An Experimental Study of the Effects of Heating and Burning on the Hard Tissues of the Human Body, and its Implications for Anthropology and Forensic Science

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Abstract

An understanding of heat-induced transformation of hard tissue is vital before a full interpretation of burned human remains can be successfully achieved. While some studies have examined this issue a lack of understanding continues to exist within the discipline. This study addresses a number of fundamental questions concerning the effect of heat on bone using a broad spectrum of analytical techniques. These include experimental burning, radiography, scanning electron microscopy, x-ray diffraction and for the first time mercury intrusion porosimetry and small angle x-ray scattering. These methods assisted in the study of heat-induced transformations in bone colour, mechanical strength, microstructure and dimension. Samples of modern sheep (*n*=60), modern human permanent and deciduous teeth and archaeological human permanent teeth (*n*=128) were analysed resulting in 5440 data points. An holistic experimental approach was undertaken exploring the bi-variable impact of heating temperature and duration of burning. Subsequent heat-induced bone changes included the progression of colour from natural through to blue-white, the significant loss of weight, the reduction in mechanical strength, the development of distinct fracture patterns, alterations in the microscopic porosity, substantial alterations in crystalline structure and the reduction and expansion in size. Collation and integration of this information demanded a fundamental revision of the four stages of heat-induced degradation of bone previously presented by Mayne Correia (1997) and Thompson (1999). The results of this study suggested that new approaches to the analysis of burned and cremated human remains within the forensic and archaeological arenas should be adopted. An examination of the role of the forensic anthropologist in mass fatality incidents alongside a retrospective study of regional fire-related deaths provides the context for this doctoral research.

Keywords: burned remains; burned bones; cremation; forensic anthropology; mass fatality incidents; SEM; Radiography; Hg-IP; SAXS.

"I would straight away place on record my considered opinion, based on experience, that cremated remains of human bones in burial urns are almost always devoid of any anthropological interest ... From an anthropological point of view, therefore, these bones are of no scientific value, and I consider that nothing is lost if they are neither submitted to nor preserved in the Museum."

Professor C.M. Furst, Chief Inspector of Antiquities in Stockholm, 1930s

"It was a pleasure to burn. It was a special pleasure to see things eaten, to see things blackened and *changed*."

Ray Bradbury, 'Fahrenheit 451', 1953

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One The Context of Burned Human Remains

OneOne Introduction

A substantial body of literature is beginning to accumulate on the subject of what happens to human remains when they are burned, and consequently how this will affect the work of forensic anthropologists (for example, Bass, 1984, Heglar, 1984). The majority of these publications derive from experimental-based studies, as is the case with the research reported here. Unfortunately publications on experimentally-gained data very often neglect to place their work within any sort of context. As such, we are left with pieces of research that must then be re-interpreted when applied to situations with a social aspect – which is all situations involving burned human remains. The point of forensic anthropological research is application, and no application is void of social, ethical and legal ramifications. The last two of these issues are discussed in Chapter 11, but the first is explored here. Therefore the function of Chapter 1 is to examine the social arena in which this research will be of relevance.

The context of application is divided into two halves. The first is the modern context - the context where the social consequences of the study, analysis and identification of burned remains are at their most obvious and immediate. The second is the archaeological context - the context where the study of cremated bone has so far been unimpressive, yet which still requires an understanding of the consequences of the application of the relevant research.

The first aim of this chapter is to provide a context within which to place all subsequent results and discussion. The second aim is to use a retrospective study into fire-related deaths to see if the results and conclusions of this doctoral research would have any application beyond the field of mass disaster management.

OneTwo The Modern Context

OneTwoOne Social Aspects of Burned Human Remains

Fire is not just a means of creating warmth and light and providing protection, it is often a potent symbol. As such, the burning of human remains is often highly symbolic too. Topp (1973) discusses the changing symbolism that fire holds throughout the Christian era. Essentially he argues that before the onset of Christianity, fire had positive associations with the deities and spirituality. With the establishment and subsequent development of Christianity, fire became increasingly associated not with God, but with punishment (Topp, 1973). Fire was often used as a means of punishment in the name of God, but with time, this relationship changed and was replaced instead by an association with reincarnation. Green (2002) highlights that there was great potency in the pre-Christian era in the sacrifice of individuals, especially women and children, by fire (Green, 2002). This was especially true since the process of cremation can remove virtually all evidence of the sacrificed (Green, 2002). The use of fire in this way can have a prospective or retrospective function (Oestigaard, 2000) in that the actions may seek to influence some future, or commemorate some past, event. Green (2002) also notes that fire was regarded as a link between society and the gods in Ancient Greece and Roman Europe, and that in circumpolar societies fire was also strongly associated with the sun. Although much of this evidence is historical, there is an increasing amount of archaeological evidence to support these statements and notions (Green, 2002; Holck, 1986; McKinley, 2000b). The spiritual and emotional power of the cremation process is even described in early texts such as the epic poems of Beowulf (Heaney, 1999; 98) and The Iliad (Homer, 1995; 314-350) after the deaths of the great heroes Beowulf and Hector respectively. In his paper, Topp (1973:81) finally concludes that in our modern society, fire is completely losing its religious connotations and is becoming

> "...an expression of either mob violence, personal and perverted vengeance, or a form of melodramatic protest for ideological reasons"

This is a rather dismissive statement, and I would instead suggest that fire is increasingly being used as a focal point for groups of individuals and as an expression of strong emotion, often displeasure and anger (for example, the Iranian protesters who set themselves on fire outside the French Embassy – BBC, 2003). Although Topp (1973) clearly emphasises the Christian associations with fire, he, Green (2002) and Oestigaard (2000) note that in many different cultural belief systems, fire has some degree of symbolism in opposing associations between punishment, reincarnation and procreation.

With the obvious religious symbolism of fire, the significance of the practise of cremating the dead should not be overlooked. Oestigaard (2000) states that ancient funerary practices and mortuary remains are a significant source of information for understanding prehistoric societies. Arguably this notion includes cremation practices and could be extended to include all societies. Downes (1999) suggests that the use of fire in this context has two emblematic functions. First it is a highly visible and powerful agent of transformation and purification that requires technical knowledge and resources to control successfully (Downes, 1999; Green, 2002). The deceased in their dead state are transformed and purified, while simultaneously the living reaffirm their position in, and control of, the world around them. Second, that the act of cremation, possibly more so than the act of inhumation, is a way of making the dead rest (Downes, 1999). Downes (1999) adds however that the burning event itself is often only a short part of a sequence of ceremonies and rituals designed to deal with the dead, all of which will be highly symbolic. Oestigaard (2000) notes the same, suggesting that it is part of a three-phase process of burning, removal-storage-transportation, and final deposition. It is interesting to note here that according to the reports commissioned by the Cremation Association of North America, there has been a substantial increase in the popularity of cremation over inhumation throughout all regions of the United States in recent years (Murad, 1998; Warren and Shultz, 2002). Cremation also accounted for seventy-two percent of funerary practices in England in 1998 (de Gruchy and Rogers, 2002). This may be seen as an increasing desire to reaffirm our control of the world around us. It may also be seen as a more efficient and clinical method of dealing with the last taboo, death. Cremation aids in a very clear emotional closure for the next of kin in that there is an end product that is inert and unthreatening (the container holding the ashes). This contrasts with the process of inhumation where the transformation of the remains is hidden and there is considerable uncertainty regarding the fate of the corpse. Nonetheless the cremation funerary practice is not an isolated event in the sphere of death (Oestigaard, 2000) as it involves a series of events and both the living and the dead.

It is likely that those who decide to take their own lives by setting fire to themselves do not choose this method simply by chance. Again there is symbolism to this use of fire. Self-immolation is an uncommon form of suicide (Leth and Hart-Madsen, 1997; Shkrum and Johnston, 1992; Sukhai *et al*, 2002). It accounted for just one percent of suicides in Ontario, Canada during the late 1980s (Shkrum and Johnston, 1992), 1.8 percent in South Yorkshire between 1985 and 1991 (Cooper and Milroy, 1994) and 9.9 percent of all suicides in Durban, South Africa during the five-year retrospective study of Sukhai *et al* (2002). The intention is either to cause self-harm, to self-mutilate, or to commit suicide (Sukhai *et al*, 2002). In addition, once begun the consequence is usually irreversible unlike with slitting one's wrists (Williamson, 2001). This method of suicide is also extremely dramatic and visible, and is a highly effective way of signalling ones feelings about oneself, ones life or a subject in a way that the authorities and public would find hard to ignore. This is not to say that all cases of self-immolation are symbolic. It may be that this particular method is chosen because it is the most accessible and with an almost guaranteed result (Leth and Hart-Madsen, 1997; Williamson, 2001). The same reasoning can be applied to murder by burning. As with self-immolation, the act itself may well be highly symbolic, but it could also be a function of ease and perceived success of application. Williamson (2001) gives details of murder by setting fire to people, while Stone and James (1995) discuss the disturbing frequency of this act within the context of bride-burning and dowry provision in modern India.

It has been reported that in the United States in 1994 alone, arson accounted for 86,000 structural fires, 550 deaths and 1, 447 billion dollars worth of property loss (Geller *et al*, 1997). Although there are problems with the definition and study of pathological fire-setting (Geller *et al*, 1997), it may be that the powerful symbolic and visual nature of fire, in addition to its ease of access, are highly significant factors.

OneTwoTwo Forensic Aspects of Burned Human Remains

Within the forensic sphere, burned human remains are recovered from a number of contexts. In England all deaths by burning and fire will fall within the forensic remit because they are definable as reportable deaths that must be referred to HM Coroner (see Dorries (1999) for further details of reportable deaths). Therefore forensic experts will investigate fire-related deaths that occur due to murder and suicide, but will also investigate deaths that have occurred in mass fatality incidents, accidental house fires, industrial fires and even natural disasters such as forest fires. Mayne Correia (1997) presents an exhaustive review of several cases involving anthropologists. However not all cases involving death by fire will require the assistance of a forensic anthropologist, although it could be argued that many investigations would benefit from having one present, especially if the human material is severely damaged. Murad (1988) argues that with the increase in the popularity of cremation as a means of disposing of the dead, forensic anthropologists should be prepared for the increasing likelihood of having to investigate cremated human material. In addition Murray and Rose (1993) argue that burning is increasing as a clandestine method of disposing of illegally killed individuals. Cases have already been reported of anthropologists sorting through burned bone removed from modern crematoria to answer forensic questions (for example, Kennedy, 1996). Burnings that have been instigated to hide other crimes will also need the service of a forensic practitioner (for examples see Eckert *et al*, 1988, Forbes, 1941 and Williamson, 2001).

Although the forensic context may vary considerably, each case will require the application of the same knowledge and understanding of the behaviour of human remains when heated. The knowledge and understanding of the behaviour of human remains when burned is expanded upon in subsequent chapters. The remainder of Section 1.2 examines certain forensic contexts in detail. Greater emphasis is placed on mass fatality incidents because not only were these contexts the impetus for this research, but they are deemed one of the most likely benefactors of this research.

OneTwoThree Mass Fatality Incidents

A mass fatality incident, or mass disaster, is difficult to define. If we use numbers of deceased, where is the section point? Do two hundred dead constitute a mass fatality incident, or fifty or fifteen? Manner of death could be an appropriate definition, but again we have problems dividing incidents. Does a mass fatality incident involve aeroplanes, ships, trains or cars? One may argue that it would not involve cars, but what then happens to our definition if ten cars are involved? Or thirty as in Alpine tunnel fires like those reported in the literature (CNN, 2001; Edwards, 1999)? Jensen (1999) in his field guide on the subject raises similar concerns, and suggests that a mass fatality incident can best be described as an event that produces more fatalities than the local resources can handle. This implies that the definition of a mass fatality incident is fluid, and will shift depending on the location of the episode. For example, the recovery of seven bodies from the Solway Harvester shipping vessel in the spring of 2000 was enough to overwhelm the limited resources of the Isle of Man, whereas the tens of individuals of the Hillsborough disaster in April 1989 could be accommodated by the resources in the Medico-Legal Centre, Sheffield. One may also add that this definition may imply that the deaths are the result of a single event, but it needs to include a chain of events that can be seen to originate from a single event.

A major mass fatality incident is inevitable and unavoidable. Arguably the real issue is not how best to stop them all occurring, since this is impossible, but

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rather how best to plan for them and then cope with them when they do occur. It should be noted that most mass fatality incident protocol and procedures are initiated and developed as a result of a mass disaster. They are reactionary. Only now, with the increasing internationality of mass disasters, that is to say, with the consequences of mass fatality incidents being seen across the globe due to the media and affecting people from many nations (for example, the victims of the Scandinavian Airways crash in Milan, 2002 came from over 8 countries), are protocols being devised before an event strikes a country or region. The increasing internationality of mass disasters is useful however for raising awareness, Ellis (2002) and Midda (1988) point out that there are many political and practical difficulties in co-

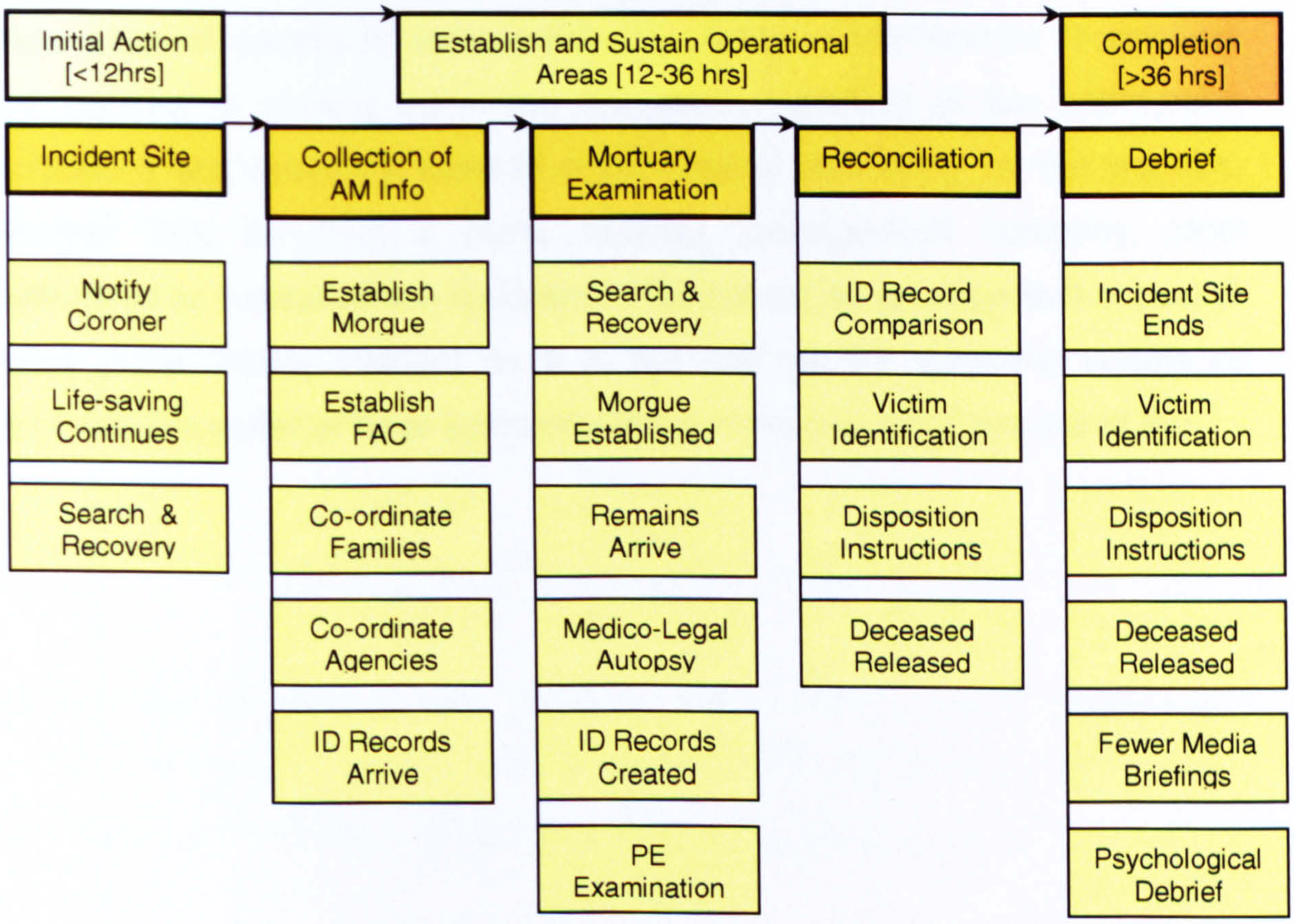


Figure 1.1 Progression of Sequential Management Stages During a Mass Fatality Incident [Note: FAC= Family Assistance Centre, ID= Identification, PE= Personal Effects]

that must be traversed immediately after a mass fatality incident. Figure 1.1 has been developed from the management stages suggested by Jensen (1999) and Ellis (2002). It can be seen from Figure 1.1 that there are five main sequential phases that a mass fatality operation must accomplish. The first phase begins as soon as the incident itself has occurred. The second, third and fourth phases concern the identification of the victims of the incident. The comparison of ante-mortem and post-mortem records, the autopsy and the examination by forensic experts all contribute to disaster victim identification. Simultaneously with victim identification is a responsibility to the surviving relatives. Help and assistance must be provided for them, not only because this will be an extremely difficult emotional and social time for them, but also because they are a valuable source of ante-mortem information regarding the victims. The fifth phase is more oriented towards to workers than the victims of the incident. It concerns the logistics of closing down the operation, reporting to the appropriate authorities and providing suitable psychological debriefing for the workers, whether they be from a mass disaster management company, local authorities or transportation company. This should be an important aspect of every mass fatality incident as it is not just be the surviving victims or relatives that suffer or have some emotional repercussions because of the

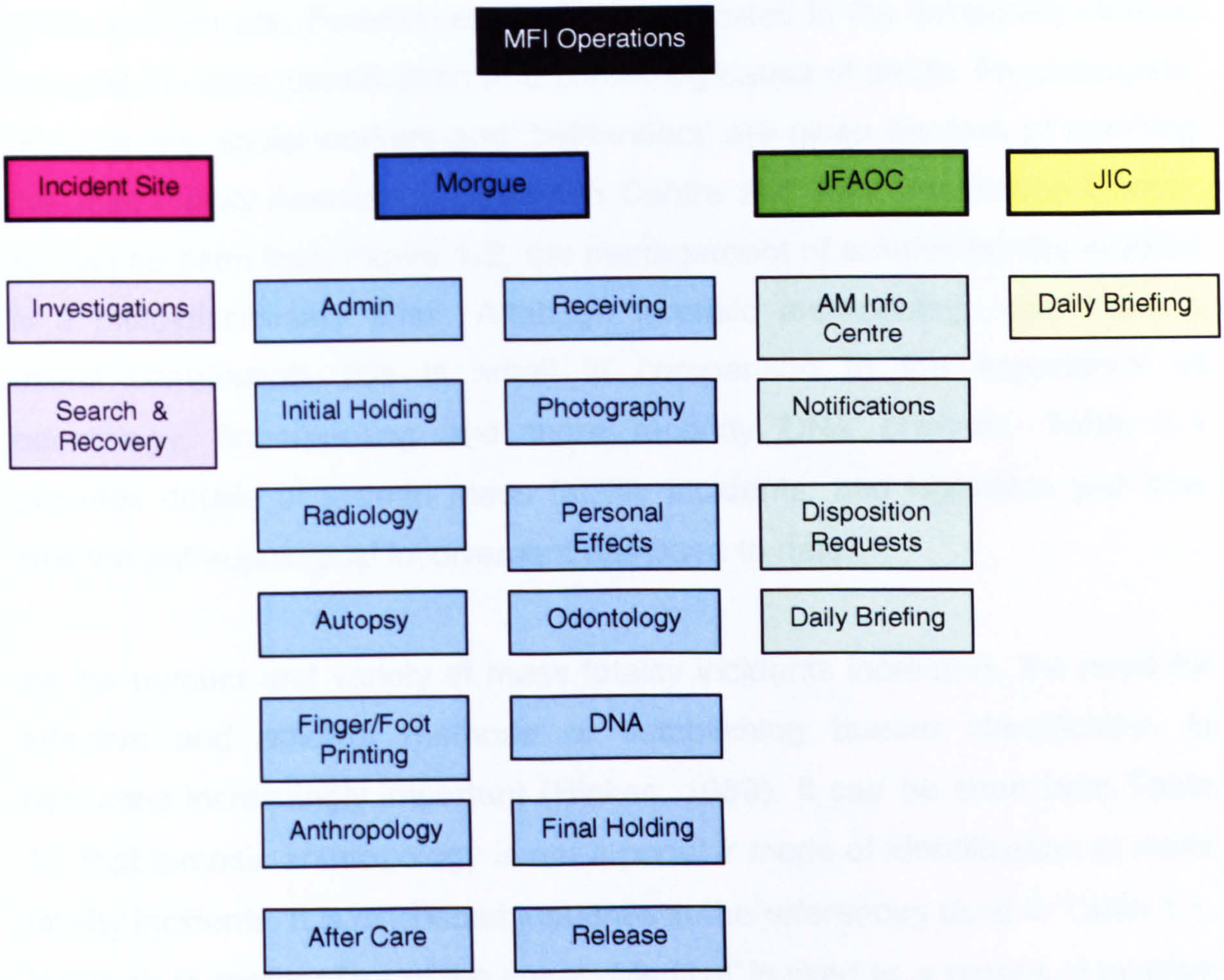


Figure 1.2 Activities Needing Management During a Mass Fatality Incident [Note: MFI= Mass Fatality Incident, JFAOC= Joint Family Assistance Operations Centre, JIC= Joint Information Centre]

event. Unfortunately it is only now that the emotional and psychological impacts of working on a mass fatality incident are being assessed in order to better help those who work on them (Linley, 2003; Webb *et al*, 2002).

Figure 1.2 is an adapted and amended version of Figure 1.3 from Jensen (1999; p10). It highlights the many activities that must be tackled during a mass fatality incident. Mass fatality incidents require considerable multi-disciplinary involvement, although for efficient execution a single person still needs to be in charge of the operation (Ellis, 2002). Successful management of the incident will require separating the myriad of tasks into groups and assigning a specialist team of experienced experts to each group. Those with experience in scene of crime protocol, surveying and body recovery are used at the incident site. Forensic experts will be posted to the temporary morgue to assist in victim identification and conferring cause of death. Psychologists, psychiatrists, social workers and 'befrienders' are given the task of manning the Joint Family Assistance Operation Centre and Joint Information Centre. As can be seen from Figure 1.2, the management of a mass fatality incident is a multi-disciplinary affair. Although forensic anthropology can make a useful contribution, this is small in comparison to the importance of odontology, fingerprinting and more recently DNA analysis. Table 1.1 provides details of several mass fatality incidents, and highlights just how little the anthropological involvement has been to date.

As the number and variety of mass fatality incidents increases, the need for effective and efficient methods of establishing human identification is becoming increasingly important (Hinkes, 1989). It can be seen from Table 1.1 that forensic anthropology is not a popular mode of identification at mass fatality incidents. It is discussed just once in the references used in Table 1.1. However in another four of the cases 'Medical' is cited as a means of positive identification. This includes the comparison of ante-mortem radiographs to films taken post-mortem. Although this technique could fall within the remit of forensic anthropology, it is most likely performed by the attending pathologist or radiologist. The question remains then: can forensic anthropology offer any benefits at a mass fatality incident? Hinkes (1989) and Sledzik and Rodriguez (2002) argue that it can, stating that forensic anthropologists are especially useful in distinguishing bone from non-bony items, in collecting information from isolated body parts, in reassociating fragmentary remains, in analysing trauma patterns and in creating a set of data to be used in excluding possible identifications. Jensen (1999) supports these points, and adds the importance of an anthropologist in separating human from non-human osseous material. The issue then is not whether anthropology can be of use, but whether anthropologists are involved early enough in the operation to be of most use. Hinkes (1989) argues that anthropologists are deemed a last resort, whereas in fact they can successfully contribute as soon as the remains are recovered (by for example, identifying bony material, establishing minimum number of individuals and creating osteological profiles). I would add that a good forensic anthropologist would be of use even earlier than Hinkes (1989) suggests, as many have experience in scene of crime surveying, recording and body location and recovery.

Incident Details	Vector	Cause of MFI	No. Dead	Main Id Methods	Reference
Copenhagen, Denmark, 1973	Hotel	Fire	35	Dental	Jakobsen *et al*, 1974
Tenerife, Canary Islands, 1977	Boeing 747 Aircrafts	Aircraft collision on runway	583	Dental, medical, fingerprints, personal effects	Wolcott and Hanson, 1980; Brannon and Morlang, 2001
Mt Erebus, Ross Is, Antarctica, 1979	DC10 Aircraft	Poor weather	257	Dental, fingerprints, personal effects, medical	Pert, 1980; Cairns *et al*, 1981
New Orleans, US, 1982	727-235 Aircraft	Impact with tree on take-off	154	Dental, fingerprints	Barsley *et al*, 1985
Abu Dhabi, 1983	737 Aircraft	-	112	Dental	Clark, 1986
Gander, Newfoundland, Canada	DC-8 Aircraft	-	256	Dental, fingerprints, anthropology	Hinkes, 1989
Reno, Nevada, US, 1985	L-188 Aircraft	Mechanical fault	70	Dental, fingerprints, personal effects	Salomone *et al*, 1987
Lockerbie, Scotland, 1988	Aircraft	Bomb	270	Dental, fingerprints, personal effects	Eckert, 1990; Moody and Busuttil, 1994
Bailen, Spain, 1996	Bus	Impact with car	28	Dental, DNA, medical, personal effects	Martin-de las Heras *et al*, 1999
Paddington, London, UK	Train	Impact with train	31	DNA, dental, fingerprints, visual, personal effects, medical	Sutherland and Groombridge, 2001

Table 1.1 Identification Techniques and the Role of Anthropology at Mass Fatality Incidents

OneTwoFour Case Study: A Retrospective Study of Fire-related Deaths

The Medico-Legal Centre in Sheffield was opened in 1977 and remains the only purpose built centre of its kind in England. It houses the Coroner's court, autopsy facilities and technicians and the University of Sheffield's Department of Forensic Pathology. The Department of Forensic Pathology is currently composed of administrative staff, five forensic pathologists, one forensic toxicologist and a forensic anthropologist. It is one of only five Forensic Pathology departments in the country. The Centre offers autopsy services, when appropriate, to police forces and Her Majesty's Coroners over a large part of the north of England including the Yorkshire counties and the Humberside region. For every autopsy performed a Report on Autopsy form is completed which summarises the post-mortem findings and provides a chain of causation regarding the mechanism of death. Approximately 1200 autopsies are performed each calendar year. Report on Autopsy forms from 1991 to 2002 were examined for cases of fire-related deaths. These years were studied because these reports had been inputted on computer, which facilitated efficient searching. Fire-related deaths were examined with the aims of suggesting whether this doctoral research has a feasible and useful practical application in standard non-mass fatality incident situations and to place this work into a social context.

Several retrospective studies have been published to date, and have provided a template for this study (Anderson *et al*, 1981a, b; Anderson and Harland, 1982; Ast *et al*, 2001; Cooper and Milroy, 1994; Escoffery and Shirley, 2002; Gerling *et al*, 2001). Most recently, Escoffery and Shirley (2002) and Gerling et al (2001) published the results of their examination of traumatic deaths in Jamaica and Lübeck, Germany respectively. Unlike Shkrum and Johnston (1992) who merely devise a generalised, non-specific list of traits that partakers in self-immolation hold, Escoffery and Shirley (2002) actually draw some useful conclusions from their descriptive data. They call for improvements in the standards of recording, preventative strategies to be focussed on those categories noted here to be at high risk of trauma-related mortality and the use of this descriptive data in policy planning.

The staff of the Medico-Legal Centre, Sheffield conducted 11889 autopsies between 1st January 1991 and 31st May 2002. Of these, 174 cases were deemed to be fire-related. This represents 1.5% of the total number of autopsies conducted at the Medico-Legal Centre, Sheffield. This percentage is lower than that for Lübeck which is 6% (Gerling *et al*, 2001) and for Jamaica, which is 4.8% (Escoffery and Shirley, 2002), and may represent better fire prevention and extinction in the north of England. It was decided that fire-related deaths included death by burn injury, inhalation of the products of combustion, inhalation of hot gases, trauma caused by attempted escape and subsequent medical complications (such as multi-organ failure, infection and physiological shock). Deaths by carbon monoxide poisoning without an associated fire, such as from faulty heaters or car exhaust pipes, were excluded from the study. Information transcribed from the Report on Autopsy forms included biological sex, age at death, location of residence, seat of fire, time of death, pathological changes, toxicological information, context of death and primary cause of death. Simple descriptive statistics were used on the data in order to summarise and highlight patterns within the data.

As can be seen from Figure 1.3, no obvious patterns exist with regard to location of fire throughout the region of study. The high peak in West Yorkshire is initially intriguing. However, it is merely a function of the type of graph used. Figure 1.3 is a frequency graph, and frequency of fire-related deaths is therefore influenced by factors that affect frequency of autopsies conducted, such as the local coroner, the local pathologists, the area of county and population size. West Yorkshire has a large population and one would expect a high peak. A more useful graph may be to examine frequency of fire-related deaths as a percentage of total deaths in the county or total population.

each year are fairly similar, although there is a slight increase in number of dead between 1998 and 2001 compared to 1991 to 1997. Two of the years require explanation. 2002 has such a low frequency simply because at the time of the retrospective study few of the 2002 Report on Autopsy forms had

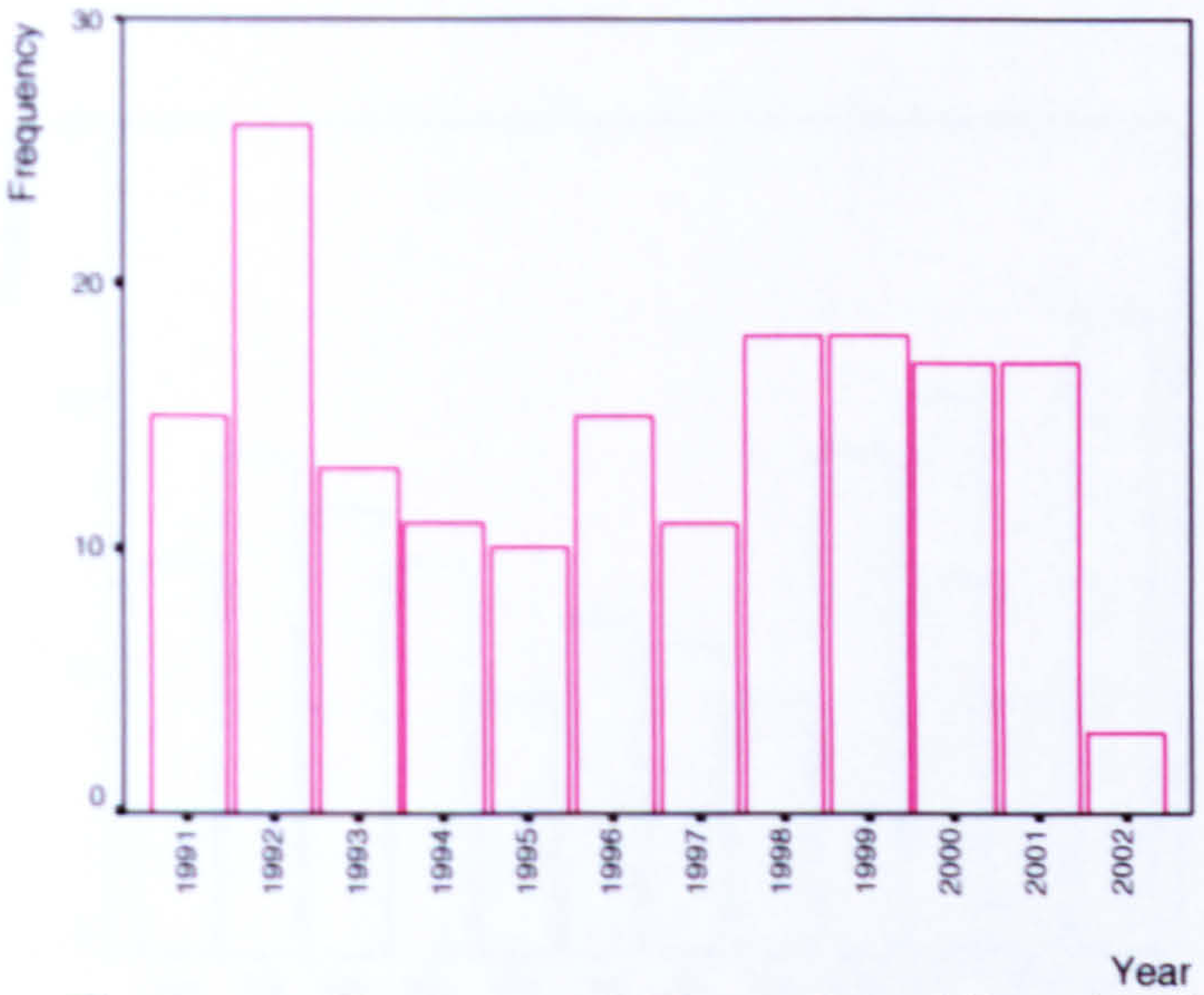


Figure 1.4 Temporal Patterns of Fire-related Deaths, in years

been filed on computer. 1992 is unique in that it has a very high frequency of fire-related deaths. An explosion in a commercial premises which killed five people has affected the value for this year. This sort of event did not happen in any of the other years, and if one were to remove those five from the bar, the value would drop from 26 to 21, which although still higher than the other years, is at least more in keeping with them.

Figure 1.5 displays the monthly pattern of fire-related deaths in the study. In Anderson *et al*'s (1981) examination of fire deaths in Scotland, it was revealed that seasonal patterns existed in the frequency of fire-related deaths. There were peaks at the beginning and end of the year. This reflects sociological and climatic patterns in the region (Anderson *et al*, 1981). This is a logical conclusion, and the principle of peak months of deaths should be universal if not the actual peak months themselves (for example, in the southern hemisphere one would expect there to be a peak in fire-related deaths in the winter when it is colder than in the summer – when their winter is our summer). Indeed this notion is seen in the data collected from the north of England. A distinct increase is seen from October through to February. If the number of fire-related deaths were random throughout the year, this period of five months would hold 42 percent of deaths. In actuality the value is 48 percent. It is not known why the frequency of fire-related deaths in November

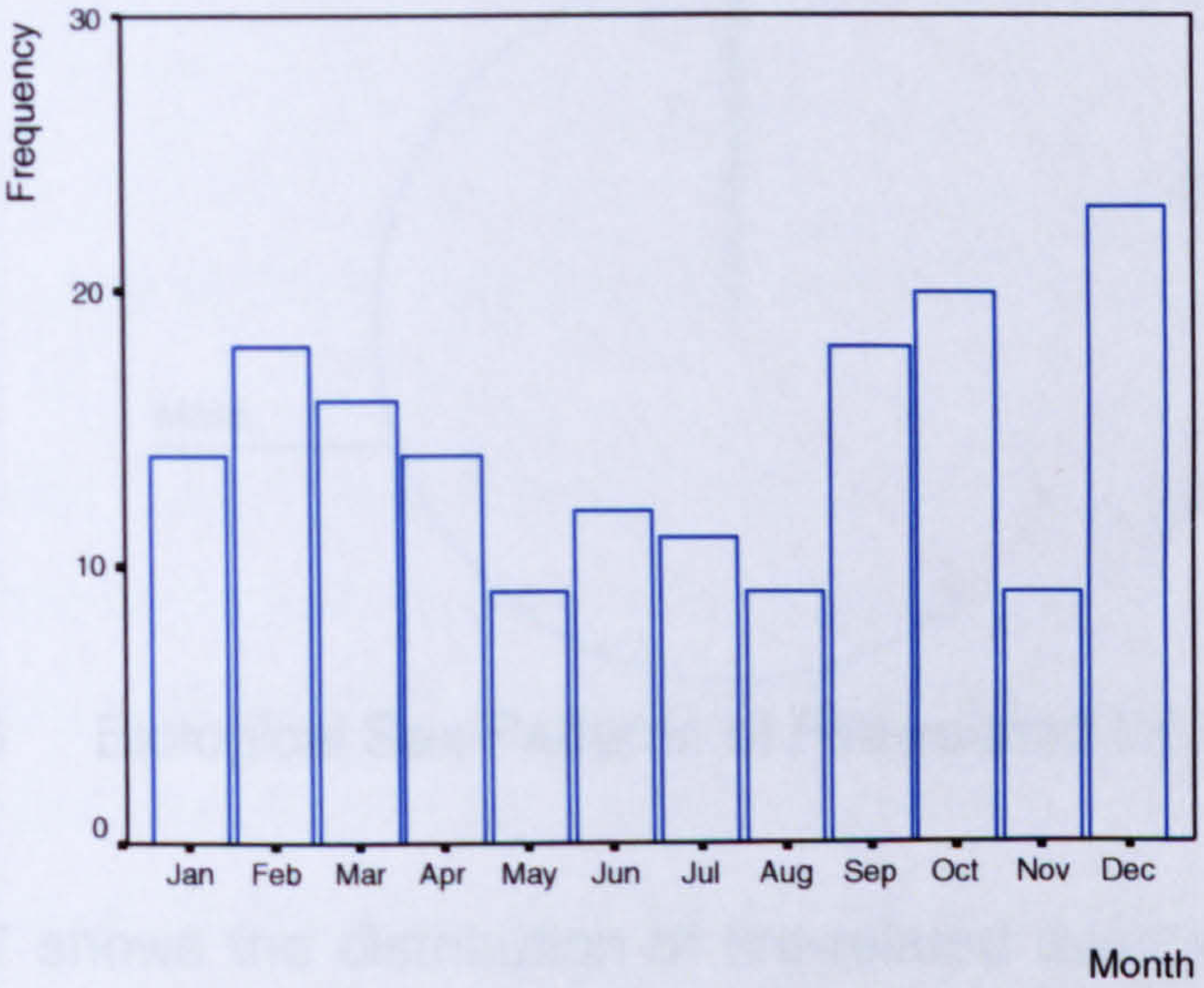


Figure 1.5 Temporal Patterns of Fire-related Deaths, in months

is so low, but as this graph represents a twelve-year period, it must be correspondingly low every year. This may correspond to a greater awareness of the hazards of fire during the traditional firework season.

