900 - 1 400				5 700		Nosib Formation		2 600		Klein Aub Formation	Dikdoorn Member	2 500		Dikdoorn Member	Upper Member	3 000				
	Calcareous Shale Stage		600 - 900						Klein Aub Formation	Dikdoorn Beds	1 500			Augas Members	600 - 1 000			Middle Member	4 000				
	Lower Conglomerate and Quartzite Stage		750 - 1 000							Augas Beds	600 - 980			Tinpaal Member	75 - 200		Nosib GROUP	Witvlei Formation	Lower Member	0 - 3 000	Ghanzi Group	Lower Ghanzi Formation		
										Tinpaal Beds	75 - 200			Leeuberg and Doornpoort Members	750 - 1 000								
										Leeuberg Beds	900												
Nosib Formation				Fordabis System	Doornpoort Formation		3 700		Doornpoort Formation including the Skumok volcanics		1 200	Nosib GROUP	Fordabis Group (or Formation) excluding the Doornpoort sediments. Composed of acid and basic volcanics with associated metasediments. Sub-divided into various Formations locally.								Kgwebe Group (Toteng diabase and Kgwebe porphyry with associated metasediments)				
					Skumok Formation		1 500																		
					Opdam Formation		1 200		Grauwater Formation		300 - 1 500														

TABLE 4: From Toens (1975), introducing his correlation of Namibian and Botswanan rocks of the Doornpoort, Klein Aub and Ghanzi Formation.

LITHOSTRATIGRAPHIC SUBDIVISION OF THE DORDABIS (WITVLEI) GROUP

Area to the west of Rehoboth			Area around Dordabis		
Lithology	Member	Formation	Formation	Member	Lithology
Fine-grained, purplish quartzite, rare gritty layers	Dikdoorn	Klein Aub			-
Shaly quartzite, shale, calcareous shale, lenses of limestone	Kagas				-
Conglomerate, in western part of outcrop also thick quartzite	Eindpaal				-
Reddish and brownish quartzite, basal conglomerate	Leeuberg				-
Red quartzite with interbedded red shale, lenses of conglomerate and of rhyolitic tuffite Non-persisting basal conglomerate with intercalated basalt and quartz-porphyry		Doornpoort			Red quartzite with interbedded red shale; lenses of intraformational conglomerate, lenses of limestone, layers of basalt in lower ptn. of sequence
			Skumok		Alternating rhyolitic rocks and quartzite Conglomerate and breccia interfingering with red quartzite
Acid volcanic rocks, Quartzite with interbedded shale and several intercalations of basic lava	Nauzerus	Grauwater	Opdam	Protea	Basic lava with intercalated quartzite, shale and lenses of conglomerate.
Acid volcanic rocks	Nückopf			Kupferberg	Reddish quartzite, shale, conglomerate, lenses of limestone, shaly quartzite, thin layers of rhyolite, lenses of coarse pyroclasts
					Amygdaloidal basic lava with intercalated quartzite and shale

a) The Skumok succession was formerly believed to represent a volcanic facies of the Doornpoort Formation; it could, however, also be a correlate of the Grauwater Formation. The outcrop is isolated.

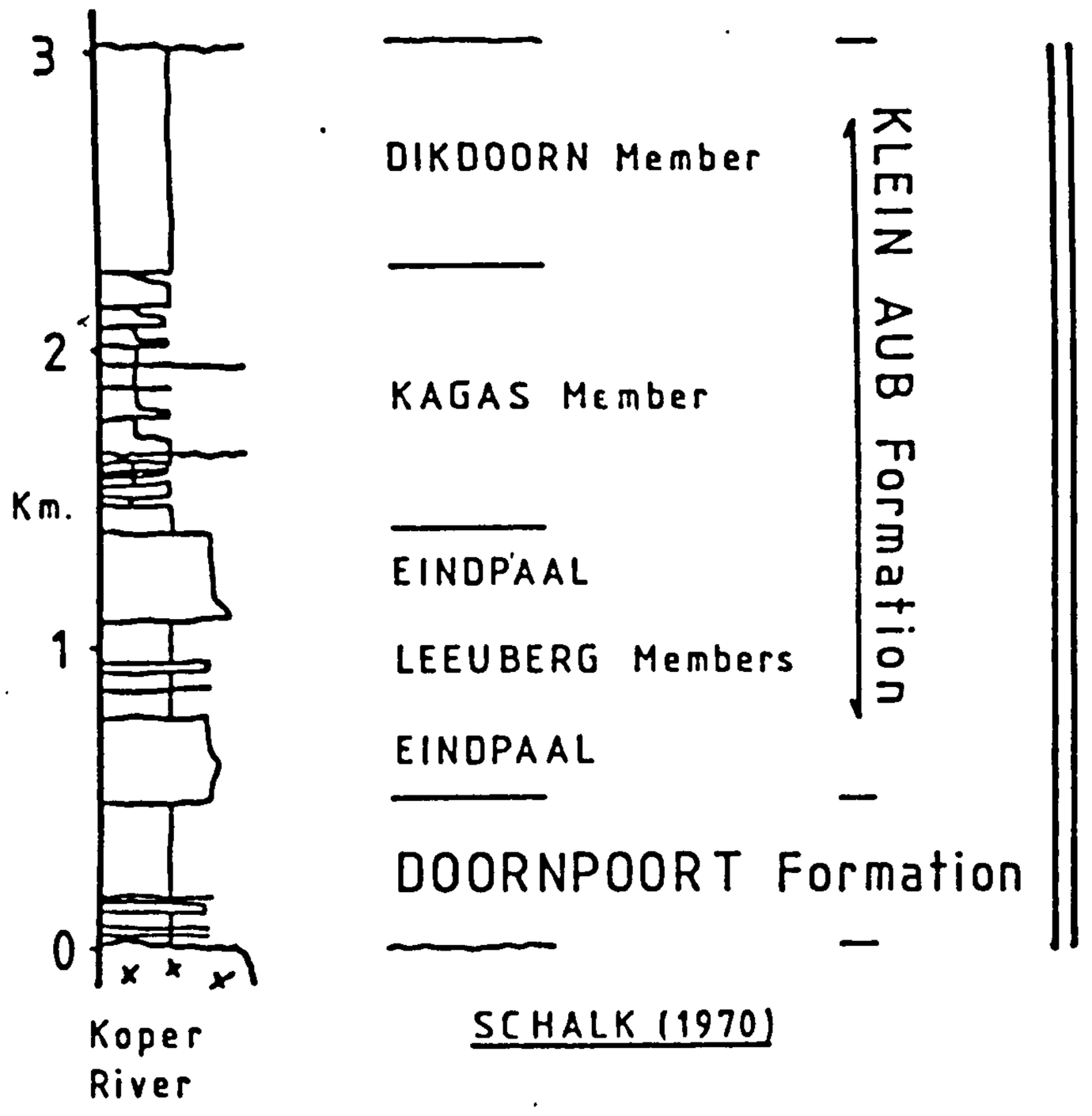
b) The relationship between the Opdam and Grauwater Formations is not known at present. Both successions underlie the Doornpoort Formation unconformably. They could be coeval.

TABLE 5: Doornpoort and pre-Doornpoort stratigraphy Committee for Stratigraphy Geological Survey South Africa.

LITHOSTRATIGRAPHIC SUBDIVISION OF THE NUWEDAM GROUP, SOUTH WEST AFRICA

Group	Formation	Symbol	Member	Lithology	Thickn.(m)	Remarks
1. Area to the south and southwest of Rehoboth.						
NUWEDAM	Kleim Aub		Dikdoorn	Fine-grained, purplish quartzite, rare gritty layers	1500	-
			Kagas	Shale, shaly quartzite, calcareous shale, lenses of limestone, breccia	600	-
			Kindpaal	Conglomerate, interfingering with quartzite	700	-
			Leeuberg	Reddish and brownish quartzite, basal conglomerate	900	-
	UNCONFORMITY					
	Doornpoort		Gravenstein	Red quartzite with interbedded red shale, lenses of conglomerate, lenses of rhyolitic tuffite	1200	-
			Naris	Non-persisting basal conglomerate, with intercalated basalt and rhyolite		
	UNCONFORMITY					
	Grauwater			Reddish and brown quartzite, shale, lenses of rhyolitic tuffite Locally coarse basal conglomerate	600	The Grauwater and Ubib successions are probably correlates
	Ubib			Quartzite, sericitic quartzite, conglomerate, acid volcanic rocks	500+	
	Areb			Quartzite, acid and basic lavas, coarse basal conglomerate	400?	Unconformably below Ubib ?
2. Area between Helmeringhausen and Hauchabfontein, Maltahöhe and Bethanie Districts						
	Auberas			Red quartzite and shale, coarse conglomerate	2600	-
3. Area to the east of Dordabis.						
NUWEDAM	Doornpoort			Red quartzite with minor intercalations of red shale; several flows of basalt in deeper part of succession	up to 3500	The Doornpoort and Eskadron successions are probably coeval; the latter unit displays greater lithological variety.
4. Area to the west and north of Witvlei.						
NUWEDAM	Eskadron			Red quartzite and shale; interbedded layers of calcareous shale and lenses of limestone; conglomerate, sedimentary breccia, brownish quartzite	up to 4500	

TABLE 6: Stratigraphy of the Doornpoort Formation, Committee for Stratigraphy Geological Survey South Africa.



Doornpoort Formation:

1. Klein Aub Member
2. Dordabis Member
3. Eskadron Member
4. Lake Ngami Member

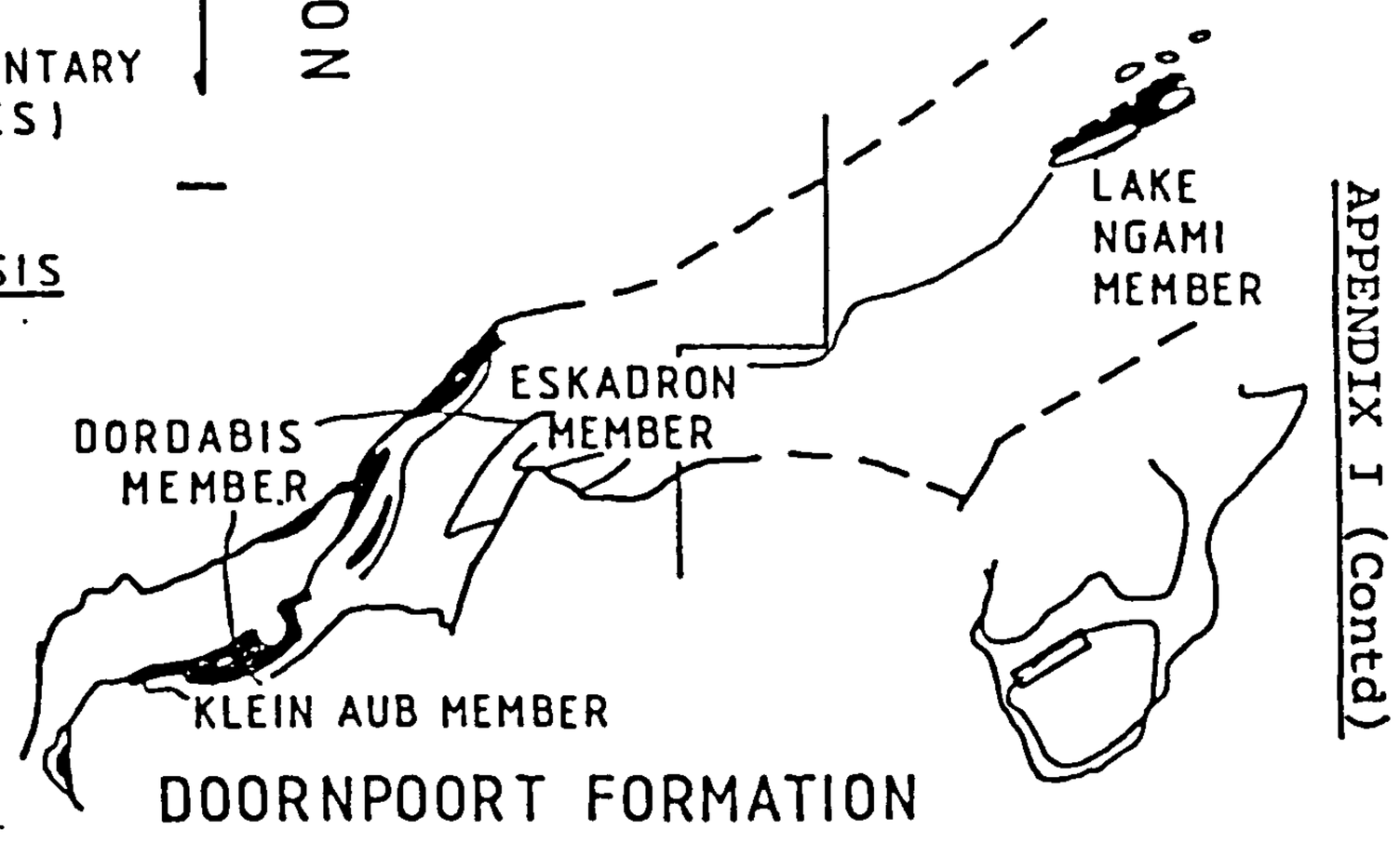


FIG. 2.6: Reclassification of the Doornpoort , Klein Aub and Ghanzi Formations into the DOORNPOORT FORMATION - composed of the Klein Aub, Dordabis, Eskadron and Lake Ngami Members.