Figure 1.6 shows that there is a clear sex difference in deaths due to fire. Biological sex was recorded from the Report on Autopsy forms rather than gender, the social manifestation of sex. 60.9 percent of those who died from fire-related causes were men, 38.5 percent were women and 0.6 percent, or one individual, was of unrecorded sex. This is extremely similar to the 60% male and 40% female figures recorded by Gerling *et al* (2001). Ratios from other studies (Anderson *et al*, 1981; Escoffery and Shirley, 2002) are much closer to 1:1. Interestingly while Cooper and Milroy (1994) found a male dominance in self-immolation suicide attempts, Sukhai *et al* (2002) found a female bias (although they did admit that this does not appear to be the norm). More males died from every classification of cause of death except the strangulation and infection cases, where only one woman and no men were recorded. In the other classifications except inhalation where the percentages are roughly equal (56.1 percent for men, 43.9 percent for women), the ratio of male deaths to female mimics the total percentages of 60.9 and 38.5 percent.

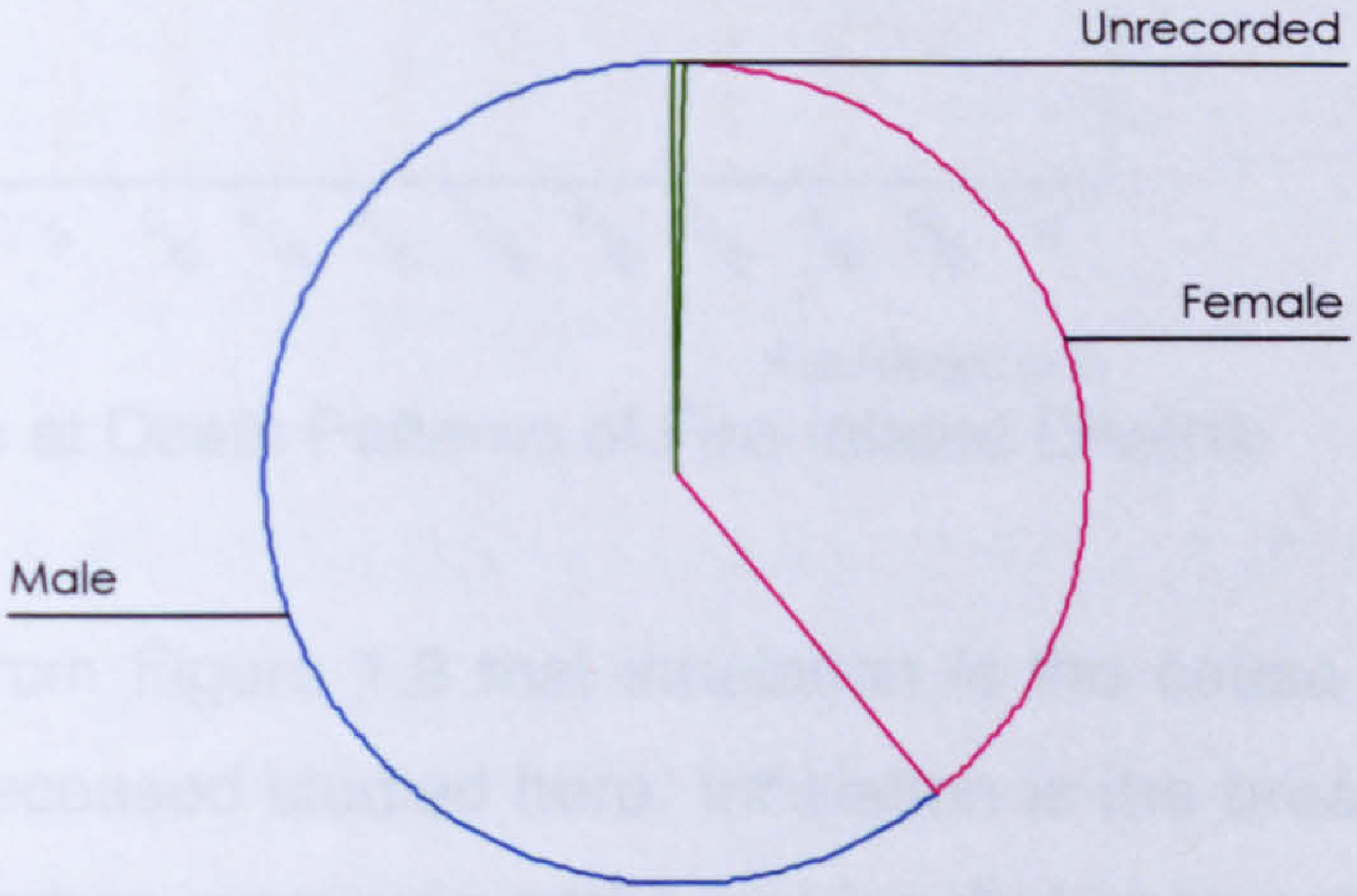


Figure 1.6 Biological Sex Patterns of Fire-related Deaths

Figure 1.7 shows the distribution of fire-related deaths for each age group. Based on previous studies (Anderson *et al*, 1981), one would expect the curve of the age-specific death rate graph to be bimodal, with peaks at the lower and higher age categories, but the curve of number of dead to be population dependent. This biomodality is because these age groups are more vulnerable and susceptible to fire-related deaths. In Figure 1.7, low numbers are seen in the older age ranges because fewer old people are living in general and therefore fewer older people die of fire-related incidents.

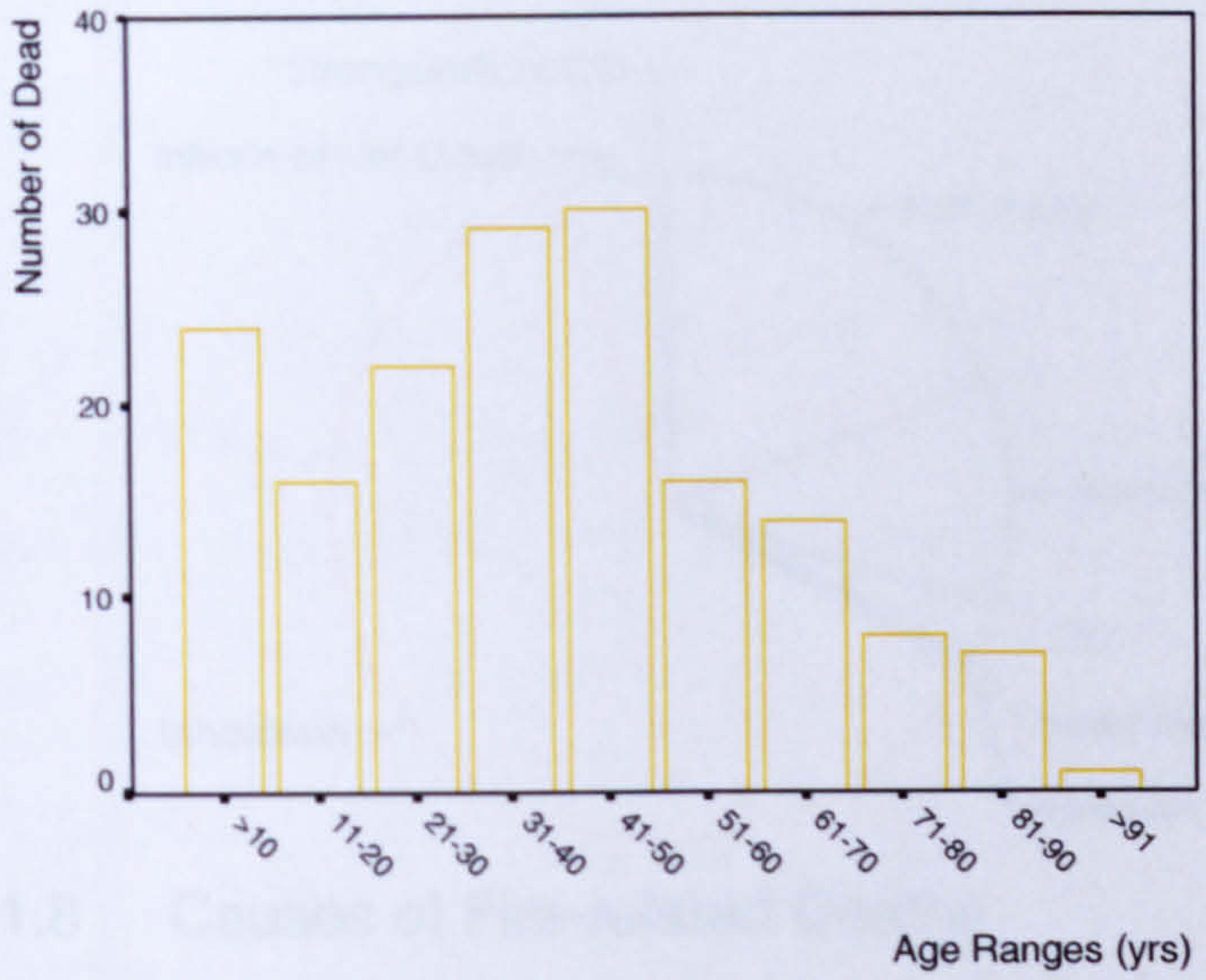


Figure 1.7 Age at Death Patterns of Fire-related Deaths

It can be seen from Figure 1.8 that inhalation is the cause of death of the majority of the deceased studied here. Inhalation is the breathing in of toxic gases such as carbon monoxide and cyanides that poison the body. This is different to the inhalation of hot gases. Here it is the physical trauma to the respiratory tract caused by the high temperature of the toxic gases that causes death. The carbon monoxide category is slightly different from the inhalation category. The former is where death can be attributed to solely carbon monoxide, the latter where it can only be said that death was due to gaseous poisoning. Unfortunately it is not possible to say whether individuals were killed by suffocation as a result of lack of oxygen. One victim died as a result of head trauma received whilst escaping the fire. Another individual died as a result of contracting an infection from her skin grafts. The strangulation/CO and Burns/Inhalation categories are situations where neither lethal factor can be separated from the other, that is, it is not possible to state which was the decisive cause. Birky and Clarke (1981) found a greater frequency of inhalation deaths of eighty percent. The extremely high percentage associated with death by simply breathing as opposed to by burn injury demonstrates that most individuals died before the fire actually reached them.

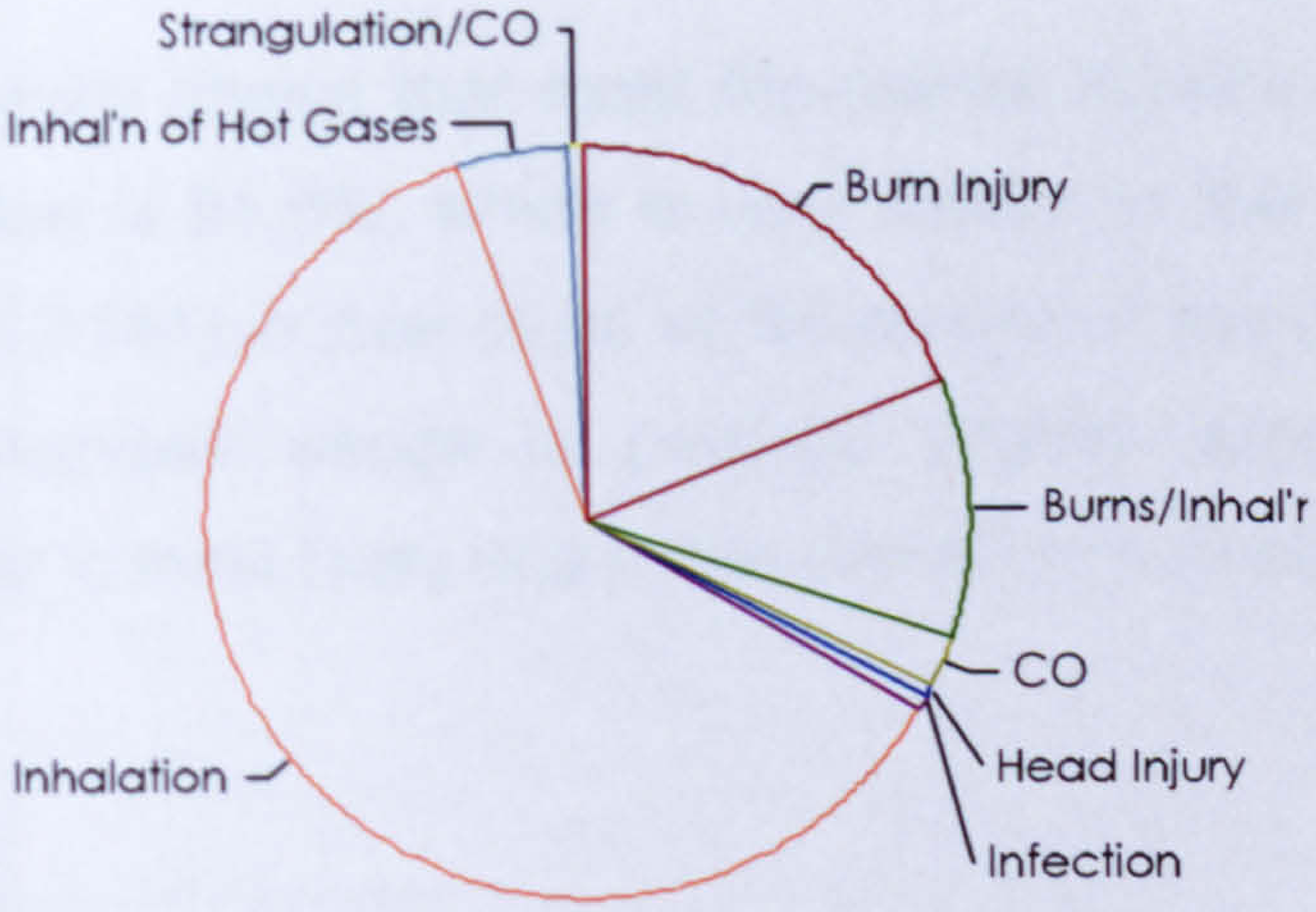


Figure 1.8 Causes of Fire-related Deaths

Figure 1.9 shows the differences in context of death, that is whether the fire-related deaths were accidental or non-accidental. Non-accidental deaths include arson, murder and suicide. At times, the Report on Autopsy could not say categorically that the death was non-accidental or merely accidental. The latter was assumed unless the former was strongly suggested by the forensic pathologist. The majority of accidental deaths occurred in the home. For example due to chip pan fires, which nationally account for twenty percent of all accidental fires (Williamson, 2001). In 1997 the county of Lancashire had 427 reported incidents alone (Williamson, 2001). The majority of non-accidental deaths occurred in disused premises or outside. This may be because these two locations are often away from the public.

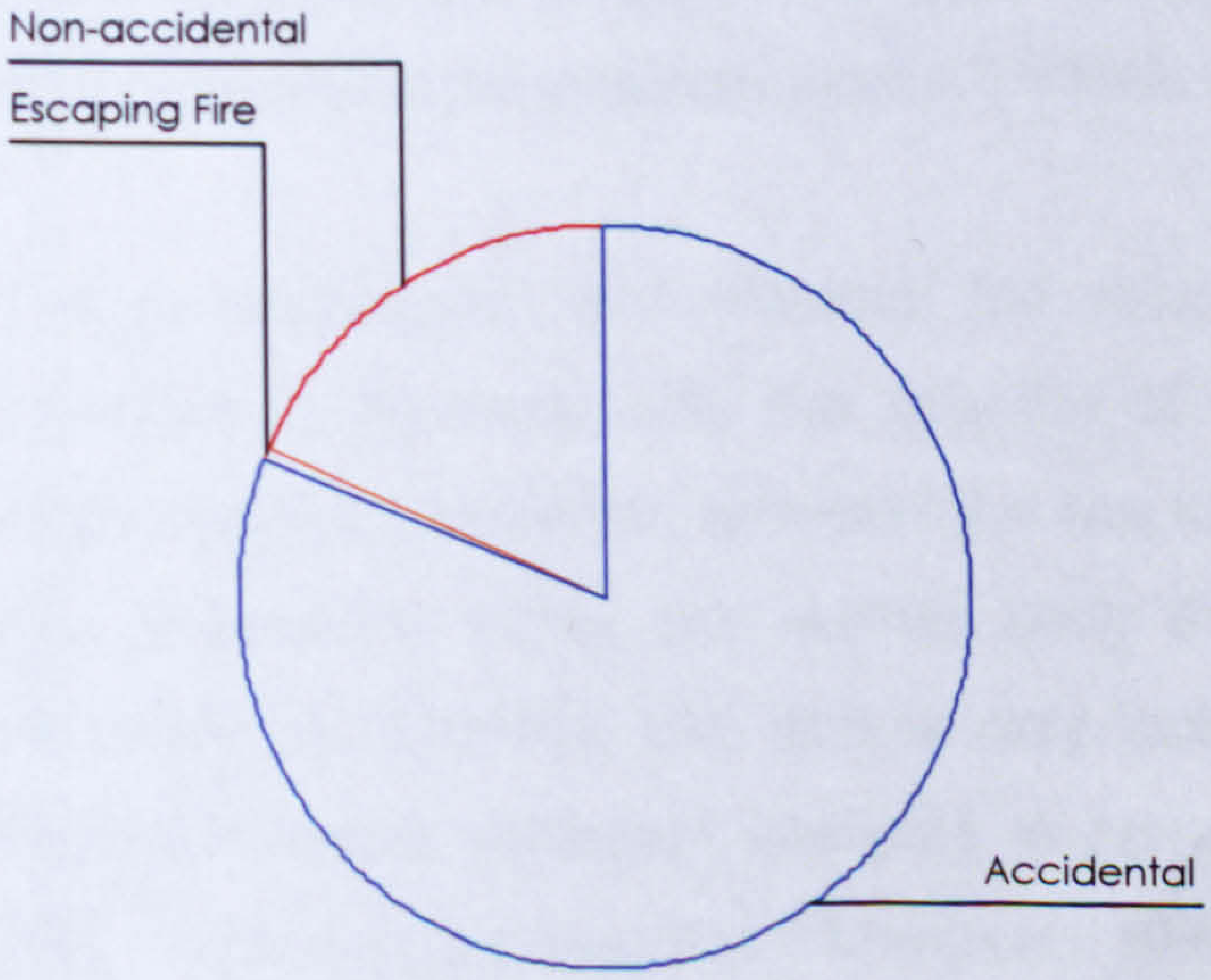


Figure 1.9 Context of Fire-related Deaths

Figure 1.10 clearly shows that most fire-related deaths occur in the home. The actual value is 81.6%, which is very similar to the 83.9% recorded by Anderson *et al* (1981) in their study of fire deaths in the Glasgow region. The commercial premises wedge is perhaps slightly larger than one would expect, and this is most likely due to the explosion that killed five. As mentioned above, this is a very rare occurrence. The deaths in vehicles caused the most identification problems as these bodies were destroyed the greatest and often required the assistance of a forensic odontologist.

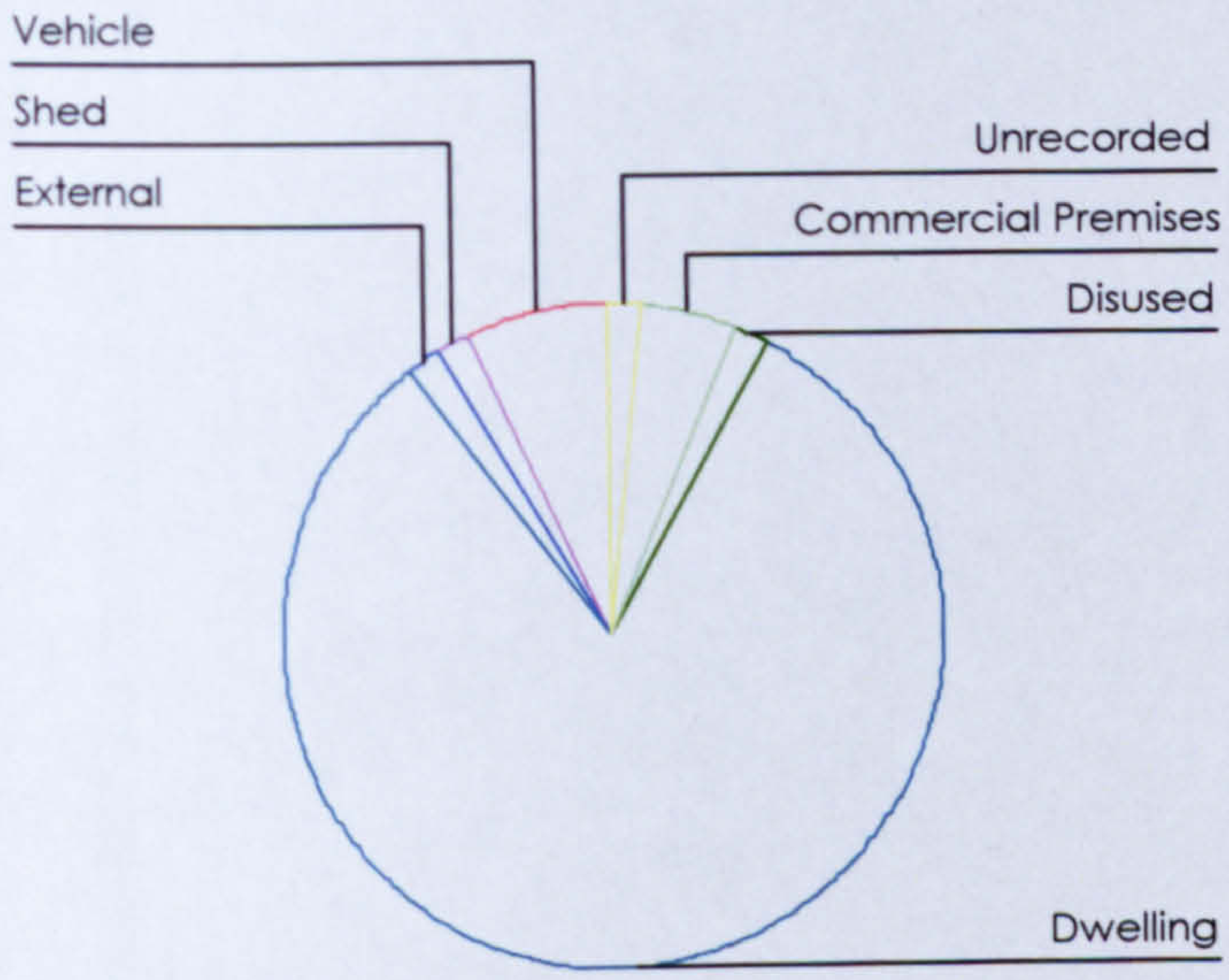


Figure 1.10 Location of Fire-related Deaths

Figure 1.11 is a scattergram that displays the relationship between the quantity of cyanide in the body with the quantity of carboxyhaemoglobin. There is a slight positive correlation between the two toxins, whereby as the one increases in quantity within the human body the other follows suit. However this graph is of limited use and is only included to illustrate the potential dangers of using statistical analyses in cremation studies (further cdiscussion of which can be found in Thompson 1999 and 2002). Both of these poisons would be expected to increase simultaneously since both are taken up by breathing. Neither poison influences the uptake of the other, and the correlation seen is not a causal relationship; Figure 1.11 is a cautionary tale of the appropriate use of statistics. Distressingly both Anderson *et al* (1981b) and Birky and Clarke (1981) report this correlation in their studies as an actual phenomenon rather than as a non-causal relationship.

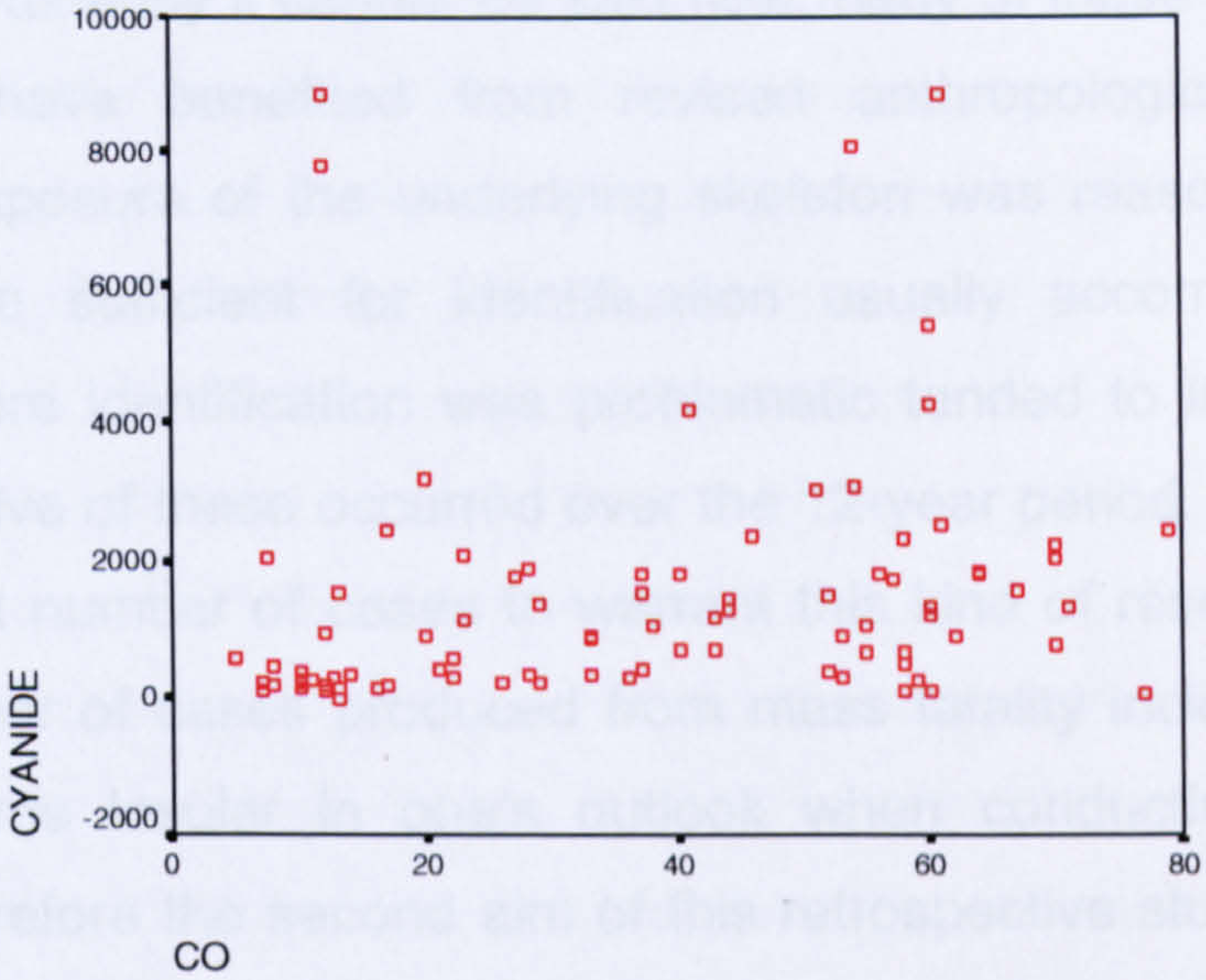


Figure 1.11 The Relationship between Cyanide (in micrograms) and Carboxyhaemoglobin (CO; in percentage in blood)

The first aim of this retrospective study into fire-related deaths was to see if the results and conclusions of this doctoral research would have an application beyond the field of mass disaster management. Between 10 and 26 people have been killed by fire each year since 1991 in the study region. Not all of these cases would require the assistance of a forensic anthropologist. However of these, 33 individuals suffered burn injuries. The total value rises to 52 if those who died from burn injury or inhalation are included. Unfortunately it cannot be said how many of these cases with burn injury would have benefited from revised anthropological identification techniques. Exposure of the underlying skeleton was reasonably common, but soft tissue sufficient for identification usually accompanied it. The occasions where identification was problematic tended to involve vehicular incidents. Twelve of these occurred over the 12-year period. This is arguably not a sufficient number of cases to warrant this kind of research alone, but the vast number of cases produced from mass fatality incidents does. It is application beyond the field of mass disaster management. Between 10 and 26 people have been killed by fire each year since 1991 in the study region. Not all of these cases would require the assistance of a forensic anthropologist. However of these, 33 individuals suffered burn injuries. The total value rises to 52 if those who died from burn injury or inhalation are included. Unfortunately it cannot be said how many of these cases with burn injury would have benefited from revised anthropological identification techniques. Exposure of the underlying skeleton was reasonably common, but soft tissue sufficient for identification usually accompanied it. The occasions where identification was problematic tended to involve vehicular incidents. Twelve of these occurred over the 12-year period. This is arguably not a sufficient number of cases to warrant this kind of research alone, but the vast number of cases produced from mass fatality incidents does. It is easy to become insular in one's outlook when conducting experimental research. Therefore the second aim of this retrospective study was to place this research within a social context. This can be achieved by reflecting on Figures 1.3 to 1.11. These graphs and charts do not just present points of data and statistics. Each value, percentage and plot relates to a person and to a family. This study had a sample size of 174. This means that 174 individuals have died as a consequence of fire. The social context is clear, and should inform the rest of this piece of work.

OneThree The Archaeological Context

OneThreeOne Archaeological Aspects of Burned Human Remains

Cremated bone is not an uncommon find during archaeological excavations. Indeed, in excess of some ten thousand cremation burials have been excavated in Britain during the last century (McKinley, 1998). In addition, as Downes (1999), McKinley (2000) and Oestigaard (2000) have stated, it should not be forgotten that cremated bone is the product of a series of ritualistic acts concerning the disposal of the dead. Nonetheless, there are still two common, although incorrect, assumptions that perpetuate in archaeology. The first is that cremated material holds little in the way of useful information. The second, highlighted by Downes (1999) and McKinley (1998), is that contexts containing cremated bone represent burials. The general acceptance throughout the discipline of the first assumption has resulted in the fact that few cremation cemeteries have been analysed, and fewer still are published. Exceptions to this are papers by Baby (1954) who examined the cremated remains and practices of the Hopewell people, Binford's (1963) study of three Late Archaic cremation sites in Michigan and several reports by McKinley including the classic study of the Spong Hill Anglo-Saxon cremation cemetery (McKinley, 1994). However this assumption is incorrect for two reasons. First because, as workers have already highlighted and as will be explained during the course of this piece of work, much anthropological information can in fact be extracted from the burned material – whether this is biological (for example McKinley, 2000; Mayne Correia, 1997; Thompson, 1999) or social (for example, Oestigaard, 2000; Richards, 1987; Richards, 1988) in nature. Second, there is a wealth of non-anthropological information that can be interpreted from cremated material and the context from which it has been removed. Although it must be noted that there are fundamental problems with interpreting archaeological evidence (Oestigaard, 2000), information on pyre sites, pyre technology and social views towards death can be learned from the osseous material, the remains of the pyre structure and the pyre debris (McKinley, 1998; McKinley, 2000; Oestigaard, 2000). The second erroneous assumption is a function of language. McKinley (1998) argues that workers tend to use the word 'cremation' to mean the cremation burial and grave rather than the ritualised event it represents. She continues by stating that this merely serves to reduce cremation deposits to isolated objects rather than upholding the view that they are the stratified remains of ritualised events (McKinley, 1998). Problems with the language and terminology used within the study of cremated material has also been highlighted by Thompson (1999) who suggested that the simplest solution to this problem may be to create a standardised glossary for all to use, thereby lessening misinterpretation. Mayne Correia and Beattie (2002) produced a table of terms and their associated definitions in response to this problem, however the definitions that they use are plagued with subjective terminology that only results in uncertainty with regard to the classifications that they suggest. It is however, a significant step in the right direction.

The importance of cremated faunal remains should not be overlooked either. Unlike with human remains, the emphasis here is not often on understanding mortuary rites. Work by Bond (1996) has examined the significance of animal bone as an offering in Anglo-Saxon cremations. Significantly with faunal remains, knowledge regarding cooking practices, economic strategies and the relationship between humans and fauna can be extracted (Bond, 1996; Gilchrist and Mytum, 1986; Lyman, 1994; Roberts *et al*, 2002; Worley, 2003). As a result of this information, issues concerning social roles, spatial relationships and hunting practices can be inferred. Nicholson (1995) concludes in her paper on the value of burned fish bones to archaeology that there are analytical problems and issues with gathering information from burned bone, but that useful information can nonetheless be gleaned. For example, she argues that burning as a result of cooking can be distinguished from burning due to waste disposal. Her differentiation does rely on colour change, which is notoriously inefficient when depended upon for answering any burning-related question (see Chapters 2 and 5 for details).

As the potential of burned remains are slowly being realised, the material is being taken along and studied in new and exciting directions. Recently, archaeologists have been studying cremated, burned and heat-altered human material in order to fully comprehend events as diverse as cannibalism in south-western Colorado (Marlar et al, 2000) and the victims in Herculaneum of the AD79 eruption of Mount Vesuvius (Mastrolorenzo *et al*, 2001).

OneThreeTwo An Archaeological Perspective

The current practice for gathering information concerning cremated remains from archaeological contexts is well established. It is simply the routine of sieving the suspected remains, whether in isolation or from the soil in which they are contained, to collect any hard tissue present. Subsequently these remains are further separated into size and body part category and weighed. The calculating of each size category as a percentage of the total cremation weight is also advocated since it is suggested that this provides a more representative view of how fragmented each cremation is (McKinley, 1994b). This has been practised and advocated in a number of archaeological case studies (McKinley, 1994b; McKinley, 2000b). One over-riding question remains however: just how useful a practice is this? Sieving the sediment containing the hard tissue is vital for the collection of as much of the remains as possible. But there seems to be little point in weighing each size fraction afterwards. Fragment size cannot provide information concerning the identity or the osteological profile of the deceased as it is mainly a function of external factors such as pyre type, frequency of stoking, collection technique, weather and so on (see Chapters 6 and 7). None of which, it should be added, can be currently reliably predicted from the fragmented remains since there are too many variables to contend with and to date, no models have been postulated. The weighing of burned remains is discussed later (Chapter 3) but it should be said that using weight as an indicator of minimum number of individuals is extremely dubious since post-burning weight is dependent on, again, a whole host of unknowable factors. In addition to which there is great disagreement concerning the accuracy of proposed weights for burned remains (Chapter 3) and the fact that, although standardised, the sieve sizes adopted are entirely arbitrary (Maat, 1997). It would appear then, that from an archaeological perspective, there is a great demand for accurate data, models and conclusions regarding the process of heat-induced transformation of the hard tissues of the human body in order to better interpret archaeological remains and their contexts.

OneFour Conclusions and Thesis Outline and Structure

The case studies detailed in Sections 1.2.4, 1.2.5 and 1.3.2 illustrate examples of contexts that burned human remains are discovered. It can be seen already that biological anthropology can play an important role in helping to allow for a full understanding and comprehension of these contexts. The study of cremated and burned human and faunal remains has potentially a great deal to offer those working in both the forensic and archaeological spheres. The use of the word 'potentially' is significant however. Workers can only benefit from analysing burned material if they have an understanding of the process of heat-induced transformation that the body undergoes when burned and the influence of these physical and chemical changes on the methods of investigating the material.

It is now appropriate to detail the structure of the thesis as a whole since it is pertinent to the full appreciation of this chapter and the entire following body of work. Chapter 1 has succeeded in discussing the context in which one tends to find burned human remains. As the results and conclusions of this research are relevant to both the forensic and archaeological sphere, both of these contexts have been examined. In the process of this discussion, the justification and the need for this new and novel research has been presented.

Chapter 2 examines the literature surrounding the process of heat-induced transformation of the human body. This chapter is important since it will allow the reader to place the results of the experimental studies within the entire process of heat-induced bodily change. Chapter 3 follows on directly from the discussion in Chapter 2 as it details the problems and issues surrounding the collection, analysis and storage of burned human remains from both forensic and archaeological contexts. This is of particular relevance to anthropologists who will progress to examining burned human remains in the field themselves. In addition this chapter is important as it again provides a context for the discussion and conclusions of Chapters 10, 11 and 12.

Chapter 4 discusses the pilot study and the initial development and ultimate justification of the experimental protocol. Discussion of previous methodology is presented here, as is a commentary on the debate surrounding actualistic versus experimental cremation studies.

The format of the next five chapters requires explanation. Chapters 5, 6, 7, 8 and 9 provide the introductions, methodologies, results and discussions for the examination of each of the heat-induced changes in bone. It was decided from the onset of this research not to use the traditional 'Introduction-Methodology-Results-Discussion' format for this thesis. Instead each heat-induced osseous transformation is examined in its own chapter, each with a self-contained introduction, methodology, results and discussion. There are therefore chapters on the examination of heat-induced change in colour (5), fracture patterns (6), mechanical strength (7), microscopic architecture (8) and dimension (9). This is because to do otherwise would take the focus off of the heat-induced phenomena and place it on the experiments. The philosophy of this study is that the experiments and scientific advancements used and developed here are merely one avenue in pursuing the broader goal of understanding heat-induced change and are not the focus of the study themselves.

Chapter 10 contains the discussion of the results and conclusions of the previous chapters and shifts the focus of the thesis from the nature of heat-induced change to the consequences, and implication for forensic science and anthropology, of these changes.

All research, and especially that which utilises human material, have legal and ethical implications. This, combined with the weight this research has placed on actual post-research application has resulted in Chapter 11. Chapter 11 discusses the legal and ethical considerations of dealing with burned human remains, with a natural emphasis on research conducted using burned human tissue.

Chapter 12 contains the conclusions of this research project, and marks the final chapter of this thesis.

Two The Transformation and Destruction of the Human Body by Fire

TwoOne Introduction

As can be seen from Chapter 1, burned human remains can be found in a variety of situations. Although these situations can vary temporally, regionally and contextually, one factor remains consistent – the human bodies have been transformed as a result of burning. The situations may differ but the degenerative process that the bodies experience is the same, and all human bodies, when heated and burned, essentially change in the same way. This chapter details those changes, and details them in a manner that has not been fully or satisfactorily attempted before. The heat-induced destructive process is explained from the outside inward, that is, from the skin to the internal organs. Importantly however both the soft and hard tissues are described so that a complete understanding of the changes experienced by the entire body is achieved. Existing literature presents the body as some sort of dichotomous entity and focuses solely on either the changes of the soft tissue or the hard tissue. This is an unhelpful concept as the human body is constructed of both types of tissue, and both tissues exist in a symbiotic relationship, which in turn will influence how each tissue will respond to burning. Section 2.4 discusses this notion in greater detail.

Before continuing, it is worth highlighting that burning can take several forms. In addition to burning by fire, which is of interest here and is referred to as a dry burn, it is possible to suffer moist thermal burns, electrical burns and cold burns. Moist thermal burns are the result of contact with hot liquids or steam, and are also known as scalds. A scald often resembles a first degree burn (see below) in that there may be reddening, desquamation and blistering but unlike in a dry thermal burn the outline will correspond to the limits of contact with the heated fluid (Knight, 1991; Knight, 1997). If severe enough a moist thermal burn can result in a macerated epidermis, swelling, emission of serum, infection and death from physiological shock, the disturbance of fluid and electrolyte levels and as a consequence of respiratory tract injury (Di Maio and Di Maio, 2001; Knight, 1991). Not all hot moist fluids produce scalds; if hot enough, such as with molten metals, the damage to the body will resemble that of dry burns (Knight, 1991; Knight, 1997). Electrical burns occur when an individual forms part of an electrical circuit, therefore allowing the flow of electrons through their tissues. The burn will occur at the place of entry or exit of the electrical current and tends to be a discrete focal point, although multiple and more extensive burns may be present (Di Maio and Di Maio, 2001; Knight, 1997). Death from electrocution usually involves ventricular fibrillation (due to the effect of the current on the myocardium), respiratory paralysis (due to the effect of the current on the diaphragm and intercostal muscles) or primary brain-stem paralysis (Knight, 1997). Unlike with dry or moist burns, the electrical burn itself does not result in death. Burns from chemicals (Di Maio and Di Maio, 2001; Telmon *et al*, 2002), microwaves (Di Maio and Di Maio, 2001) and radiation can also be incompatible with survival.

Fire damage to the body is classified using a system whereby the extent of damage is placed into one of three stages. The first stage is known as first degree burns. Burns in this category are restricted to the epidermis of the skin. They involve erythema (reddening of the skin), blistering, dilatation of the capillaries and transudation of fluid into the tissues resulting in swelling (Knight, 1991; Knight, 1997). Second degree burns involve the full thickness of the skin. Coagulation or charring of the epidermis and the production of a central area of necrotic tissue will occur (Knight, 1991). The central area of necrotic tissue will be surrounded by first degree burns, an area of hyperaemia, or both, and will eventually come away from the skin allowing the epidermis to develop in from the margins (Knight, 1991). The injury cannot heal without scarring (Knight, 1991). The final category of damage is third degree burns. Here tissues deeper than the skin are involved (Knight, 1991; Knight, 1997). These deeper tissues would include muscle, bone and the internal organs. The extent of a burn injury is not just dependent on the temperature of the fire, but also on the duration of contact with the body and on the ability of the body to conduct excess heat away from itself (Knight, 1991). With regard to temperature a perhaps surprisingly low value is required to damage the soft tissue. It is quantity not quality that is significant when it comes to assessing ones chances of surviving a burn injury. A large area of first degree burns is more threatening to survival than a localised third degree burn injury (Knight, 1991). In an average man, greater than thirty percent involvement of the total body surface is usually incompatible with survival (Cooper et al, 1983; Knight, 1991; Knight, 1997), but this has been placed as low as twenty percent (Baxter, 1990). This value is lower in the elderly and higher in the young (Knight, 1991; Knight, 1997).

TwoTwo The Soft Tissues

Changes to the soft tissues, which are first to encounter any burning, will therefore be discussed first.

TwoTwoOne Skin

The integumentary system, or skin, will likely be the first of the tissues, soft or hard, to encounter a fire. Skin is formed of two layers, the epidermis and dermis, which contain a variety of specialised derivatives including nails, hair, sebaceous and sweat glands and apparatus of bloodflow (Abrahams *et al*, 1998). The application of heat to the skin of the human body will initiate a reddening of the tissue. This reddening, or erythema, is the result of dilation of congested vessels in the dermis (Di Maio and Di Maio, 2001) and is often accompanied by the formation of blisters. A red area around the margins of the blister, usually between five and twenty millimetres in width, will be present (Knight, 1991). Erythema and blistering may be accompanied by desquamation of associated necrotic epidermal cells (Di Maio and Di Maio, 2001). When they finally burst, the blisters possess a red base and an erythematous areola (Knight, 1991). When collapsed, sheets of epidermis lie across this red base. Heat-induced blisters may be present in the main burn or along the periphery, and as a single large feature or as a collection of smaller blisters (Knight, 1991; Knight, 1997). As well as being a function of blistering, localised swelling can result from a build-up of steam and evaporated gases within the dermal layers (Eckert *et al*, 1988; Evans, 1963). More severe burning may cause the skin to stiffen due to irreversible protein coagulation, and become a yellow-brown colour with a leathery texture (Evans, 1963; Knight, 1991). This is associated with coagulation necrosis of both the epidermal and dermal layers of skin (Di Maio and Di Maio, 2001). In addition, serum will be ejected from the skin (Knight, 1991). In situations where the skin itself actually ignites, the subcutaneous fat will act as a fuel and prolong burning (De Haan and Nurbakhsh, 2001). The skin will then become black and brittle (Knight, 1991). Continued burning will cause the skin to split due to heat contracture (Di Maio and Di Maio, 2001; Knight, 1997). These splits may be misinterpreted as being the result ante-mortem trauma. Finally, the skin can completely disintegrate. It is unusual for the entire body surface to experience the same levels of damage. Areas closer to the fire will suffer greater changes, whereas other areas may be offered protection from clothing or from walls and the floor. Research (Klein *et al*, 1995) has also shown that significant damage to the skin can affect other parts of the body. For example, involvement of forty percent of the total body surface of an individual will not only cause the effects discussed above, but will also cause a reduction in the extent of bone formation. This reduction is not associated with a reduction in bone resorption, thereby causing a risk of bone loss and lowered bone density (Klein *et al*, 1995).

It is entirely possible for these physical heat-induced changes to occur post-mortem as well as ante-mortem. Distinguishing the two has important medico-legal ramifications. The traditional distinction has been the presence of a vital reaction in ante-mortem heat injuries. Knight (1991; 1997) dismisses this view and argues that in his experience this reaction can also occur post-mortem. Even a red base and erythematous areola are not confined to just ante-mortem blistering (Knight, 1991). Biochemical differences would therefore seem a more reliable determinant than gross physical appearance. It is suggested that protein and chloride levels may be higher in the fluid of ante-mortem blisters, but this has yet to be rigorously and satisfactorily tested and scientifically verified (Knight, 1991; Knight, 1997). Because of the fact that similar changes occur before and after death and that subtle ante-mortem injuries can be masked by post-mortem changes, distinguishing between ante- and post-mortem blistering cannot be performed with any confidence. It should be noted that, as expected, the process of embalming will increase the time taken to burn a human body (Evan, 1963).

Briefly worthy of note is the phenomenon of spontaneous human combustion. This is the peculiar spectacle of intensive fire damage to a human individual with minimal damage to the surrounding furnishings (Christensen, 2002; De Haan and Nurbakhsh, 2001). The typical victims are elderly women (Christensen, 2002) which is in contrast to the age and sex profiles seen in Section 1.2.4. Reports of spontaneous human combustion are not only a Western European/Northern American feature but are also apparently on the increase (Christensen, 2002) – although this last point could be a function of better reporting. Research has shown (De Haan and Nurbakhsh, 2001; Richards, 1977) that rather than people simply bursting into flames for no apparent reason, an external flame source must be applied to the body for a prolonged period of time which causes the subcutaneous fat to render. This impregnates the clothing of the individual and a candle effect begins. Since an adequate supply of fat is required to sustain the slow-burning fire, those portions of the body with limited subcutaneous fat (such as the distal limbs) will not support continuous combustion and are often recovered at the scene (De Haan and Nurbakhsh, 2001). Criticism of De Haan and Nurbakhsh's (2001) study centres on the fact that they did not manage to destroy the bone, a vital defining feature of spontaneous human combustion (Christensen, 2002). Christensen's (2002) experimental study showed that for this to occur, the victim must also have osteoporosis. This is in keeping with the victim profile. Such fires are thankfully rare as they require several factors to be present: adequate fuel, an external ignition, an adequate material to act as a wick, time and a disease to weaken the skeleton (Christensen, 2002; De Haan and Nurbakhsh, 2001).

TwoTwoTwo Keratinous Tissue

Keratinous tissue includes the hair and nails of the body. Hairs are filamentous keratinised structures and nails are constructed of horizontal layers of compacted, anucleate, keratin-filled squames. Keratin is protein-based, and comes as both acid and base varieties. When heated to low temperatures, hair will singe and become ‘clubbed’. ‘Clubbing’ is where the distal end of the hair melts and then subsequently resolidifies upon cooling to create a terminal blob on the hair shaft (Evans, 1963; Knight, 1991). These features often contain many minute air bubbles (Evans, 1963). All body hair, including eyelashes, eyebrows, nasal, pubic and axillary hair may be affected in this way (Knight, 1991). In cases of extreme burning, hair can become reddish and stiff (Eckert *et al*, 1988) and eventually burn completely away.

TwoTwoThree Muscle Tissue

Beneath the skin lies the body's muscle tissue system. At low burning temperatures the muscles may become pale and brown and have a ‘part-boiled’ appearance (Knight, 1991). As burning continues, the heat from the fire causes the muscle fibres to dehydrate and the proteins to denature resulting in the shortening of the muscles themselves (Di Maio and Di Maio, 2001; Evans, 1963; Knight, 1991). Although the percentage contraction of the flexors and extensors of the limbs are similar, the larger size of the flexors means that their pull exceeds that of the extensors which results in the body adopting a position of general flexion (Knight, 1991). This position is known as a pugilistic attitude. This pose is a post-mortem phenomenon, as the deep heating effects required to produce pugilistic attitude in an individual are incompatible with survival (Knight, 1991). Temperatures of around 200°C to 250°C (Baxter, 1990) or burning for ten minutes in a crematorium (Bohnert *et al*, 1998) are sufficient to initiate a pugilistic pose. Instant thermal coagulation of the muscles is possible in cases of extreme and sudden heating such as from an advancing volcanic nuée (Baxter, 1990). Other muscles also contract and cause the body to twist and contort. For example the reduction in size of the paraspinal musculature may result in marked opisthotonos (Knight, 1991). A lack of pugilistic attitude in burned remains may indicate that the muscles were destroyed quicker than they contracted (Evans, 1963). The pugilistic attitude is a perfectly normal physical response to burning and is not related to any ante-mortem activity, such as fighting. Acknowledging this point however, the ante-mortem positioning of the corpse will influence a pugilistic attitude in terms of extent and exact pose. Continued high-temperature burning will finally lead to the splitting of the muscles and muscle walls (Mason, 1962).

TwoTwoFour The Internal Organs

The internal organs are particularly susceptible to heat damage through the respiratory tract and after the skin and muscles have been removed. Although the skin and muscles may offer little protection from injury and the internal organs can still be affected by heat even when these two outer systems are in existence.

Unlike the inhalation of the products of combustion which essentially result in death by poisoning, and is discussed in Section 2.2.5, the inhalation of hot gases can cause death as a consequence of direct physical damage to the respiratory tract. At the upper end of the respiratory tract, the tongue, pharynx and glottis may be scorched while the mucosa becomes blanched grey-yellow (Knight, 1991). If the heat is too low to cause actually burn injuries, the interior surfaces of the larynx, trachea and main bronchi will either become inflamed and blanched or inflamed and reddened (Knight, 1991). Burn injury to the larynx can result in fatal obstructive oedema (Di Maio and Di Maio, 2001). Deeper bronchial changes can include bronchiolitis, the production of copious mucus and the formation of fibrin-like pseudo-membranes (Harrison, 1966). In addition, these features may act as a barrier to trap bacteria (Harrison, 1966) further increasing the chances of infection and death. The response of the lungs to burning is the formation of pulmonary oedemas. These may occur even when there is no obvious damage to the bronchial tree (Knight, 1991). Burns to the respiratory tract are relatively rare however, as the upper respiratory tract rapidly conducts heat from inspired air away (Baxter, 1990; Di Maio and Di Maio, 2001). When the burns are present they are usually caused by steam, which contains 4000 times more heat than air (Anderson *et al*, 1981; Di Maio and Di Maio, 2001). In addition to damage by heat, the respiratory tract may further suffer from the effects of soot deposition. If an individual was breathing while the fire was active, then soot will penetrate beyond the larynx and coat the trachea and lungs, which may also result in pulmonary oedemas (Knight, 1991). These pulmonary oedemas are a consequence of injury at the endothelial-epithelial junction, alveolar collapse due to reduced production of surfactant and bronchocilliary injury (Di Maio and Di Maio, 2001). The stomach may also be coated in soot (Mason, 1962), although the vector will be swallowing not respiration. Ninety-one percent of the victims examined in Anderson *et al*'s (1981) study of fire-related deaths in Glasgow suffered soot penetration, and in seventy percent of individuals the soot had travelled to the bronchi. The percentage of those with soot penetration of the respiratory tract in the retrospective study undertaken as part of this research was fifty-seven (see Chapter 1), although forty percent of the deceased did not have this feature recorded. The extent of soot penetration is a useful indicator of the state of the individual at the time of the fire. If they were alive when the fire was burning then there may be soot present deep into the lung spaces, however no significant amount of soot will penetrate beyond the larynx if the individual was not breathing (Knight, 1991; Knight, 1997). The absence of soot particle does not mean that the individual was definitely dead when the fire began (Di Maio and Di Maio, 2001; Knight, 1997; Mason, 1962). Explosions, flash fires and conflagrations in vehicles produce very little soot.

The viscera are also vulnerable to heat-induced damage. This is especially true once the surrounding skin and muscle have been destroyed, which Bohnert *et al* (1998) demonstrated may occur in only thirty minutes in ideal (crematorium) conditions. This rapid occurrence seems to contradict Evans' (1963) statement that the burning of the internal organs is a slow process. Evans (1963) may be referring to real-life situations however, which are far from the optimum burning conditions created in crematoria. As well as being destroyed directly by fire, the surrounding skin and muscle may be damaged by the swelling of the abdominal cavity due to the collection of steam and heat-induced gas expansion (Bohnert *et al*, 1998; Evans, 1963). The heat will cause coagulation of the organs so that they may become unrecognisable as distinct organs. Charring may also occur (Bohnert *et al*, 1998; Di Maio and Di Maio, 2001). Before full destruction, the internal organs will shrink, become spongy and adopt a net-like structure (Bohnert *et al*, 1998).

Intense heat may also damage the brain. Burning forces the dural layers to shrink which constricts the brain and squashes it into a dense mass (Knight, 1991). The resulting tension may cause the dura to split, allowing the brain tissue to ooze into the space within the cranium (Knight, 1991). Continued heating may convert this neural mass into a frothy paste (Knight, 1991).

The severity of injury to the internal organs may mean the development of further complications some time after the initial fire. Harrison (1966) notes that sustained hyperventilation, mild hypoxemia, alkalosis, pulmonary inflammation, dyspnea and sternal retraction are all possible physiological post-fire occurrences. Baxter (1990) also notes the potential danger to survival of subsequent respiratory problems, but also highlights the risks from developing infection of the damaged tissues. Added to these the increased energy cost of breathing and survival (Harrison, 1966) and it is easy to appreciate the high numbers of those victims who die in hospital even after surviving the fire.

TwoTwoFive Blood

There are two main factors of interest with regard to the influence of burning on the blood of the human body. First, there are the physical changes that blood undergoes as a consequence of heating. Second, there are the toxins produced by burning that are absorbed into the blood system and taken around the body at varying, often lethal, expense.

When heated, the red blood cells breakdown as a consequence of the heat, anoxia and osmotic shock due to fluid loss through the burn wounds

(Anderson *et al*, 1981). In addition, the haemoglobin itself is reduced to haematin (Evans, 1963). This all means that the body has a much reduced oxygen carrying capacity as well as an electrolytic imbalance due to the release of potassium from the red blood cells (Anderson *et al*, 1981). Venous congestion is not uncommon in these situations (Mason, 1962). Although the components of blood can be clearly destroyed by burning, albumin blood proteins are still detectable after cremation. Cattaneo *et al* (1994) demonstrated this was true of both modern experimentally burned bone and cremated archaeological material. However an important consideration and a substantial doubt remains regarding their study. If the albumin survived for only 10 minutes at 300°C in the experimental aspect of their study, one wonders how so much was removed from the archaeological cremations. Not only would the proteins need to endure hundreds of years of subterranean storage, but also the seemingly thorough cremation process. That is to say, one would expect that the temperatures that the pyres achieved to have surpassed 300°C in order to achieve the degree of tissue destruction witnessed and the full colour change from natural to white. This latter point in itself implies that the organic component has been removed (see Chapter 5). In addition, Cattaneo *et al* (1995) themselves state that bone integrity is vital for protein survival. This is unlikely in burned remains (see Chapter 6). Cattaneo *et al* (1994) only present a preliminary study, and further work is obviously required to clarify this issue.

One of the most discussed effects of the heating of the blood system (see for example, Di Maio and Di Maio, 2001; Eckert *et al*, 1988; Knight, 1991; Knight, 1997) is the production of a heat haematoma. A heat haematoma is where the cranium becomes so hot that the blood essentially boils out of the diploic space, via the emissary venous channels, or out of the venous sinuses and collects between the skull and the dura (Knight, 1991; Knight, 1997). The collected blood is usually spongy, due to the presence of gas bubbles, and brown in colour (Di Maio and Di Maio, 2001; Knight, 1991; Knight, 1997). An understanding of the aetiology of this feature is important for those working in medico-legal contexts, as the heat haematoma closely resembles a traumatically-induced extradural haematoma. The two can be distinguished because a heat haematoma will often have evidence of burning on the cranium above the haematoma, although heat-induced fractures can mislead (Knight, 1997), and will have a similar level of carboxyhaemoglobin to the rest of the blood in the deceased individual (Knight, 1991; Knight, 1997). If the haematoma was a genuine ante-mortem injury it would have formed before carbon monoxide was taken into the blood stream, and would therefore have a much lower level than the rest of the body.

There are two main toxins that are produced by burning and are readily taken up by the human body. These are carbon monoxide and cyanide. Carbon monoxide (CO) is produced from combustion in a low oxygen environment where there is simply not enough free oxygen to form the double oxygen component of carbon dioxide. Slow burning fires with little flame are traditionally thought to produce more carbon monoxide (Knight, 1991). Conversely rapid flash fires and explosions produce very little. Carbon monoxide is so dangerous to life because it has a significantly greater affinity to haemoglobin than oxygen. Lowry *et al* (1985) state that the affinity is 250 times greater. It therefore binds preferentially with haemoglobin at the expense of oxygen and renders the haemoglobin unavailable for oxygen transport. Carbon monoxide also displaces oxygen from its haemoglobin partner (Terrill *et al*, 1978), has a half-life of four to five hours (Anderson *et al*, 1981b) and when bound as carboxyhaemoglobin is 300 times more stable than oxyhaemoglobin (Anderson *et al*, 1981a). As well as binding to haemoglobin, carbon monoxide also attaches to myoglobin in muscle tissue and to intracellular cytochrome oxidases (Lowry *et al*, 1985). Consequently the various organs of the body do not receive the required amount of oxygen for successful respiration, and the body suffocates. Conversion of only forty percent of oxyhaemoglobin to carboxyhaemoglobin is incompatible with survival (Knight, 1991), although many put this value at fifty percent (Anderson *et al*, 1981a; Birky and Clarke, 1981; Gormsen *et al*, 1984; Terrill *et al*, 1978). This value can be as low as twenty-five percent in the old and debilitated (Knight, 1991), or three to five percent in those with conditions that impede the oxygenation of the tissues of the body, such as anaemia and lung and heart disease (Birky and Clarke, 1981; Eckert, 1981). Fifty-one percent of those who died from fire-related deaths studied by Anderson *et al* (1981) died from only carbon dioxide poisoning, this value was sixty percent in those studied by Birky and Clarke (1981), but less than five percent in the retrospective study performed here. That said, in sixty-eight point four percent carbon dioxide contributed to death. This value is lower than the other studies either because of the slightly unspecific nature of the post-mortem reports used here or because these previous studies have failed to distinguish fatal carbon monoxide poisoning from the simple presence of carbon monoxide. Carbon monoxide poisoning can be seen from a visual examination of the remains. The muscles, internal organs and blood all become cherry-red in colour (Di Maio and Di Maio, 2001; Eckert *et al*, 1988; Knight, 1991; Knight, 1997). The absence of the cherry-red colouring does not mean that lethal levels of carbon monoxide are not present in the body (Di Maio and Di Maio, 2001; Lowry *et al*, 1985). Hydrogen cyanides are also extremely lethal products of combustion. They are produced when plastics, upholstery, varnishes and other synthetic materials are burned. Cyanide reacts with the trivalent iron of cytochrome oxidase to form a cyanide complex that inhibits cellular respiration, known as cytotoxic hypoxia, and reduces the electrical activity of the brain (Anderson and Harland, 1982; Birky and Clarke, 1981; Lowry *et al*, 1985). The inhibition of cellular respiration is similar to that caused by the uptake of carbon monoxide as described above. However it is argued by Di Maio and Di Maio (2001) that cyanide poisoning is rarely a cause of death in fire-related incidents. Not all cyanide in burned human remains may have originated from the fire. Cyanide can be produced naturally during life (Anderson and Harland, 1982) and in significant quantities as part of the process of decomposition (Di Maio and Di Maio, 2001; Knight, 1991; Terrill *et al*, 1978).

The uptake of carbon dioxide creates a biological feedback loop. The inspiration of carbon dioxide increases the frequency and depth of respiration (Gormsen *et al*, 1984) which in turn draws more carbon dioxide into the body. Unfortunately it is not possible to demonstrate the presence or absence of carbon dioxide or oxygen in autopsy material (Gormsen *et al*, 1984), so this means that this form of fire-related death is often overlooked. Hypoxia is not only caused by the removal of oxygen by combustion or the eviction from the area by the products of burning. Tracheobronchial occlusion and circulatory collapse will also inhibit the uptake and distribution of oxygen around the body (Harrison, 1966).

As with soot penetration, this particular feature of fire-related death can be an extremely useful indicator of the condition of the deceased while the fire was burning. The presence of a higher percentage of carboxyhaemoglobin than would be expected in a smoker, which is five percent (Knight, 1991), or a higher level of cyanide, indicates that the deceased was breathing and therefore alive while the fire was developing. Airborne toxins such as carbon monoxide and cyanide are extremely common causes of death in fires (see Chapter 1), and most victims of fire-related deaths have succumbed to these poisons before the flames of the fire have actually reached their bodies.

Other toxins found in the blood of victims of fire-related death include sulphur dioxide, nitrogen dioxide, hydrogen chloride, aldehydes and various organic compounds (Anderson *et al*, 1981; Eckert *et al*, 1988; Lowry *et al*, 1985; Terrill *et al*, 1978).

TwoTwoSix Deoxyribonucleic Acid

Considering the importance of DNA in the realm of human identification, and the vital role it would play in mass disaster management situations, it is extremely surprising and concerning that very little research has been conducted into the consequences of burning the human body on the double-helix structure. Questions regarding the accuracy of DNA identification of human remains following high temperature incidents have yet to be fully investigated. These questions are especially pressing considering that heat is a common method of denaturing DNA in the laboratory (Easteal *et al*, 1991). Polymerase Chain Reaction has the potential to be very useful for the study of DNA from burned bodies since it does not need the entire strand to function – it amplifies merely the shorter target sequence (Tsuchimochi *et al*, 2002) which is more likely to survive.

It should be noted first that the post-mortem stability of DNA is not consistent throughout the body. Good stability is maintained in muscle, but inconsistency is present in the blood (Bär *et al*, 1988). Similar trends may be true of heat-induced decomposition. Tomita *et al* (1984) argue that it is possible to successfully detect Y-chromosomes from human blood that has been extracted from severely burned bodies. Sajantila *et al* (1991) also found that burning may not necessarily negate DNA analysis. They state that successful analysis can be performed on the D1S80 and HLA-DQα loci and that sufficient quantities of DNA can be extracted from burned tissues (Sajantila *et al*, 1991). They also note that post-mortem blood yielded less DNA than muscle or bone marrow (Sajantila *et al*, 1991). In contrast, Duffy *et al*'s (1991) experimental study on human teeth found that it was only possible to determine the sex of an individual from their DNA if their tissues were heated to no more than approximately 100°C. Tsuchimochi *et al* (2002) found this temperature to be 300°C, but they only heated their samples for two minutes. In addition it is likely that enamel offers more protection to the DNA structure than soft tissue that surrounds the blood. Duffy *et al*'s (1991) work and Goodwin's (2002) discussion do indicate however, that protection of the tooth by alveolar bone and oral soft tissue can allow sex determination after burning at a higher temperature and for a greater duration than if the tooth is burned in isolation. Although Duffy *et al* (1991) produce interesting results, they state that one must not forget that their sample of human teeth were not burning *in vivo*, and therefore the specifics of the results may not be entirely true for real cases. In addition their sample size for their fleshed tests was only three sets of jaws.

The extraction of DNA from hard tissues is more time consuming and laborious than extraction from soft tissues (Sajantila *et al*, 1991). The extraction of DNA from ancient hard tissues is racked with problems and has been discussed at length elsewhere (for example, Brown, 2000). Nonetheless, the removal of DNA from ancient burned hard tissues has been attempted. Brown *et al* (1995) examined cremated remains from a Bronze Age cemetery cairn lifted from Bedd Branwen, Anglesey, for the presence of

DNA. They concluded that by using polymerase chain reactions it was possible to extract and amplify the cremated ancient DNA. One does have to question the resounding success that they achieved however, as extracting ancient DNA alone is difficult and slightly controversial, without the added and relatively unknown complications of the effects of burning on the DNA. As it stands, this is an enticing project that should be revisited in light of eight years of refined ancient DNA extraction techniques. Until then, this study should be accepted with caution.

TwoThree The Hard Tissues

This section of Chapter 2 concerns the heat-induced changes in the hard tissues of the human body. To be more precise, it concerns the fundamental heat-induced changes of the hard tissues rather than the manifestations of these changes. These manifestations, which depend on more basic structural changes for their origin, are discussed elsewhere. See Chapter 5 for a discussion of colour changes, Chapter 6 for a discussion of fracture pattern evolution, Chapter 7 for a discussion of changes in mechanical strength and Chapter 9 for a discussion of dimensional changes. These following chapters rely on Section 2.3 of this chapter for contextualisation. It is only from a position of full understanding of the primary-level, heat-induced structural changes of bone that these secondary-level changes can be fully interpreted. Once the soft tissue has been removed, the hard tissues are exposed directly to the heat and fire. As with the soft tissues, bone and teeth will undergo a number of changes. These changes are far from being fully understood, but a broad pattern can be seen from experimental and actualistic studies. It should be noted that it is not necessary for the soft tissue to be removed before heat-induced damage is done to the hard tissues, but they do offer a significant level of protection.

TwoThreeOne Bone: General Macroscopic Changes

Most of the macroscopic changes that burning induces in bone have been deemed of the secondary-level, and are discussed elsewhere. Chapters 5, 6, 7 and 9 are dedicated to specific macroscopic changes. Discussion of the aetiology of macroscopic changes is limited as they are a function of the changes at the primary-level, microscopic scale. It must be remembered at all times that hard tissues are a complexe material involving moisture, blood and bone marrow (De Haan and Nurbakhsh, 2001). As such any heat-induced transformations will be complex phenomena.

TwoThreeTwo Bone: General Microscopic Changes

The main microscopic primary-level stages of heat-induced bone degradation have been outlined and tabularised by Mayne Correia (1997). Table 2.1 is a reproduction of this summary. The importance of this table lies in the simplicity and effectiveness of its description of the complex changes that bone undergoes when it is burned.

Stage	Description	Approximate Temperature Range (°C)
Dehydration	Removal of Water	100-600
Decomposition	Removal of Organic Components	500-800
Inversion	Removal of Carbonates Conversion of HAP→β-tricalcium phosphate	700-1100
Fusion	Melting of crystals	1600+

Table 2.1 Stages of Heat-induced Bone Degradation (Mayne Correia, 1997)

It can be seen that bone, when heated, progresses through four stages of degradation. These four stages are analogous to the changes associated with the production of ceramics (Mayne Correia, 1997). The first stage is Dehydration. Here the hydroxyl- bonds break and both the loosely-bound water (physisorbed) and bonded water (chemisorbed) are lost (Mayne Correia, 1997). The Decomposition stage is when the organic components of the bone are removed by pyrolysis (Mayne Correia, 1997). The third stage is Inversion, and is identified by the loss of the carbonates (Mayne Correia, 1997). Associated with this is the conversion of the hydroxyapatite crystal structure to B tricalcium phosphate (Mayne Correia, 1997). The final stage is Fusion and is characterised by the melting and coalescence of the crystal matrix (Mayne Correia, 1997). Based on more recent literature and experiments, Thompson (1999) mildly revised this table, removing reference to the conversion of the hydroxyapatite, which was far from being accepted as the norm, and lowering the commencement temperature of the Fusion stage. Table 2.2 is a reproduction of this revised tabular summary.

Stage	**Description**	**Approximate Temperature Range (°C)**
Dehydration	Removal of Water	100-600
Decomposition	Removal of Organic Components	500-800
Inversion	Removal of Carbonates	700-1100
Fusion	Melting of crystals	1000+

Table 2.2 Stages of Heat-induced Bone Degradation (Thompson, 1999)

However, both of these tables suffer from the same major problems as summaries of the stages of heat-induced bone degradation. The implication of both Mayne Correia's (1997) and Thompson's (1999) tables is that these four stages are discrete entities. But they are not discrete; they are a continuum. As such, it is entirely possible for burned hard tissue to be experiencing more than one of these stages at a given moment. In addition, it is difficult to appreciate from Tables 2.1 and 2.2 the extent of the overlapping Temperature Ranges for each stage. As a consequence of these issues, Figure 2.1 has been devised.

The overlapping Temperature Ranges are now more obvious and much easier to appreciate, as is the notion of a continuum of change. The revision of this table is not complete however, and in Chapter 10 a final version is presented which takes into consideration the data and results collected from this study.

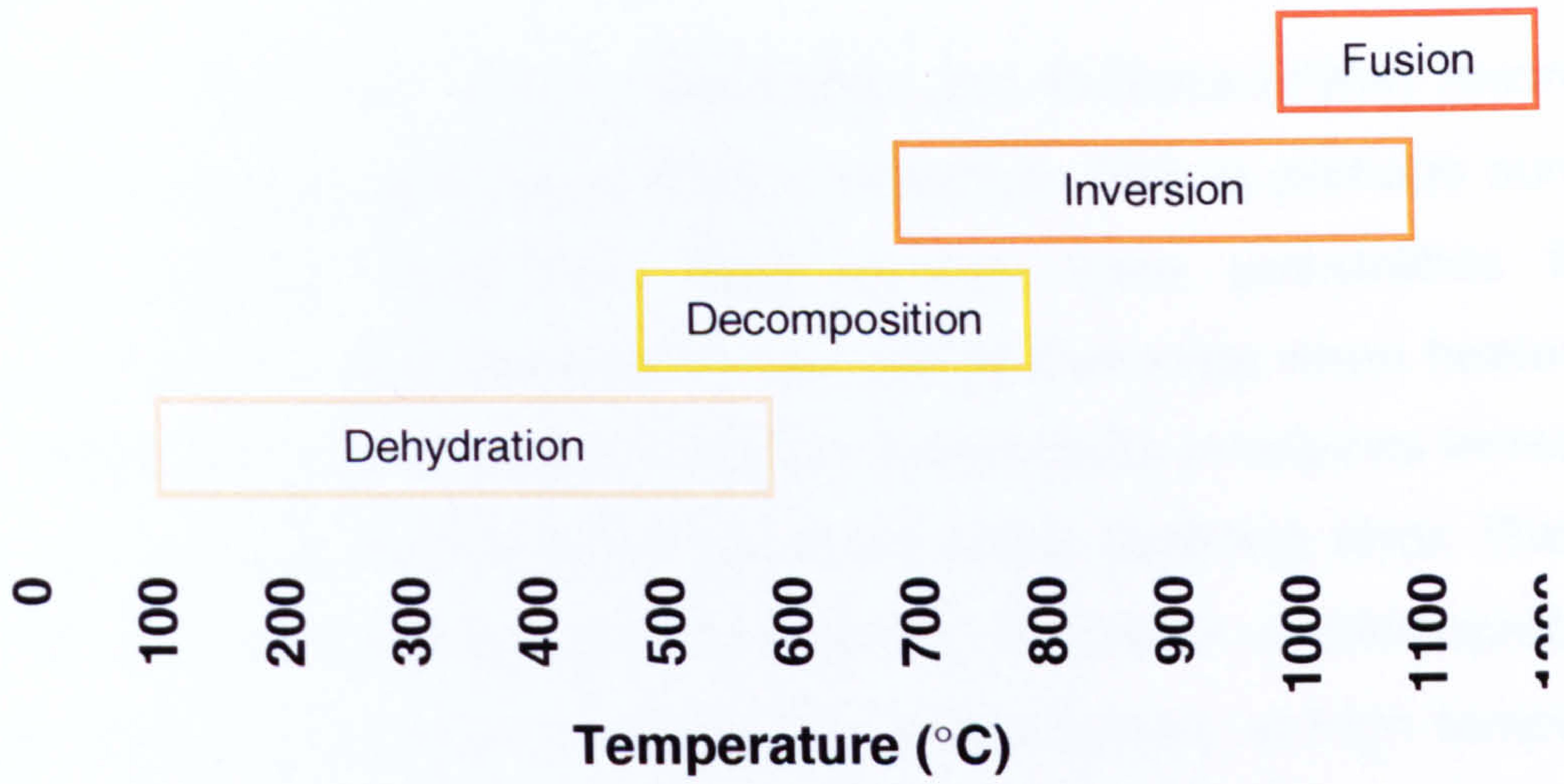


Figure 2.1 Stages of Heat-induced Bone Degradation

TwoThreeThree Bone: Changes in Histological Structure

With the possible exception of dehydration, most heat-induced changes to the hard tissue should potentially be histologically visible. Any changes at the histological level are not just interesting, but extremely significant, especially considering the histological section has an important role to play in estimating age at death (see Chapter 3).

Herrmann (1977) found that even after extensive cremation, human bone could maintain its microstructure. Bradtmiller and Buikstra (1984) concluded the same, and added that the structures were easily identifiable regardless of whether the surrounding soft tissue had been removed or not. Forbes (1941) recorded similar findings to a point, however he also noted that with continued burning the histological structure was completely lost. This was true of both the compact and cancellous bone (Forbes, 1941). This loss may be indicative of the bone entering the Fusion stage (Tables 2.1 to 2.3). Unfortunately Forbes (1941) does not provide details of the burning conditions of the bone and so without knowing the temperature and duration of heating this idea cannot be confirmed. Differences between the results of

Forbes (1941) and Herrmann (1977) and Bradtmiller and Buikstra (1984) are likely to be due to differences in experimental protocols and heating regimes.

Contrary to Herrmann (1977), Bradtmiller and Buikstra (1984) recorded an increase in osteon size rather than a reduction. This is perhaps surprising, and the authors state this. They provide three possibilities for this occurrence: bone may increase in size before shrinkage when heated, bone may shrink but microstructural rearrangement results in osteons increasing in size, and osteons do shrink but that there was a sampling error. They reject the first two and accept the third option. However a reinterpretation is required as can be seen from Chapter 9. In addition, at high temperatures microstructural remodelling will also occur (see Chapters 8 and 9). One feels that Bradtmiller and Buikstra (1984) reluctantly opted for the third option because they felt that there was no evidence to support first two suggestions. This evidence now exists.

More recent investigations by Nelson (1992) refute Bradtmiller and Buikstra's (1984) results and support those of Herrmann (1977). Nelson (1992) found that not only did osteons shrink as a result of heat, but that the shrinkage was statistically significant ($P<0.01$). Further he notes that canal dimensions increase relative to overall osteon dimension. Forbes (1941) also notes this relative increase. This may mean that either there is a decrease in the area of the osteon taken up by the concentric lamellae through shrinkage, there is a burning away of the soft tissue within the canal (Nelson, 1992), or there is flaking away of the central bone (Forbes, 1941). These explanations, along with the differences in experimental protocol and burning temperatures, may go some way towards explaining the differences between this study and that of Bradtmiller and Buikstra (1984).

Removal of collagen by heating will influence the nature of the histology of burned bone. As one would expect, at the appropriate temperatures bone collagen will denature and shrink (Bonar and Glimcher, 1970). However, this may not be irreversible. It has been shown that if the collagen is not completely destroyed, a period of cooling will allow the structure to return to pre-burning conditions (Bonar and Glimcher, 1970). The loss of collagen is not straightforward however, due to the mechanical stabilising effect of the presence of inorganic mineral in the collagen fibrils physically restricting their uncoiling and shortening (Bonar and Glimcher, 1970). Once this relationship is disrupted, the loss of the collagen will become increasingly rapid (Smith *et al*, 2002).