TABLE 7 Appendix I.

Appendix II

CHEMISTRY OF THE DOORNPOORT LAVAS

Only four samples of Doornpoort lava were analysed, partly due to the lack of outcrop and partly to the small volume of volcanic material in the sequence. This study is of limited use due to the weathered nature of the samples and the low analytical totals.

Samples LB and LD contain copper in amygdaloidal fills in the form of bornite and malachite. The high copper content of these lavas corresponds to high cobalt, nickel and strontium values, suggestive of magmatic enrichment.

Three basalts (LB, LC and LD) are plotted on a Zr, Ti/100 and Y x 3 (A2(1)) and a Ti against Zr (A2(2)) diagram following Pearce and Cann (1973). The results suggest that the volcanics are bimodal and alkaline-typical of volcanics of late stages of orogeny and of molassic association.

(Sample locations shown in Figure (A2(3)).

MAJOR AND TRACE ELEMENT CHEMICAL ANALYSIS OF FOUR LAVAS FROM THE DOORNPOORT FORMATION

MAJOR ELEMENTS (%)

Element	LA	LB	LC	LD
SiO_2	74.70	48.97	46.94	46.86
Al_2O_3	11.97	11.62	13.69	14.10
$Fe_2O_3(Tot)$	1.96	15.47	9.39	13.75
MgO	0.30	3.69	1.79	5.05
CaO	0.49	10.94	7.97	10.36
Na_2O	5.05	2.77	4.61	3.20
K_2O	3.54	0.32	4.80	0.77
CrO_2	0.00	0.01	0.01	0.01
TiO_2	0.20	3.50	1.86	2.35
P_2O_5	0.02	0.34	0.46	0.23
MnO	0.04	0.15	0.06	0.16
TOTAL %	98.27	97.78	91.58	96.82

TRACE ELEMENTS (ppm)

Element	LA	LB	LC	LD
Cr	-	-	-	-
Co	6	48	28	50
Ni	3	69	77	150
Cu	13	286	20	363
Zn	23	67	59	80
Rb	89	7	107	33
Sr	12	212	116	326
Y	50	41	35	31
Zr	209	196	351	131
Nb	27	19	32	11
Pb	10	-	13	-
Ba	-	-	-	-

LA = Skumok micro-granodiorite - Dordabis
LB = Doornpoort farm - Copper-bearing lava
LC = Amygdaloidal lava - Bitterwater farm - Dordabis
LD = Intermediate lava - Bitterwater farm - Dordabis

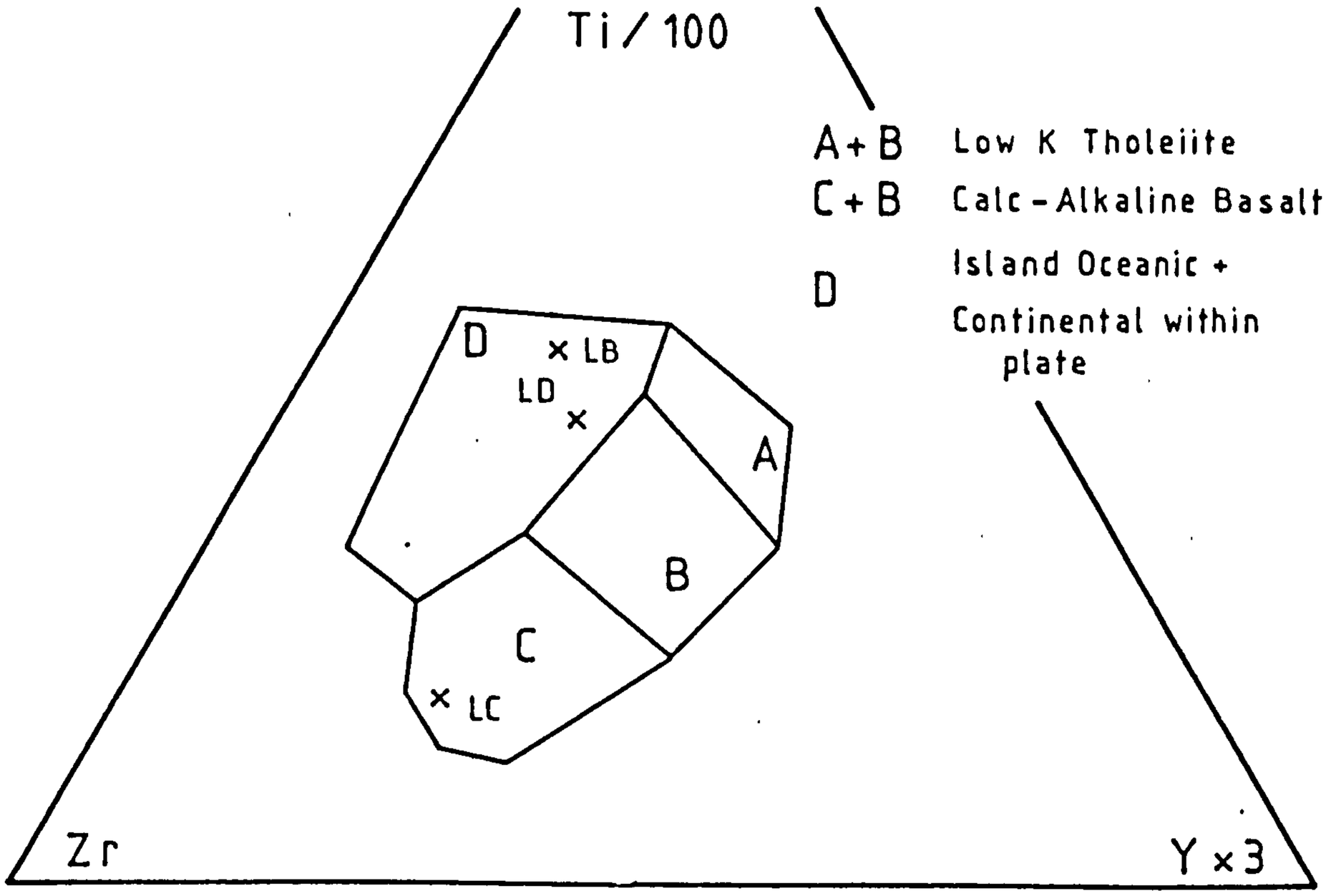


FIG. A2(i): A triangular plot of Zr, Ti/100 and Yx3, after Pearce and Cann (1973) indicating the scatter of the Doornpoort Lava samples.

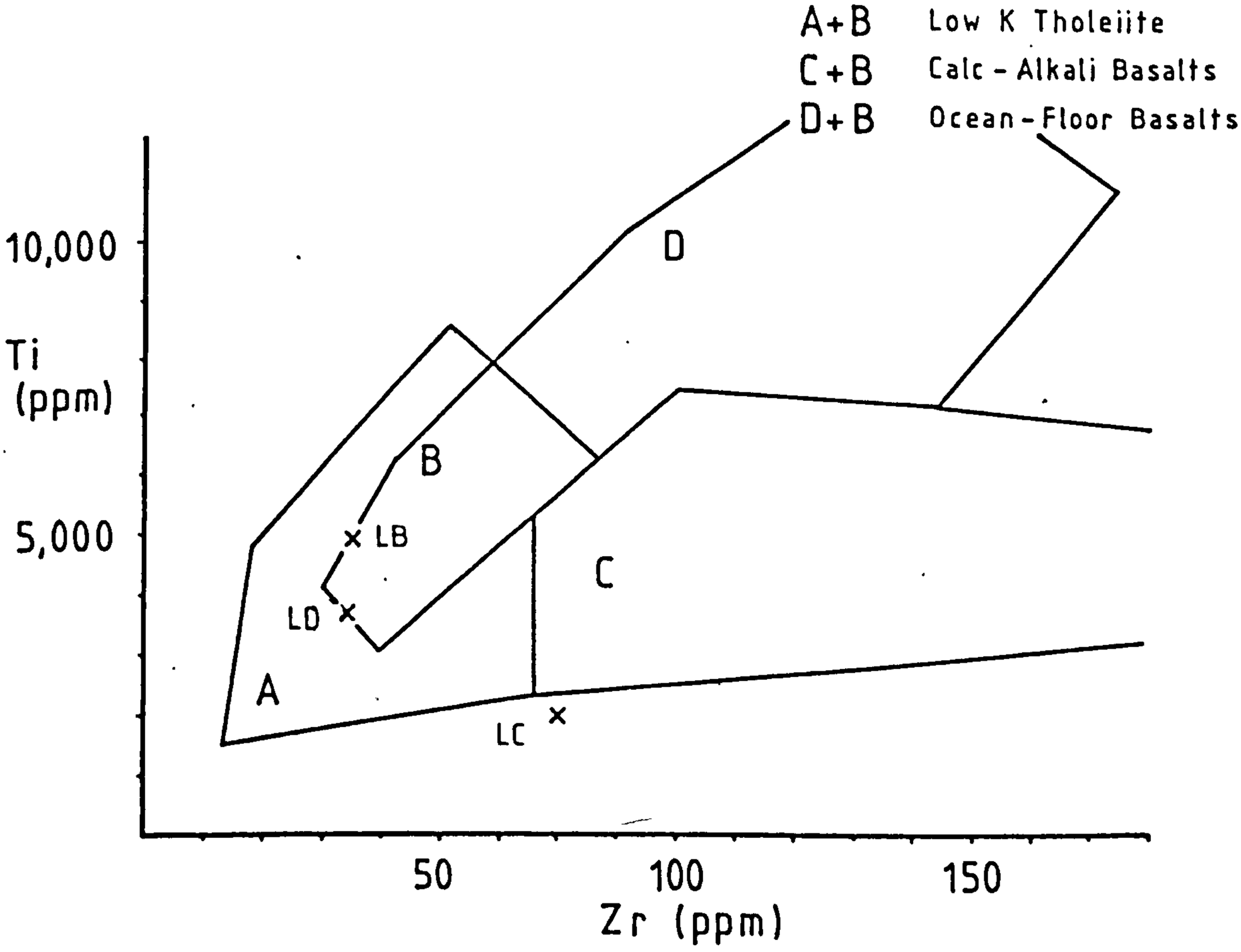


FIG. A2(ii): A plot of Ti against Zr, indicating the scatter of Doornpoort Lava samples relative to the defined Basalt Fields.