An area of current initial interest with regard to changes in bone histological microstructure is in attempting to quantify changes in pore size. This is discussed in greater detail in Chapter 8. Changes in osteological porosity necessarily relate to change in the physical structure of bone, which may be due to variations in the organic or inorganic components (Nielsen-Marsh and Hedges, 2000a). It is expected that during burial, macroporosity (pores of >4nm) will increase while conversely microporosity (pores of <4nm) decreases (Nielsen-Marsh and Hedges, 1999; Nielsen-Marsh and Hedges, 2000a; Nielsen-Marsh and Hedges, 2000b). Processes that mimic natural bone diagenesis, such as the action of acetic acid (Nielsen-Marsh and Hedges, 2000b) also cause these changes in porosity. It is accepted that heating bone also mimics natural bone diagenesis, so it is expected that similar changes in porosity will be seen.

TwoThreeFour Bone: Changes in Crystal Structure

Approximately seventy percent of bone is made up by the inorganic mineral component. This mineral component is comprised mainly of the calcium phosphate $Ca_{10}(PO_4)_6(OH)_2$, or hydroxyapatite (Posner, 1969). It is known that at high temperatures, Herrmann and Grupe (1988) suggest 1000°C, hydroxyapatite becomes unstable. This instability may be observable and predictable in burned skeletal remains, and a number of studies have set out to investigate this.

In Shipman *et al*'s (1984) classic study of the effects of burning on bone and teeth, they examined the changing nature of the crystal structure of the inorganic matrix. Using X-ray diffraction they noted that there was a gradual increase in hydroxyapatite crystal size which was associated with an increase in temperature. The bones that were burned at 645°C and higher had clearly different diffraction curves than those heated to lower temperatures. Shipman *et al* (1984) explain this increase in crystal size as a function of some crystals enlarging at the expense of others. The most significant change in crystal size occurred between 525°C and 645°C. Above and below these temperatures only slight crystal size increases are seen. Contrary to Posner (1969) and Mayne Correia (1997) no conversion of hydroxyapatite to β-tricalcium phosphate via pyrophosphate was observed here.

Building on Shipman *et al*'s (1984) conclusions, Stiner *et al* (1995) used infra-red spectrometry to analyse the changing crystal structure of burned bone. This technique tracks the separation of two absorption peaks, at 603 and 565 cm^{-1}, which reflect the relative sizes of the atoms and the extent to which these atoms are ordered (Stiner *et al*, 1995). This separation is referred to as the Splitting Factor (SF). These absorption peaks separate from each other with increasing recrystallisation, therefore the larger the Splitting Factor value the larger and more ordered are the crystals (Stiner *et al*, 1995). Unfortunately Stiner *et al* (1995) do not associate Splitting Factor with temperature directly. Rather they associate Splitting Factor with bone colour, which they assume is a reflection of burning intensity. This is a sound assumption to make, but nonetheless removes the association of recrystallisation and burning condition by one level of interpretation. Their results show that as the bony samples progress through the heat-induced colour change spectrum (see Chapter 5 for greater detail), there is an increase in Splitting Factor values. That is, with increased burning comes increased crystal size and order. Although this finding agrees with Shipman *et al* (1984), the detection of a possible conversion of hydroxyapatite to β-tricalcium phosphate does not.

Changes in the crystal structure of heated bone were also noted by Holden *et al* (1995). Scanning electron microscopy was used to examine microscopic heat-induced changes in experimentally burned human femoral bone. New crystal formation and recrystallisation was seen to begin at only 600°C. These new crystals were small and spherical in morphology. As heating continued increasing numbers of these spherical crystals were formed in addition to new crystals with a hexagonal morphology. Both crystal types increased in size with increasing temperature, although the hexagonal form remained larger than the spherical variety. At approximately 1000°C the hexagonal crystals started to fuse and a third variety of crystal, this time rhombohedral in shape, was formed. Crystals of rosette, irregular and platelet shapes were also recorded. Interestingly an increase in duration while at a constant burning temperature did not result in an increase in crystal size (Holden *et al*, 1995)

There is a consensus then that increased burning brings with it an increase in crystal size. This may be as Shipman *et al* (1984) argue, due to the coalescing of crystals. This issue may be resolved if one were to count the changes in crystal numbers, although this may be confusing if, as Holden *et al* (1995) suggest, new crystals are being formed as well. It is interesting to note that these heat-induced crystal changes are extremely similar to the crystal changes one would expect to see in bone as a result of normal bone diagenesis (Stiner *et al*, 1995). The main difference being the time-scale. In the burial environment these changes may take hundreds of years while in burning conditions these changes are near instantaneous (Stiner *et al*, 1995). Both Shipman *et al* (1984) and Holden *et al* (1995) suggest that significant crystal changes begin at around 600°C. This would coincide with the Decomposition and Inversion stages of Tables 2.1 to 2.3. It is difficult to see how the removal of the organic component would affect crystal morphology, but the removal of the carbonates may. It may be then that the changes in crystal structure recorded by these studies force the commencement temperature of the Inversion stage in Figure 2.1 to the left.

TwoThreeFive Bone: Changes in Elemental Composition

Exposure to high temperatures will not only lead to a change in the morphology of bone, but also to a change in the trace elemental composition (Grupe and Hummel, 1991). Changes in trace element composition may result from heat-induced recrystallisation evicting elements from the bony matrix or uptaking elements from the firewood, soft tissues or burning context (Grupe and Hummel, 1991). Experimental analyses on pig femora allowed Grupe and Hummel (1991) to produce linear regression equations to describe the changes in certain elements. Changes in calcium, phosphorus and strontium provided the most robust formulae. Changes in barium and lead were less robust, while the changes in copper, zinc and magnesium appeared not to be related to temperature changes at all. The useful regression equations are:

Ca: $y = 0.074x - 19.707$
P: $y = 0.096x - 16.180$
Sr: $y = 0.149x - 65.740$
Ba: $y = 0.012x + 10.096$
Pb: $y = 0.136x - 20.075$

Where y = percentage change in the elemental content following burning, and x = temperature (°C).

Unfortunately these regression equations can only be used to predict post-burning trace elemental concentrations if x, the temperature of burning, is known. This is extremely unlikely.

Herrmann and Grupe (1988) also found increases in concentrations of calcium and phosphorus, but recorded decreases in strontium and barium. The differences between the two studies could be due to sample variation or experimental methodologies. Herrmann and Grupe (1988) do warn however, and this is also true for Grupe and Hummel (1991), that the recorded increases in trace elements may not be simply due to elemental uptake, but also due to reductions in the organic component of the bone, thereby apparently increasing element concentration relatively, not absolutely.

As attempted by Sillen and Hoering (1993), it may be possible to use the concentrations of elements to state whether bone has been burned or not. Unfortunately, with regard to changes in the mineral component, heat-induced diagenesis is similar to normal bone diagenesis (Herrmann and Grupe, 1988). Therefore trace element concentration alone can only identify that the bone has suffered some form of diagenesis, and not what the cause of that diagenesis was. Throughout this discussion it should be borne in mind that element substitutions are dependent on space considerations, symmetry factors, polarisation behaviour and charge distribution in the lattice space of the hydroxyapatite (Newesely, 1988).

TwoThreeSix Dentition

It must not be forgotten that the dentition forms an essential part of the hard tissue of the human body. Most of the investigative research conducted on burned teeth involves examination using scanning electron microscopy. Unlike with the bone discussed above, very little work has been conducted on the physio-chemical changes in teeth as a result of burning. Proportionally however, a large number of case study-based examinations have been conducted.

It is widely accepted that teeth are extremely resistant to heat-induced damage. It is this reason that makes them so valuable in the management of mass fatality incidents. Other than their apparent resilience to burning, two other important points need making. First, their resilience is due, in part, to the relative protection that they are provided by the oral soft tissues and the alveolar bone in which they are secured (Botha, 1985; Carr *et al*, 1986; Clark, 2002; Wilson and Massey, 1987). As burning continues however, this protection is gradually lost (Carr *et al*, 1986). Second, variables such as tooth age and the presence or absence of caries and restorations will affect the behaviour of dental tissue to burning (Wilson and Massey, 1987).

It would appear that teeth react in a similar way to the other hard tissue when heated. At the macroscale, heat-induced changes in colour and fracture patterns occur alongside the removal of the organic components, while microscopically tissue restructuring exists (Wilson, 1978; Wilson and Massey, 1987). As would be expected with microscopic restructuring, shrinkage results. Chandler's (1987) small experimental study witnessed mean shrinkage values as great as fourteen percent. Chandler (1987) also highlights the relationship between temperature of burning and colour changes in the experimentally burned teeth. Unfortunately he neglects to describe the colour changes he sees. The small sample size does limit the weight that one can place in these results however. An important heat-induced feature of burning teeth is the ejection of the enamel crown from the root. Chandler (1987) suggests that this feature may be the result of the crown splitting away from the dentine or the build up in pressure within the pulp cavity forcing the crown away when the stresses become too great. The former suggestion seems the most sensible, however Chandler (1987) does not attempt to assign a cause to the splitting away. It could be argued that the crown splits away from the root because the two structures shrink and expand differentially resulting in stresses that exceed the limits of the enamel-dentine junction; that is, the differential coefficient of expansion is too great for the structure to bear.

Harsányi's (1975) study of thermal damage to teeth involved heating isolated teeth in a furnace and subsequently examining the tissue using a scanning electron microscope. He noted several key heat-induced structural changes in the dentition. The cementum is the first structure to disintegrate due to burning, and this may occur at approximately 500°C. The enamel survives heating longer, but will begin to be destroyed itself between 700°C and 900°C. This begins with the proliferation of both microglobular and fracture patterns (Wilson and Massey, 1987). The dentine appears to be the most robust dental tissue, and will maintain it's canalicular structure until 1000°C. As with enamel, the destruction of the dentine begins with the globular metamorphosis of all the dentine, including the peritubular dentine (Wilson and Massey, 1987). It is not until 1300°C that the teeth will be affected by the heat in such a way as to melt into indistinct globular formations. In addition to the changes in microstructure, Harsányi (1975) recorded clear changes in tissue weight after burning. Between thirty and thirty-six percent weight loss was recorded. Wilson and Massey's (1987) study tends to support the earlier findings of Harsányi (1975).

Care must be taken when extrapolating the results of experimental studies to forensic or archaeological situations. The burning contexts of experimental studies can be quite different from those in real-life situations. Carr *et al* (1986) directly compare the heat-induced features of teeth removed from a victim of a road traffic accident to Harsányi's (1975) data in order to determine the temperature that the fire achieved. The problem with this sort of comparison is not that it occurs at all but rather that, as is the case with Carr *et al* (1986) the implication to the reader is that such comparisons are accurate and precise because of a lack of acknowledgement that different experimental procedures may mean that heat-induced features are seen at different temperatures.

TwoFour A Unified System

There is a very clear distinction in the literature between the heat-induced changes of the soft tissues and those of the hard tissues. This is emphasised by the fact that the papers used in Section 2.2 do not refer to those used in Section 2.3, and *vice versa*. To an extent, this situation is understandable. Complicated processes need to be separated into more manageable sections for easier and more efficient discussion. However, it is disappointing that no-one has attempted to combine the two sections before now. This dichotomy, which is entirely created and perpetuated by workers, ignores the fact that the two tissue types are intrinsically connected; they are a unified system. The enormity of this connection has been highlighted recently by a number of workers (Sture, 2002; Thompson, 2002b). Examples can be given to illustrate the unified nature of these two tissue types. Klein *et al* (1995) demonstrated how heat damage to the soft tissue may influence the behaviour and function of the hard tissues. Bonar and Glimcher's (1970) study showed how the heat-induced effects on collagen were greatly influenced by the penetration of the hard tissue into the fibrils of this soft tissue. While in turn a number of studies (Botha, 1985; Klein *et al*, 1995) have convincingly revealed how heat-induced changes in the hard tissues can be affected by the presence of surrounding soft tissues.

It is imperative that discussions of heat-induced changes in the literature mention the influence of the unified state of these two tissue types. This is most important in the archaeological and anthropological literature. Here the focus is on the skeleton, which will be damaged by burning only after the soft tissue has been damaged, the burning of which will effect the changes in the hard tissue.

Three The Identification of Burned Human Individuals

ThreeOne Introduction

Positive identification of the remains of recently deceased individuals is vital not only for the benefit of the surviving relatives, but also for such reasons as insurance claims, inheritance, remarriage and the prosecution of individuals in criminal cases (Midda, 1988). In some countries visual identification alone is deemed as irrefutable for legal purposes (Midda, 1988). This is a dubious principle to uphold and is of little use when the remains have been severely burned. As can be seen in Chapter 1, anthropology is not the most popular of identification techniques, however there are times when it can assume greater importance than other identification techniques.

It has been a long held assumption, particularly in archaeology, that cremated human remains can provide very limited information. The fragility of and the difficulty in identifying burned bone may limit the application of many standard anthropological techniques of analysis (Bennett and Benedix, 1999; Bond, 1996). Gladykowska-Rzeczycka (1965) argues that the practice of cremation deprives anthropologists of adequate material for the study of former populations. Because of this assumption, little analytical work is conducted on the material, and few cemeteries have been studied in any detail. This assumption is as unhelpful as it is incorrect. Unhelpful as it suggests that there is little point in conducting research on burned hard tissues because we can never glean much useful information from them anyway. In fact the converse is the case: greater research leads to a greater understanding of the material, which in turn allows a greater amount of information to be garnered. Incorrect because not only can a substantial amount of demographic information be extracted from burned human remains, but also information regarding funerary practice, burial customs and pyre technologies. This chapter focuses on the demographic information that can be reaped from studying burned human skeletal material.

ThreeTwo The Collection of Burned Human Remains

ThreeTwoOne The Scene and Initial Collection

Whether dealing with a forensic or archaeological situation, the anthropologist will have to work within the constraints of the scene itself. The scene refers to the location of the remains and their immediate surroundings. Mayne Correia and Beattie (2002) note that important factors to initially consider at the scene before recovering cremated material include the safety implications for the investigators, weather conditions, prior disturbance of the scene and remains, time constraints (especially in criminal cases) and scene complexity. They add that there are three goals that the anthropologist must achieve regardless of the individual scene conditions (Mayne Correia and Beattie, 2002). These goals are to minimise the loss of information during recovery, to document thoroughly the recovery process and to transport the remains safely to an appropriate facility for analysis.

Before removal of the burned material from the scene, whether it be in a forensic or archaeological situation, it is important to examine the scene itself. Dirkmaat (2002) notes that the recognition of unusual relationships, such as the position of the body in relation to fire patterns, in particular is extremely significant. In addition the relative location of artefacts such as unburned material, documents, wiring and machinery are all potentially informative (Eckert, 1981). If this is not attempted *in situ*, this information will be lost (Dirkmaat, 2002). It is at this point that the process of detailed recording and documentation should begin (Dirkmaat, 2002). This would include documenting scene details, initial information on the remains and details regarding the workers at the site. Detailed documenting should be practiced using standardised forms, as well as photography and videography

(Dirkmaat, 2002). Detailed and accurate documentation is vital because once the remains are removed and the investigators (and their Fire Investigation dogs – Lyon, 2002) move in, a great deal of scene information and associations are lost forever.

The collection and recovery of burned remains should be performed cautiously since the burned material can be damaged by shifting debris (Heglar, 1984). Standard collection practices exist for the collection of burned bone from forensic scenes in North America. They involve placing the recovered material into paper or plastic evidence bags and then assigning a unique but appropriately coded number and form to carry the necessary investigator and scene information. Fragile items can be placed in separate packaging, or in plastic bags lightly inflated with air and then sealed with tape (Mayne Correia and Beattie, 2002). Other materials such as cotton batting, bathroom tissue or crumpled acid-free paper can all provide extra stability to the burned bone (Mayne Correia and Beattie, 2002). For large masses of remains, a body bag strengthened with a solid underlay can be used (Dirkmaat, 2002). In general, the remains should be handled as little as possible to ensure survival (de Gruchy and Rogers, 2002). In addition to planning site collection protocol, the appropriate facility to be used for the subsequent analysis needs to be prepared and ready (Mayne Correia and Beattie, 2002). This is especially pertinent in forensic cases where efficiency and speed are extremely important. Mayne Correia and Beattie (2002) conclude with a warning which is equally applicable to those working in forensic as well as archaeological contexts, in that time saved at the scene very often increases the time required to unpack, repair and analyse the remains later, as well as losing valuable information. These sentiments are supported by Grévin *et al* (1998) too.

McKinley and Roberts (1993) produced an Institute of Field Archaeologists Technical Paper on the excavation and post-excavation treatment of cremated and inhumed human remains in which they suggest appropriate methods of dealing with burned human remains. At the scene and during the initial collection stage they suggest a number of policies based on the condition of the remains. For undisturbed urned cremations they recommend lifting the urn whole, with the addition of supportive bandages if necessary and bagging any loose cremated bone separately. If the vessel is lidded great care must be taken to ensure that the remains are not disturbed during collection. If the urn is broken in any way and is haemorrhaging its contents, the surrounding soil should be recovered as well. Undisturbed unurned cremated bone should be excavated in 20mm spits and placed in clearly labeled bags. In all cases dampening the soil is recommended to reduce the possibility of further fragmenting the remains, and remains from waterlogged soils should to kept damp. Wet-sieving of the soil samples using a 2mm sieve is recommended to ensure that as much skeletal material, pyre debris and pyre goods are recovered as is realistically possible.

By examining the variety of situations that anthropologists have had to work in it is clear that there is a need to adapt recovery strategies to individual situations. Examples of these adaptations are presented and detailed as case studies by Bass (1984), Dirkmaat (2002), Heglar (1984), Kennedy (1996), Mayne Correia and Beattie (2002), Murray and Rose (1993) and Owsley (1993).

ThreeTwoTwo Post-collection Handling and Transportation

The main problem with handling and transporting cremated bony material is the fragile nature of the remains. Mayne Correia and Beattie (2002) have successfully strengthened burned bone by soaking it for one minute in a solution of PVC glue and water (at a glue to water ratio of 1:4). They note that material treated in this way has been preserved in a very good condition for over a decade. This method of stabilising burned bone is not appropriate for bone with substantial amounts of soft tissue remaining. Cyanoacrylate glues are advised against because of the fact that glued fragments are difficult to separate and usually results in damage to the bone. Burned fragments joined by the PVC glue solution can be separated by simple soaking in water. De Gruchy and Rogers (2002) emphasis the usefulness of epoxy preservation too. Since the insertion of glues and resins may damage the microstructure or organic component of the burned bone, it is important to decide on the future uses of the bone fragments before using this method of stabilisation. It is important to note that not all cremated bone will require stabilising (Mayne Correia and Beattie, 2002).

In archaeological specimens the cremated material may well have to be removed from the surrounding soil matrix. McKinley and Roberts (1993) suggest that this should be done using a set of sieves with 10, 5 and 2mm meshes. Large stones should be removed as soon as possible to avoid unnecessary damage to the fragile burned bone. Weighing of the material collected from the pyre site is also recommend in order to determine the proportion of bone that has been collected from the pyre for subsequent burial (McKinley and Roberts, 1993). It is unclear how this accounts for original incomplete recovery from the pyre site however, or if multiple individuals were burned on the same pyre or pyre site.

With modern burned material, it may be necessary to clean the bone of soft tissue before it can be examined. This could be done with water, however Grévin *et al* (1998) suggest the use of ultrasound, as this does not damage the potentially fragile bone. This technique may be applicable to archaeological material encrusted with soil too.

Material that has been recovered under the assumption that they are burned human skeletal remains need to be checked to ensure that this is so. This can be done visually, or with the aid of microscopy or histology. Henderson *et al* (1997) for example utilised scanning electron microscopy and X-ray diffraction. Ubelaker *et al* (2002) report the use of scanning electron microscopy in conjunction with energy dispersive X-ray spectroscopy to determine bone from non-osseous material. Energy dispersive X-ray spectrometry creates a compositional profile of the material being scanned that may be unique to that material. While this proved successful with normal bone, the heat-induced changes in the chemical composition and crystal structure of burned bone may make this technique less reliable and accurate for distinguishing burned bone from burned non-osseous material. These changes however, may facilitate the efficacy of distinguishing burned bone from unburned bone.

ThreeThree The Analysis of Burned Human Remains

ThreeThreeOne Human Versus Non-human Remains

Mayne Correia and Beattie (2002) argue that it is easy to distinguish human from non-human burned remains because the typical characteristics of faunal bone can still be determined. Questions remains as to how true this statement is with regard to highly fragmented burned remains however. Cattaneo *et al* (1999) compared the usefulness of histological, immunological and DNA analysis for the differentiation of burned human and non-human bone. The results of their experiments showed that the differentiation of human and non-human species was most reliable using quantitative histological methods rather than immunological or DNA analysis. Unfortunately their experiments suffered two main flaws. First the authors burned thin sections of long bones, much like Holden *et al* (1995), which will react in an unrealistic manner when burned when compared to whole bones. This increases the unreliability of any population inferences. Second, in their statistical analyses of the osteon dimensions, they differentiate human material from non-human material, which is essentially the differentiation of species. However they have grouped together a number of non-human species for the sake of this comparison. This means that the non-human differences are being averaged out, and it may be that while the non-human species as a group show statistical significance in osteon dimensions, some individual non-human species may not. Immumological methods were more useful than DNA analyses due to the apparent resilience of albumin to heat relative to DNA (Cattaneo *et al*, 1999). Other studies have also demonstrated the potential of histology in determining human from faunal burned remains, usually by simple comparison of histological slides from human bone to faunal bone (Cuijpers, 1997). It is not yet fully known however whether the reduction in size of the osteons creates problems when attempting to distinguish human from non-human bone.

ThreeThreeTwo Minimum Number of Individuals

Calculating the minimum number of individuals is based on the principle of detecting repeating bony elements or obvious age-related skeletal differences. This principle will hold with burned remains, although in this situation is more dependent on the more robust skeletal elements that survive burning. This will include the dens of the second cervical vertebra, the glabella and the supraorbital region (Gejvall, 1969). Warren and Shultz (2002) suggest that the presence of artefacts (such as dental bridges and pacemakers) may be used to indicate the commingling of cremated remains from modern contexts. Unfortunately there may be specific problems when attempting to calculate minimum number of individuals on cremated remains due to the heat-induced changes in morphology, higher probabilities of incomplete recovery and the increased degree of fragmentation. It has been suggested that weight could be used to determine the number of individuals contained in a cremated bone assemblage (Heglar, 1984; McKinley, 1993; 1994b; McKinley and Bond, 2001; Maat, 1997; Murad, 1992; Murray and Rose, 1993). However the weight ranges produced with the aim of permitting this are created in optimal crematoria conditions and will therefore be unlikely to represent true field contexts (Mayne Correia and Beattie, 2002). In addition, weight ranges can vary considerably, with for example, some single cremations weighing more than multiple cremations (Holck, 1986; McKinley, 2000), and are influenced by the sex and age of the individual (Maat, 1997).

ThreeThreeThree Estimating Biological Sex

Both morphological and metric methods for the estimation of sex have been applied to cremated material (Mayne Correia, 1997). Both of these forms of sex estimation depend on two things: the presence of sex-specific osseous features on the skeleton and the general trend that female skeletons are smaller and more gracile than those of male individuals. Both of these factors are affected by burning. Sex-specific osseous features may be destroyed or not recovered and the skeleton as a whole is liable to alter in size due to heat-induced shrinkage. The first point suggests that sex estimation techniques that focus on the more robust portions of the skeleton will be of greater use. As such, the external occipital protuberance, nuchal crest and linea aspera have all been used (Owsley, 1993). The petrous section of the temporal bone is another such portion, and it is frequently recovered (McKinley, 2000). Sexual dimorphism is present in this part of the skeleton, and successful classification rates of cremated bone of sixty-seven percent (based on known sex samples) and higher have been recorded (McKinley, 2000). Unfortunately this first point also implies that the more delicate portions of the skeleton will not be generally useful for sex determination. This would include the pelvis and the humeral and femoral heads (McKinley, 2000). The problems associated with heat-induced shrinkage are discussed in more detail in Section 3.3.8.

Morphological sex assessment techniques can be applied successfully to cremated material. Unfortunately the use of the pelvis is limited in burned material. Pelvic fragments are uncommon or are too fragmentary to be of real use (McKinley and Bond, 2001). Sections of the cranium often survive burning and often the supra-orbit, mastoid process and mandible can be used (Baby, 1954; McKinley and Bond, 2001). As stated above there is a dependence on the more robust and denser portions of the skeleton. Unfortunately due to heat-induced fragmentation and incomplete recovery, the determination of sex is often reduced to general observations of size and robusticity (McKinley and Bond, 2001). Since the pelvis may not be available it may only be possible to place the remains within the ?Male to ?Female range.

Van Vark (1974; 1975) published the results of his investigations into the usefulness of multivariate statistical methods in the analysis of cremated remains, with an emphasis on sex estimation. They are most accurate when created from the population that the cremated material originates, but when this is not possible, an alternate population must be used (Van Vark, 1974).

Van Vark made two important points with regard to their application. He stated that problems arise due to the heat-induced changes in bony dimensions and the incomplete recovery of the fragmentary skeleton (Van Vark, 1974). Both of these issues will inhibit the use of techniques that rely on unmodified bone dimensions and many planes of measurement. Van Vark (1974) comes to the conclusion however, that despite these issues, multivariate statistical methods can still be used to successfully discriminate biological sex. There are two methodological limitations however. First the multivariate functions often cannot be applied to burned specimens which have only a small amount of recovered hard tissue (Van Vark, 1974). This is likely to be a common situation, especially when dealing with archaeological remains. Second, he states that often only proportional measures can be used (Van Vark, 1974). By this he means indices. In theory this is a sound principle. His rationale being that proportional measures will not be affected by shrinkage. However, since 1974 it has become clear that a bone does not undergo shrinkage uniformly. This will therefore affect the outcome of indices due to the changing relationship between the variables being measured (McKinley, 2001; Thompson, 1999; 2002). Misclassification of sex can therefore occur, with males being assigned as females and *vice versa* (Thompson, 1999; 2002). In a follow-up paper (Van Vark, 1975) Van Vark devised a series of fifty-three osteometric measures and twenty-nine bodily measures to aid multivariate analyses of cremated remains. From an anthropological point of view, the problem with having so many variables to measure is that it is unlikely that cremated remains will have all fifty-three planes of measurement in a state of completeness so as to facilitate measurement. Other metric methods have been applied to cremated bone. For example, Wells (1960) used the diameters of the femoral and humeral heads to estimate sex. This is especially dangerous considering the accepted notion that spongy bone shrinks appreciably more than compact bone (McKinley, 1994; Van Vark, 1970).

Gejvall (1969) has developed a method of determining the biological sex of cremated remains based on bony wall thickness. This is based on two assumptions. First that there is a statistically significant difference between the thickness of the walls of the bones of males and females (shown by Gejvall (1969) to exist). Second that cortical bone does not shrink when burned (Gejvall, 1969). This has since been proved to be untrue, and means that there is the distinct possibility that the thicker walls of the males will decrease in size and slip under the given section point into the female category. This principle of the misclassification of sex when using metric methods is discussed in greater detail in Thompson (1999). The advantage of this technique is that it circumvents the problems of incomplete survival of the traditional sexually dimorphic elements. Indeed this method would be simpler to perform on fragmented remains.

Sexual dimorphism may be evident in the weight of the skeleton after burning. Gladykowska-Rzeckycka (1965) however argues that there are simply too many variables that act to determine the post-burning weight of human skeletons to allow for accurate weight-based sex estimation. Variables put forth include, character of the body, intensity of burning and the efficiency of collection and storage of the cremated remains (Gladykowska-Rzeczycka, 1965). Holck (1986) notes that there is great variation in the average weights of cremations. This implies that it would be extremely difficult to separate the two sexes.

Little work has been conducted on the usefulness of DNA as a means of determining the biological sex of cremated individuals. Isolated studies using dentition have shown that sex-specific genes can survive limited burning (Duffy et al, 1991; Tsuchimochi *et al*, 2002), but the general consensus is that DNA does not survive continued and prolonged burning (Cattaneo *et al*, 1999; Goodwin, 2002).

ThreeThreeFour Estimating Age at Death

Cranial suture fusion has been used to estimate age at death in those that have been burned and cremated regardless of the fact that the cranium often explodes due to the rapid expansion of the fluids within the skull (Bass, 1984; Heglar, 1984). Wells (1960) regards this as the only technique that can age cremated material with any confidence. Cranial sutures are of use because sections of the cranium often survive burning (Baby, 1954; McKinley, 2000; McKinley and Bond, 2001; Spence, 1967), and because the technique, especially the popular version devised by Meindl and Lovejoy (1985), only requires small portions of sutures. There has been criticism of this technique in general often focussing on the fact that there is a great deal of variability in the onset and speed of suture obliteration (Brooks, 1955; Molleson, 1995; Powers, 1962). Damage to the sutures may also occur as a result of the cranium bursting along its natural lines of weakness – the coronal and sagittal sutures (Bohnert *et al*, 1997). In addition the method suggested by Meindl and Lovejoy (1985) requires specific sections of the sutures to be examined which may be difficult to identify in fragmented crania. As such, some workers do not recommend this age estimation technique on burned material either (Mayne Correia, 1997).

The extent of epiphyseal fusion can be used as a useful age at death technique for immature skeletons as these features are quite distinguishable from heat-induced changes seen in burned bone (Baby, 1954; Mayne Correia and Beattie, 2002). In addition, long bone length, pubic symphyseal changes, auricular surface changes, sternal rib ends, cranial bone thickness, tooth density and osteon remodeling have all been applied to burned skeletal material (Grosskopf, 1997; Mayne Correia, 1997; Smits *et al*, 1997). McKinley (2000) and McKinley and Bond (2001) argue however that pubic symphyses, auricular surfaces and sternal rib ends are very rarely recovered, if at all. This disparity of opinion could be due to the fact that Mayne Correia tends to work on modern forensic material while McKinley on archaeological material. In the forensic field soft tissue, although in a state incompatible with identification, may be present in a quantity to preserve the hard tissues to a greater extent than seen in archaeology.

Age at death estimation has also been attempted in cremated juvenile remains. Gejvall (1969) argues that these remains can be aged no less accurately than non-cremated juveniles. Kennedy (1996) in his investigation into the possibility of commingled remains from a commercial crematorium measured the burned long bones of a child. Based on a humeral diaphysis length of 5.42cm he calculated a fetal stature of less than 42cm. This took into consideration a 1.1mm heat-induced shrinkage value. This is an important factor to take into consideration, however in this case it is unclear where this value originates. Dental eruption has the potential to be very useful when estimating the age at death of burned juveniles as the alveolar bone will protect the unerupted deciduous and permanent dentition. In addition even if the enamel crowns have been destroyed, the surviving tooth sockets and roots can give an indication of the state of dental development. It has been suggested that the teeth of younger individuals survive burning better than those of elderly individuals (Holck, 1986).

Histological methods of age at death estimation have been applied to burned bone material. As McKinley (2000) suggests and subsequently reiterates (McKinley and Bond, 2001), this has the potential to circumvent the problems of fragmentation and unrecovered morphological age-related features. The best results were found when qualitative methods were used in preference over quantitative methods; that is comparison with unburned material of known age rather than osteon counting (McKinley, 2000). Hummel and Schutkowski's (1993) comparison of three histological techniques concluded the same, adding that one of the failings of the quantitative methods was that they relied too heavily on the precise distinction of structures which was often difficult with cremated bone.

Contrary to Wells' (1960) statement, it would seem that teeth could provide a very useful age indicator in burned human remains. The protection offered by the alveolar bone and neighbouring soft tissue results in a high occurrence of tooth recovery from remains in both forensic and archaeological settings. However, as is detailed in Chapter 2, the ejection of the enamel crown is significant. Once released from the tooth, it is vulnerable to destruction. As a result, few crowns are recovered from cremated material, while dental roots are fairly common. This would suggest that the potential of techniques such as dental wear as an age at death indicator might be limited. The frequency of incremental lines in the dental cementum has been used to estimate the age of cremated material (Grosskopf, 1997; McKinley, 2000). Unfortunately this has proved less than satisfying, and the lack of accuracy is further compounded by other problems associated with burned remains, such as the lack of estimated sex and the identity of the tooth being analysed (McKinley, 2000). An alternative is suggested by Botha (1985) who notes that impressions from erupted teeth are often present in the lateral borders of the tongue after heating. This feature would be of limited use to anthropologists other than to indicate which of the teeth were present at the time of burning. Since the roots of the teeth are often protected from serious damage it may be possible to use root dentine transparency. This has yet to be attempted however. Finally there is a question mark concerning the initial assignment of burned dental remains to tooth type. Chandler (1987) reports that accuracy is as low as 25.5% rising to 40% when classifying by type and quadrant and then 83% when simply stating whether the burned tooth was an incisor, canine, premolar or molar.

It should also be appreciated that the age of the individual will also influence the consequences of burning. It has been stated that the reason that few infants are found in the archaeological record is because their delicate skeletons are completely destroyed. However this runs contrary to Holck's (1997) experiments using modern children. He noted that infant bodies do not burn well at all, and he attributed this to the low numbers of fats, proteins and other combustible materials in the bodies of babies relative to adults. The skeletons of older individuals are thought to be destroyed to a greater degree than younger adults because of the age-related structural changes of the hard tissues of their skeletons. The presence of osteoporosis has been noted as predisposing individuals to increased heat-induced destruction (Christensen, 2002; McKinley, 1993). With osteoporosis, the situation is further complicated because the condition is more frequent in older women than men (as a result of post-menopausal changes; Brickley, 2000). This causes a bias in the degree of destruction in older individuals. Many older individuals also tend burn less effectively than younger adults because their bodies are thinner and contain fewer fats and other combustible materials. This is an important consideration for those working in modern crematoria.

ThreeThreeFive Estimating Stature

Grévin *et al* (1998) state that stature estimation is the only measurement that can be envisioned within the forensic anthropology framework. This seems to ignore the myriad of metric techniques devised for sex, age at death and ancestry estimation. The estimation of stature in particular seems to provide considerable problems with regard to the analysis of burned human remains. Mayne Correia and Beattie (2002) provide some excellent advice on how to work with burned human remains based on their considerable experience. They do worryingly state that stature estimations have not been attempted in some of their cases because of extreme fragmentation. It is true that stature estimations based on fragmented long bones will be less accurate than those based on whole long bones. However, it is likely that heat-induced shrinkage and warping will also affect the accuracy of any attempt at stature estimation. This will affect fragmented and whole bones, and stature estimations should be performed with caution for this reason and less so because of the practical problems associated with fragmentation. Mayne Correia (1997) also notes that any stature estimations based on cremated bony material must be broad. Smits *et al* (1997) seemingly ignore the influence of shrinkage on metric equations when calculating stature. While Grévin *et al* (1998) describe how they used colour change to estimate the temperature of the fire in which the bones were placed. This in turn was used to select an appropriate shrinkage range. This is problematic for several reasons. First, as is discussed in Chapter 5, colour change is an extremely poor predictor of the conditions of burning. Second, there is no simple relationship between colour change and burning conditions as colour change is dependent on heat-induced eviction of carbon which is influenced by many factors of which temperature is but one. Third, no paper has yet to fully explain the causes of shrinkage to allow the creation of appropriate shrinkage ranges. Fourth, shrinkage ranges do not take into consideration the differential amounts of shrinkage that are present along the different aspects of the bones. Fifth and finally, the authors make no reference to any of these concerns therefore giving the impression that their method of correcting for the influence of burning on stature estimation is sound. However they do advise against the use of exact stature estimations but rather placing the individuals into qualitative height ranges of small, medium and large (Grévin *et al*, 1998). The issues that surround shrinkage are discussed in greater detail in Section 3.3.8 and in Chapter 9. These points alone strongly suggest that the estimation of stature should not be attempted without further research.

ThreeThreeSix Estimating Ancestry

Although the estimation of ancestry of cremated material has been successful by reconstruction of the orbit (Gladykowska-Rzeczycka, 1965), Mayne Correia (1997) notes that the estimation of ancestry should only be attempted if substantial facial, cranial and long bone skeletal material is present. This however is less to do with the assessment of burned material in particular. Rather it is more to do with the fact that any aspect of the osteological profile requires as many relevant characteristics to be examined as possible in order to increase accuracy and reliability. Holland (1989) attempted to reconstruct the cranial base of burned skeletal material with a view to its use in the estimation of ancestry. He noted minimal shrinkage and concluded that methods that utilise the cranial base are appropriate when dealing with burned material. It would seem that this notion is supported by the statement of Bohnert *et al* (1997) who claim that the base of the skull is well protected during burning by thick soft tissue, the vertebral column and the facial bones. However Holland's (1989) conclusion only applies to remains that have been burned at low temperatures as he only investigated burning up to 800°C. It is after this temperature that shrinkage will become significant enough to effect the results of anthropological techniques.

ThreeThreeSeven Determining Pathology and Trauma

Mayne Correia and Beattie (2002) state that one can detect both pathology and trauma in burned material. This is because burning does not produce features that look like pathologies, although it should be noted that certain pathologies may influence how bone reacts to burning (Mayne Correia and

Beattie, 2002). For example, the production of dense areas of bone (as in sclerosis) will make that part of the bone more resistant to heat-induced transformation (Mayne Correia and Beattie, 2002), whereas the presence of osteoporosis will predispose that portion of bone to transform due to heat (McKinley, 2000). The matter is more complicated when dealing with trauma. Certain traumas can look like heat-induced transformations, and this is especially true of fracture patterns. Examples from the literature of pathologies being detected in burned remains include: cribra orbitalia, porotic hyperostosis, temporo-mandibular joint degeneration, dental disease, osteoarthritis, gout, osteomyelitis, osteitis and peristitis, Harris lines, Paget's disease, Mönckeberg's sclerosis (arteriosclerosis) and calcined atherosclerotic blood vessels (Baby, 1954; Clark, 1986; Holck, 1986; Johanson and Saldeen, 1969; Reinhard and Fink, 1994; Spence, 1967; Warren and Schultz, 2002; Warren *et al*, 1999; Wilson and Massey, 1987).

Certain types of trauma are easier to identify on burned remains than others. The results of the experimental preliminary study conducted by Herrmann and Bennett (1999) show that while sharp-force trauma could be readily detected the identification of blunt-force trauma required rigorous examination of the burned remains. Hausmann and Betz (2002) could distinguish between gunshot trauma and heat-induced feature after reconstructing a burned skull, but Herrmann and Bennett (1999) could not. Bohnert *et al* (1997) assert that fractures to the cranial base are the result of ante-mortem mechanical traumatisation as their study showed that this region of the skull does not readily produce heat-induced fractures. McKinley and Bond (2001) argue that traumatic fractures in general are rarely observed. De Gruchy and Rogers' (2002) study investigating the identification of chop marks on skeletal material found that the characteristics of chop marks were largely unaffected by burning. They do note the possibility of a reduction in size due to heat-induced shrinkage. Of the one hundred and fifty chop marks experimentally inflicted on their faunal analogues, ninety-nine were successfully identified after burning (de Gruchy and Rogers, 2002). Bond (1996) also successfully detected chop marks on the faunal remains from Anglo-Saxon cremations. Although still remaining identifiable, the presence of chop marks can increase the likelihood of the bone to fragment at or near the site of the trauma (de Gruchy and Rogers, 2002). Magnetic resonance computed tomography has been used as a means of differentiating ante- and post-mortem trauma. Iwase *et al* (1998) scanned the cranium of a potential murder victim to examine possible ante-mortem blunt force trauma. The imaging detected the presence of a blood clot at in the area of the fracture, thus indicating that the injury was not heat-induced.

Indirect evidence for pathologies and traumas can also survive cremation events. Although evidence of dental disease on the teeth themselves may be rare due to the fragility of burned enamel, any effects on the supportive structures or roots can be evident (McKinley and Bond, 2001). Harris lines occur in the epiphyses of long bones and indicate the cessation of growth as a consequence of stress (Roberts and Manchester, 1997). Such stresses include episodes of malnutrition and childhood diseases (Holck, 1986; Roberts and Manchester, 1997). Holck (1986) successfully detected these features in cremated remains using radiography. Dental hypoplasia is also detectable although enamel crowns do not survive burning and recovery well. Common items to be recovered from forensic cases are orthopedic accessories and dental attachments such as fillings, screws and dental bridges (Clark, 2002; Eckert *et al*, 1988; Jakobsen *et al*, 1974; Johanson and Saldeen, 1989; Murray and Rose, 1993; Owsley, 1993; Warren and Shultz, 2002). These are indirect evidence of dental disease or traumas. Bennett and Benedix (1999) report a case where an internal fixation device was found attached through the tenth to twelfth thoracic vertebrae of the burned victim of a concealed murder. The device was later revealed to be an Osteostimulator that provides a continuous electrical current to the connected bone in order to facilitate the production of new bone. In this case the device therefore provided evidence for lower back injury.

The main problem with identifying evidence of pathologies and trauma on burned remains is not that the act of burning destroys the feature itself, but that the act of cremation reduces the percentage of the skeleton that is recovered. That is, the number of pathologies detected is more dependent on the condition of the bone than it is on the prevalence of the disease (McKinley, 2000). This is mainly due to the heat-induced fragmentation of the skeleton. Although Reinhard and Fink (1994) argue that the process of burning lessens the chances of recovering identifiable pathologies, their own data seems to contradict this. By comparing the frequency of pathologies in cremated material to those from non-cremated assemblages, Reinhard and Fink (1994) concluded that there was no significant difference in the occurrence of osteophytosis, vertebral and appendicular osteoarthritis, cribra orbitalia, porotic hyperostosis and temporo-mandibular joint degeneration. There was a statistically significant decrease in the observation of dental disease (Reinhard and Fink, 1994). Although not stated, this may reflect the lower recovery of pathology-infected enamel.

ThreeThreeEight The Identification of Burned Human Remains using Anthropological Techniques

As Thompson (1999) states, the only heat-induced change in bone that will significantly affect the results of anthropological techniques is dimensional change. Changes in colour will not influence the techniques, although may cause some degree of uncertainty with regard to whether the bones are burned or simply stained as a consequence of their depositional environment. However inaccuracy can result from using colour change as a means of determining the degree of shrinkage during the implementation of a metric correction factor as in Grévin et al (1998). Fragmentation will make the application of certain techniques more problematic, but there are corrections in existence that allow one to compensate for broken bones. Anthropological techniques rely on unmodified bone dimensions that are altered by warping and shrinkage. Warping is relatively straightforward to cope with as an understanding of the unburned skeleton will allow one to dismiss bones that appear to be bent and twisted. Unfortunately heat-induced shrinkage is much more subtle and impossible to detect without *a priori* knowledge of the pre-cremation dimensions.

Wells (1960) states that shrinkage is negligible. He was only partially correct. Shrinkage is small during the first three stages of degradation of bone as a result of heating. During the Dehydration, Decomposition and Inversion stages (see Figure 2.3) the water and organic matrix is lost causing a small degree of shrinkage. Accepted values range from nil to five percent. Once the Fusion stage commences, which Mayne Correia (1997) placed as high as 1,600°C and Thompson (1999) redefined as being closer to 1,000°C, the shrinkage becomes much greater. Values as high as thirty percent have been recorded. The effects of these shrinkage percentages will be seen to a greater extent in any metric analyses conducted rather than with morphological techniques with the latter the feature itself may shrink but will still be present. Heat-induced shrinkage can affect the conclusions of uni-, bi- and multi-variate metric analyses by causing misclassification of one group as another (McKinley, 2001; Thompson, 1999; 2002). This problem is only compounded by the large overlap that often exists between the groups of study (for example, sex) within a population. Holck (1986) in his doctoral thesis describes how the frequency of females is greater than males in the archaeological cemeteries that he studied. He acknowledges this as an acceptable outcome, although it may be the result of the misclassification of some males as female due to heat-induced shrinkage.

The fragmented nature of burned bone can also cause problems when applying anthropological techniques. Diagnostic pieces are often missing and measurements cannot always be taken. In addition a lack of representation of certain body parts will lead to problems of misinterpretation. These are the outcome of heat-induced bony destruction and incomplete recovery. Any anthropological techniques that can be performed are often done with less assurance than on non-cremated material.

Positive identification, that is the stating of the specific and unique identity of the deceased, is still possible. This is only really an issue in forensic contexts. Ante-mortem records can still be compared with the post-mortem remains, although burning will damage some of the more common sites of comparison. The chest cavity is particularly susceptible to heat damage which is unfortunate since it is an extremely useful site for comparison due to the prevalence of medical chest X-rays. Dental comparison is still possible, and is an exceptionally common positive identification tool in forensic cases. (see Table 1.1 for examples of mass fatality incidents from the literature).

There is also a problem with comparing demographic information from cremated populations directly with other cremated populations. Since both of sets of populations may be suffering the same heat-induced transformations it is probable that both populations will be experiencing bias and inaccuracy in the results of anthropological techniques. For example, Holck (1986) states that his age at death estimations conform to other cremated bones examined from the same area. This could mean that a population with misclassification of age at death information due to heat-induced change is being compared to another population with misclassification of age at death information due to heat-induced. It may therefore be more informative to compare assemblages of cremated remains to those of non-cremated remains (although it is acknowledged that these assemblages could have their own sets of misclassifying variables).

ThreeFour The Storage of Burned Human Remains

Dry cremated bone can be stored in clearly labeled plastic bags (McKinley and Roberts, 1993). Labeling of the storage containers is extremely important considering McKinley and Roberts' (1993) view that cremated bone is impractical to mark. Cremated bone can be quite brittle so the overpacking of storage containers must be avoided (McKinley and Roberts, 1993). These points are equally pertinent to those working on burned remains extracted from forensic contexts as well as archaeological contexts.

ThreeFive Conclusions

The collection, analysis and storage of cremated human remains is difficult and fraught with problems and complications. But these are surmountable and should not deter one from dealing with human material in this condition. It is clear however that there is, even after around sixty years of serious, although somewhat sporadic, study a great deal that we still do not understand regarding not only the transformative processes that heating causes in bone, but also the most appropriate methods for studying this material. The over-riding aim of this piece of research is to provide a substantial body of knowledge regarding the nature of heat-induced change in bone, and then to take that knowledge and use it to make statements pertaining to the most suitable anthropological techniques for use on the material. This must all be conducted within a proper social context, otherwise it will not be possible to apply the research fully to current anthropological situations, whether they be of a forensic or archaeological nature.

Four The Pilot Study

FourOne Introduction

The purpose of devising a pilot study was not to see if burning bone would produce changes in the hard tissues. A number of previous experiments have shown that this would be so. The purpose instead was simply to verify that the chosen methodology was reliable. As such the use of an animal analogue unsuitable for human comparison in this pilot study was not important. The methodology of interest concerned the experimental protocol for the burning of the hard tissues rather than the methodology for the analyses on the burned material (such as the scanning electron microscopy or mercury-intrusion porosimetry). Those methods are described in later chapters.

It is important to note that the purpose of this research was to determine the fundamental changes in bone as a consequence of burning. Since very little coherent work has been conducted on this aspect of heat-induced change it was necessary to heat the specimens in such a way as to facilitate the understanding of the change in solely the bone. It was felt that once the changes in bone itself were understood it would then be possible to add variables (such as soft tissue and clothing) in subsequent post-doctoral experiments. Therefore the hard tissues used here were removed of all attached soft tissue, thereby removing potentially influential variables. It is acknowledged that this reduces the realism of the changes but the main purpose of this research is osteological understanding rather than immediate application.

FourTwo Comparative Cremation Methodologies

The problems associated with the lack of standardised terminologies and methodologies within the experimental cremation literature has already been highlighted (Thompson, 1999). Examination of Table 6.3 of Thompson (1999) highlights the great variety in methodological protocols that have been applied to the examination of the influence of burning on the hard tissues of human and faunal skeletons. This lack of standardisation means that the comparison of any results and conclusions becomes complicated (Thompson, 1999). Attempts need to be made to reduce these problems.

The main differences in experimental protocol revolve around the concepts of experimental versus actualistic burning. Experimental studies utilise furnaces in order to control certain burning variables. Common variables to be controlled are heating temperature, duration of burning and rate of cooling. The advantage of controlled experimentation is that it makes it possible to understand the influence of the chosen variable on the process of heat-induced transformation. The disadvantage is one of applicability. Concerns have been raised over the appropriateness of applying results from experimental studies to forensic or archaeological contexts (Chandler, 1987; Holden *et al*, 1995b). Holden *et al* (1995b) note that experimental studies often lack important variables such as contaminants, differential heating and cooling rates, realistic air pressures and variable temperatures. These all seem valid points, however Holden *et al* (1995b) undermine these slightly by stating that they found no significant difference between experimental studies and real cases. Actualistic studies (such as those devised by Sigvallius, 1994) utilise burning conditions more akin to real situations, such as by burning the remains on wood pyres. As Thompson (1999) states, this may create results that allow more appropriate comparisons with real situations, however the great number of variables present results in low levels of replicability. In an attempt to unite these polar protocols, Thompson (1999) adopted a semi-actualistic approach. Here a wood-fuelled fire was used within a fire-brick furnace and the experiments were conducted outside. Therefore an element of realism was present, but certain undesirable variables (such as the effects of the weather) were limited. Limited levels of replicability were achieved.

The success of any one approach lies in their appropriate use. The questions one seeks to answer will determine which of the approaches to implement (Thompson, 1999). The nature of the aims of this piece of research meant that it would be inappropriate to use anything other than an experimental approach. Variables need to be controlled so that reliable statements can be made regarding the effects of temperature and duration on the changes seen in the hard tissues as a consequence of burning.

The use of animal analogues in cremation experiments is common-place. They are often necessary because the use of human remains has many legal and ethical ramifications (see Chapter 11 for a fuller discussion on the legal and ethical consequences of burning human material). There are obvious concerns with using faunal remains, especially when the results of the experiments are then applied directly to situations involving human remains. Common analogues are sheep, goat and pig. The question of how representative a quadrupedal animal is of a bipedal human should be raised (Thompson, 1999). Different anatomy, biometrics and activity patterns place different pressures on the skeleton, which in turn will influence the morphology and structure of the soft and hard tissues. Buikstra and Swegle (1989) argue that animal analogues are useful in the investigation of human material, although Thompson (1999) adds that certain animals are likely to be more appropriate than others. For the investigation of the effects of burning on the soft tissues, pig remains are argued to be appropriate (De Haan and Nurbakhsh, 2001). This is likely due to the similarity in soft tissue size and composition (Milroy, pers. comm.). For the investigation of the effects of burning on the hard tissues, sheep remains are appropriate because their bone density is more comparable to humans than other accessible species (Mayne, 1990). Access to fresh human material is extremely restricted in the United Kingdom, and this means that experimental cremation studies will invariably rely on animal analogues. This study is no different. Heat-induced shrinkage is of interest here, and this is mainly dependent on changes to the hard tissue microstructure. Therefore for this research a sheep analogue was selected due to the relatively similar microstructure noted by Mayne (1990).

Access to human teeth is considerably easier than access to skeletal elements. This is because informed consent can be given from patients having dental surgery. Therefore it was possible to use modern human dentition rather than an animal analogue in this study. Access to research material is discussed in Chapter 11.

FourThree The Pilot Study

FourThreeOne Formulating the Experimental Cremation Methodology

Eighteen faunal teeth comprising thirteen sheep (*Ovis aries*) and five fox (*Vulpes vulpes*) were extracted from modern dry skulls of specimens located in the Department of Archaeology and Prehistory, University of Sheffield.

A Carbolite electric muffle furnace was used to heat the teeth. This piece of equipment allowed for control over the temperature of heating and the rate of temperature increase. An IMO extractor fan was used in conjunction with the furnace to remove the smoke produced.

Three measurements were taken on each tooth before and after burning. They were the maximum mesiodistal diameter, the maximum buccolingual diameter and the maximum crown height. All three measurements are detailed in Buikstra and Ubelaker (1994). These three measures were chosen because they characterise the multidimensional change caused by burning. The measurements were taken using digital callipers precise to one hundredth of a millimetre. The weight of the teeth was recorded using a digital weighing scale and the colour noted using a Munsell Color Chart (1992). The same dimensional, weight and colour measurements were recorded after burning. Each of the metric measurements (dimension and weight) was taken three times in order to reduce observer error. The mean value will be used in subsequent analyses. The eighteen teeth were burned under the conditions as set out in Table 4.1.

value will be used in subsequent analyses. The eighteen teeth were burned under the conditions as set out in Table 4.1.

The specimens were placed into the furnace once the temperature had reached 200°C. This was to reduce the effect of unrealistic rapid heating if the teeth were placed in at the desired temperatures. If the hard tissues were placed into the furnaces at 0°C and allowed to heat up with the furnace, the teeth would be destroyed before reaching the temperature of interest. No information regarding the transformative effects of heating would then be possible. This relates back to the experimental approach to cremation methodology that, although not necessarily realistic, allows a great deal of control over several important variables.

Duration (mins)	**400°C**	**600°C**	**800°C**
10	2	2	2
20	2	2	2
30	2	2	2

Table 4.1 Burning Conditions of the Pilot Study Specimens

Figure 4.1 Carbolite Electric Muffle Furnace, Department of Archaeology, University of Sheffield

FourThreeTwo Results

The faunal dentition exhibited signs of heat-induced transformation. Colour change, fragmentation and shrinkage were all present and recordable. As such it was decided that the muffle furnace would be suitable for this study.

The recording forms were rarely completed in full, especially at higher temperatures. This is because the teeth crumbled when manipulated. Eventually measurements were not taken at 0mins after burning in order to allow the material to cool to an extent that measurement was possible.

It was noted that the skeletal material became more friable with increasing temperature, although specimen P-0009-01 was quite robust, probably as a result of crystal fusion. The roots and crowns of the teeth behaved differently with regard to colour and fragmentation: roots remained darker, stronger and did not peel.

FourThreeThree Implications for this Research

The main problem that the pilot study highlighted was with the recording form. Several changes needed to be made and it was therefore decided that it was necessary to alter the recording sheet. Reference to measurements at 0mins after heating was removed so that the heated material could cool before handling and reduce the chance of damage. Space was also created on the form to allow the recording of general observations. To reduce recording error the form was redesigned to be simpler and clearer.

Although reliably accurate and precise, it was decided not to continue using the digital callipers for the study. They were found to be too heavy and not delicate enough for measuring the friable hard tissues. Many of the pilot study specimens were damaged beyond use due to the callipers themselves. For all subsequent dimensional measurements a Rabone dial calliper with nylon jaws precise to one tenth of a millimetre was used.

As has been mentioned above, it was decided that the furnace was suitable for the burning experiments. Unfortunately it was thought that the extractor fan would not be powerful enough to cope with the smoke produced by the burning bones. The IMO fan removed most of the smoke emitted from the heated teeth, but some still escaped into the furnace room. Burning bones produce a great deal more smoke, and this would have overflowed into the lab and surrounding rooms. As the fan could not be used, the furnace above could not be used. A replacement furnace was chosen for the rest of the study. This was a Carbolite electric muffle furnace in the Department of Chemical and Process Engineering, University of Sheffield.

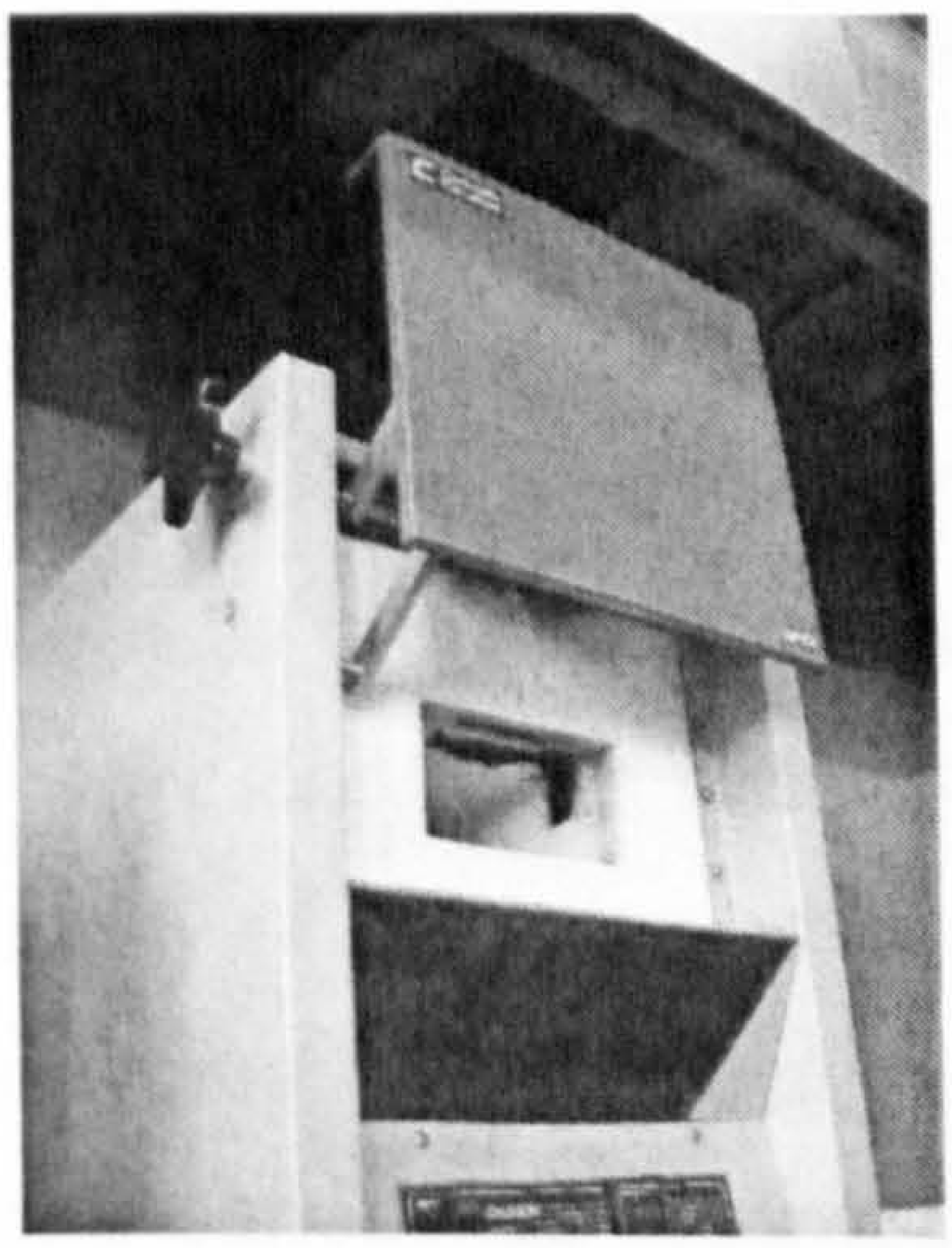


Figure 4.2 Carbolite Electric Muffle Furnace, Department of Chemical and Process Engineering, University of Sheffield

FourThreeFour Methodology for the Burning of the Long Bones

The protocol for the burning of the long bones remains essentially the same as for the burning of the faunal dentition used in the pilot study.

The remains were collected from the Peak District. Sheep were used for the reasons discussed in Section 4.2. The sheep were recently deceased, and the bones were still quite greasy. Some soft tissue was attached to the long bones, especially at the limb joints. Long bones were chosen as they are easy to measure and are important in many anthropological techniques. The bones were not collected from a local butcher due to financial restrictions and the fact that the removal of meat for sale often damages the bone underneath. Epiphyseal fusion was used to ensure that all of the sheep were older than one year. This was performed in an attempt to reduce the impact of any age-dependent physiological differences in the bones.

Any soft tissue adhering to the bones was removed using a scalpel, following gentle heating in water. It is acknowledged that heating alters the constitution of bone, indeed this fact is the focus of this research, however it is accepted that changes begin after heating at 100°C, and the water used here never reached that temperature. Following removal of the soft tissue, the bones were allowed to dry on a wire rack.

Eleven dimensional measurements were taken on the long bones. They are detailed in Table 4.2, with the raw data collected in the Appendix.. These measurements were chosen in order to examine heat-induced dimensional changes in a variety of aspects across the hard tissues. Each measurement was taken three times and the mean was used in all further analyses. The weight of the long bones was recorded. This was done three times and the mean was used in all further analyses. Colour was determined using a Munsell Color Chart (1992).

Dimension	Measurement
1	Maximum Length of Bone
2	Maximum Proximal Epiphyseal Width
3	Minimum Proximal Epiphyseal Width
4	Maximum Proximal Epiphyseal Length
5	Maximum Distal Epiphyseal Width
6	Minimum Distal Epiphyseal Width
7	Maximum Distal Epiphyseal Length
8	Maximum Proximal Diaphyseal Width
9	Minimum Proximal Diaphyseal Width
10	Maximum Distal Diaphyseal Width

11	Minimum Distal Diaphyseal Width

Table 4.2 The Dimensional Measurements Recorded from the Experimentally-burned Hard Tissues

The bones were placed on heat-proof ceramic trays and inserted into the muffle furnace at 200°C and allowed to heat up to the desired temperature. This was done in an attempt to replicate actual conditions. It is rare for bodies to be instantly heated to the temperature within the fire. Instead the body will gradually heat up as the fire moves closer to the body and begins to engulf it. The effect of suddenly heating the bones to a given temperature such as in explosions is interesting in its own right and should be the subject of later experimentation since it falls outside the remit of this particular project. The bones were then kept at that temperature for the necessary period of time. After removal from the furnace the bones were allowed to cool for five minutes before being re-measured. The eleven dimensional measurements, the weight and the colour changes were noted.

The cooled material was stored in clearly labeled plastic bags in the Department of Archaeology and Prehistory, University of Sheffield until they were needed for further analysis. Further analysis included photography, radiography, scanning electron microscopy, mercury-intrusion porosimetry, small angle X-ray scattering and mass spectrometry. Storage in this way will not affect the nature of the burned bone and therefore will not influence these subsequent tests.

FourThreeFive Conclusions

It was decided, based upon the success of the pilot study, that an electric muffle furnace would be appropriate for the heating aspect of this project. In addition, the sets of dimensional measurements taken from the teeth and bone were seen to be appropriate for assessing the multi-dimensional nature of heat-induced change. The Munsell Color Chart (1992) and the digital weighing scales were also found to be ideal for the examination of heat-induced change in hard tissues.

The results of the pilot study in combination with the body of previous research (see Chapter 2) indicated that the experimental burning for this research should be successful in producing recordable heat-induced change. The research project proper could therefore begin, subject to the necessary methodological modifications of Section 4.3.3.

Five The Examination of Heat-induced Colour Change

FiveOne Introduction

Colour change is arguably the most obvious heat-induced change that the hard tissues of the body exhibit. There is an accepted general trend regarding heat-induced colour change that has been supported by many publications (Gejvall, 1969; Gilchrist and Mytum, 1986; Heglar, 1984; Lyman, 1994; Mayne Correia, 1997; Nicholson, 1993; Quatrehomme *et al*, 1998; Shipman *et al*, 1984; Sillen and Hoering, 1993; Stiner *et al*, 1995). This trend is for the bone to alter from its natural colour of creamy white, through dark greys and black and then if burning continues, to travel through light greys and finally resulting in white bone with occasional light blue patches. Little has been written regarding colour change in the other hard tissue - teeth. Although the scant literature present does describe similar colour changes to bone (Chandler, 1987; Harsanyi, 1976; Shipman *et al*, 1984). The cause of this colour change has been attributed to the alteration of the organic components of the bone (Buikstra and Swegle, 1989; Mayne Correia, 1997). It has also been ascribed to the supply of oxygen (Parker, 1985) although this was not fully explained. Presence of oxygen seems less likely to be a direct cause of colour change, although indirectly it may affect colour changes by influencing the efficiency of burning and therefore the degree of carbon eviction. Differences in heat-induced colour change seen in teeth compared to bone could be explained by the differences in the presence of organic components between these two forms of biological hard tissue. Not all colours found on burned bone are related to the incomplete combustion of carbon-rich compounds. Although the presence of browns has been associated with the presence of haemoglobin, other colours such as greens, yellows and pinks have been linked to trace metals and various contaminants from the burial and cremation contexts (Dunlop, 1978; Gejvall, 1969; Gilchrist and Mytum, 1986).

Colour change has been suggested, with varying degrees of conviction, by several workers (for example, Chandler, 1987, Grévin *et al*, 1998, Parker, 1985 and Shipman *et al*, 1984) as a means of predicting the temperature of the fire that the remains were burned in. There are several flaws with this approach however. First, there are simply too many variables at work to claim that temperature is the main determinant of colour. Can one say with any certainty that the progression of bone from natural through black and grey to white is a function of temperature as opposed to duration of burning, soft tissue cover, rapidity of heating or oxygen supply? We cannot say this with certainty because studies tend not to examine colour change from a bi- or multi-variate point of view. The main focus of the previous work has been the temperature of burning at the expense of many other potential influences. Second, it has been argued convincingly by Mayne Correia (1997) that colour change is not a result of temperature exactly, but rather the loss of carbon from the osteological matrix. As the carbon is removed from the bone, the tissue becomes black as a consequence of the colour of carbon and somem carbon-based compounds. The subsequent grey and white colours occur when the carbon is lost from the bone completely. This loss of carbon may be the result of many variables, as discussed above, with temperature being just one of them. Third, a comparison of colour changes noted in earlier work (Thompson, 1999) reveals that although the general trend of colour change is fairly consistent across studies, there is enough variation present to negate the production of a standard scale of temperature and colour change. Any scale created using several studies (which is a necessity, for we should not place too much emphasis on just a single study) would contain significant overlaps with regard to the beginning and end of the periods of colour development. These would be so overlapping as to be useless. Fourth and finally, temperature prediction is further confused due to the fact that staining from the burial environment can potentially mislead workers. Stiner *et al* (1995) note how the black colour of excavated bones was thought to be indicative of burning, but on more detailed investigation (particularly of the internal surface of the bones) was found to be the result of post-depositional environmental factors. Shipman *et al* (1984) recommend using microscopic analysis to distinguish between burned and non-burned bones. However clarification of the burned status of ancient bones in particular, is made more difficult because the heat-induced changes in the hard tissue microstructure are very similar to those produced by normal diagenesis. In these situations Stiner *et al*'s (1995) suggestion of examining the surface of the medullary cavity may prove useful if used in conjunction with microscopic methods. Their argument being that this surface would be altered by diagenesis but not by burning. However as has been seen from this study, the medullary cavity is also affected by burning, even if to a lesser degree. The removal of the organic component (and therefore the changes in colour) can even occur in bone buried under a source of fire (Bennett, 1999; Stiner *et al*, 1995). Due to the protection of the surrounding soil matrix the loss of the organic matter is not as great as if the bones were directly in the fire (Bennett, 1999).

FiveTwo Methodology

FiveTwoOne Digital Imaging

Digital photographs were taken in the Department of Archaeology and Prehistory, University of Sheffield, using a Kaiser Copystand with natural lighting and a Fujifilm Finepix 4700 digital camera, at a resolution of 1280*960 pixels on normal image quality. This resolution was selected as there is a need to balance image quality with the data storage burden imposed by large image file size. A higher resolution (2400*1800 pixels) results in clearer images, but the file sizes are operationally restrictive, while a lower resolution (640*480 pixels) resolves file storage issues but at the expense of crisp images. The camera was connected to a 700 MHz PC with 128Mb of RAM via a USB cable when downloading the images from the Fujifilm MG-16SW 16Mb smart media card. Some of the images needed to be rotated 90° or 180° in order to ensure that all images were oriented the same direction. This was achieved using Paint Shop Pro 5 by Jasc Software.

The photographs were taken over several days. It was deemed unnecessary to photograph every bone and tooth sample, so instead samples were photographed if they were either the most representative of their particular temperature and duration of burning, or possessed a heat-induced morphological feature of relevance to the research questions of this work. Table 5.1 provides details of the samples photographed.

Cell Number	Sample Number
2-1	1
2-2	2
2-3	2
2-4	3
2-5	1
2-6	3
3-2	6
3-2	8
3-3	4
3-3	5
3-4	1
3-4	7
3-5	1
3-5	2
3-5	6
3-5	8
3-6	7
3-6	8
3-7	3
3-7	5
3-7	9
4-1	4
4-2	3
4-3	1
4-4	4

Table 5.1 Details of samples photographed

FiveTwoTwo Recording Colour

The main problem with recording colour, and this is true of any experiment, is that the definition of a given colour is entirely subjective. This therefore makes inter-experiment comparison extremely difficult. Colour has been recorded in a number of important previous studies (for example, Dunlop, 1978, Gejvall, 1969, Harsányi, 1976) without due consideration for the problem of the subjective nature of colour. The solution is to somehow standardise the definitions of the colours. For many years sedimentologists and geologists have used the Munsell Soil Color Charts to define not only the colour of the soil, but also the structure and texture of the material. The charts contain reproductions of 251 colours that the researcher simply compares to their sample (Munsell, 1992). The charts attempt to quasi-quantify these colours by assigning a value for the hue, value and chroma of each colour.

Shipman *et al* (1984) were the first group of anthropologists to use this system of defining colour in the examination of heat-induced colour change. Although this allows for a significant increase in the potential for inter-experiment comparison, few other studies have adopted this approach. The use of a Munsell Color Chart seemed an appropriate method for standardising the allocation of colour in this study. Colours recorded in this study are therefore standardised, not only with other studies but also with themselves, thereby reducing inter- and intra-observer error. The exact degree of observer error of the Munsell Color Chart has yet to be investigated in anthropology however.

When recording colour, the values assigned for each of the 251 colours are simply noted down. For example, a light red colour is assigned the value 10R 6/8. Anybody with a Munsell Color Chart will know exactly the shade of light red that that value refers to, but when set out in the Results section of a paper, such as in Shipman *et al* (1984), it is difficult to mentally visualise the colour. Plotting the numerical values on a three-dimensional graph would help, but would not remove this problem of interpretation entirely. In order to resolve this problem it was decided that each colour that was recorded from the Munsell Color Chart would be scanned into a computer using a UMAX Astra 1210P A4 flat-bed scanner. The charts in Section 5.3 could then be produced by using the Dropper Tool of Paint Shop Pro v5.01 to select the exact colour from the scanned page of the Munsell Color Chart, and placed into the chart using the Fill Tool. The charts produced are therefore graphic representations of the exact Munsell Color Chart values for each of the heat-induced colours recorded. It is therefore possible for the reader to visualise all of the standardised and quasi-quantified colours. However it should be noted that there will be slight differences due to the properties of the printer used.

FiveThree Results

Figures 5.1 to 5.10 show images of samples with representative heat-induced colour changes.