APPENDIX II (Contd)

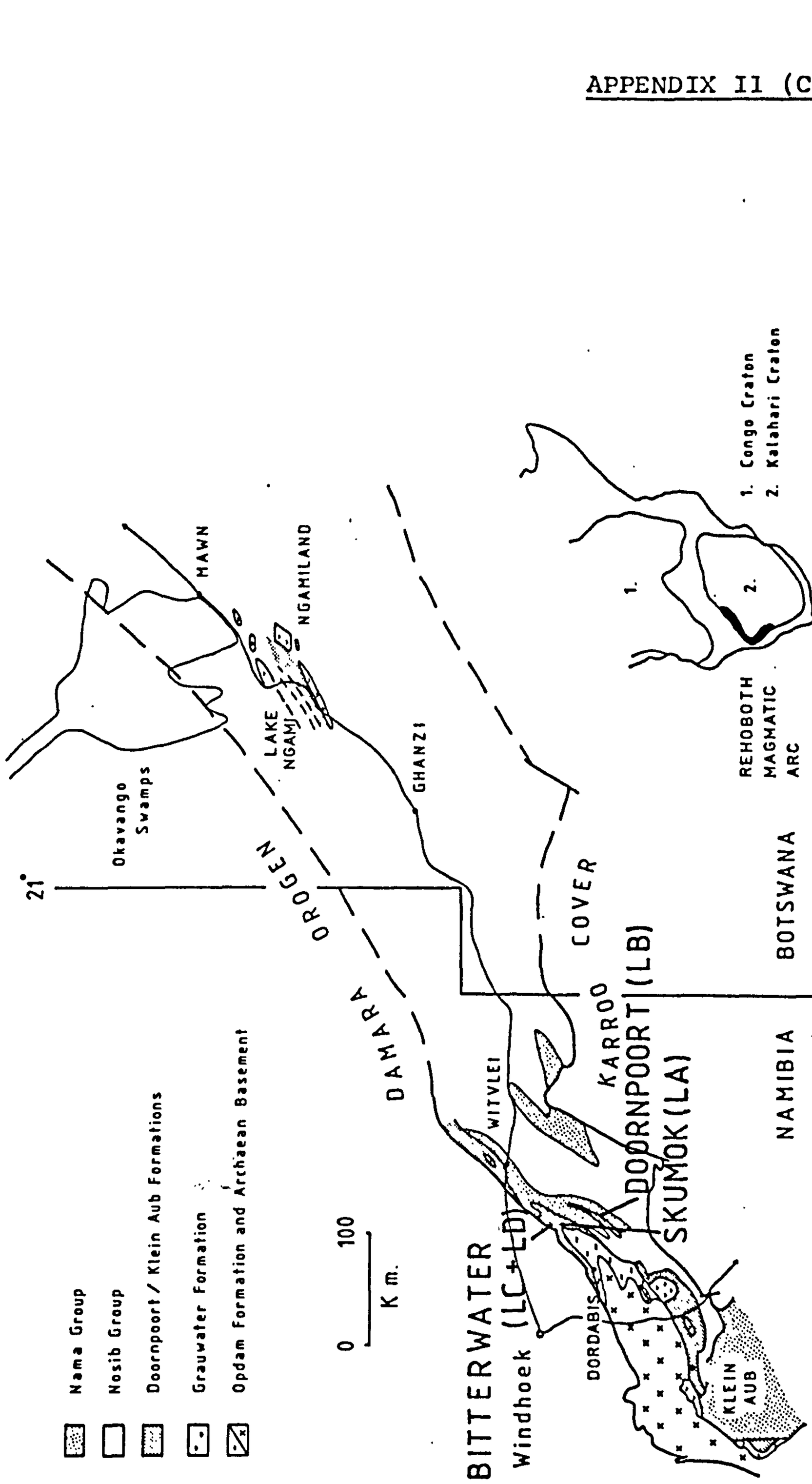


FIGURE A. 2(3)

FIG. 2.1: Precambrian rocks of the Southern Margin of the Damaran Orogen Belt form the Northern arm of the Rehoboth Magmatic Arc, on the NW. margin of the Kalahari Craton.
LOCATION OF ANALYSED DOORNPOORT LAVAS.

APPENDIX III

EXPERIMENTAL METHODS

1. SULPHUR ISOTOPES

Sulphur isotopic analysis was carried out at the Institute of Geological Sciences, Stable Isotope Division, Grey's Inn Road, London, under the supervision of Dr. M. Coleman. For details of the extraction and methods used, the reader is referred to Dr. Coleman.

In this study, sulphide and sulphate (1) samples were separated from their host rock (as far as possible) and ground into a powder. The samples were predominantly monomineralic. Cuprous oxide was added and the samples roasted in a furnace - 1040°C for sulphides and 1100°C for sulphates - for about 20 minutes. The resultant gas contains predominantly SO_2, SO_3, CO_2, H_2O, plus minor quantities of nitrogen and rare gases. SO_3 is converted to SO_2 using a copper furnace (140°C), H_2O removed in an acetone bath and SO_2 separated from CO_2 and other impurities by freezing in an N-pentane trap (Fig. A.31). The resultant SO_2 gas was collected and the yield of SO_2 relative to sample, measured. The extraction method is more clearly outlined by Coleman and Moore (1978) and Robinson and Kasakabe (1975).

The clean gas sample was measured in a double collector Micromass 602-C gas-sourced mass spectrometer against a reference gas. The inlet system was heated to prevent machine fractionation of isotopes. After due machine corrections the sulphur isotopic results were standardized to the Canön Diablo Triolite standard and the origonal $S^{34}S$ value obtained.

2. LEAD ISOTOPES

Lead isotopic analysis was undertaken at Leeds University, under the supervision of Dr. J. Kramers (Zimbabwe University).

Trace lead in sulphides, whole rock lead and lead from galena were analysed; 100-50 mg. of pure sulphide or 0.5 g. of sulphide-bearing sediment were used. Lead from sample galena was diluted before electro-deposition and loading. Extraction of lead from sulphides and whole rocks was accomplished using aquaregia (1 part HNO_3 to 3 parts HCl) and HF + HNO_3, respectively. The samples were evaporated and converted to bromides using bromic acid. The solutions were passed through clean ionic-exchange columns (cleaned with 6M HCl and distilled water) for purification, using bromic acid and 3M HCl and collected by addition of 6M HCl. Samples were then evaporated, converted to perchlorate by adding $HClO_4$ and lead was extracted by electrode-deposition. Sample lead was then loaded on to a single rhenium filament bead with H_3PO_4 and fused in silica gel.

Five aliquots were spiked with Pb. and U. in order to determine sample concentrations of these elements. Uranium measurements were made on solutions which were passed through the ion-exchange columns, converted to the chloride form and added to triple filament beads of tantalum and rhenium in aqueous solution.

More detailed explanations of the methods used are covered in Marlow (1981).

All samples were measured on a solid source V.G. Micromass 30 mass spectrometer and data reduction was completed by an on line Digico micro 16 V. computer. Lead samples were run at 2.2 amps

and 3.5 Gauss and at 4.0 amps and 3.5 Gauss for Uranium.

The Isochron was fitted using a computer program devised by Roddick (Leeds) based along the lines of the work of MacIntyre et al (1966) and York (1969).

Samples	U. ppm	Pb ppm
40980	0.838	48.6
AK10	0.288	2384.5
40996	1.032	678.6
4051	3.760	93.8
KOBOS	0.374	4875.0

3. CARBON AND OXYGEN ISOTOPES

Carbon and oxygen isotope analyses on carbonate samples were carried out at the I.G.S. Stable Isotope Division, Grey's Inn Road, London, under the guidance of Dr. M. Coleman.

Carbonate samples were powdered and converted to CO_2 gas using the extraction method of McCrea (1953) (see Fig. A.32). Carbon dioxide gas was measured relative to a reference gas on a triple collection Micromass 903 gas-sourced mass spectrometer. The results were corrected for machine drift and referenced to the international P.D.B. standard (a Cretaceous belemnite). Both $S^{13}C$ and $S^{18}O$ were measured.

4. X-RAY FLUORESCENCE SPECTROMETRY

Major element analysis was carried out on fused discs. 0.4 g. of rock powder and 2.6 g. of dehydrated Spectroflux 110 of Johnson Matthey Ltd (Li tetraborate based) was heated and mixed in a furnace at 1,000°C for 1/2 hour in a Au-Pt crucible. The weight of any

volatiles lost on combustion was made up by the addition of flux and the mixture melted over a bunsen burner. The molten fluid was poured onto a metal slab and pressed into a disc.

Trace element analysis was done on powdered rock pellets, formed from about 7 g. of rock powder bound by Moviol organic solution, and dried in an oven.

Analyses were carried out on a Philips PW 1400 X-Ray Spectrometer. Majors were run at 60 ma. and 40 kv., whereas traces 30 ma. and 80 kv. Calibration and data processing of results were carried out using programs devised at Leeds by G. Hornung and A. Grey.

5. ELECTRON MICROPROBE

A Joel JXA-SOA wavelength dispersive electron microprobe was used to analyse authigenic and detrital feldspar grains under conditions of 20 kv., 30 nanoamps and a count-time of 40 seconds for each element. Analysis and corrections were completed by an on line Horizon computer based on a correction programme frame (Yakowitz et al, 1973).

The same machine was used for Scanning Electron Microscopy.

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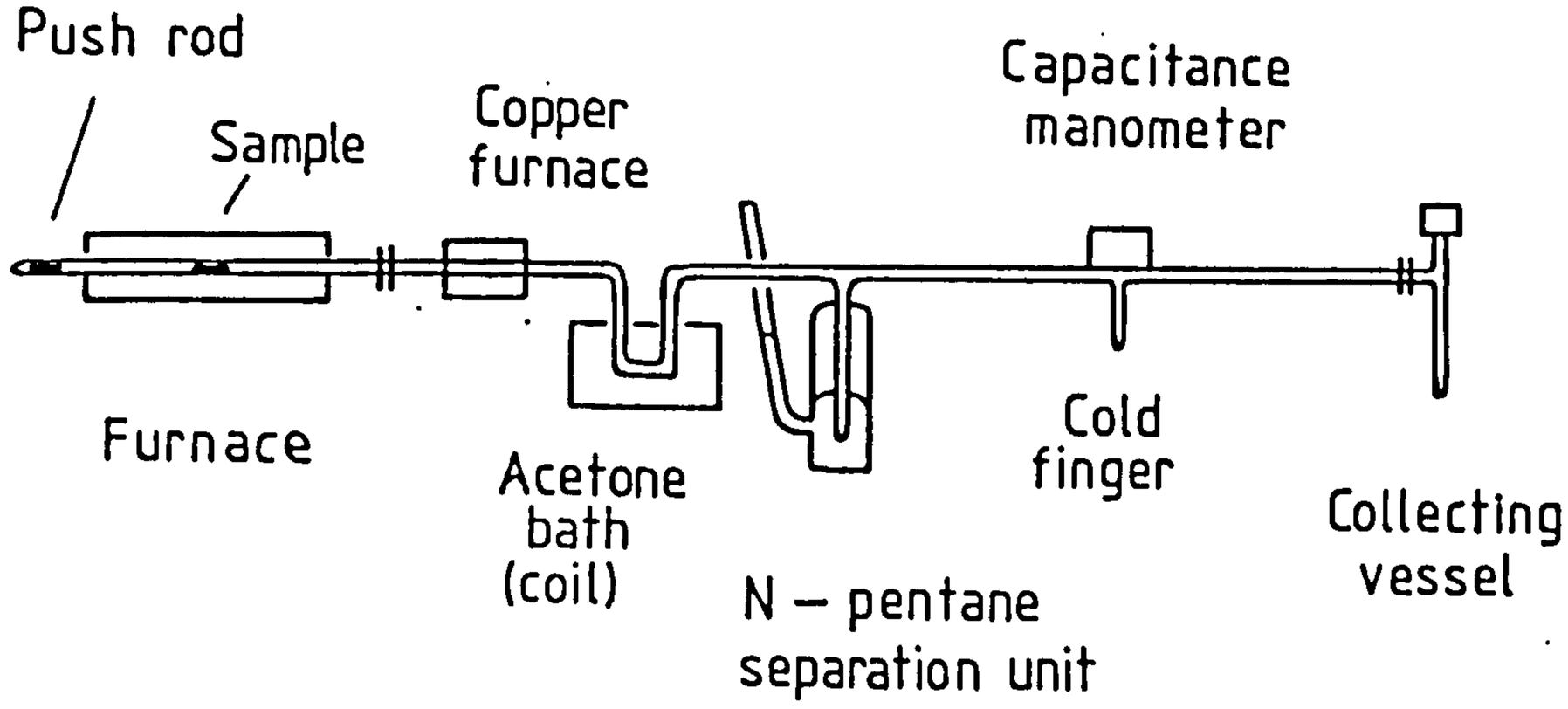
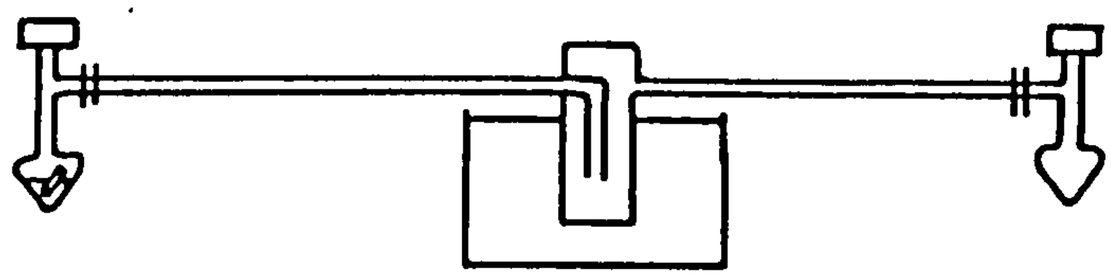
APPENDIX III (Contd)

SULPHUR (Sulphide + sulphate - Sulphur dioxide)



CARBON (Carbonate - Carbon dioxide)



FIGS. A.3(i) & A.3(ii). Extraction lines for sulphides to sulphur dioxide and carbonates to carbon dioxide respectively.

APPENDIX III (Contd)

LOCATION OF ISOTOPIC SAMPLES

1. BASEMENT

a). KLEIN AUB.(Map, 1)

Sulphur. + Lead.

Kobos
Galena - farm Marienhof
AK.10 - farm dymoeb

b). ABBABIS INLIER,(MARLOW,1981). (Map, 2)

Lead.

614
416
415
251

2. SEDIMENTARY

a). KLEIN AUB.(Map, 1)

Sulphur.	Lead.	Carbon/oxygen.
B2HMM	B2HMM	S.R.H.
B3TSM	B3MTS	40524
40980	40980	Vein
4051	4051	
B4Py	B4Py	
A.UN.Py	40996	
Bn	B2CUME	
	B2M1	
	B1UMT	
	B2UM8	

b). KAGAS NOORD.(Map, 1)

Sulphur.	Carbon/oxygen.
K.N.	Pyrite

c). WITVLEI.(Map, 1)

Sulphur.	Carbon/oxygen.
ESK 9	Esk
ESK 54	MAT
OKW 5	
ESK 60	
Gypsum	

d). LAKE NGAMI.(Map, 1)

Sulphur.

ZP 21
ZP 31

APPENDIX III (Contd)

e). CHILEAN SAMPLES.(Map, 3)

Sulphur.

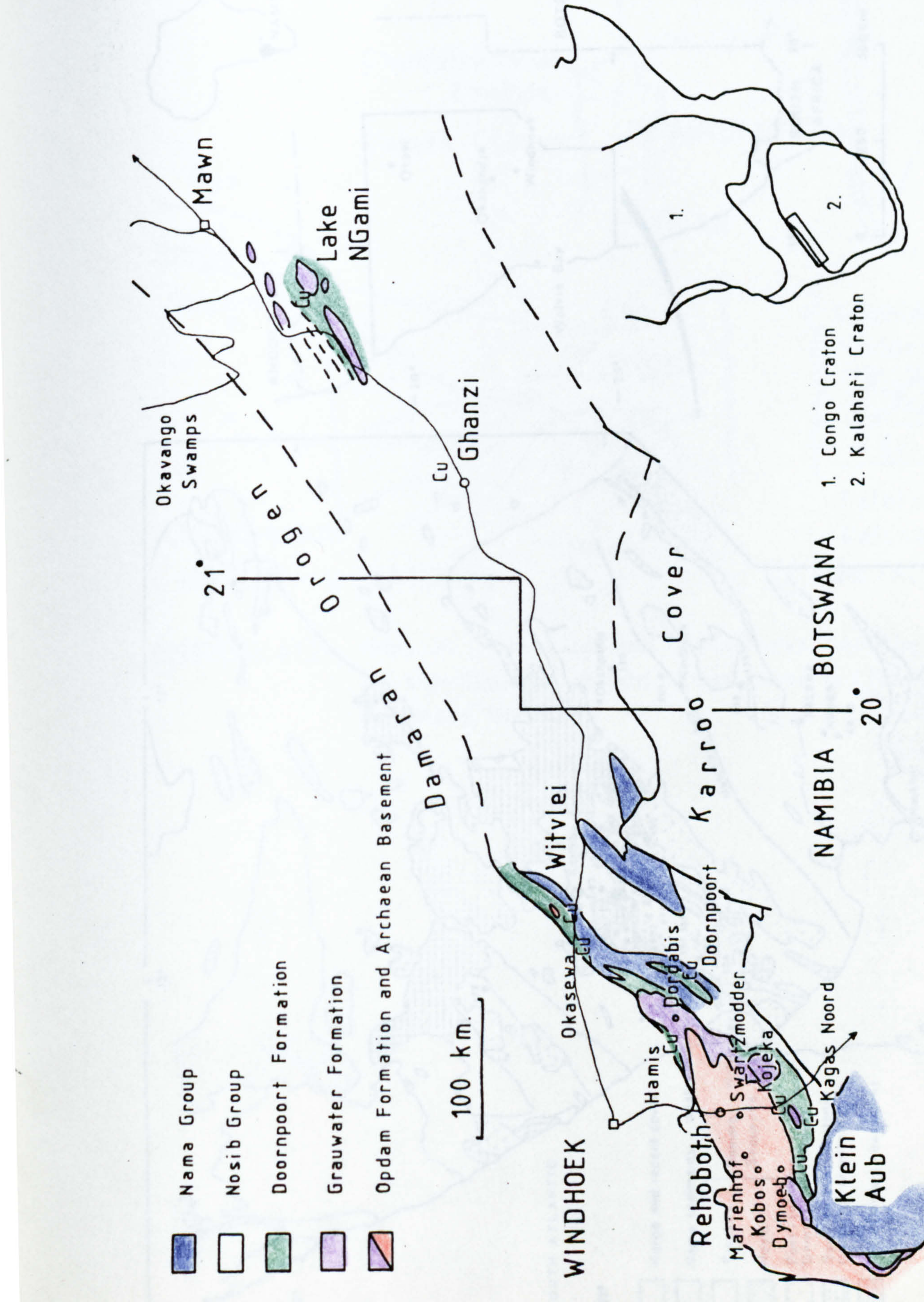
Cps 3
Cps 4
Cs 5
Cs 6
Cos 7
Cos 1
Cgc 2
Cgc 8

****

LEAD ISOTOPIC DATA - Abbabis Inlier (Marlow, 1981)

Sample	206/204	207/204	208/204
614	16.980± .016	15.537± .011	36.845± .028
416	18.055± .003	15.620± .003	39.897± .008
415	18.988± .014	15.753± .013	38.009± .036
251	19.893± .015	15.840± .014	39.685± .036

APPENDIX III (Contd)



APPENDIX III. Map, 1.

Precambrian rocks on the Southern Foreland of the Damaran Orogenic Belt.

APPENDIX III (Contd)

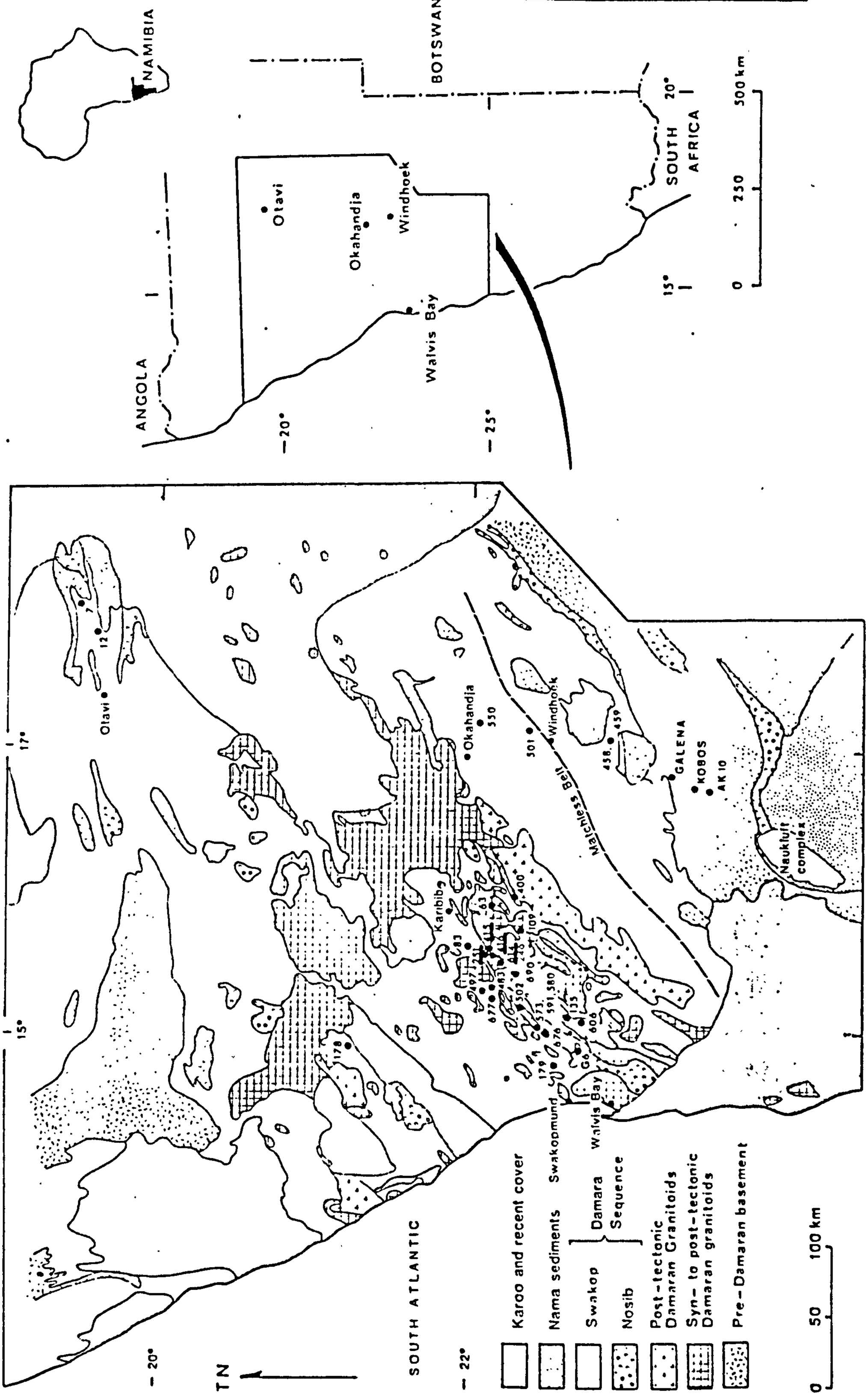
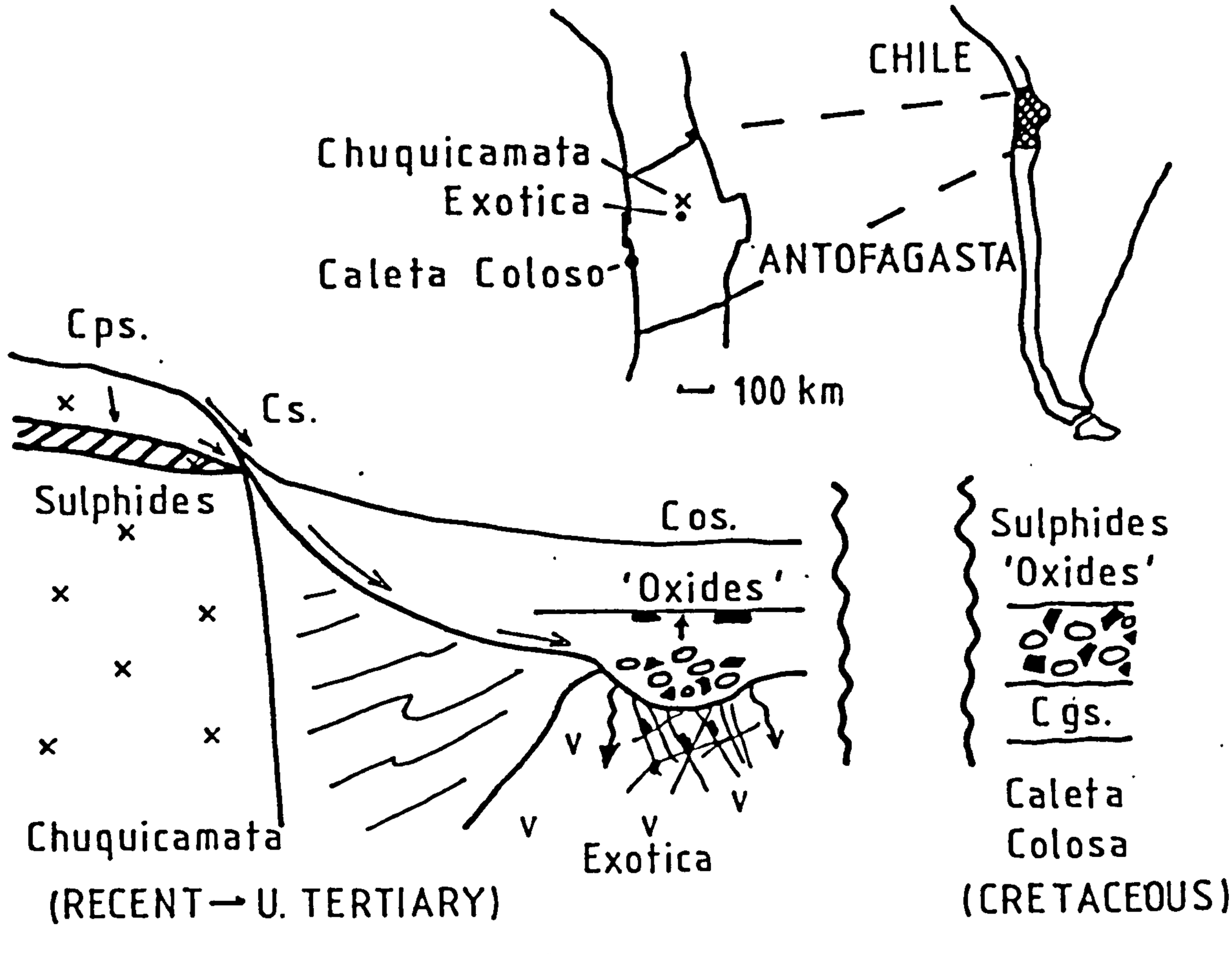