Figure 5.1 Sample 3-0004-07 [900°C for 15 minutes]

Figure 5.2 Sample 3-0002-06 [500°C for 15 minutes]

Figure 5.3 Sample 3-0006-07 [700°C for 45 minutes]

Figure 5.4 Sample 3-0007-05 [900°C for 45 minutes]

Figure 5.5 Sample 3-0007-09 [900°C for 45 minutes]

Figure 5.6 Sample 2-0001-01 [500°C for 15 minutes]

Figure 5.7 Sample 2-0003-02 [700°C for 15 minutes]

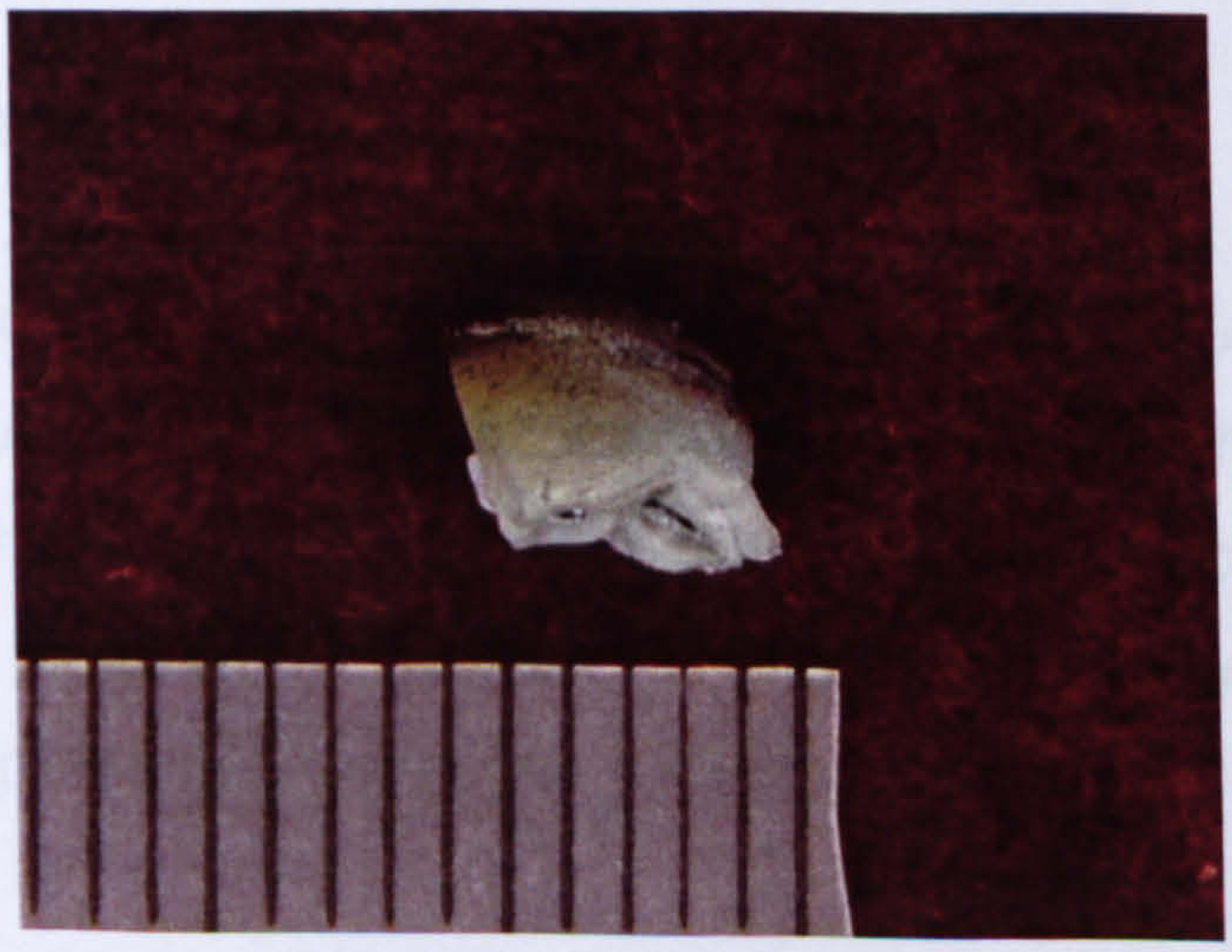


Figure 5.8 Sample 2-0004-03 [700°C for 45 minutes]

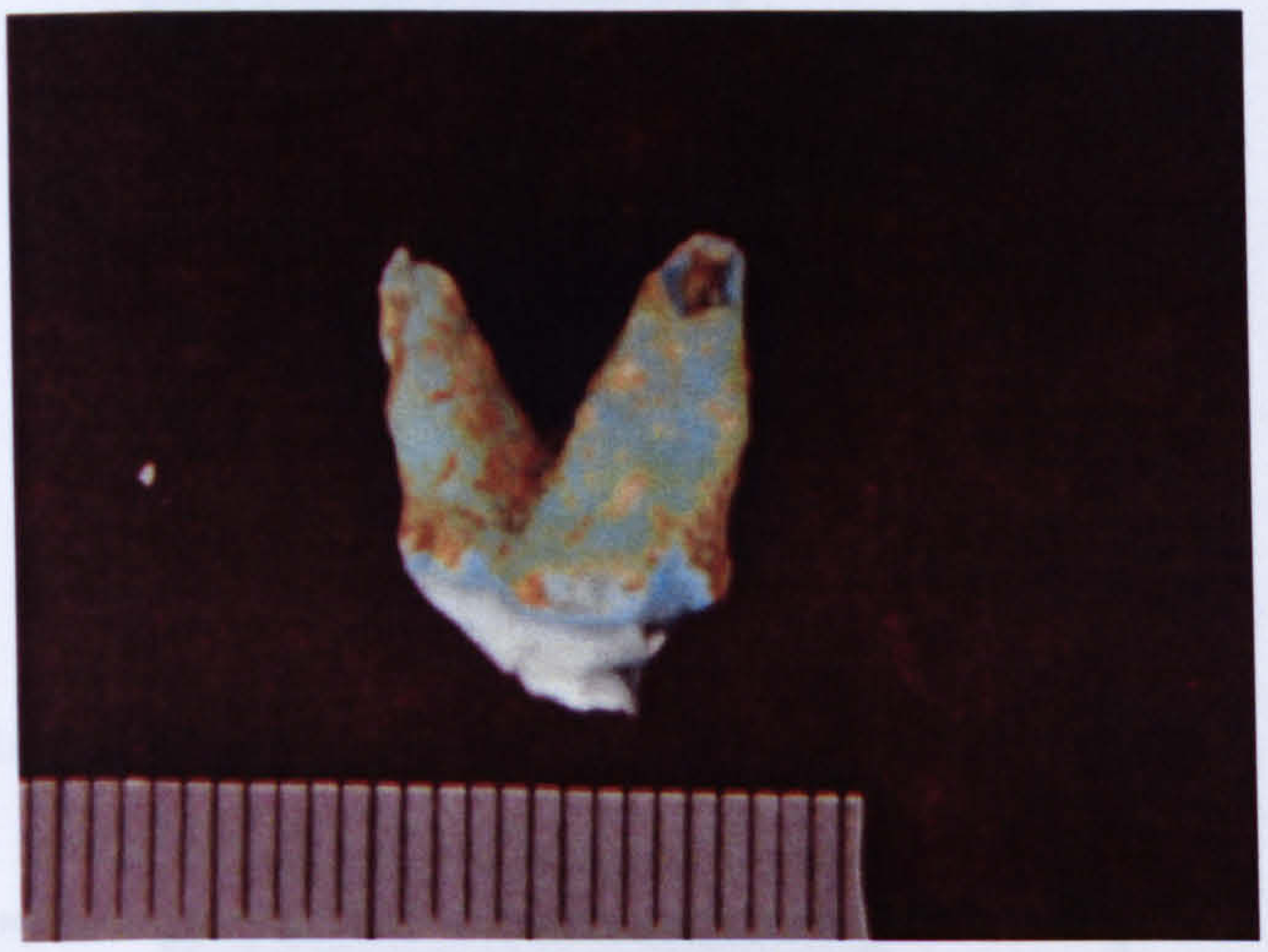


Figure 5.9 Sample 4-0001-04 [500°C for 15 minutes]

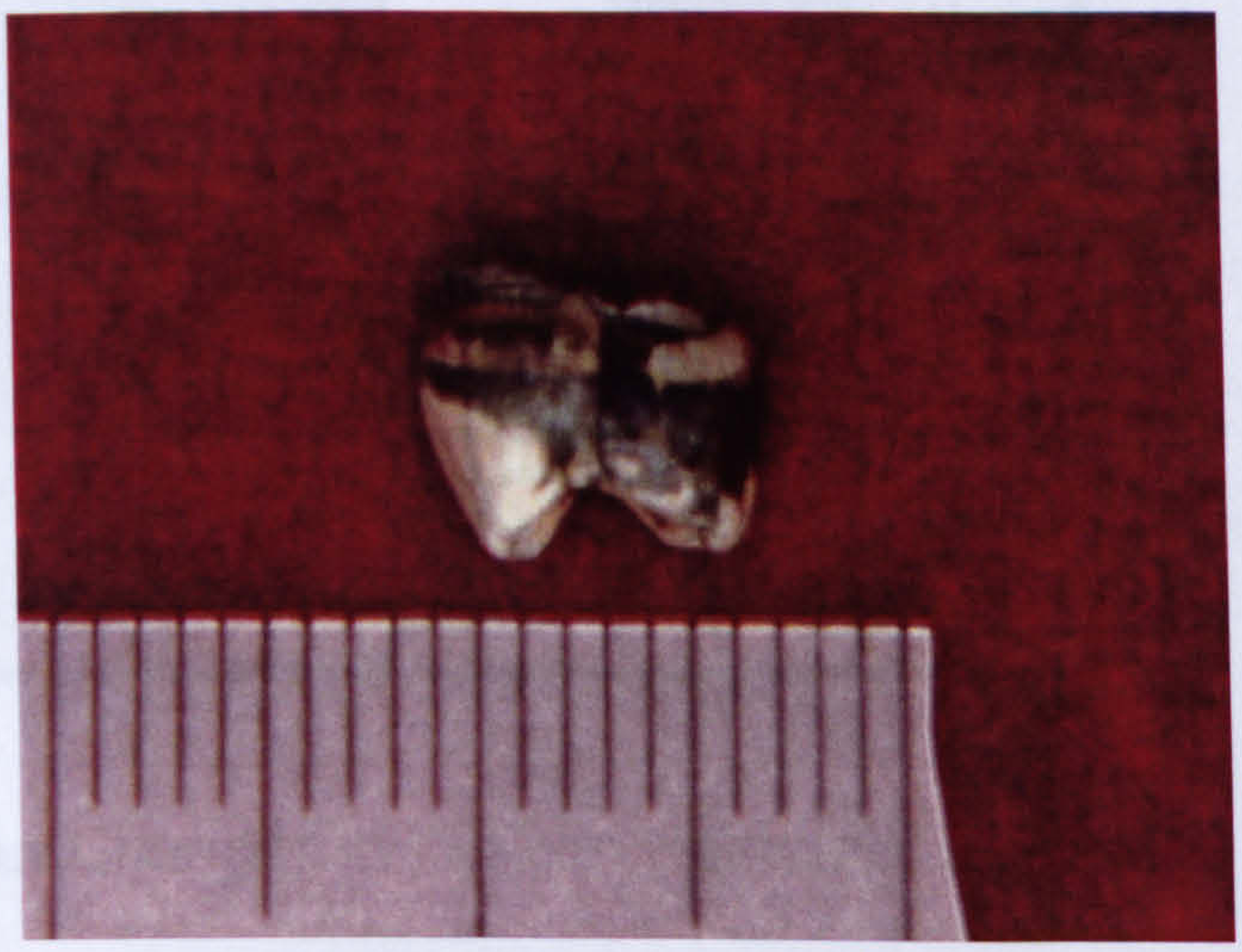


Figure 5.10 Sample 4-0004-01 [700°C for 45 minutes]

Figures 5.11 to 5.14 show the influences of temperature and duration on heat-induced colour change. The bottom row of each graph shows the natural colour of the hard tissue before burning. Each block of colour represents the modal colour seen on the tissues for those samples being burned at each particular temperature (*y-axis*) and duration (*x-axis*).

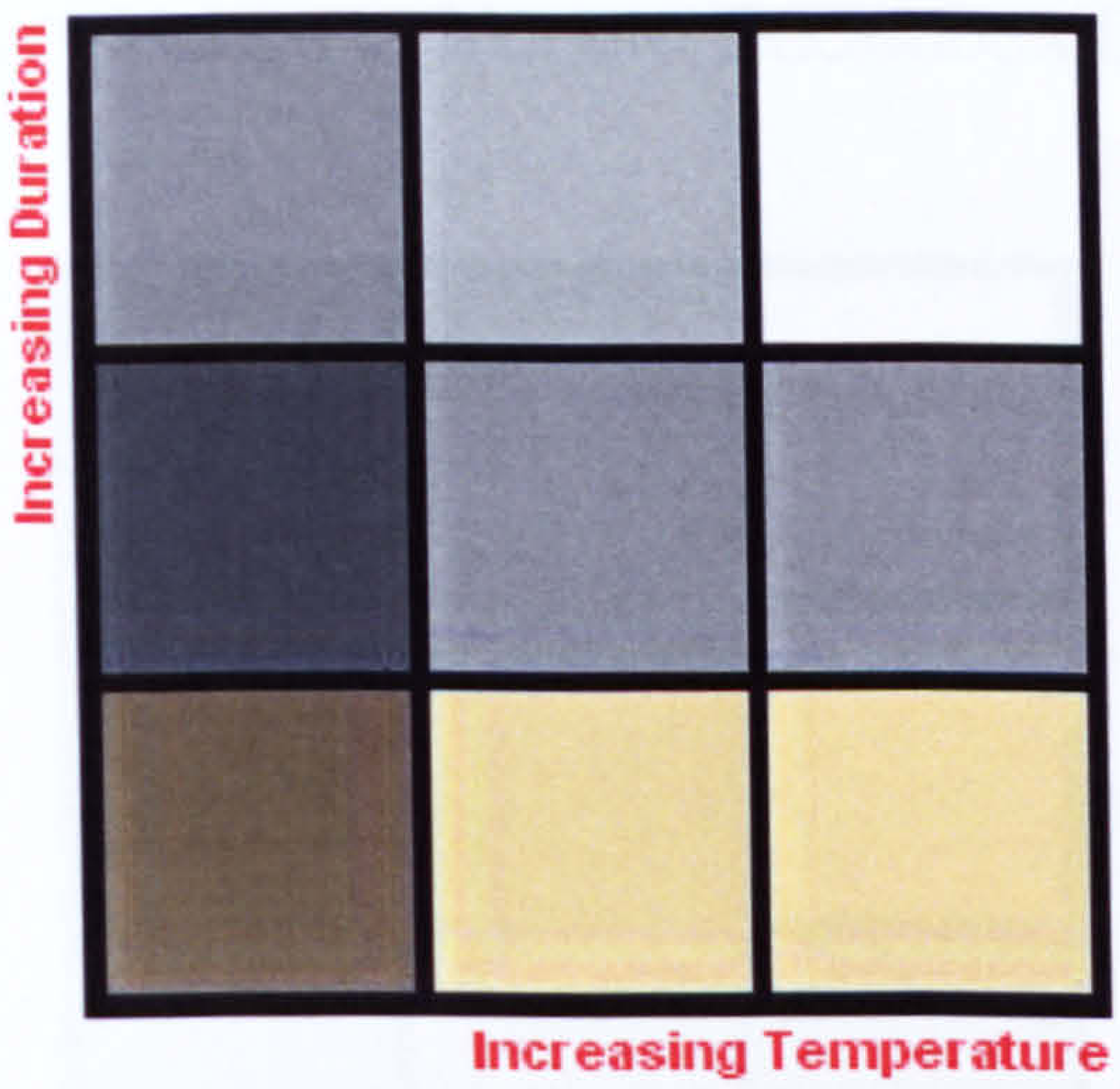


Figure 5.11 Colour Changes in Modern Sheep Bone

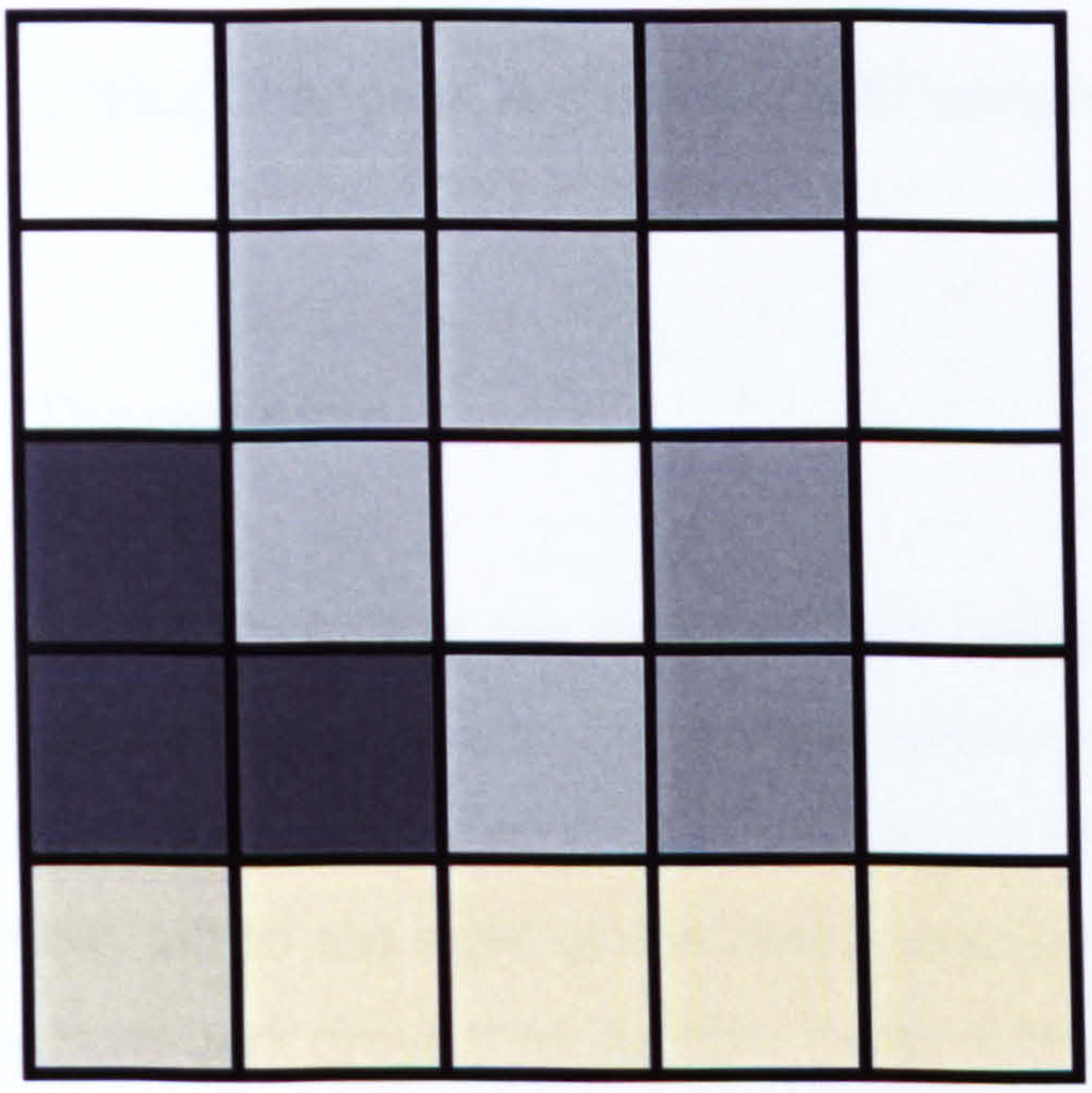


Figure 5.12 Colour Changes in Modern Permanent Dentition

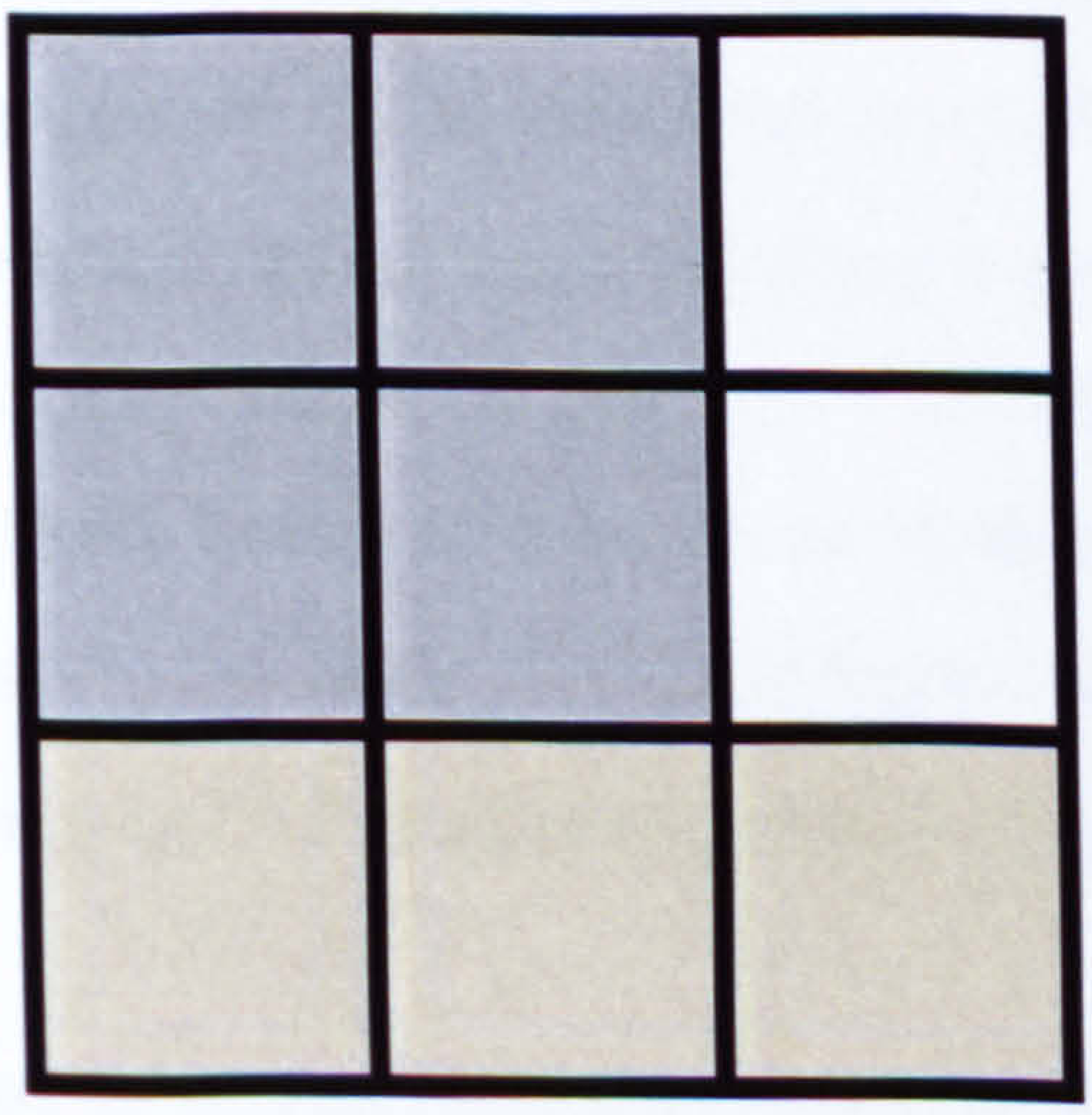


Figure 5.13 Colour Change in Modern Deciduous Dentition

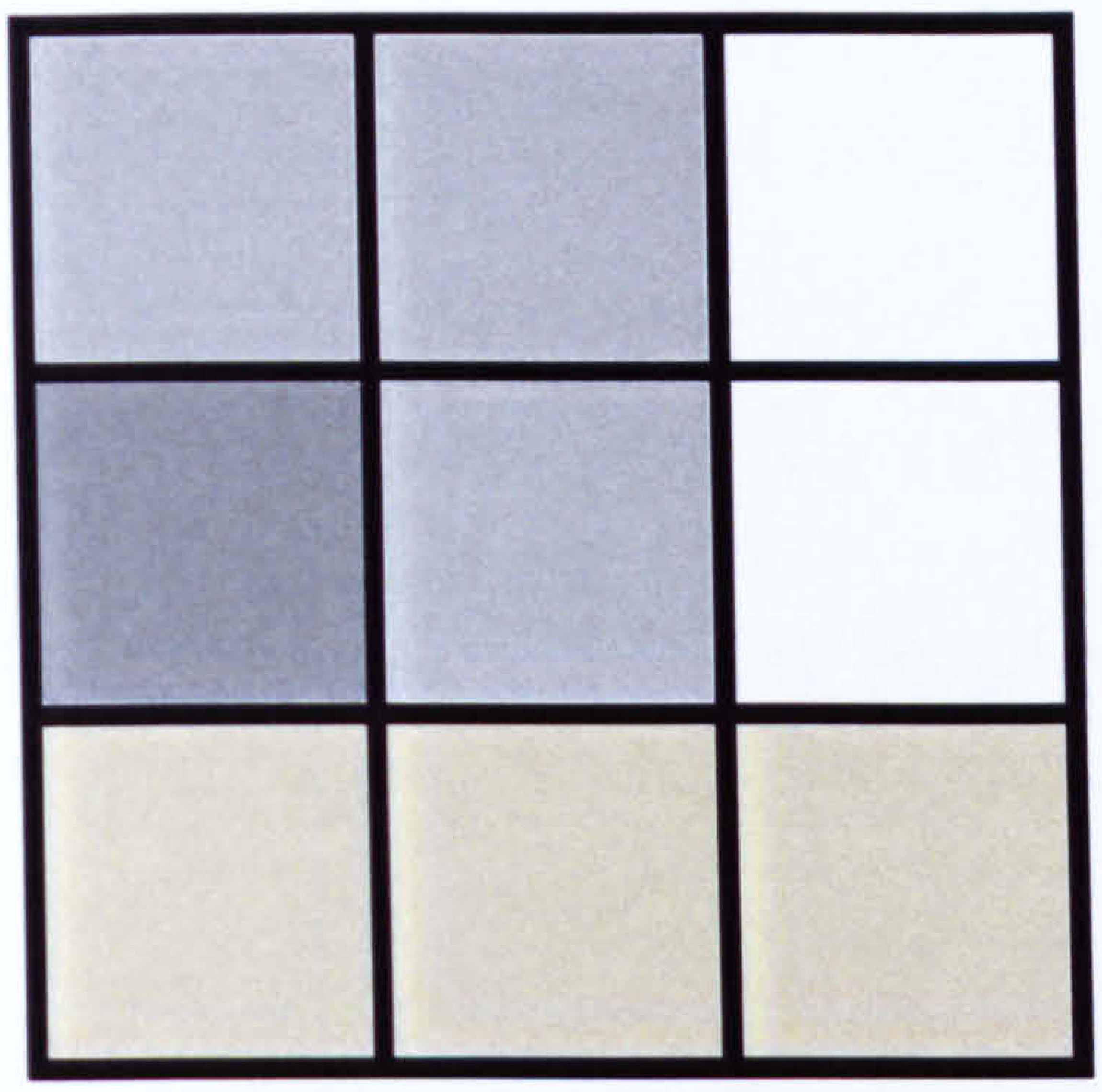


Figure 5.14 Colour Change in Archaeological Permanent Dentition

FiveFour Discussion

Figures 5.1 to 5.14 show that the heat-induced colour changes noted in this study are highly comparable with the general trend detailed above. It can be seen in all of the four sample groups that as burning intensifies (as one moves from the bottom left to top right of the colour charts) the colour of the bone transgresses from dark greys through light greys and ends in white. In Figures 5.11, 5.13 and 5.14 this progression of colour is quite clear. However this is not quite the case with Figure 5.12 – the modern permanent teeth. The general trend is present, but the flow of colour from dark to light is interrupted by the colour changes of those samples burned at 800°C. This is probably due to normal variation rather than anything more significant. It is interesting to note that the colour black is not seen in these four charts, as may be expected. This is likely because the carbon is already significantly depleted by the time the first samples were removed from the furnace. That is, by 500°C, most of the carbon must have already been evicted.

One of the main aims of this research was to investigate the influence of both temperature of burning and duration of burning. It is suggested that burning hard tissues at a high temperature for a short period of time will produce similar heat-induced changes to those produced as a result of prolonged low temperature burning. This notion can be examined by simply adapting the above colour change charts. Figures 5.15 to 5.18 shows these adaptations.

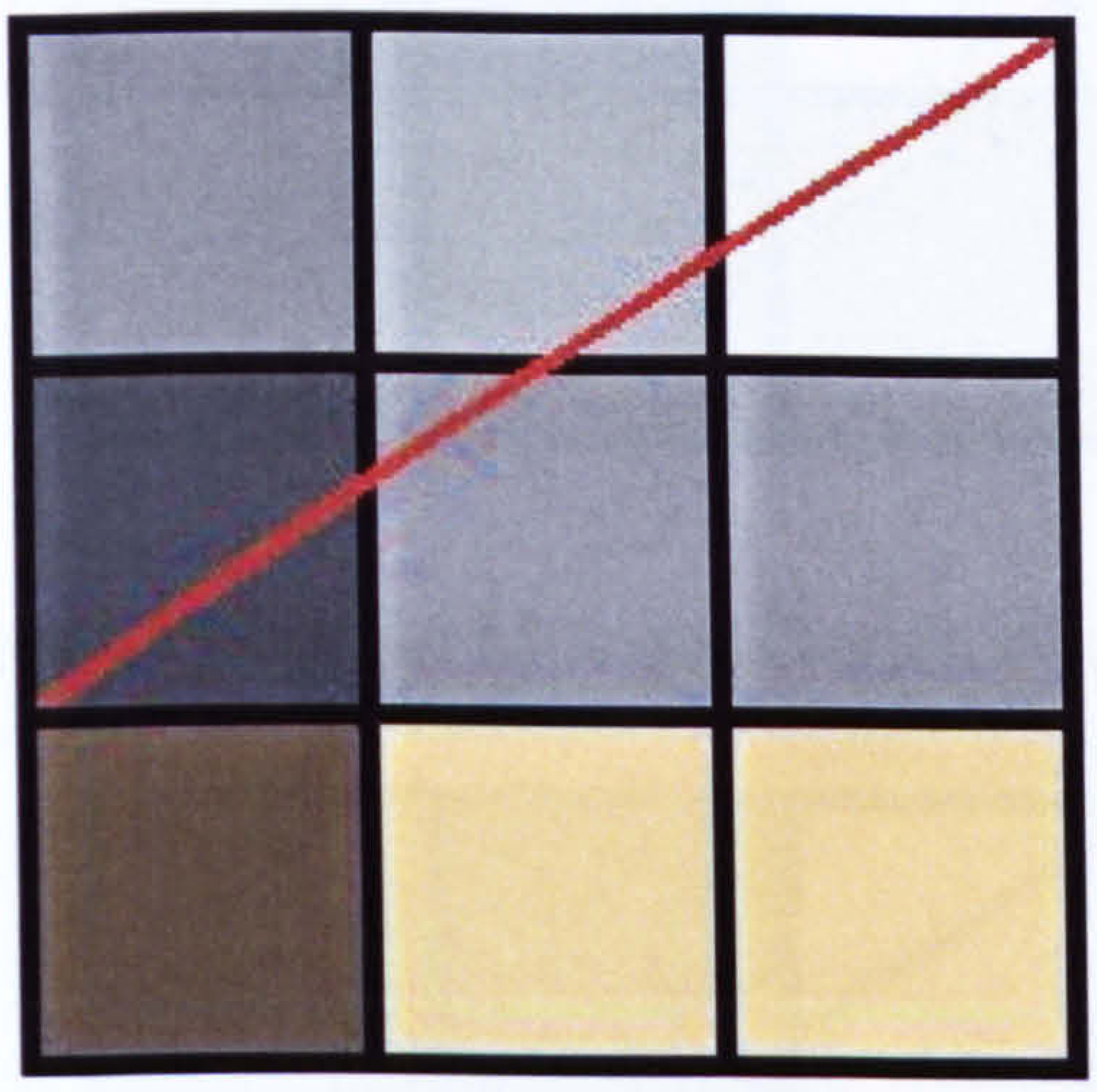


Figure 5.15 Colour Changes in Modern Sheep Bone

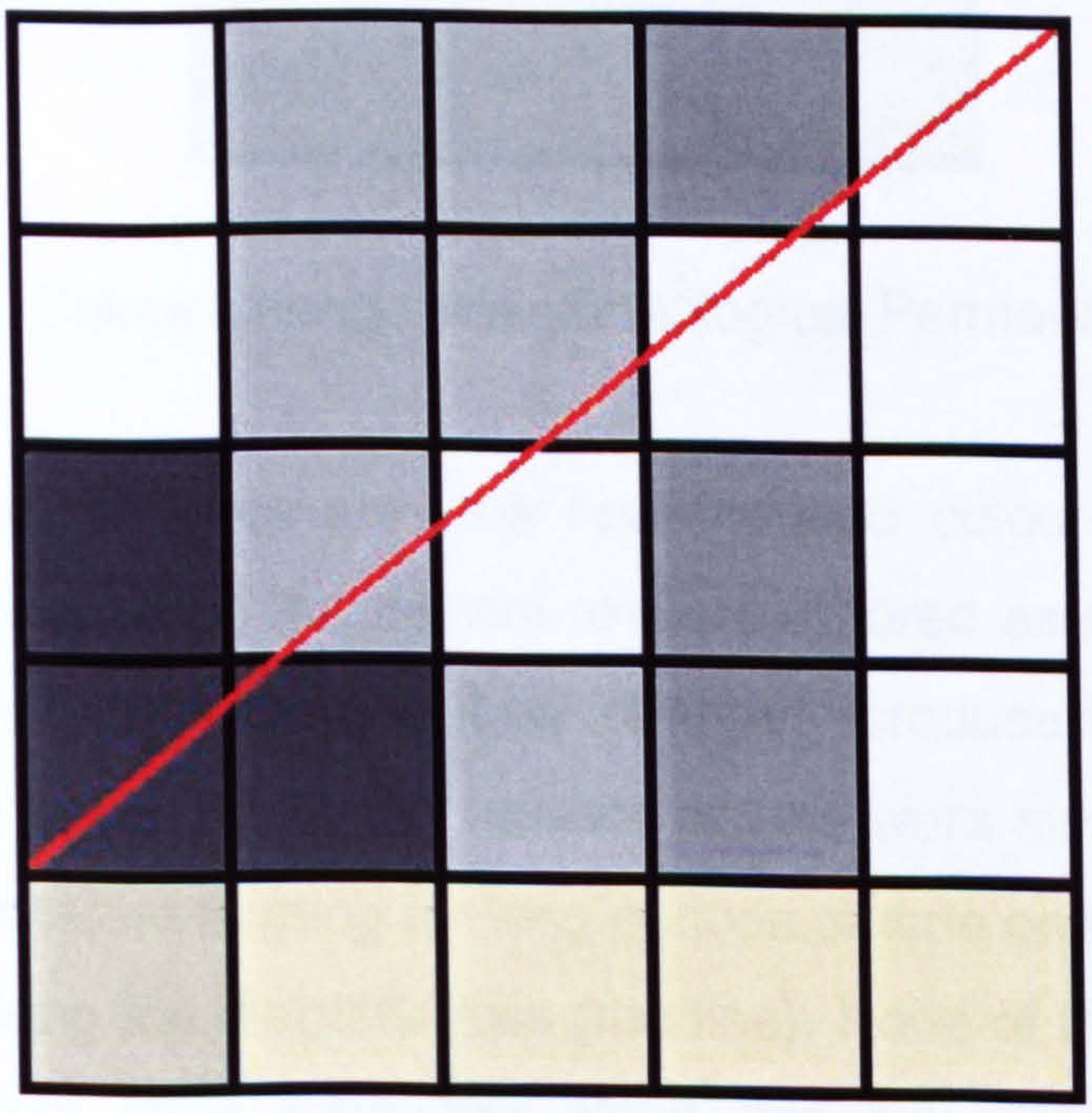


Figure 5.16 Colour Changes in Modern Permanent Dentition

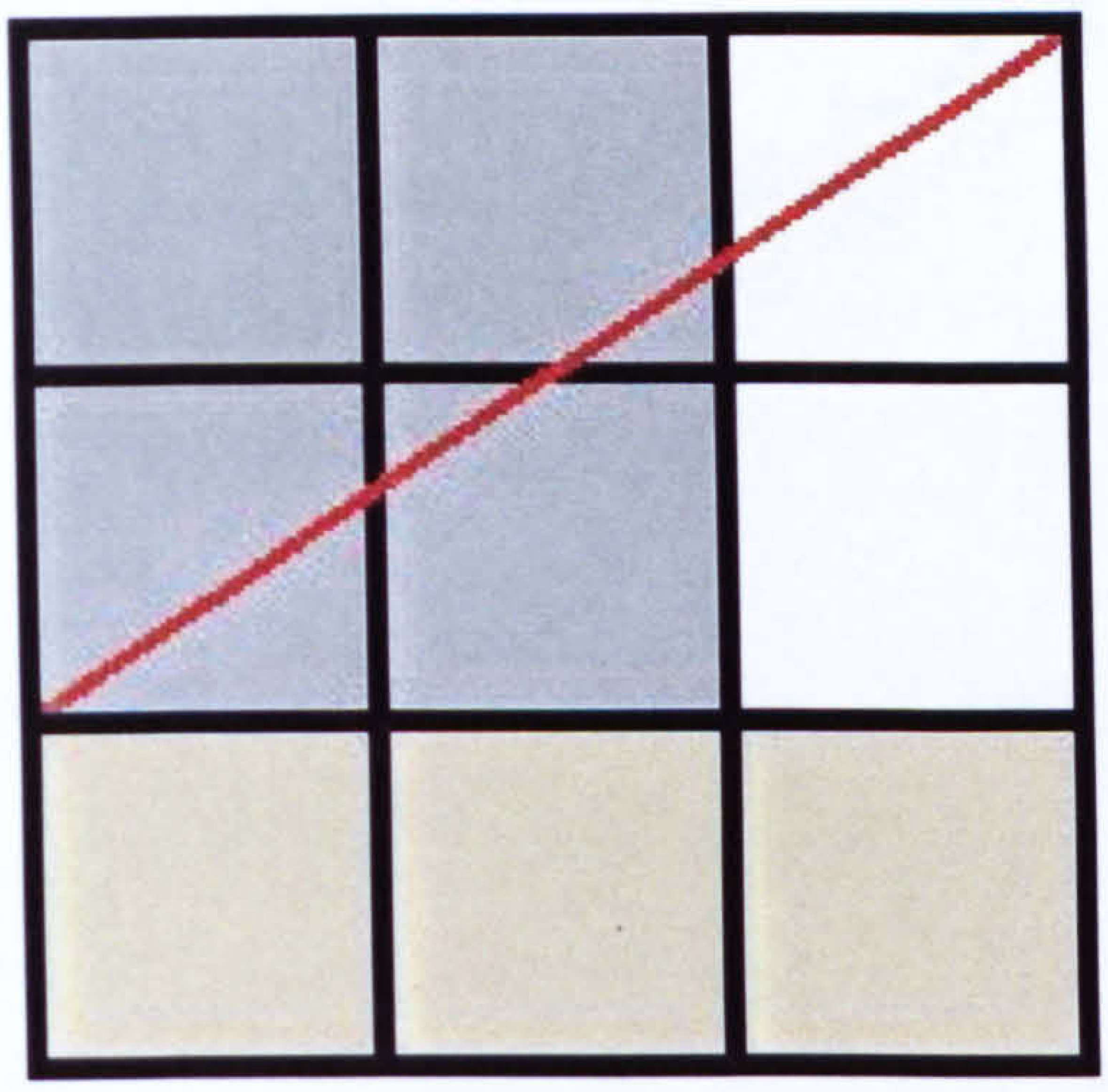


Figure 5.17 Colour Change in Modern Deciduous Dentition

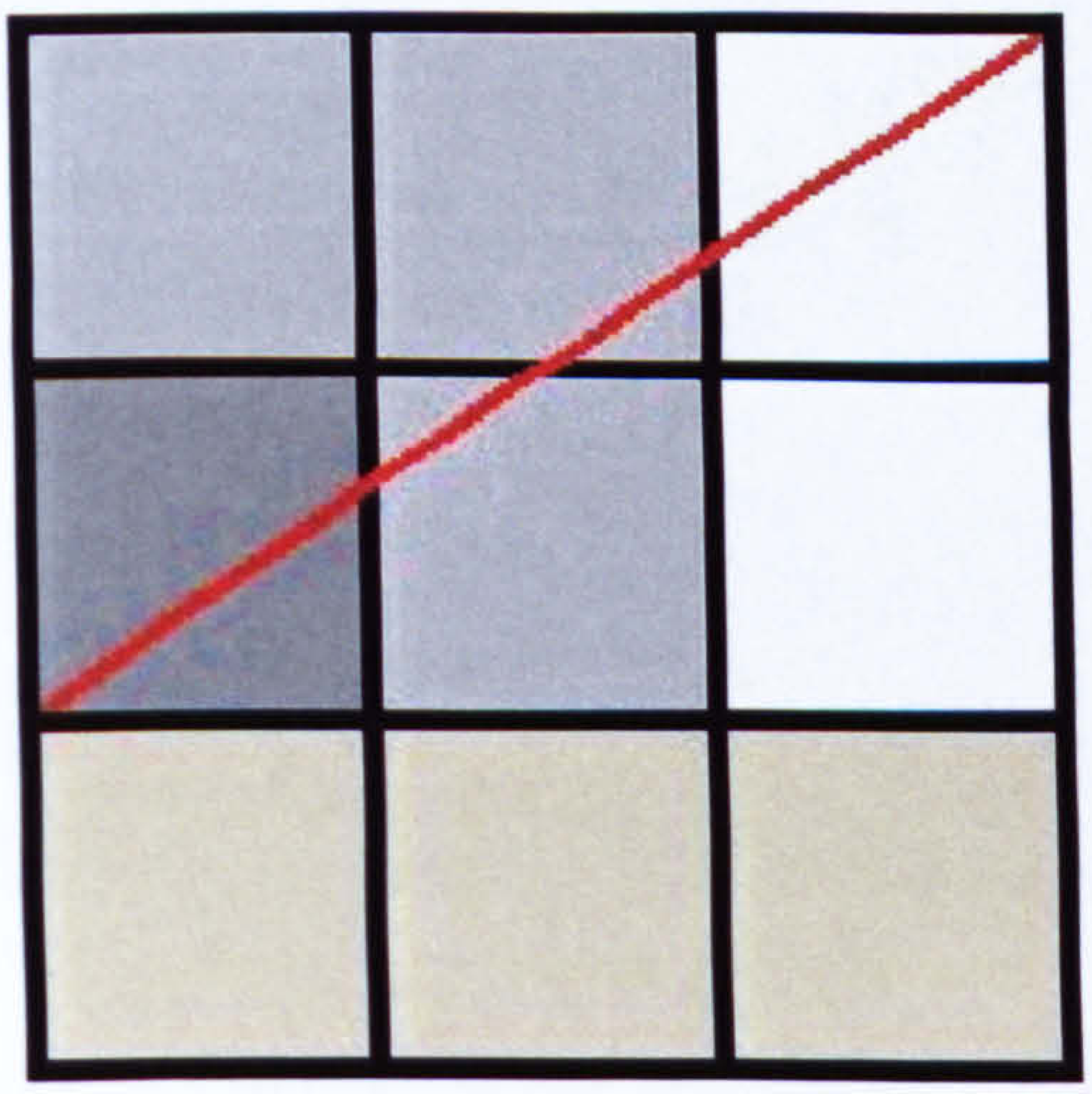


Figure 5.18 Colour Change in Archaeological Permanent Dentition

The diagonal red lines split the heat-induced colours in half. The natural colours running along the bottom row are ignored as they are of no interest here. If the heat-induced colour changes produced as a result of high temperature burning for short periods of time were similar to those produced by low temperature burning for long periods of time one would expect to see a symmetry along the diagonal axis (red line). None of the charts (Figures 5.15 to 5.18) show clear symmetry along this axis. There is an element of symmetry in Figures 5.15 to 5.18 however, which suggests that similar heat-induced changes may be occurring. The lack of clear symmetry could be the result of natural variation in colour change that a larger sample size may overcome. It could, of course, also suggest that high temperature burning for short periods of time does not produce the same features as those created during long low temperature burning, or that temperature and burning have different effects on colour change. Based on just an examination of colour change, it would be impossible to say whether the determining variable with regard to final tissue colour was temperature or duration of burning.