Fig. Map, 2. Location of samples 614,416,415, and251 analysed by MARLOW(1981).

APPENDIX III.

APPENDIX III (Contd)



APPENDIX III. Map, 3. Location and Geological Setting of the Chilean sulphide samples; collected by Harry Clemmey.

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INSTITUTE OF GEOLOGICAL SCIENCES.

GEOCHEMISTRY and PETROLOGY DIVISION.

ISOTOPE GEOLOGY UNIT.

Stable Isotope Report No. 59.

Isotopic studies of sedimentary copper ores, Namibia and Botswana.

P.A. Ruxton, M.L. Coleman, H. Clemmey.

Supported by the NATURAL ENVIRONMENT RESEARCH COUNCIL.

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GENERAL KEY TO LOGS

LITHOLOGIES

Conglomerate

Sandstone

Mudstones/Siltstones

Limestone

Carbonate layers

Carbonate nodules

SEDIMENTARY STRUCTURES

Large-medium scale trough cross-bedding

Low angle plamar cross-stratification

Asymmetrical small scale ripples

Tabular ripple cross-stratification

Oscillation ripples

Symmetrical ripples

Migration ripples

Flaser bedding

Syneresis crack

Desiccation crack

Laminations (or laminites)

Syn-sedimentary deformation

Syn-sedimentary faults

Convolute laminations

GENERAL SYMBOLS

Mud-flakes

Vugs (voids)

PALAEOCURRENTS

Trough cross-stratification

Small scale cross-stratification (ripples..)

Cu Copper mineralization

Erosive base

Flat boundary

Scales

Hammer - head = 180mm
- shaft = 360mm

Clinometer = 100mm

Hand-lense = 40mm

Grain Size

mudstone
siltstone
fine sandstone
medium sandstone
coarse sandstone
conglomerate

m s fs ms cs cong

ISOTOPE GEOLOGY UNIT

Stable Isotope Report No.59

Isotopic studies of sedimentary copper ores, Namibia and Botswana

P.A. Ruxton, M.L. Coleman and H. Clemmey

Analyses performed by P.A. Ruxton

Project application 09/0980: Dr. H. Clemmey,
University of Leeds

February 1981

The analytical and other data presented in this report are made available on the understanding that extracts or references will not be published in any form without the prior approval of the authors and the Officer in Charge, Isotope Geology Unit.

ISOTOPIC STUDIES OF SEDIMENTARY COPPER ORES, NAMIBIA AND BOTSWANA

INTRODUCTION

Stratabound copper ores occur within a molassic sedimentary sequence on the Southern Foreland of the Damaran Orogenic Belt. The sediments rest unconformably on a copper-rich Kibaran basement, composed of metamorphic and granitic rocks. Deposition commenced with a series of alluvial fan deposits which were partially reworked by a northerly transgressing sea. The sediments are Late Proterozoic (1,100 – 750 M.Y.) in age.

Sedimentary copper/silver deposits lie in reduced playa lacustrine and tidally reworked alluvial sediments, in several localities throughout the region. The ores reach economic grade at Klein Aub Copper Mine.

Sulphur and carbon isotope studies were made to elucidate the source of mineralization and the mode of copper fixation within the sediments.

AIMS

Using sedimentological, textural and lead isotopic data, a sedimentary model for ore genesis has been formulated for these Namibian ores. The model involves the release of copper during weathering of a cupriferous basement; transport of copper in an alluvial system; and its concentration and deposition in lacustrine and shallow marine sediments. Sulphur and carbon isotope compositions were studied to indicate the source of the mineralization, its mode of transport within the fluvial system, and its method of fixation in reduced sediments.

In addition sulphur isotopic analysis of Chilean copper porphyry sulphides, related groundwater, precipitates and ore deposits were studied in order to understand the effects of weathering on copper deposits. These samples vary in age from Cretaceous to Recent.

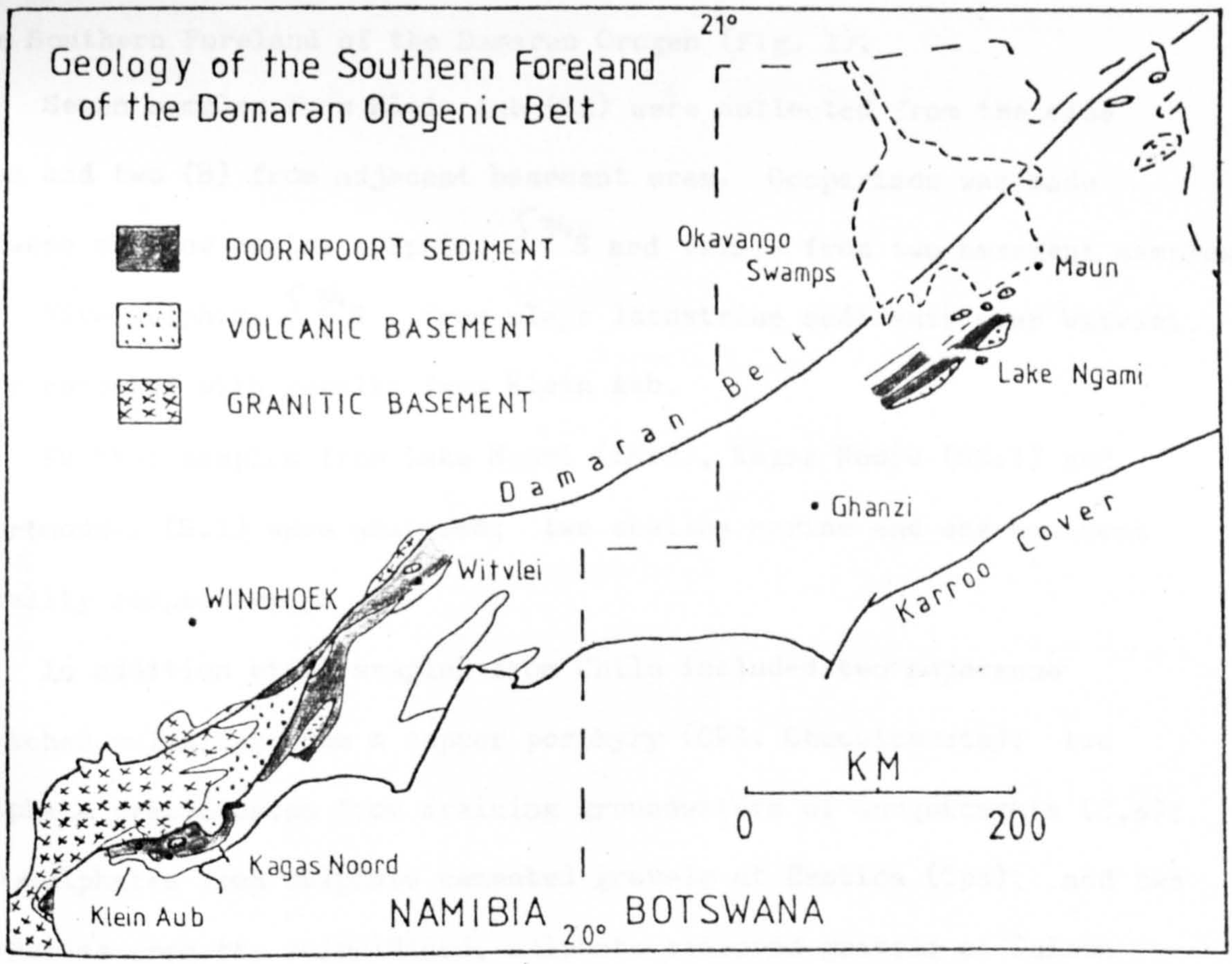


FIG 1 Basement and sediment distribution on the Southern Foreland of the Damaran Orogenic Belt

SULPHUR ISOTOPES

SAMPLE DESCRIPTION

Samples were chosen from basement and sedimentary sulphides throughout the Southern Foreland of the Damaran Orogen (Fig. 1).

Seven samples from Klein Aub (KA) were collected from the mine area and two (B) from adjacent basement ores. Comparison was made between shallow marine sulphide $\delta^{34}S$ and values from two basement samples.

Five sulphide $\delta^{34}S$ from playa lacustrine sediments near Witvlei, were compared with results from Klein Aub.

Further samples from Lake Ngami (LN:2), Kagas Noord (KN:1) and Swartmodder (S.1) were analysed; two shallow marine and one basement locality respectively.

In addition eight samples from Chile included two supergene enriched sulphides from a copper porphyry (CPS. Chuquicamata); two sulphate precipitates from draining groundwaters of Chuquicamata (C,s); two sulphates from sulphate cemented gravels at Exotica (Cps); and two sulphides from the sulphidized, sulphate cemented gravels at Caleta Coloso (CGc). These samples trace the passage of copper movement from weathered copper porphyry rocks into groundwater precipitates and on into copper cemented gravels (Fig. 2). This Phanerozoic example of copper movement may provide clues as to the transport of copper during development of copper ores in the Late Proterozoic.