It is important to bear in mind that burned bone very rarely transforms into a single uniform colour. Most hard tissues display a range of colours within a single sample. Figures 5.19 and 5.20 are examples of this.

Figure 5.19 Multiple Colours on Sample 3-0005-08 [500°C for 45 minutes]

Figure 5.20 Multiple Colours on Sample 2-0005-01 [900°C for 15 minutes]

These variations in colour can be explained by their positions in the furnace, that is their proximity to the heat source and furnace 'hot-spots', the hard tissues are not burned uniformly. Some parts of the material will be burned more than others, resulting in the differential loss of carbon and therefore variations in colour. In addition, there is a variation in colour as one travels from the outside to the inside of the material. This phenomenon is also noted in Parker's (1985) study. Figures 5.21 and 5.22 highlight this occurrence.

Figure 5.21 Variations in Colour in Sample 3-0005-01 [500°C for 45 minutes]

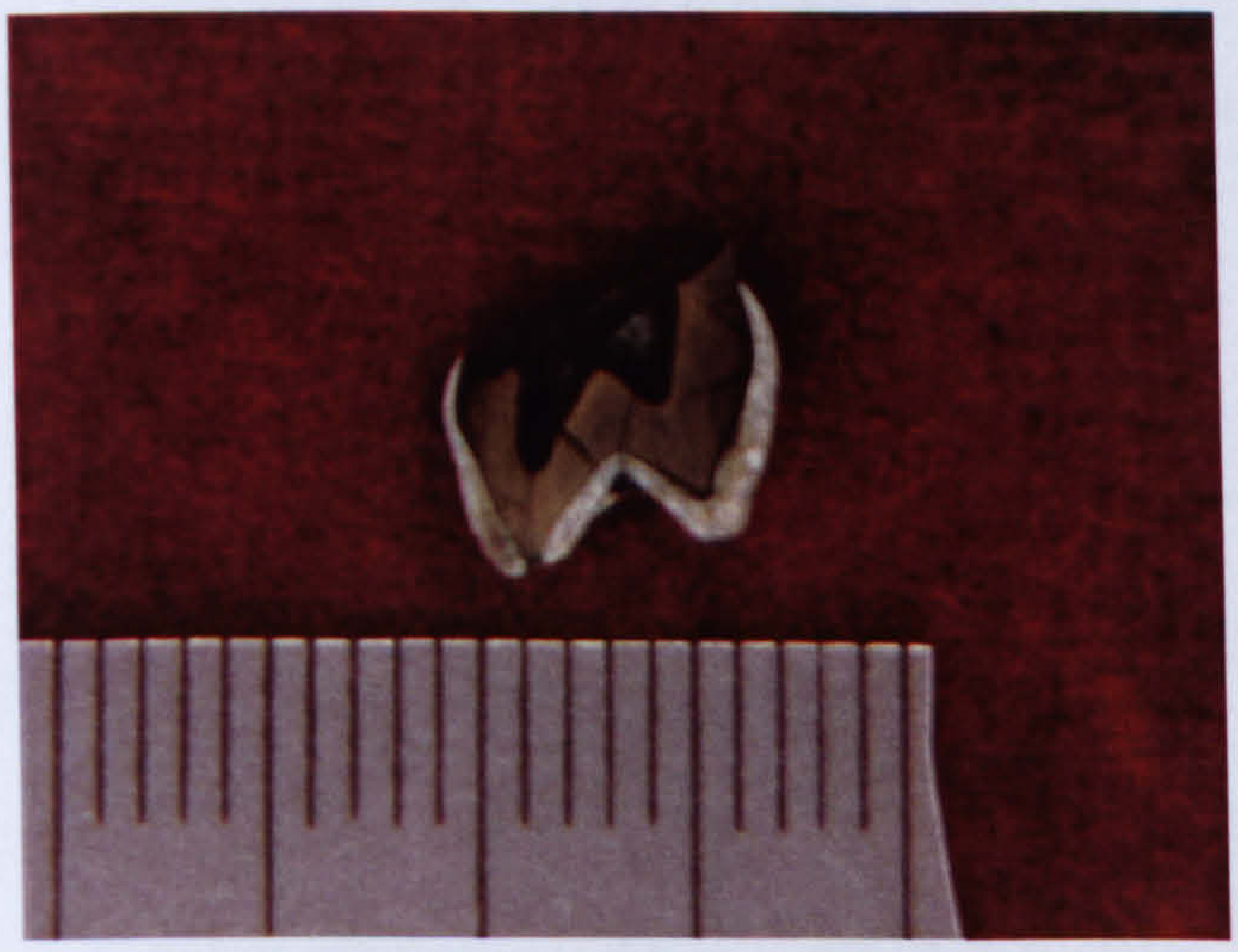


Figure 5.22 Variations in Colour in Sample 4-0001-04 [500°C for 15 minutes]

As can be seen in Figures 5.21 and 5.22, which are typical of the samples burned, the inside of the bone is a darker colour than the outside. This is because the medullary cavity is protected from burning whereas the external surface is exposed and suffers the effects of the heat more. This results in a greater loss of carbon from the external aspect of the tissues.

Three different dental samples were burned in order to investigate whether there were any differences in the consequences of burning modern adult and juvenile and archaeological adult teeth. Differences may be expected, especially between the modern and ancient teeth. Here the decreased quantities of organic matter within the archaeological tissue relative to the modern material may have an effect. From Figures 5.12 to 5.14, it can be seen that the greatest differences in heat-induced colour changes seem to be between the modern permanent dentition and the modern juvenile and archaeological adult teeth. When examining the differences between the modern adult samples and the others, one must take into consideration the differences in colour charts. Figure 5.12 contains more cells, in keeping with the larger sample size and higher number of temperature and duration of burning variables tested. Figure 5.23 reproduces the cells from Figure 5.12 that can be directly compared with those of Figures 5.13 and 5.14. Inspection of these charts at a more appropriate scale reveals that there are no significant differences between any of these samples. Only the 500°C for 45 minutes cell of Figure 5.23 appears incongruous, but this can be explained by natural variation – the general trend still exists within this chart.

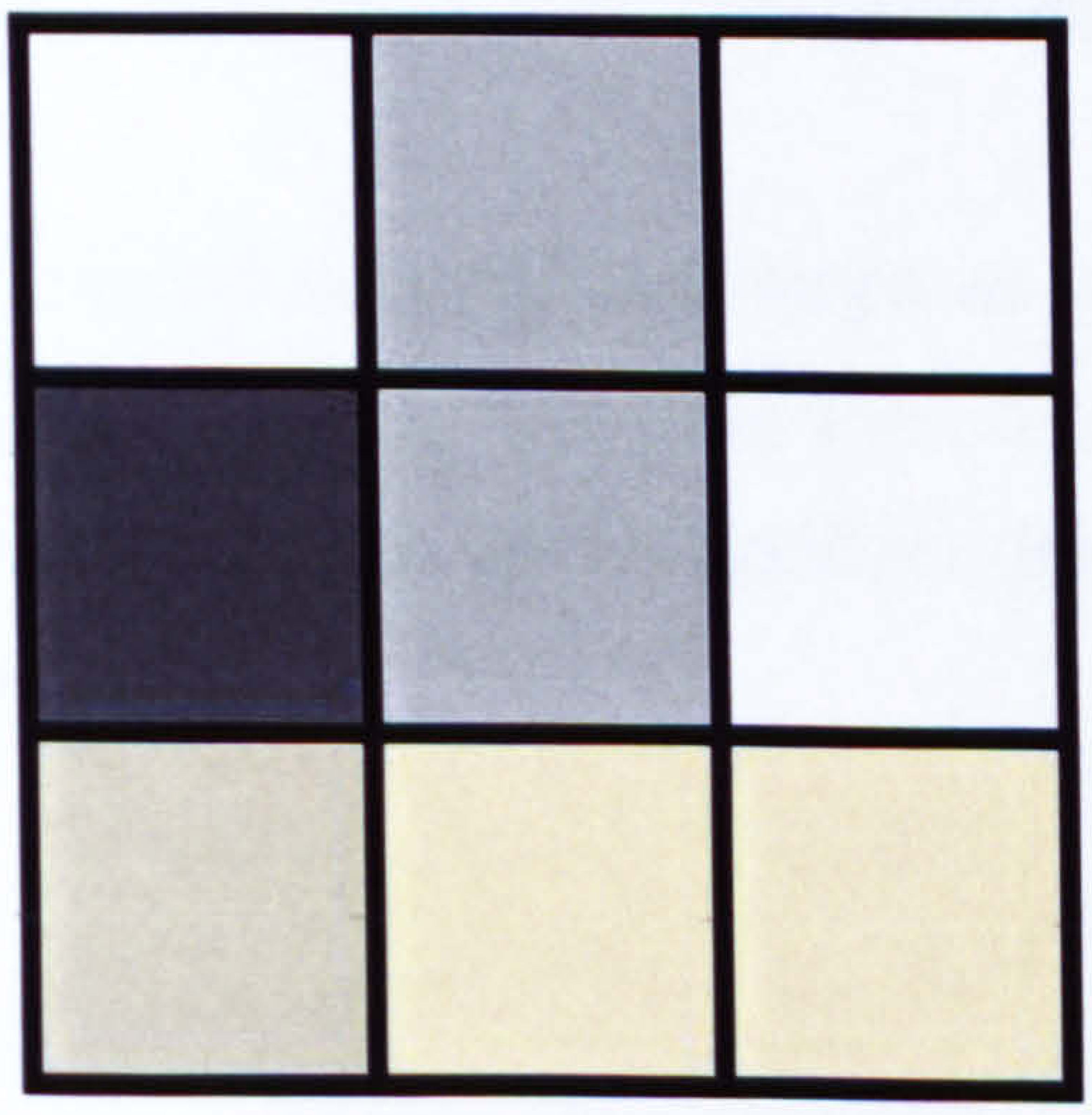


Figure 5.23 Colour Change in Modern Permanent Dentition

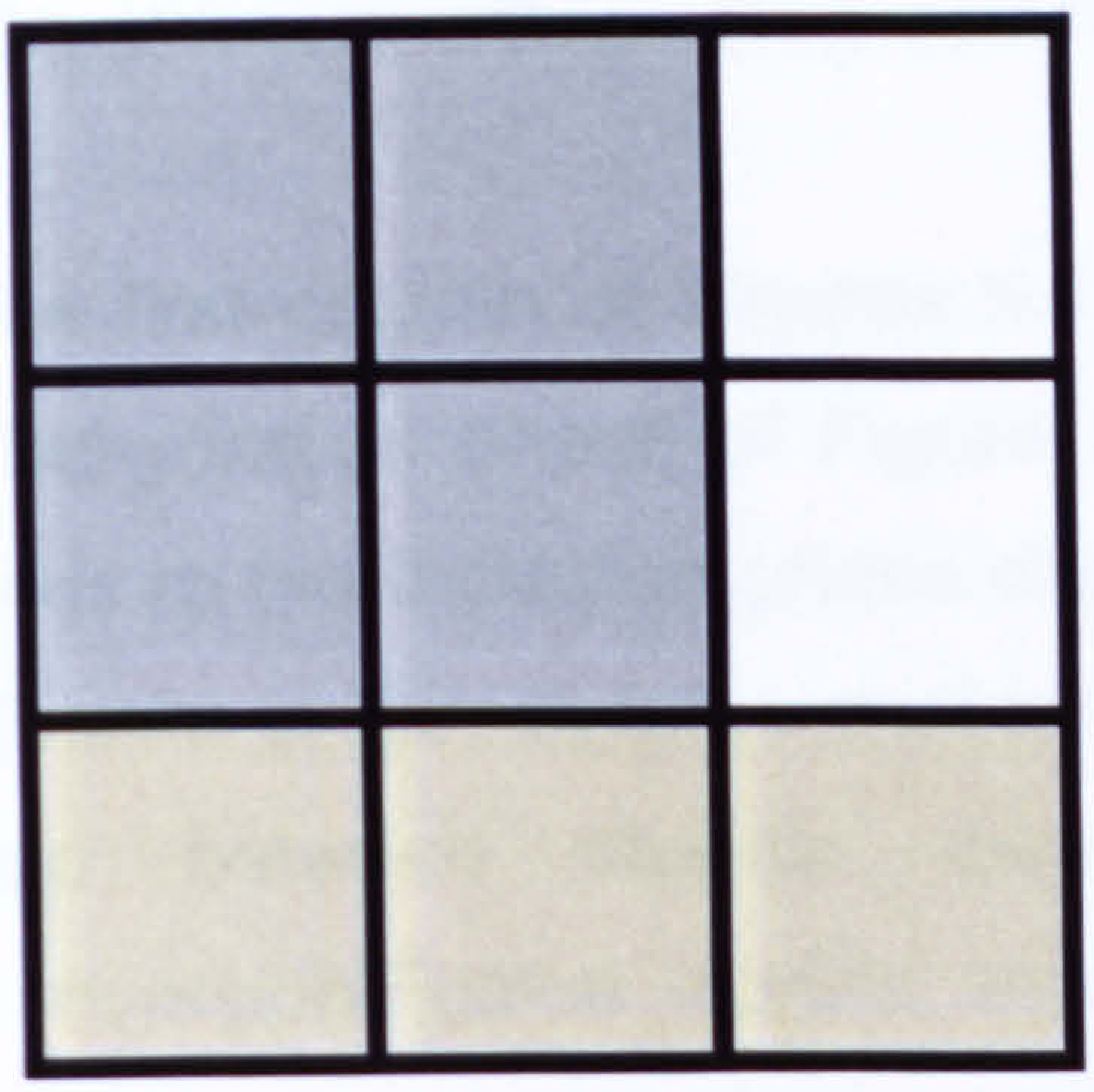


Figure 5.13 Colour Change in Modern Deciduous Dentition

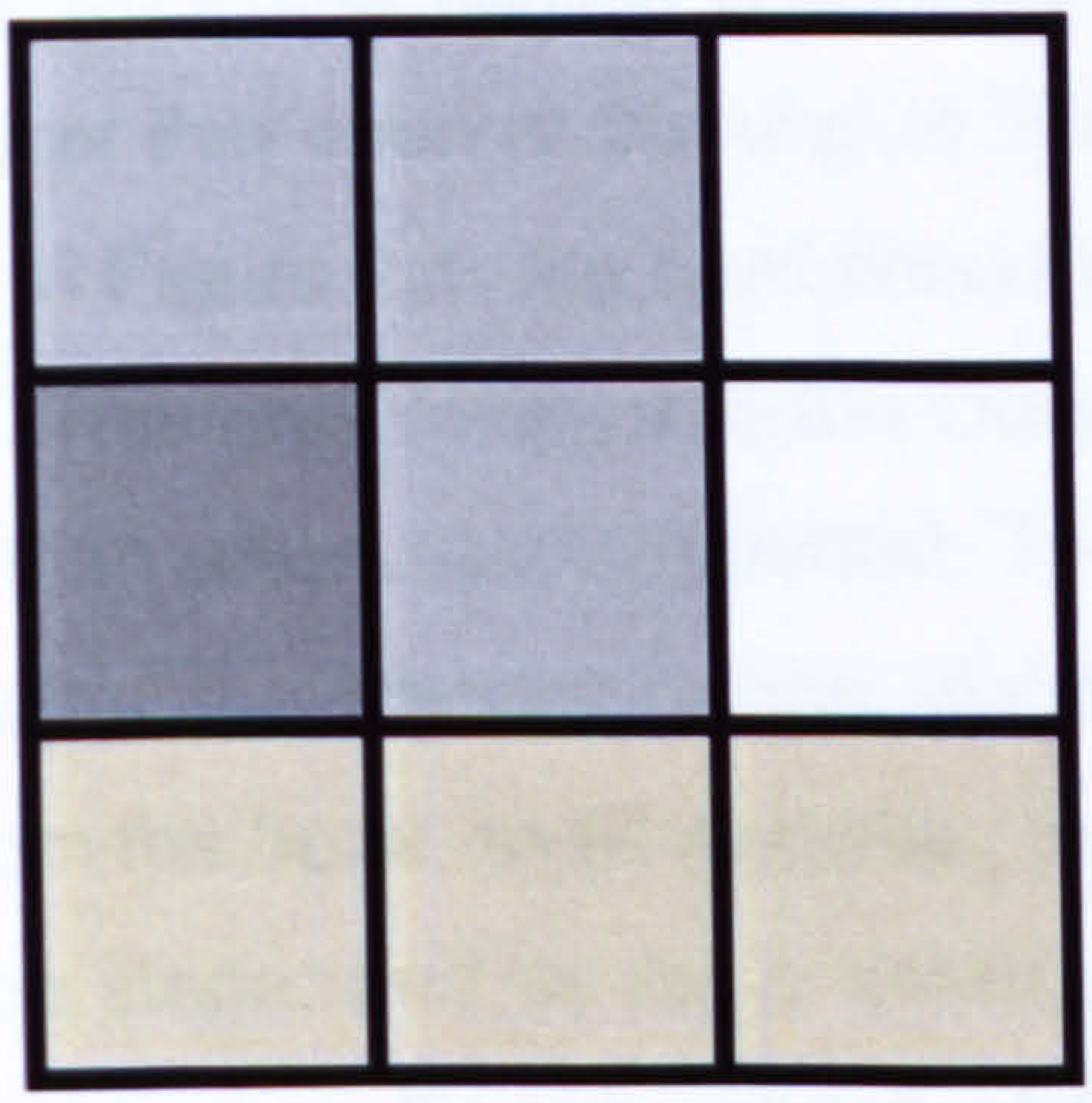


Figure 5.14 Colour Change in Archaeological Permanent Dentition

Although one should not use colour change as a predictor for temperature of burning, it may be possible to associate the colour changes to the four broad stages of heat-induced bone decomposition discussed in Chapter 2. Figure 2.1 is reproduced below.

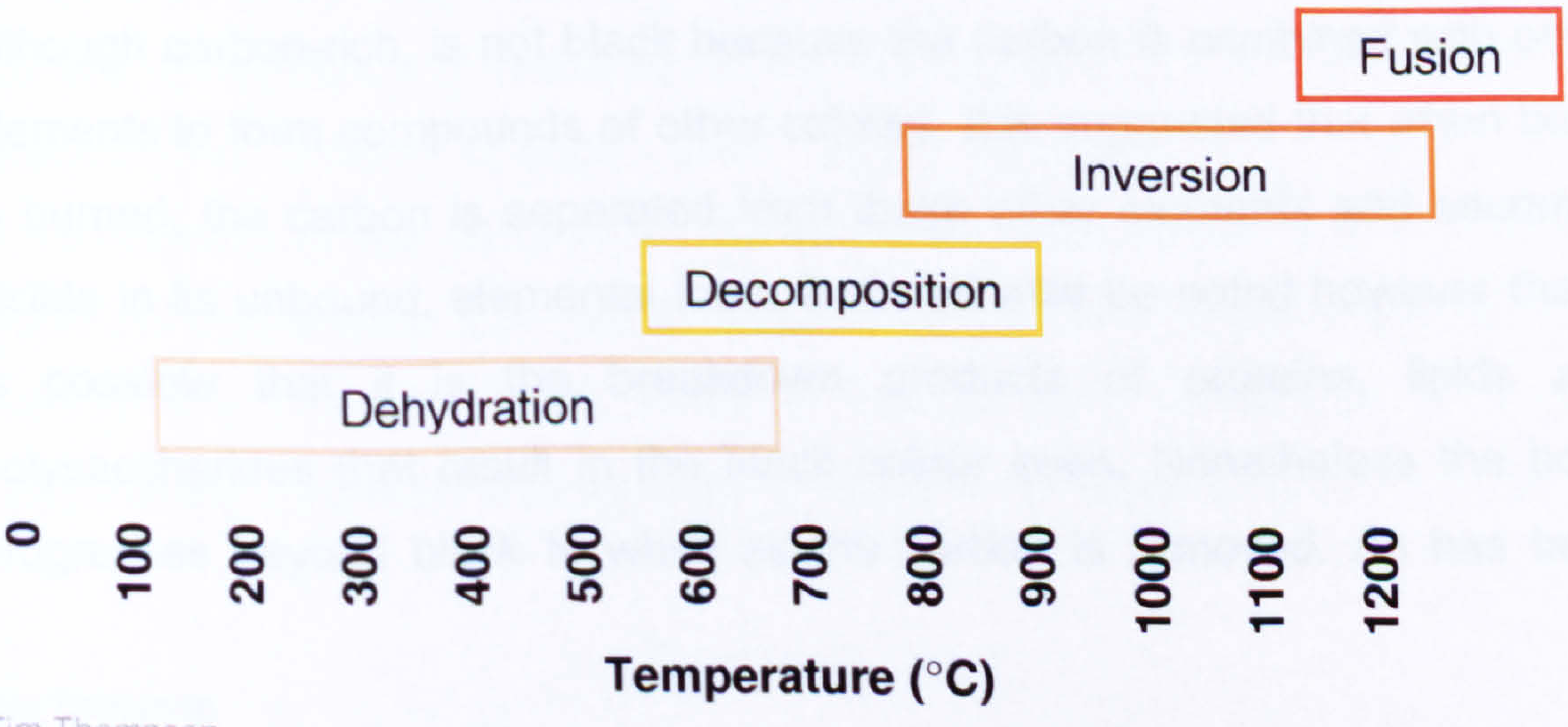


Figure 2.1 Stages of Heat-induced Bone Degradation

Temperature wise, the first column of Figures 5.11 to 5.18 is 500°C, which corresponds to the Dehydration phase of Figure 2.1. The middle column is 700°C and corresponds to the Inversion phase and the last column of 900°C corresponds to the Fusion stage. Caution should be taken however and the considerable overlap between stages, especially the Dehydration-Decomposition and Inversion-Fusion stages, means that any allocation of colour change to a given stage should not be deemed to hold great accuracy. One would expect that burned hard tissues would become black during the Decomposition stage, when the carbon and other organic components were being removed. The fact that even at burning of 500°C, which is at the start of this phase according to Figure 2.1, the hard tissue had gone beyond the black colour into the greys. This may mean that the Decomposition stage begins at a lower temperature than previously suggested. The change in colour to white would be expected after the Decomposition stage, that is, once the carbon has been fully lost from the bone. In all samples, this has happened by 900°C, well into the Inversion stage, and as such would not demand any change to the Approximate Temperature Range column of Figure 2.1. Changes to the Approximate Temperature Range of the Fusion stage could only occur after examination of the change in a feature indicative of the melting of the crystal component. Colour change is not one of these features, although mechanical strength (Chapter 7) and bony dimensions (Chapter 9) are.

It is widely known that bone becomes black when it is burned, but the reason for this is not discussed. In one of its elemental forms carbon is black. Bone, although carbon-rich, is not black because the carbon is combined with other elements to form compounds of other colours. It is suggested that when bone is burned, the carbon is separated from these other elements and becomes visible in its unbound, elemental form. It should also be noted however that it is possible that it is the breakdown products of proteins, lipids and polysaccharides that result in the black colour seen. Nonetheless the bone progresses beyond black to white as the carbon is removed. As has been noted above, unexpected colours (such as browns, greens and yellows) seen on burned bones have been relatively straightforward to explain. None of these colours were evident here. In both the dental and bony samples however, a light blue to turquoise colour was noted. Usually any light blue colours in burned materials are attributed to metal oxides. This cannot be the case here, as there is not enough of this element contained within the bone and teeth to satisfactorily explain the amounts produced here. As the blue is a reasonably common colour in these samples, it could be a direct product of the methodological protocol or equipment used. However, other burned bone studies have also noted the arrival of patches of blue at high temperatures (Gejvall, 1969 – although he links it erroneously with the presence of the organic component of the bone since the colour only appears long after the organic phase is lost).

It is important to note that colour change will be different if soft tissue has been present during the burning process, that is in most real-life situations. As discussed in Chapter 4 the soft tissue has been removed in order to reduce the number of variables acting upon the heat-induced changes in bone itself.

FiveFive Conclusions

Heat-induced colour change is often seen as an extremely important consequence of the burning of hard tissues. This is because colour change is usually quite obvious. However, other than being an indicator of the close proximity of fire, it has few analytical uses. It is a very poor predictor of the temperature of burning, and the presence of colours of a non-bony origin can confuse identification of cremation in the first place. What the examination of heat-induced colour change does allow however, is a more solid understanding of the process of heat-induced degradation. But this is only when it is appreciated that colour change is not a direct result of temperature, but rather a loss of carbon, which in turn is likely to be due to several independent variables. Now that our collective understanding of cremation is more advanced than when Shipman *et al* (1984) published their pioneering work, workers do not need to dwell upon colour change to the same degree as many still are. Further knowledge will only come with the examination of more telling features of burning with a new approach to the examination of heat-induced features.

Six The Examination of Heat-induced Fracture Patterns

SixOne Introduction

Second only to colour change, the development of fracture patterns is the most clearly expressed heat-induced change in hard tissue. Fracture, or structural failure, occurs when any stress in a material exceeds the strength of that same material (Dowling, 1999; Herrmann and Bennett, 1999). Fractures develop through two distinct stages: crack nucleation and crack propagation (Courtney, 1990). There are two biological units that work in tandem to provide bone with its structural integrity. The hydroxy- bonds of the inorganic phase provide compressive strength while the collagen fibres that penetrate the mineral phase provide tensile strength (Herrmann and Bennett, 1999). Burning removes the collagen and alters the hydroxy- bonds thereby reducing elasticity and changing the tensile strength (Herrmann and Bennett, 1999). An understanding of their formation in burning environments is clearly vital for a full understanding of the effects of heating on bone and teeth. In addition, it has been argued (Baby, 1954; Binford 1963; Buikstra and Swegle, 1989; Thurman and Willmore, 1981) that recognising specific fracture patterns will allow one to state whether the remains were fleshed, recently defleshed or dry when burned. This has important medico-legal and archaeological implications. It is also argued that the literature discussing this topic is contradictory (Mayne Correia, 1997), and therefore data from a large sample size such as the one used here, will help to clarify this issue.

Three different methods of imaging were used in order to allow for an in-depth analysis of any fracture patterns created as a consequence of burning: digital imaging, radiography and scanning electron microscopy. These three methods facilitated analysis at both the macroscopic and microscopic scales. By combining these methods, and not restricting imaging to either the macro- or microscopic scales, a fuller appreciation of the development of thermicallyinduced fractures is possible. A holistic approach to data collection is required in cremation studies to counter the trend for focussed studies which do not appreciate the entirety of the transformation process.

The three forms of imaging applied to the burned remains were standard photography using a digital camera, radiography and scanning electron microscopy. It can be said that there is a progression along these imaging techniques from focussing on the gross to the minute. Standard digital photography was chosen over wet-film photography as the photographic process is quicker and easier, for example there is no need for photograph development and mistakes can be promptly deleted. In addition no flat-bed scanning is required in order to incorporate the images into written documents or for image manipulation, as the image is already in a suitable digital format. Radiography was used because, unlike standard photography and scanning electron microscopy, it permits the radiologist to view all of the fracture lines at once. This is of greater use when attempting to compare fracture patterns from different bone samples. Finally scanning electron microscopy was chosen as it allows for examination of microscopic fractures. Scanning electron microscopy was selected over transmission electron microscopy because the latter is designed to examine the internal structures of samples, while the former examines the surface of samples. It is the surface that is of relevance when assessing fracture patterning.

SixTwo Methodology

SixTwoOne Digital Imaging

The protocol for the photography of the samples relevant to the examination of heat-induced fracture patterns is the same as that for colour change, the details of which are presented in Chapter 5.

SixTwoTwo Radiology

X-rays are man-made ionising radiation which are produced in an X-ray tube and shot through the specimen of interest onto photographic film (Roberts *et al*, 1998; Weir and Murray, 1998). X-rays are absorbed by biological material in differing quantities depending on the density of that material (Roberts *et al*, 1998). Dense material absorbs more X-ray radiation and therefore produces whiter images on the photographic film. Darker areas on the radiograph are the result of less radiation absorption by less dense material (Roberts *et al*, 1998; Weir and Murray, 1998).

The main application of radiology in the forensic realm is for human identification. There are numerous examples of radiology being of invaluable use after mass fatality incidents (for example, Kahana *et al*, 1997), although this is often of greatest use if only a small number of bodies remain to be identified (Midda, 1988). It is also of use in situations where the identification of individuals has not been possible using standard identification methods (as demonstrated by Bowers and Johansen, 2002, Johanson and Saldeen, 1969, Kahana *et al*, 1997, Kuehn *et al*, 2002 and Murphy *et al*, 1980). Radiology has been adopted more readily by forensic odontologists than by forensic pathologists or anthropologists. This is probably due to the prevalence of dental radiographs and the general acceptance of dental comparison as a means of positively identifying a person. Forensic research also tends to focus on the positive identification aspect of the use of radiology (as in Kahana *et al*, 1998; Kuehn *et al*, 2002; Mann, 1998), but also includes the development of anthropological techniques (such as by Chrysostomou, 2002, Garn et al, 1979).

The radiography was conducted using a Vinten Instruments 43804N Faxitron Series X-Ray System in the Department of Forensic Pathology, University of Sheffield (Figure 6.1). The bony samples were exposed to 45 kV of radiation for 1.25 minutes. These settings were chosen as they gave the clearest images. Other variations of dosage and exposure time were tried and disregarded due to the poor images subsequently developed. The images were taken on 30cm by 20cm Kodak Industrex AA400 film. After exposure, the films were placed in 600ml of developing solution (450ml Kodak Professional Industrex Manual Developer and 150ml water) for two minutes. They were then rinsed in flowing tap water and placed into 600ml of fixative solution (450ml Ilford Hypan Rapid Fixer and 150ml water) for three minutes. They were then rinsed a final time in flowing tap water, and allowed to dry in a Marrutt heater.

Figure 6.1 The Vinten Instruments 43804N Faxitron Series X-Ray System, Department of Forensic Pathology.

As with the standard photography not all samples were X-rayed. Three representative samples from each cell were used. Table 6.1 provides details of the samples used.

Dose (kV)	Duration (mins)	Cell Number	Sample Number
45	1.25	2	3
45	1.25	2	6
45	1.25	2	7
45	1.25	3	2
45	1.25	3	4
45	1.25	3	7
45	1.25	4	3
45	1.25	4	6
45	1.25	4	7
45	1.25	5	1
45	1.25	5	2
45	1.25	5	8
45	1.25	6	2
45	1.25	6	6
45	1.25	6	9
45	1.25	7	1
45	1.25	7	4
45	1.25	7	10

Table 6.1 Exposure Details and Samples Used for Radiography.

SixTwoThree Scanning Electron Microscopy

It is not appropriate to discuss in great detail the theory of operation of scanning electron microscopes here. Detailed descriptions of the function of these microscopes and the process of sample preparation can be found in texts such as Bozzola and Russell (1992) and Flegler *et al* (1993). A brief summary will prove useful however. The scanning electron microscope functions by firing a beam of electrons from the electron gun at the top of the machine. The beam is attracted through an anode, after which a condenser lens condenses the beam so that it can then be focussed onto the specimen. Scan coils, present within the objective lens, are subjected to an electric current that results in the formation of a magnetic field. This magnetic field is used to deflect the beam of electrons across the surface of the specimen in a raster pattern. Upon striking the specimen, the electrons interact with the specimen in a variety of ways. Most significantly, secondary electrons are produced from the sample. These are collected by a detector, transformed into an electric current and amplified. The current is then sent to a cathode-ray tube for viewing. A projection from the surface of the sample will result is a larger amount of secondary electron emission, and therefore a more powerful current will be sent to the cathode-ray tube, resulting in a brighter spot on the display. A depression in the sample will therefore result in a dimmer spot on the display. A degree of preparation is required before the sample can be successfully scanned and viewed. First the sample must have all water removed. Water will negate the production of a vacuum inside the microscope, which is necessary for operation. This can be achieved, for example, by oven drying the material. Second the sample must be mounted. Third the specimen must be electrically conductive. Conductivity will ensure that the bombardment by electrons will not cause a build-up of negative charge that would impair image production. The appropriate method for achieving conductivity is to coat the sample with a metal such as gold. Once these three stages are complete, the specimen can be placed inside the microscope for analysis.

As mentioned above, the key profit to using scanning electron microscopy is that topographic surfaces can be examined in fantastic detail. Any discipline that seeks to examine the surface of a structure should be able to apply this form of microscopy. Scanning electron microscopy has proved to be a useful tool in much archaeological research. It has been successfully applied to work as diverse as archaeometallurgy, palynology and osteology. In the forensic sphere, it has been utilised in both case work and research projects. Examples of applications within a legal context include the microscopic analysis of trace evidence (Platek *et al*, 1997; Taylor, 1973), stomach contents (Platek *et al*, 2001), gunshot residue (Lebiedzik and Johnson, 2002; Zeichner, 2001) and tool marks (Bartelink *et al*, 2001; Rawson et al, 2000; Taylor, 1973). As with the radiology-assisted archaeological research (Olsen, 1988), scanning electron microscopy has been used to help answer a wide variety of research questions in forensic science, pertaining to such issues as subsistence and diet (Mainland, 1994; Teaford *et al*, 2001) and human identification (Carr *et al*, 1986; Wilson and Massey, 1987). With regard to this project, scanning electron microscopy was deemed the most efficient tool for investigating the microscopic nature of heat-induced fracture patterns of the tissue surface.

Small blocks of bone were removed from the burned sheep long bones using a small hacksaw. The blocks were taken from one representative bone from each temperature and duration regime. Table 6.2 displays details of the samples used for the scanning electron microscopy. The blocks were then taken to the Electron Microscopy Unit, Department of Biomedical Sciences, University of Sheffield where they were mounted onto 0.5-inch aluminium pin stubs using double-sided tape. The mounted specimens were then coated in gold using an Edwards Sputter Coater S150B. It was decided that the samples would not require prior oven drying as they were already suitably dry due to their decomposition histories. The scanning electron microscopy was performed using a Philips PSEM 501B operating at 30kV (Figure 6.2). The images were recorded on Ilford FP4 120 film.