TABLE 1. NAMIBIAN ISOTOPIC RESULTS

BASEMENT

No.	Sample	Description	$\delta^{34}S$ CDT °/oo
B1	Kobos	Volcanogenic pyrite	+ 0.2 °/oo
B2	Galena	Vein Galena	- 0.8 °/oo
S	Swart.	Metasedimentary chalcopyrite	+ 5.3 °/oo

KLEIN AUB

No.	Sample	Description	$\delta^{34}S$ CDT °/oo
KA1	B2 HM M	Chalcocite/Green silt	- 35.2 °/oo
KA2	B3 TS M	Chalcocite/Green sandstone	- 34.5 °/oo
KA3	40980	Chalcocite/Green silt	- 21.4 °/oo
KA4	4051	Chalcopyrite/vein	- 28.9 °/oo
KA5	Bn	Bornite/replace pyrite cubes	- 20.9 °/oo
KA6	B4 Py	Pyrite/cubes	- 30.4 °/oo
KA7	A. UN. Py	Pyrite/cubes	- 27.4 °/oo

WITVLEI

No.	Sample	Description	$\delta^{34}S$ CDT °/oo
W1	Esk 9	Bornite/disseminated	- 22.2 °/oo
W2	Esk 54	Bornite/chalcocite/green silt	- 11.8 °/oo
W3	OKWS	Chalcopyrite/red + green lanc.	- 8.9 °/oo
W4	ESK 60	Chalcopyrite/vein	- 17.4 °/oo
WS	Gypsum	Gypsum/nodular	- 16.0 °/oo

OTHER

No.	Sample	Description	$\delta^{34}S$ CDT °/oo
KN	K.N.	Pyrite cubes Kagas Noord	- 20.3 °/oo
LN1	ZP21	Bornite/strataform vein	- 25.5 °/oo
LN2	ZP31	Chalcopyrite/strataform vein	- 37.9 °/oo

(All values ± 0.5 °/oo)

NAMIBIAN RESULTS

(A) KLEIN AUB

Basement Sulphides

Chalcopyrite from the volcanogenic massive sulphide ores of Kobos Mine and galena from vein deposits on Marrienhof farm were analysed. From field studies both deposits had magmatic sources. $\delta^{34}S$ values of about .0 °/oo substantiate this (Table 1).

Shallow Marine Sulphides

$\delta^{34}S$ values of copper and iron sulphides from the shallow marine ores and rocks of Klein Aub are negative between - 20°/oo and - 40 °/oo The data suggest that these sulphides formed by bacterial reduction of sulphate in an open system. Since conditions appear "normal" at Klein Aub, and "normal" fractionation of $\delta^{34}S$ values by bacteria in an open system leads to a change in -20 °/oo to -40 °/oo the original isotopic value of the sulphate was about 0 °/oo. Two sulphide samples from the adjacent basement at Klein Aub give $\delta^{34}S$ values of about 0 °/oo.

Closed system fractionation would result in a spread of values from the source to a value of - 20°/oo. These results may be interpreted as having a source of - 20 °/oo and bacterial fractionation in a closed system having occurred. This however is very unlikely since no source material with a $\delta^{34}S$ value of - 20 °/oo has been detected.

This evidence strongly suggests that the sulphur within the shallow marine sulphides was derived from basement sources. A model whereby weathering of basement sulphides produces sulphate of similar $\delta^{34}S$ value which is transported in solution and reduced within these sediments is proposed.

One problem arises from the results. The sulphides occur in tidal sediments and must therefore have been in contact with sea water. Yet the sulphides have $\partial^{34}S$ values from basement derived sulphate and not sea water sulphate (+ 30 °/oo in the Proterozoic Claypool et al. 1980). Sedimentological studies reveal the answer. The sedimentary sequence is dominated by alluvial deposition. Tidal/intertidal/subtidal reworking occurred within restricted

horizons during deposition predominantly effecting the finer alluvial sediments. This resulted in the development of argillite bands, usually between one and two metres thick. These bands are separated by variable thicknesses of medium grained fluvial sandstones, on average fifteen metres thick. During deposition the tidal sediments contained interstitial sea water. However shortly after, fluvial sedimentation resumed and continental ground waters percolated in the tidal deposits, flushing out the sea water and reducing to a negligible extent the amount of sea water sulphate.

Textural studies on these copper and iron sulphides indicate post-depositional formation. The sulphides occur dominantly in pore spaces and cement detrital grains. Sulphide formation is therefore not directly synchronous with sediment deposition. The sulphides formed during diagenesis, after sea water sulphate was flushed from the system.

Other shallow marine sulphate deposits; Lake Ngami and Kagas Noord, have similar geological settings and show similar $\delta^{34}S$ values to those of Klein Aub.

(B) WITVLEI

Playa lake sulphides

$\delta^{34}S$ values from Witvlei playa lake sulphides range between -8.9 °/oo and -22.2 °/oo (Table 1). These values result from bacterial reduction of sulphate. Reduction could have occurred in an open system with an initial $\delta^{34}S$ value of + 10 °/oo or in a closed system from a value of around 0 °/oo. The lack of sulphide samples from the adjacent basement hinders interpretation of these results. The source of sulphur appears to lie between a sea water sulphate value of + 25 °/oo and an inferred basement value of 0 °/oo.

However it is known that the playa lake sediments occur on the edge of alluvial fan conglomerate facies which lie on basement rocks. There is no evidence for any marine activity within the palaeodrainage path of the alluvial fan between basement and playa lake nor within metasediments from the basement. The source of sulphur can therefore be deduced to be primary

basement sulphides (0.°/oo — +5.3 °/oo Table 1). The spread of $\delta^{34}S$ values found within the sulphide ores reflects a closed system of fractionation.

Evidence for organic matter within the playas is variable and probably reflects the original distribution of bacteria. Any variation in the availability of sulphate for reduction would result in variable stages of reaction completion giving a spread of $\delta^{34}S$ values. Thus the distribution of organic matter within the playa sediments reflects a closed system of kinetic fractionation.

(C) CHILEAN RESULTS

Weathering of primary porphyry copper sulphides at Chuquicamata, and the downward percolation of the resultant fluids, led to the development of a supergene sulphide blanket immediately below the water table, within the porphyry. Lateral fluid movement out of the porphyry produced various precipitates and cements within surrounding gravels and bedrock (Robinson 1978, Clemmey pers. comm) Draining surface waters contain precipitates of iron and aluminium, gypsum and copper sulphate. Sub-surface movement of large volumes of supergene fluid has led to the development of huge areas of copper cemented gravels and secondary basement mineralization. At Exotica the resultant cements and precipitates from the supergene fluids of Chuquicamata have formed an economic ore body. (Clemmey pers. comm.). An analogous deposit at Caleta Coloso contains copper oxide and sulphide cements in red bed gravels (Summary Fig. 2).

~~Sulphur isotopic measurements from the supergene sulphides of Chuquicamata have formed an economic ore body (Clemmey pers. comm.). An analogous deposit at Caleta Coloso contains copper oxide and sulphide cements in red bed gravels (Summary Fig. 2).~~

Sulphur isotopic measurements from the supergene sulphides of Chuquicamata, the draining surface water precipitates, copper oxides from Exotica and the equivalent sulphides from Caleta Coloso are presented in

TABLE 2. CHILEAN ISOTOPE RESULTS

Sample		Description	$\delta^{34}S$ °/oo
C (Ps)	(3)	Supergene chalcocite	+ 1.3 °/oo
C (Ps)	(4)	Supergene chalcocite/Primary? pyrite and chalcopyrite	- 6.8 °/oo
CS	(5)	Copper Sulphate precipitate	- 3.6 °/oo
Cs	(6)	Gypsum precipitate	- 0.6 °/oo
Cos	(1)	Gypsum cemented gravel	- 2.5 °/oo
Cos	(7)	Gypsum plus Copper Sulphate cement from oriented gravel	- 3.5 °/oo
C Gc	(2)	Sulphide from cemented gravel	- 7.5 °/oo
C Gc	(8)	Sulphide from cemented gravel	- 3.6 °/oo

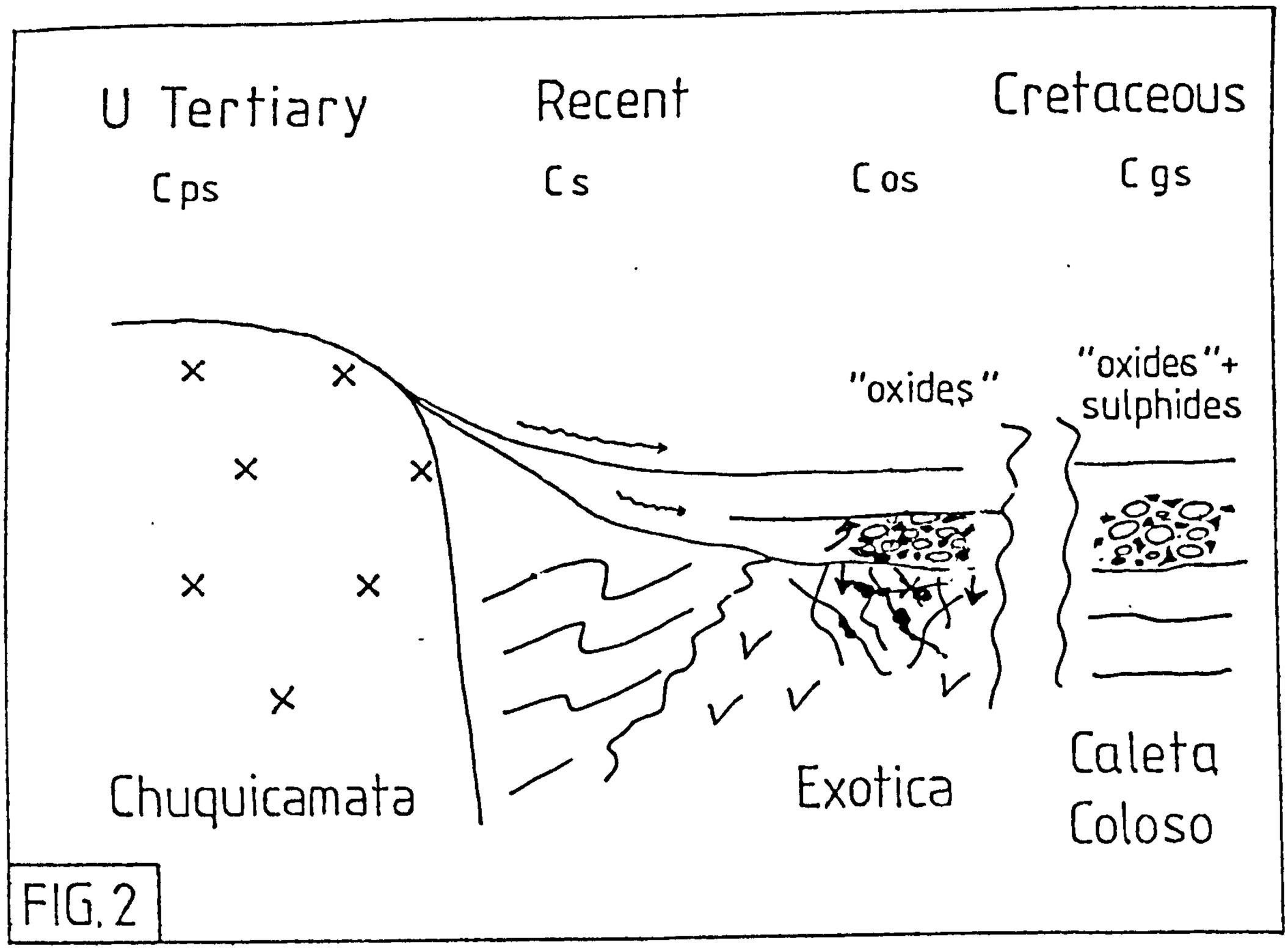

U Tertiary
Recent
Cretaceous
Cps
Cs
Cos
Cgs
"oxides"
"oxides"+
sulphides
Chuquicamata
Exotica
Caleta
Coloso

FIG. 2

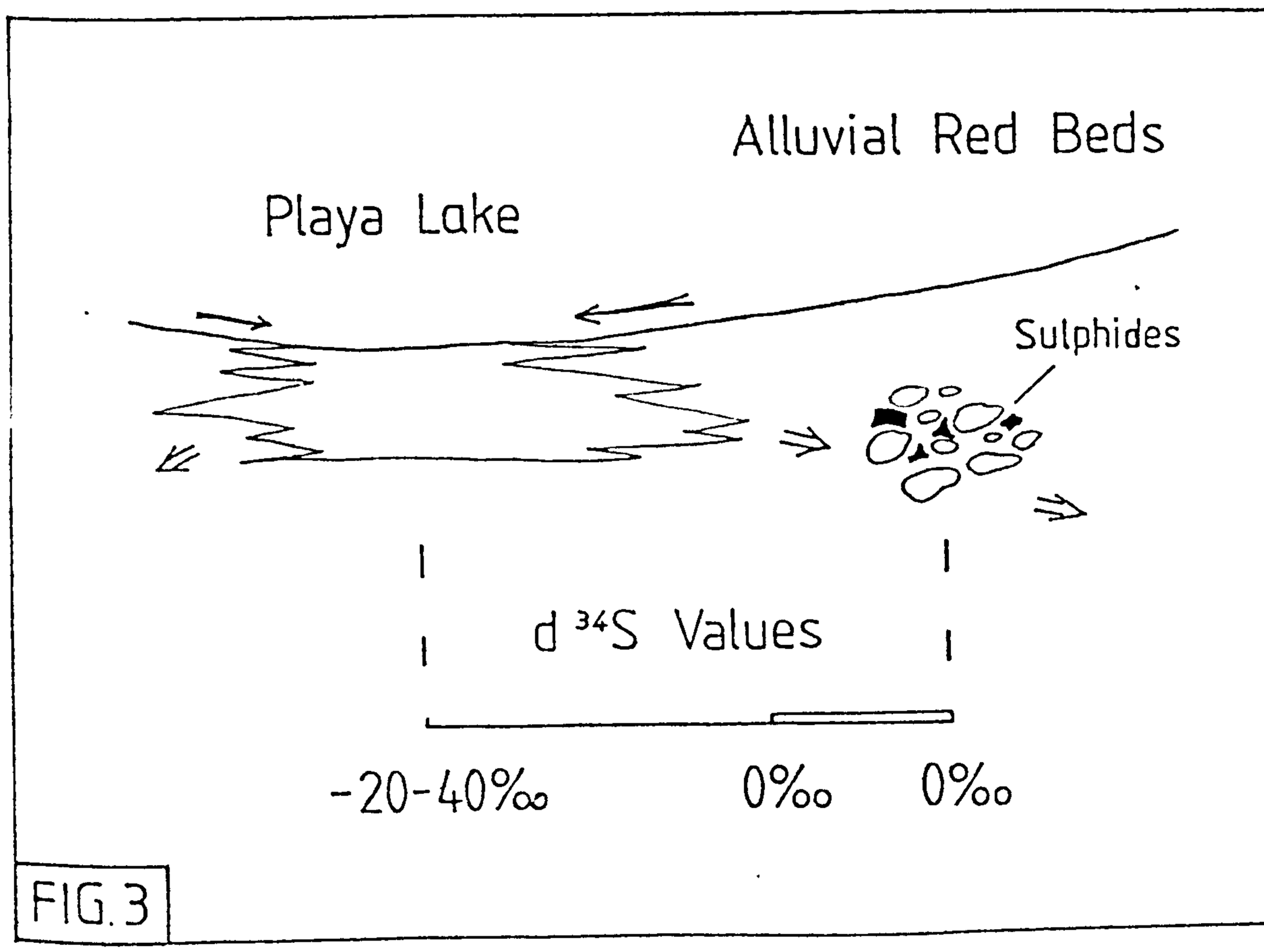

Alluvial Red Beds
Playa Lake
Sulphides
d ³⁴S Values
-20-40‰
0‰
0‰

FIG. 3

The results show little or no fractionation of sulphur isotopes through the cycle from supergene to cemented sulphides. All $\delta^{34}S$ values remain between +1.3 and -7.5°/oo. Initial supergene sulphide values +1.3°/oo and -6.8°/oo provide the range within all but one (a Caleta Coloso cemented sulphide) sample fall. During the oxidation of sulphide to sulphate little isotopic fractionation is expected (Nakai & Jensen, 1964). Very little occurs during the precipitation of sulphate from solution (Thode et al. 1961). However during reduction of sulphate to sulphide at Caleta Coloso fractionation would have occurred. The low $\delta^{34}S$ values from these sulphides indicates that fractionation would have had to occur in a closed system; in other words with a completed reaction involving all the sulphur present. These sulphides occur as small pockets within copper oxide cemented Red Bed gravels. There is little or no organic matter present for the reduction. The model envisaged involves the migration of reducir groundwaters from playa lacustrine sediments within the sequence, into the surrounding Red Beds. The fluid encountered pockets of sulphate which were totally reduced forming sulphides of copper and iron with $\delta^{34}S$ values of the original sulphate (Fig. 3).

4) Comparison between Playa and Red Bed Sulphides (Witvlei and Chilean)

The Chilean sulphide formation is in some ways analogous with the Witvlei playa lacustrine deposits. On Red Bed alluvial fans groundwaters drain into topographically low areas. Lacustrine sediments result and salts plus organic matter are concentrated there. Sulphate is concentrated in central playa lake areas. Organic growth is more abundant in central areas also but may be variable depending on the micro-environments present. The reduction of sulphate to sulphide will produce variable $\delta^{34}S$ values, depending upon the relative abundances of sulphate and organics In central playa areas sulphate concentration is high relative to organics (generally) and open system isotopic fractionation results in the concentration of ^{32}S

in sulphides. Towards the edge of the playas the amount of organic matter may exceed that of sulphate and closed system fractionation effects results in a spread of $\delta^{34}S$ values moving towards the original value of the sulphate. Thus ideally there is a zonation of $\delta^{34}S$ values from depleted to original when moving from central to marginal playa sediments (Fig.3+4). Reducing fluids migrating into adjacent Red Bed sandstones and conglomerates totally reduce sulphate pockets to sulphide providing original sulphate $\delta^{34}S$ values.

Sulphur isotopic results from Witvlei show this zonation of $\delta^{34}S$ values within playa sediments (Fig. 4) although there are far too few analyses.

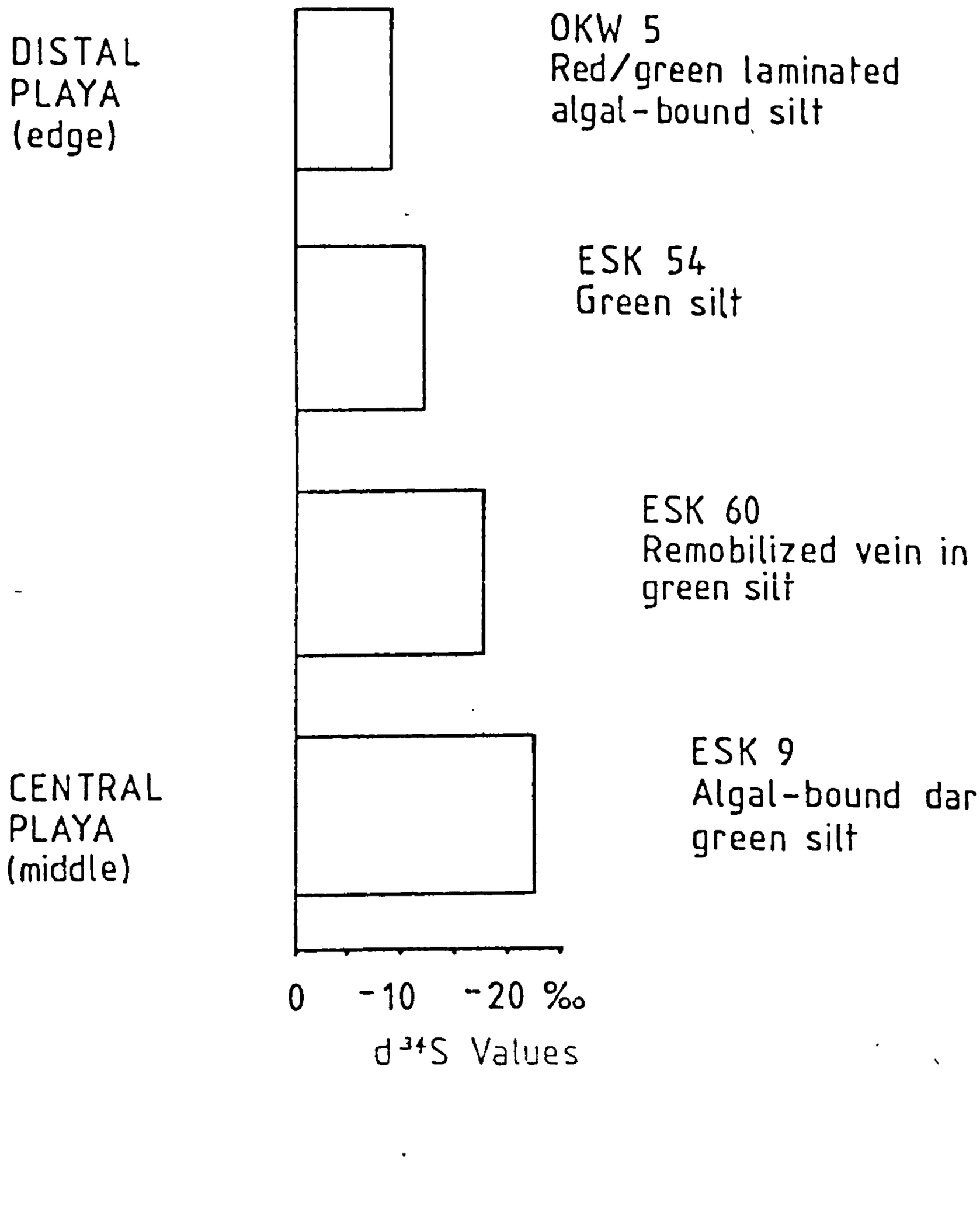


FIG. 4 Indication of sulphur isotopic zonation within playa lake sediments : Witvlei.

TABLE 3. CARBON/OXYGEN ISOTOPE RESULTS

No.	Sample		$\delta^{13}C$ P.D.B.	$\delta^{18}O$ P.D.B.
KC1	S.R.H.	Carbonate nodules in a possible sabkha replaced horizon.	-1.4°/oo	-19.35°/oo
KC2	40524	Carbonate cement - replacive associated with sulphides	-2.0°/oo	-19.18°/oo
KC3	Vein	Vein Carbonate associated hematite and feldspars	-1.98°/oo	-18.43
KN1	Pyrite	Carbonate associated with pyrite (KN)	-2.1°/oo	-18.97
WC	ESK	Pink carbonate from playa lake	+1.9°/oo	-16.47
WC2	MAT	Replaced gypsum-mat carbonate	+1.2°/oo	-15.67°/oo

(All values ± 0.05 °/oo)

ON AND OXYGEN ISOTOPES

AMPLE DESCRIPTION

Two marine and one vein carbonate samples from Klein Aub were analysed. Sample KC1 (S.R.H.) forms part of a sequence of laminar and nodular carbonates, which may be replaced sabkha concretions. KC1 (40524) is from carbonate cemented green laminated silts within a copper bearing horizon.

Two playa lacustrine carbonates were studied, WC1 pink layered and nodular carbonate and WC2 carbonate from a replaced gypsum mat horizon.

In addition one sample from Kagas Noord was analysed.

RESULTS

Carbonates from Klein Aub and Kagas Noord give tyical marine $\delta^{13}C$ values and lie within shallow sea sediments (Table 3, Fig. 5). Precipitation of carbonate was early diagenetic filling pore spaces and replacing detrital grains. Sample KC3 has remobilized calcite $\delta^{13}C$ values.

Although the oxygen values are very much lighter than those more recent carbonates they are not unlike other Precambrian data (Schidlowski et al., 1975).

Playa lacustrine carbonates from Witvlei give slightly heavier $\delta^{13}C$ but the oxygen isotopic values too are heavier than those of Klein Aub and Kagas Noord. These are interpreted as evaporative carbonates. Pseudomorphs of calcite after gypsum support this evaporitic origin (WC 2).

The source of carbon in these sediments was either from sea water or was derived from marine carbonates within the basement.

SULPHUR AND CARBON ISOTOPIC RESULTS

Sulphur isotopes from sulphides and carbon isotopes from carbonates within the same rock units were analysed and interpreted in the hope of discovering which formed first.

Sulphur from both shallow marine and lucustrine sulphides probably originated from bacterial reduction of basement-derived sulphate. Associated carbonate was derived from marine carbonate or evaporitic carbonate sources and showed no evidence of organic derived carbon typical of sulphate reduction.

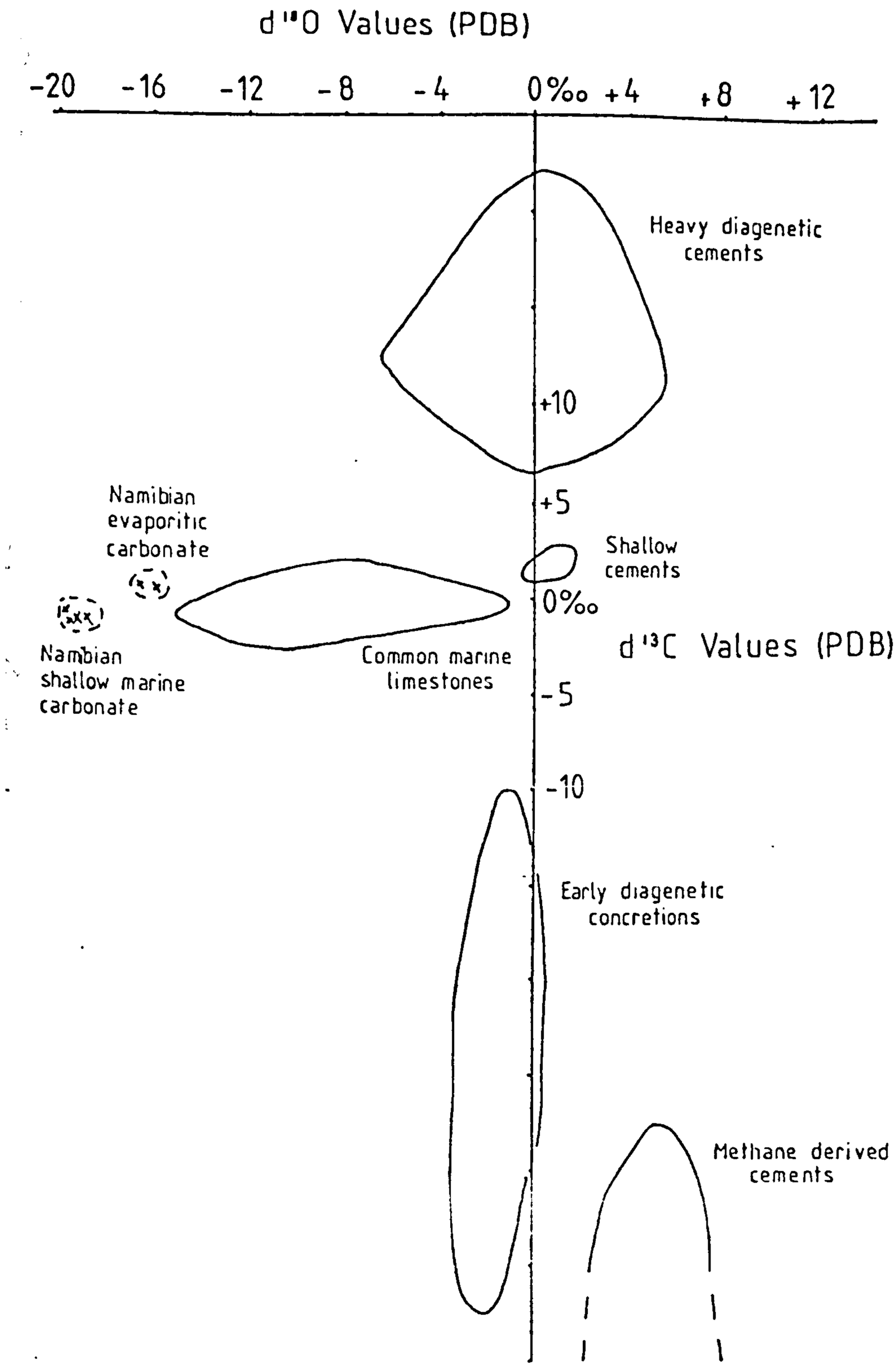


FIG 5 Common Carbon isotopic values plus $d^{13}C$ results from carbonates at Klein Aub and Witvlei , Namibia. (after HUDSON '77)

Carbonates from the marine sediments at Klein Aub and Kagas Noord formed during tidal/intertidal and subtidal reworking of the alluvial sediment. $\delta^{13}C$ values indicate a marine source. The carbonate grains fill pore spaces within the sediment and replace detrital minerals. They are therefore presumed to have formed very shortly after sediment deposition. Following their development, the sea water was flushed from the system by repeated alluvial discharges and sulphides formed. The distribution of sulphides is dependent upon that of carbonate within the sediments.

CONCLUSIONS

Sulphur isotopic evidence from sedimentary sulphides indicates formation by bacterial reduction of basement-derived sulphate, in both lacustrine and marine, copper and iron sulphides. Carbon isotopic data indicates marine and evaporitic carbon in tidal and playa sediments respectively.

Data from trace lead isotopic studies in basement and sedimentary sulphides combined with this sulphur isotopic work, suggest that the lead and sulphur were derived from basement rocks. This result strongly implies that the copper and silver were derived from the same source. From this and other evidence the above assumption is accepted, enabling a model of ore genesis to evolve. The model runs as follows:

Copper and silver were derived from basement rocks, released by the weathering attack on sulphides to form copper and silver sulphates during the Late Proterozoic. Movement of the sulphates in solution within fluvial discharges resulted in their distribution on the alluvial fan surface. The sulphates were concetrated in playa and shallow marine horizons and reduced to form orebodies. Reduction took place in early diagenesis with the aid of sulphate reducing bacteria in open or closed systems.

EXPERIMENTAL METHODS

Sulphur

Sulphides and sulphates were where possible separated from host minerals and ground into a powder. Most samples were monomineralic. The sulphur was then converted into sulphur dioxide using cuprous oxide (see Coleman and Moore 1978 and Robinson & Kusakabe 1975, Figure 6). As high a yield as possible was obtained from the samples to cut down fractionation effects of the ^{32}S and ^{34}S isotopes. The extraction line used is shown in Figure 6.

Isotopic measurements were made in a Micromass 602-C Mass-spectrometer with a heated inlet system to avoid machine isotope fractionation, and a double collector. Sample gases were measured relative to a standard gas and then calculated with respect to the Cañon Diablo troilite international standard. The following equation was used:

$$\delta^{34}S = \frac{(^{34}S/^{32}S)_{\text{sample}} - (^{34}S/^{32}S)_{\text{STD}}}{(^{34}S/^{32}S)_{\text{STD}}} \times 1000, {}^{o}/_{oo}$$

(STD = Canon Diablo Troilite)

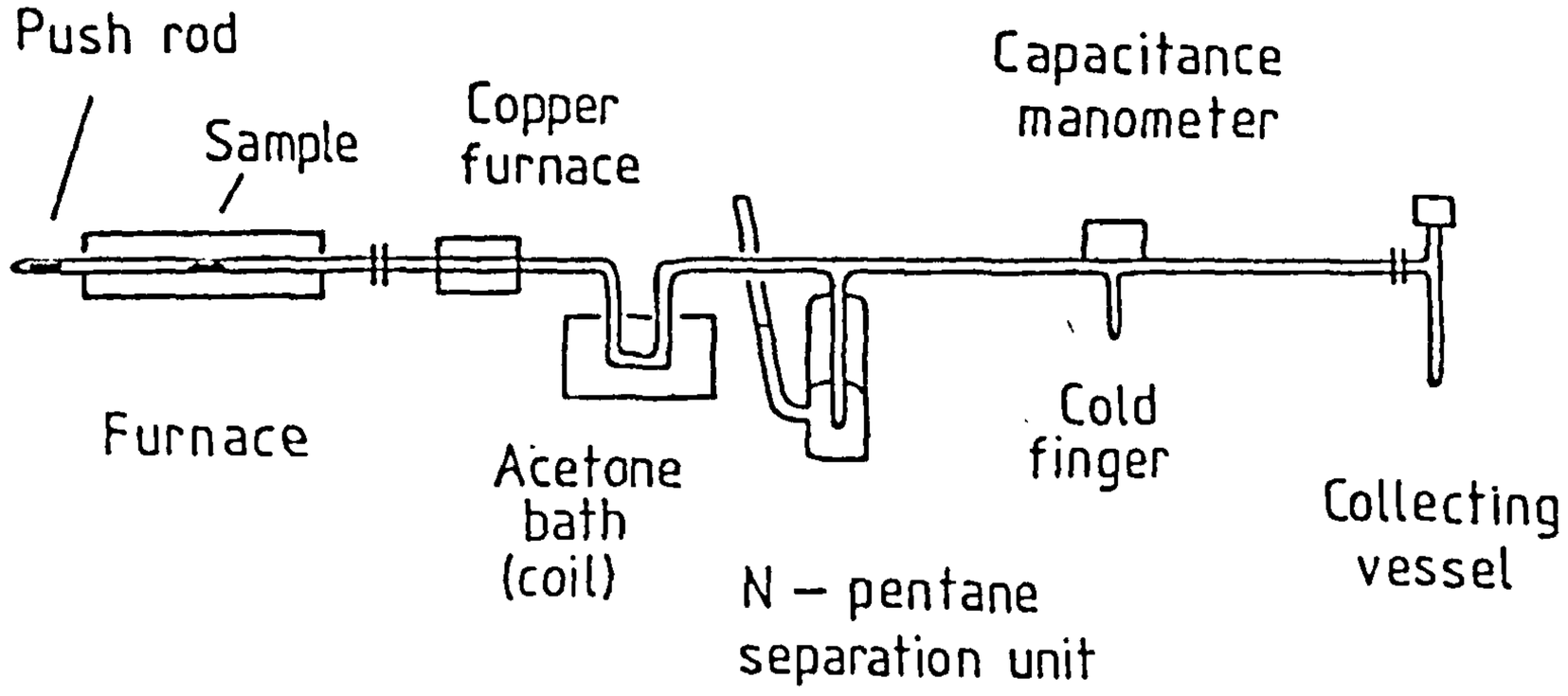
Carbon

Carbonate samples were powdered and extracted according to McCrea (1953, Figure 6). Carbon dioxide gas was collected and measured in a triple collector Micromass 903 mass-spectrometer. The results were related to the international P.D.B. standard, a Cretaceous Belemnite, according to:

$$\delta^{13}C = \frac{(^{13}C/^{12}C)_{\text{sample}} - (^{13}C/^{12}C)_{\text{STD}}}{(^{13}C/^{12}C)_{\text{STD}}} \times 1000, {}^{o}/_{oo}$$

Both $\delta^{13}C$ and $\delta^{18}O$ were measured.

SULPHUR (Sulphide + sulphate - Sulphur dioxide)



CARBON (Carbonate - Carbon dioxide)

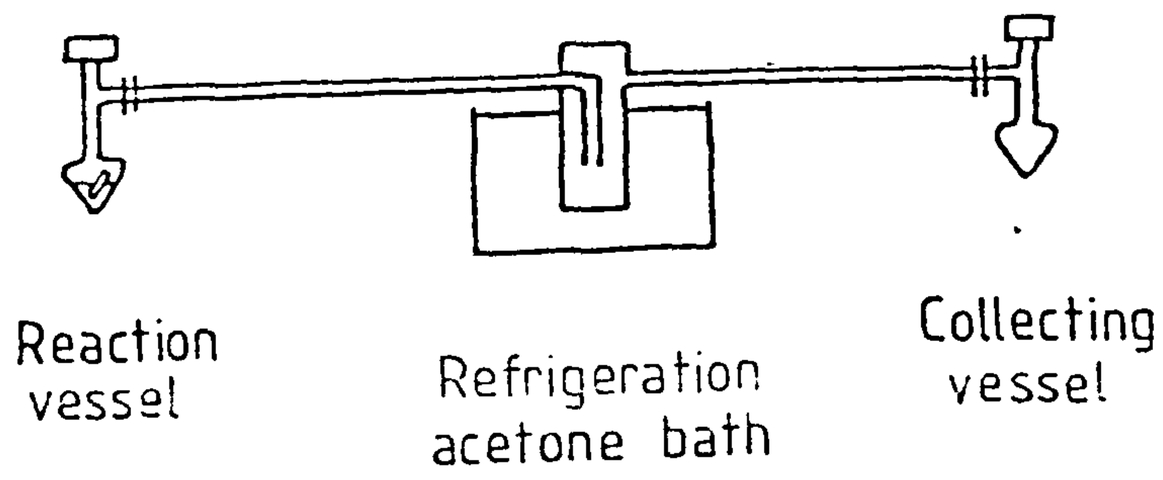


FIG 6. Sulphur and Carbon Extraction lines.

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