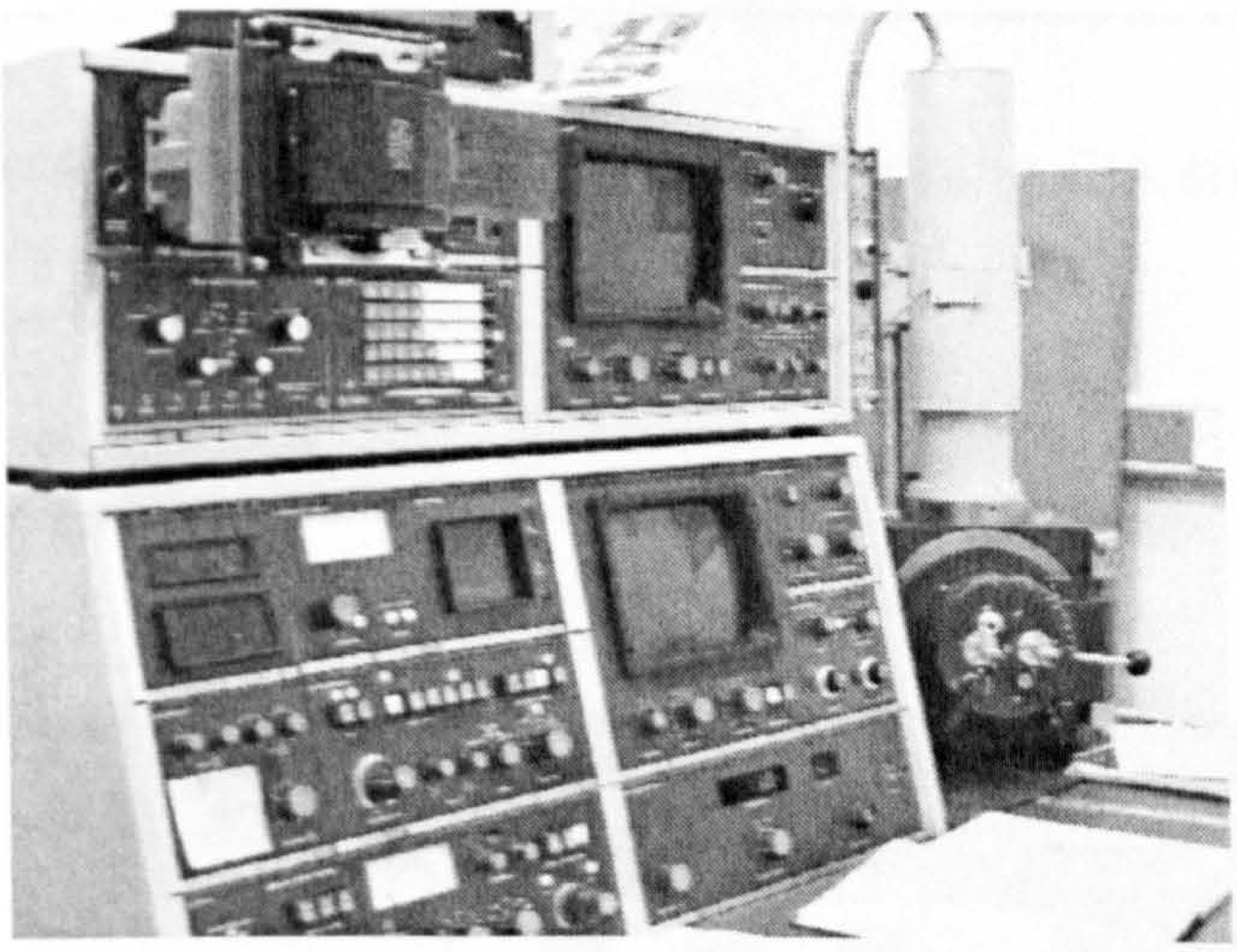


Figure 6.2 The Philips PSEM 501B, Department of Biomedical Sciences.

The specific magnification scales selected were a balance between maintaining microscopic detail and surface area coverage. After examination of the bone surface, images were produced of the most representative areas. John Proctor of the Department of Biomedical Sciences developed the photographic film containing the surface images.

Number	(kV)		
98	30	160	351 outer
99	30	160	351 outer back
100	30	640	351 inner
101	30	160	pre outer
102	30	640	pre inner
103	30	160	332 outer
104	30	160	332 outer back
105	30	1250	332 outer fracture
106	30	80	332 inner fracture
107	30	640	332 inner
108	30	1250	3710 outer
109	30	160	3710 outer
110	30	80	3710 inner
111	30	640	3710 inner
112	30	160	343 outer
113	30	160	343 outer
114	30	640	343 inner
115	30	160	327 outer
116	30	640	327 inner
117	30	160	362 outer
118	30	640	362 inner
119	30	40	362 inner

Table 6.2 Details of Samples Used for Scanning Electron Microscopy.

SixThree Results

Figure 6.3 Sample 3-0002-08 [500°C for 15 minutes]

Figure 6.4 Sample 3-0005-01 [500°C for 45 minutes]

Figure 6.5 Sample 3-0003-05 [700°C for 15 minutes]

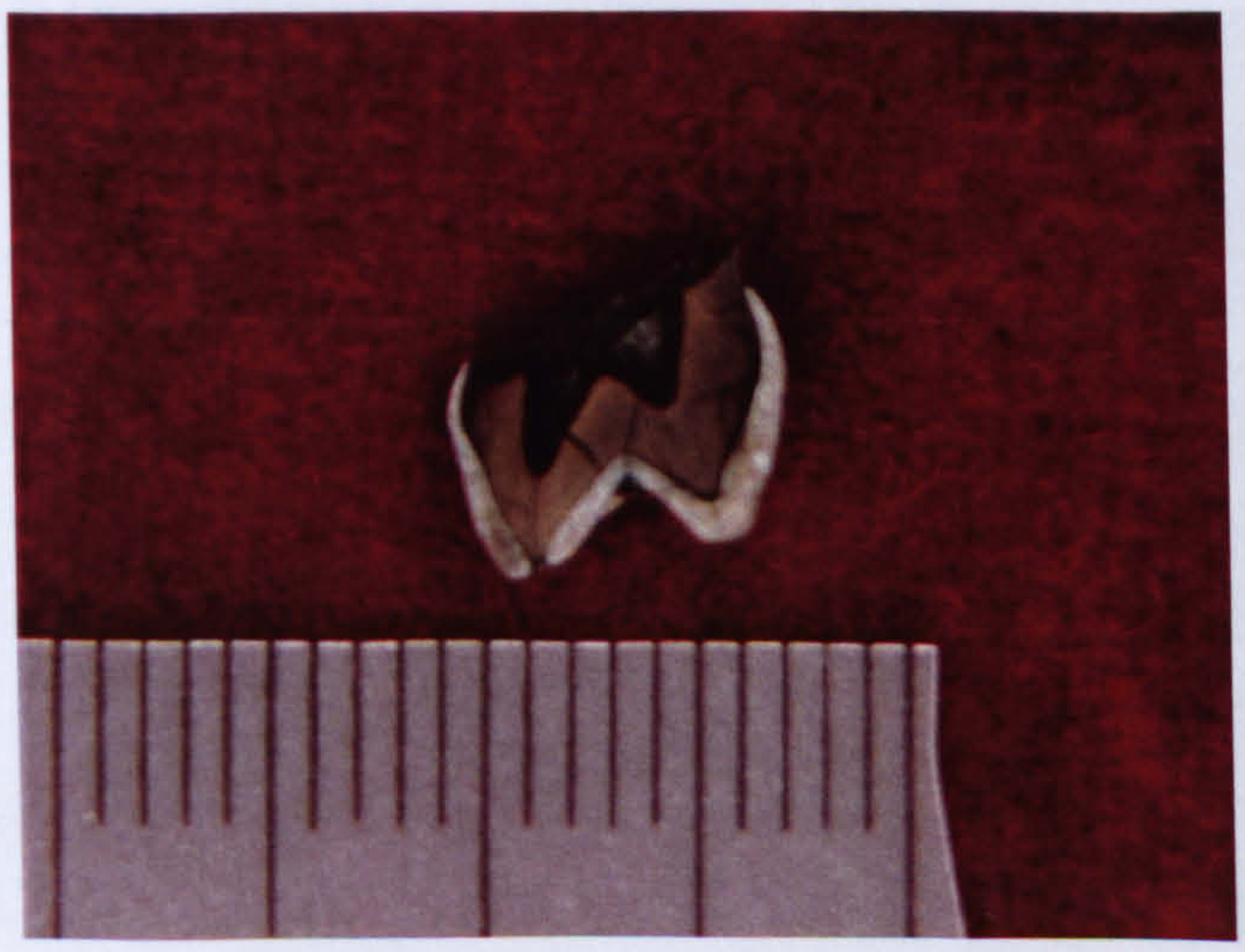


Figure 6.6 Sample 4-0001-04 [500°C for 15 minutes]

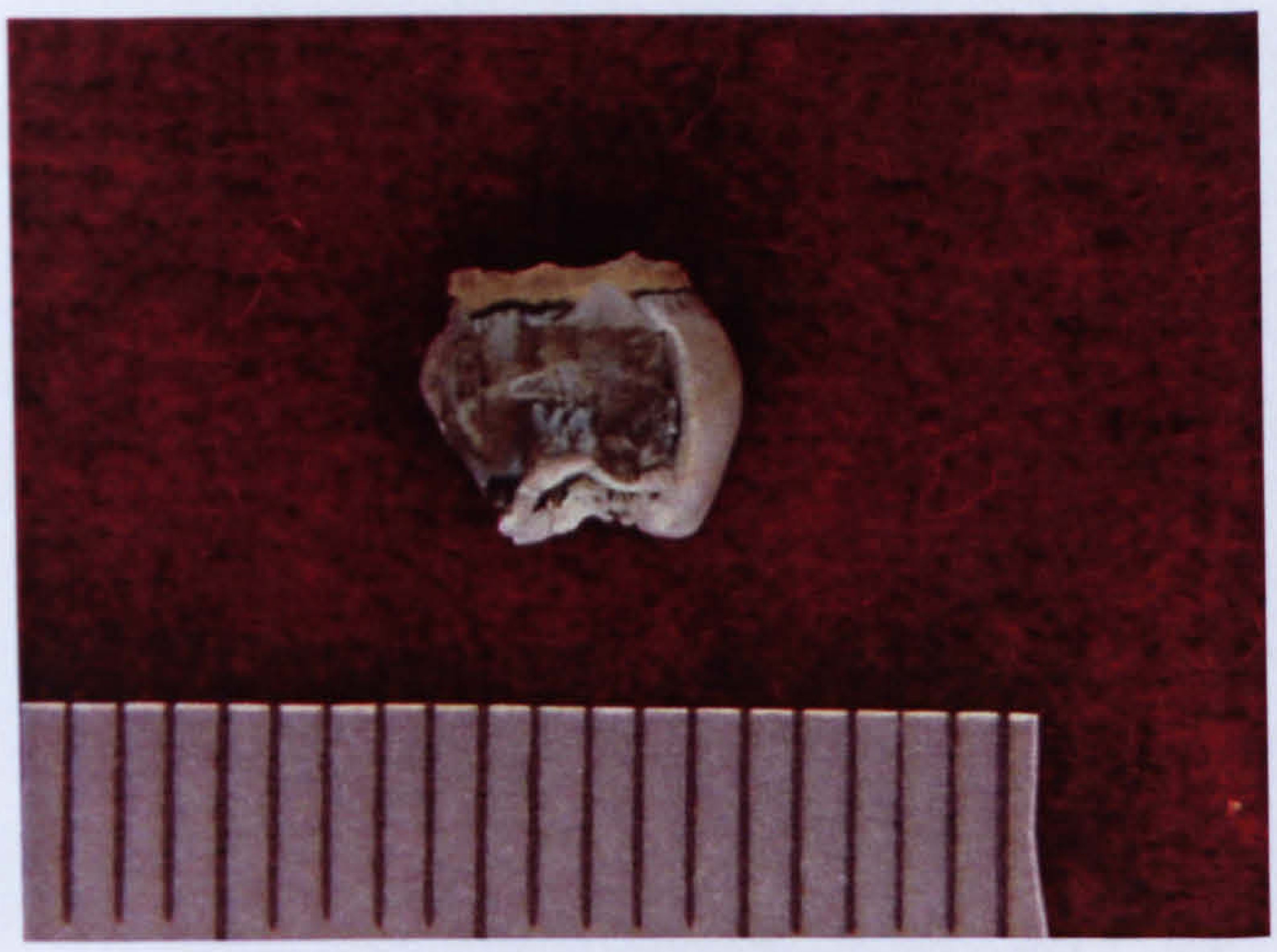


Figure 6.7 Sample 4-0002-03 [500°C for 45 minutes]

Figure 6.8 Sample 2-0001-01 [500°C for 15 minutes]

Figure 6.9 Sample 2-0002-02 [500°C for 45 minutes]

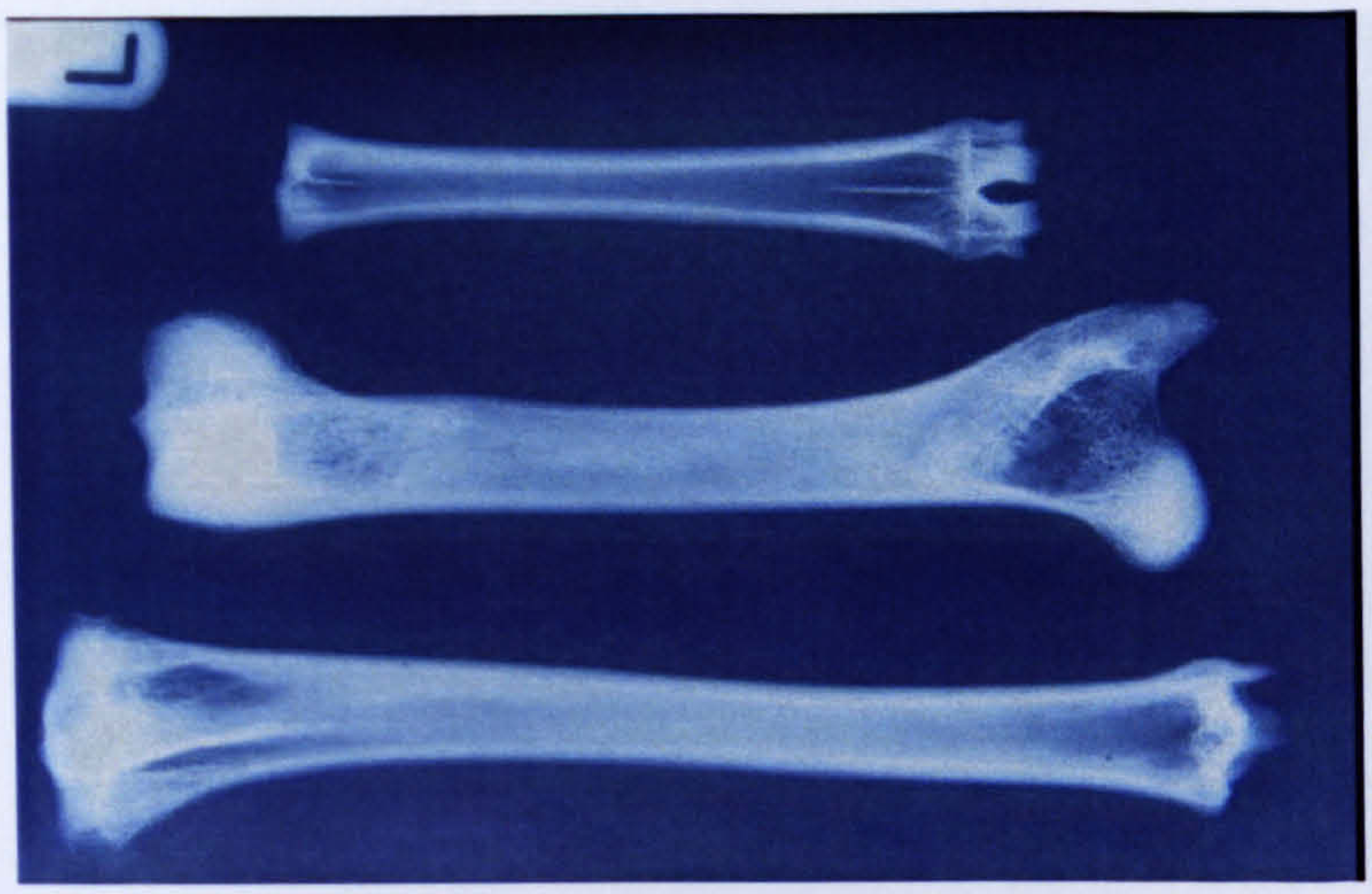


Figure 6.10 Radiograph of Unburned Bones

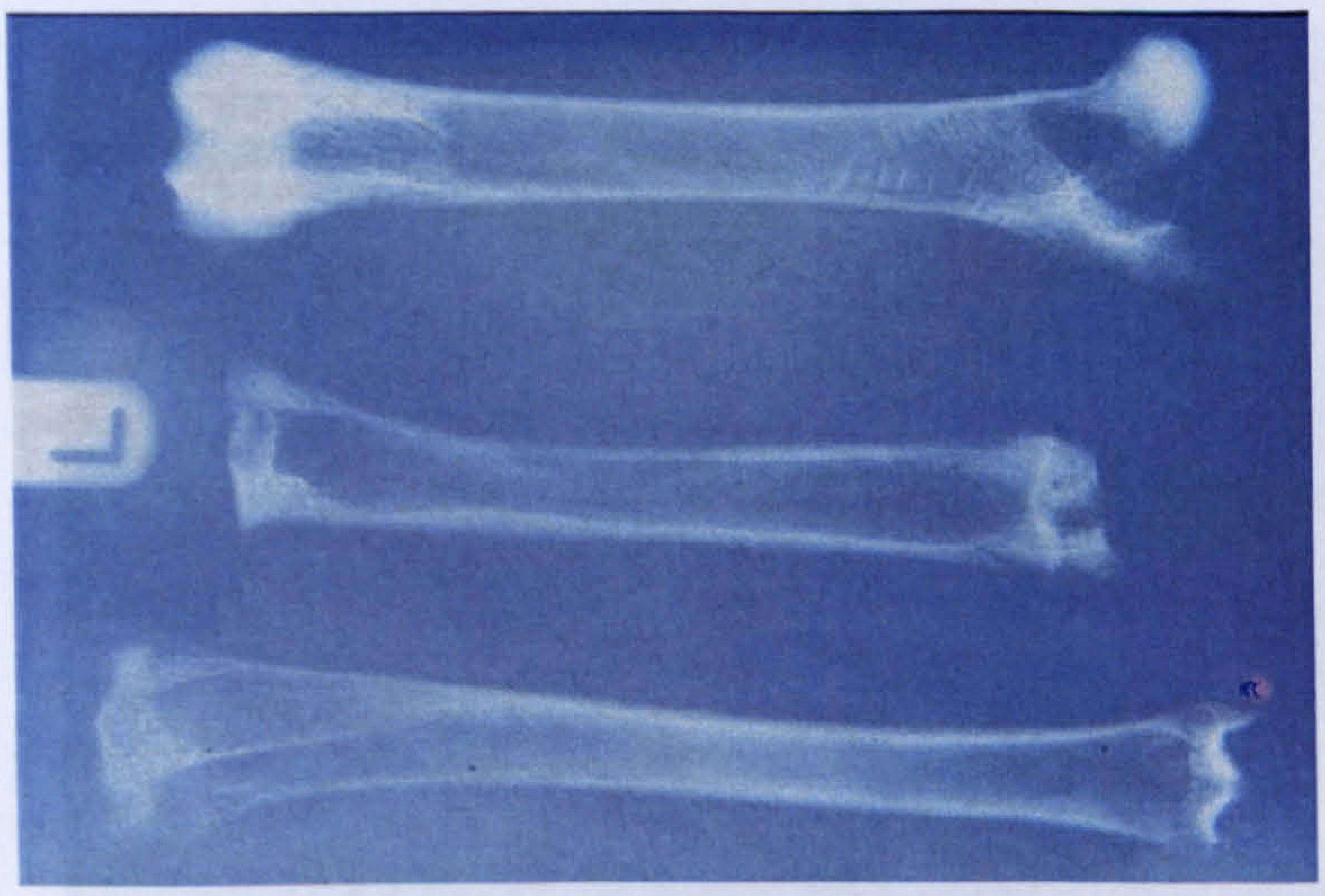


Figure 6.11 Radiograph of Bones Burned at 500°C for 15 Minutes

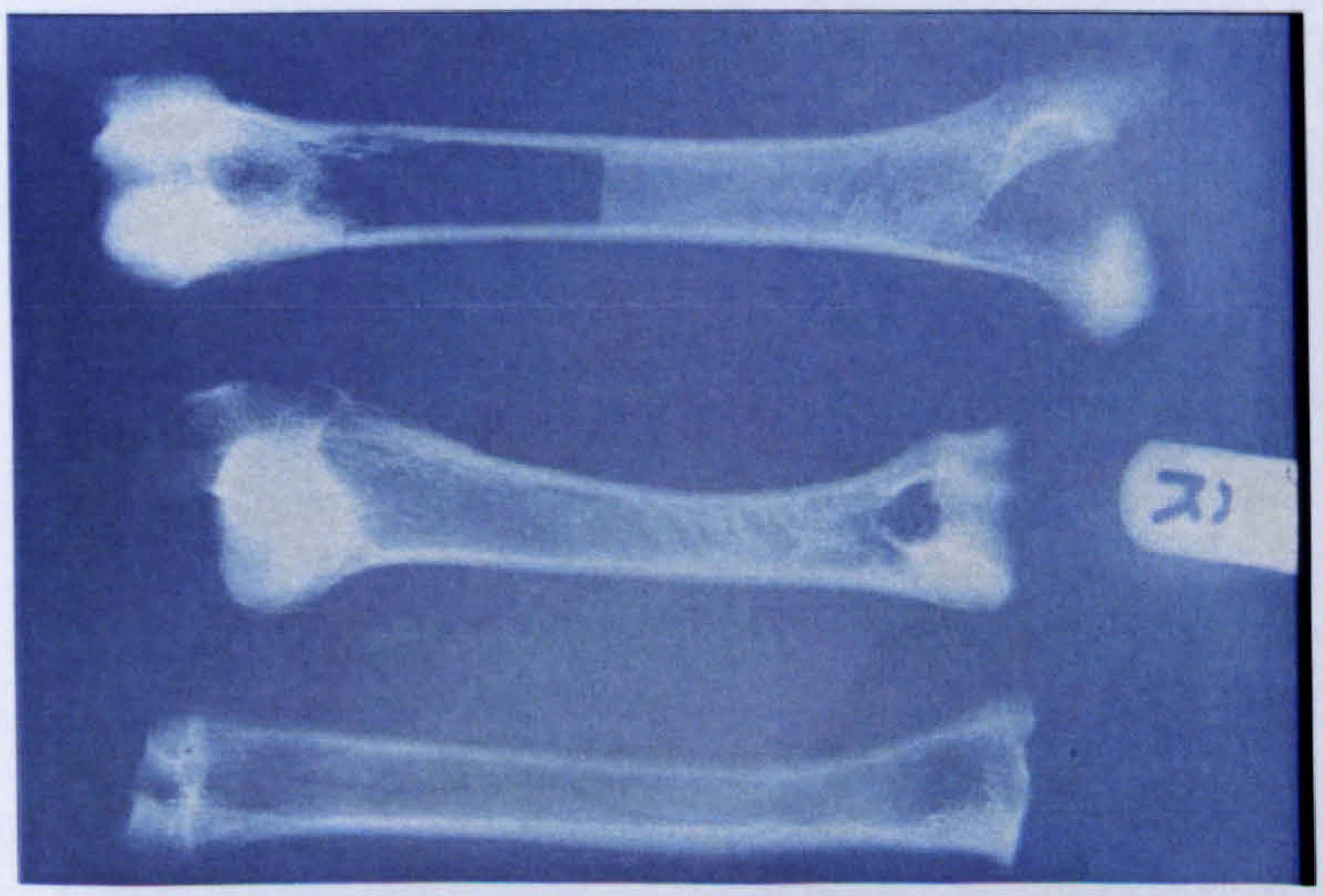


Figure 6.12 Radiograph of Bones Burned at 500°C for 45 Minutes

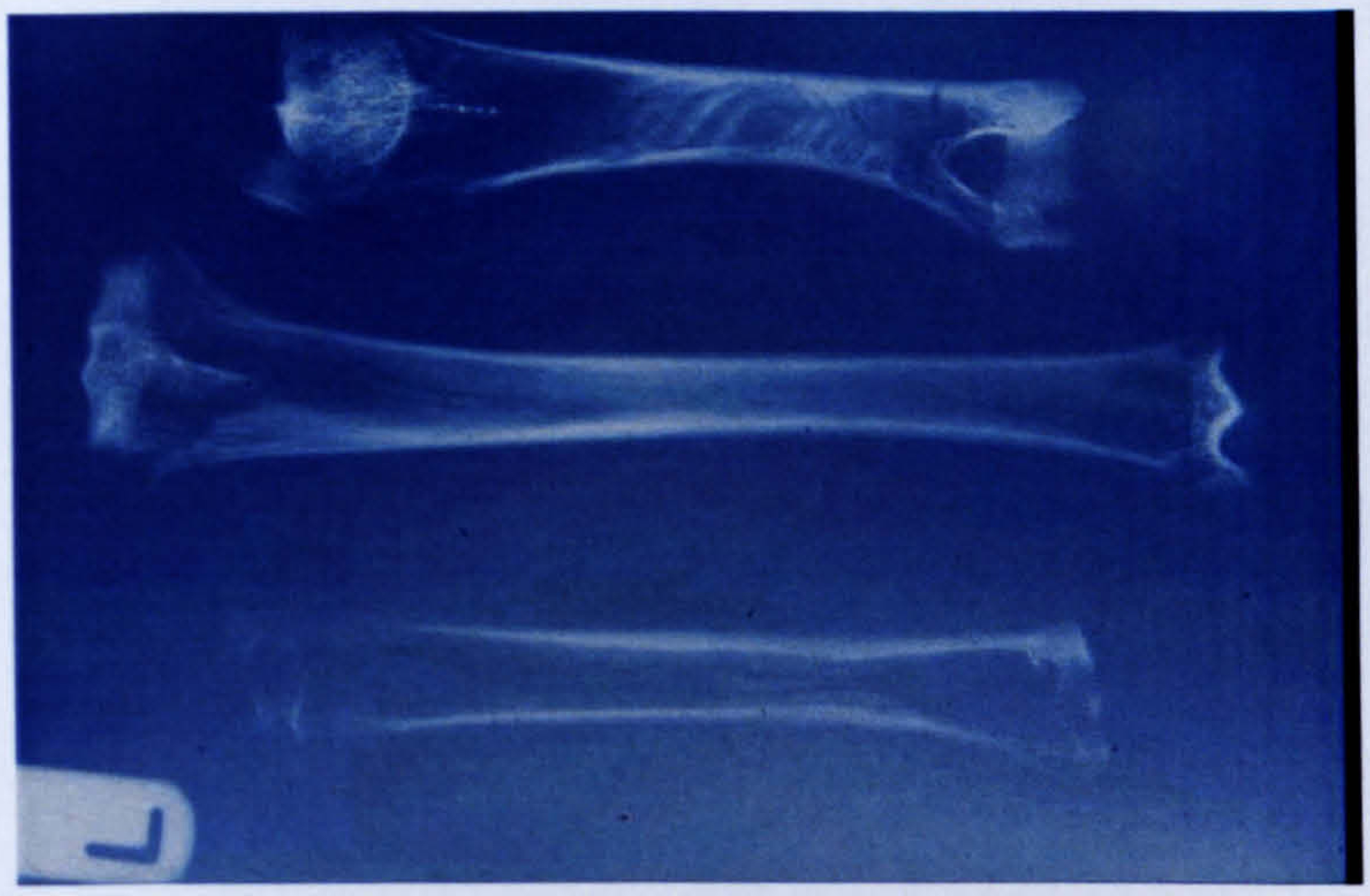


Figure 6.13 Radiograph of Bones Burned at 700°C for 15 Minutes

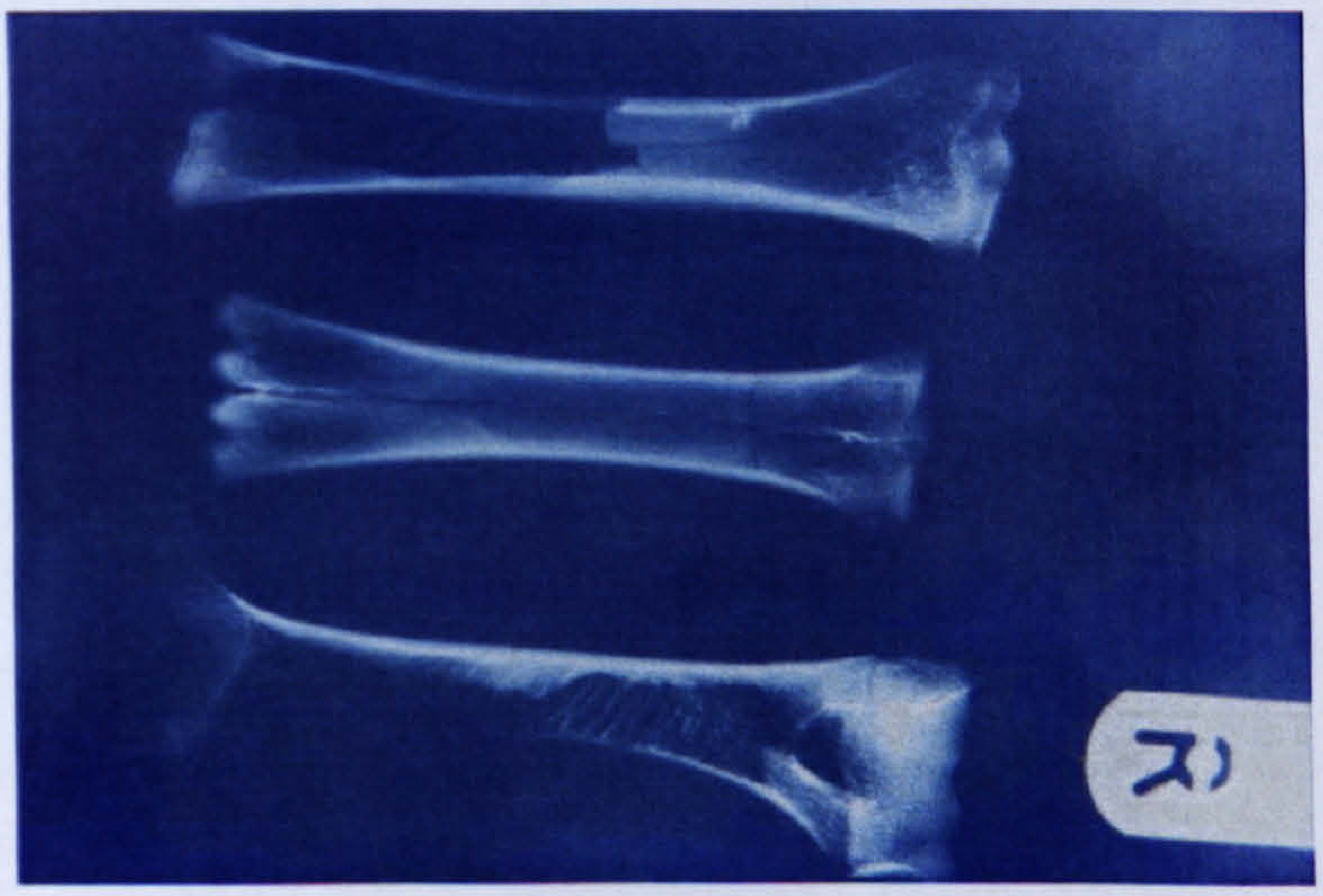


Figure 6.14 Radiograph of Bones Burned at 700°C for 45 Minutes

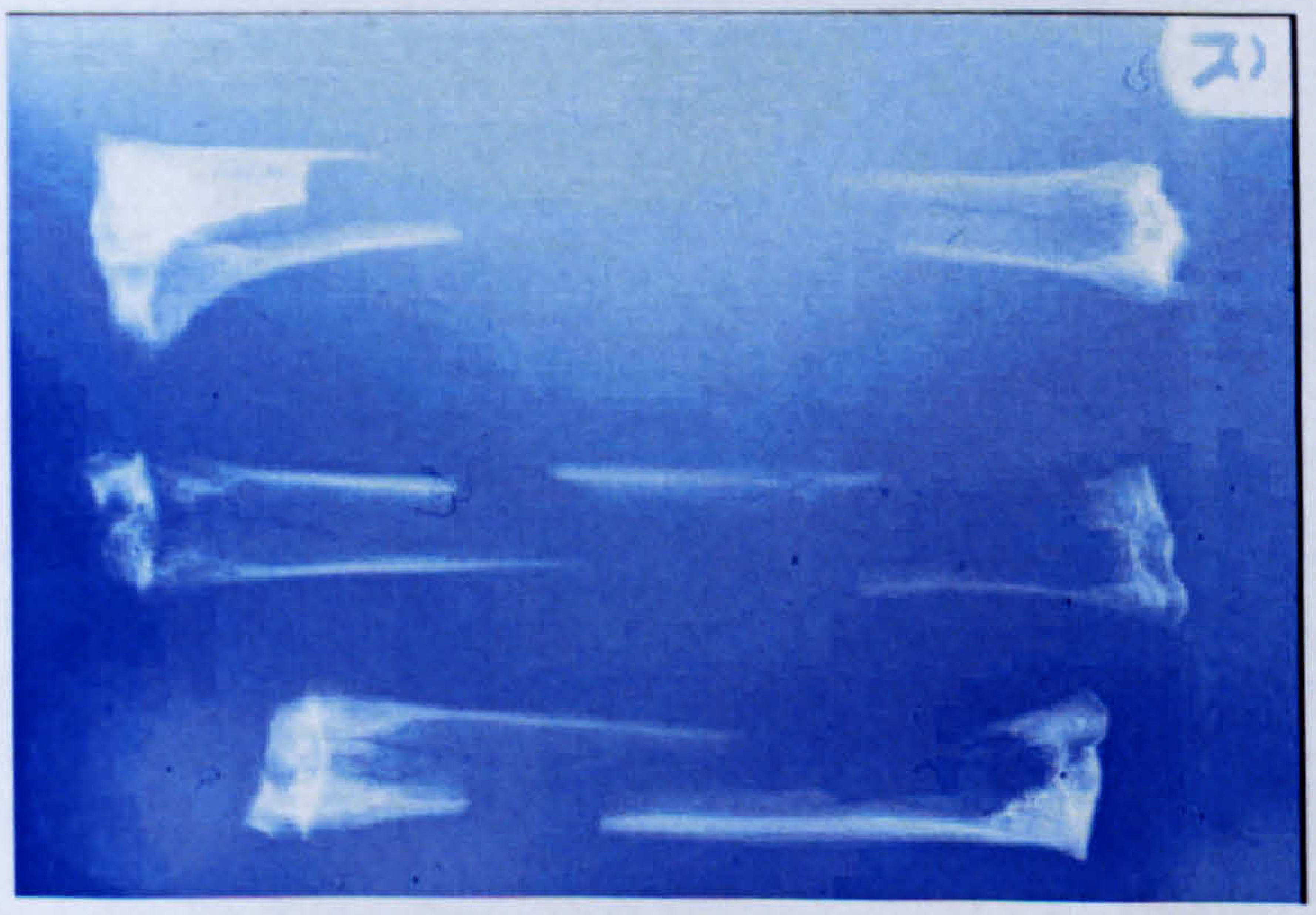


Figure 6.15 Radiograph of Bones Burned at 900°C for 15 Minutes

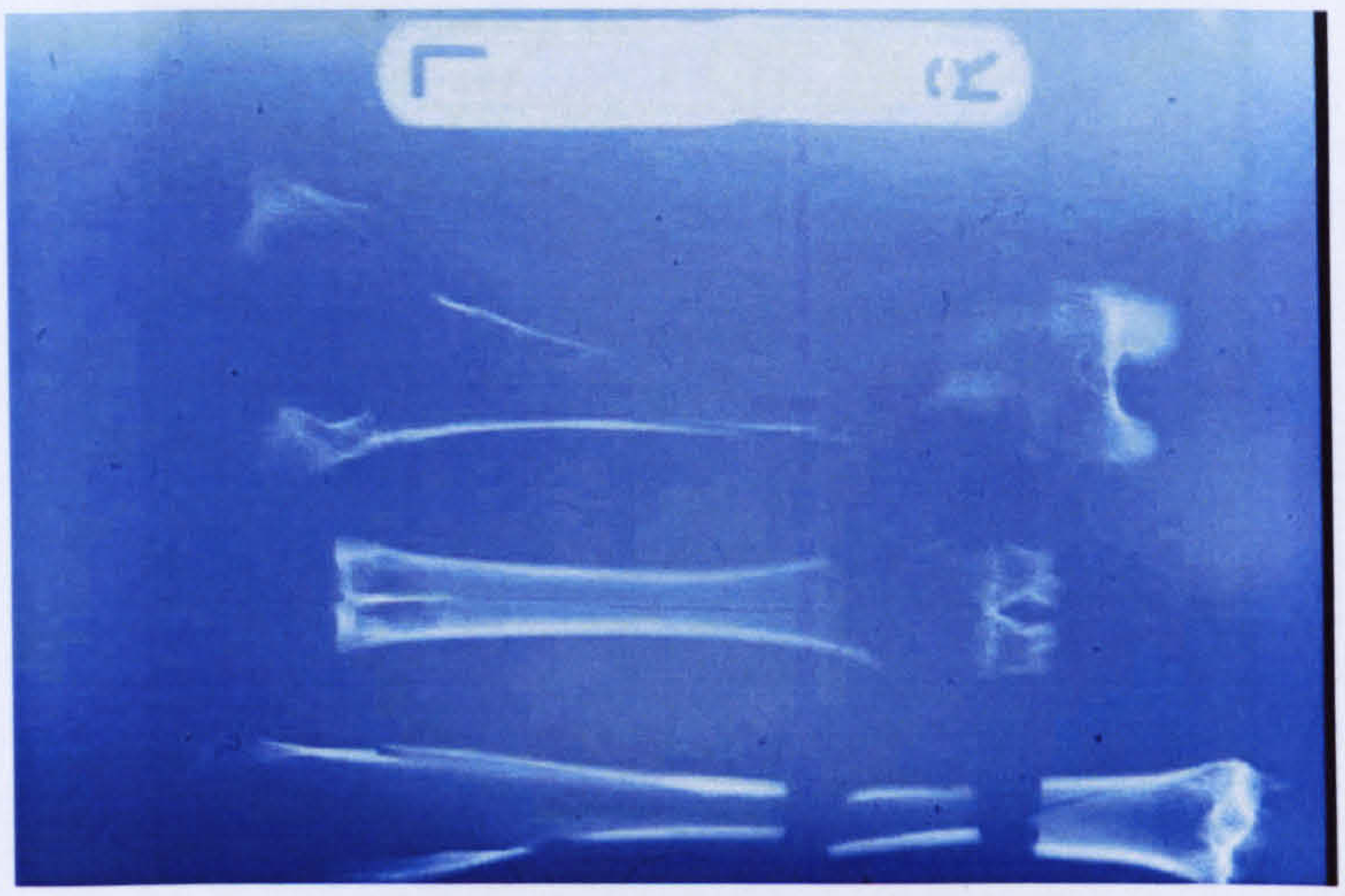


Figure 6.16 Radiograph of Bones Burned at 900°C for 45 Minutes

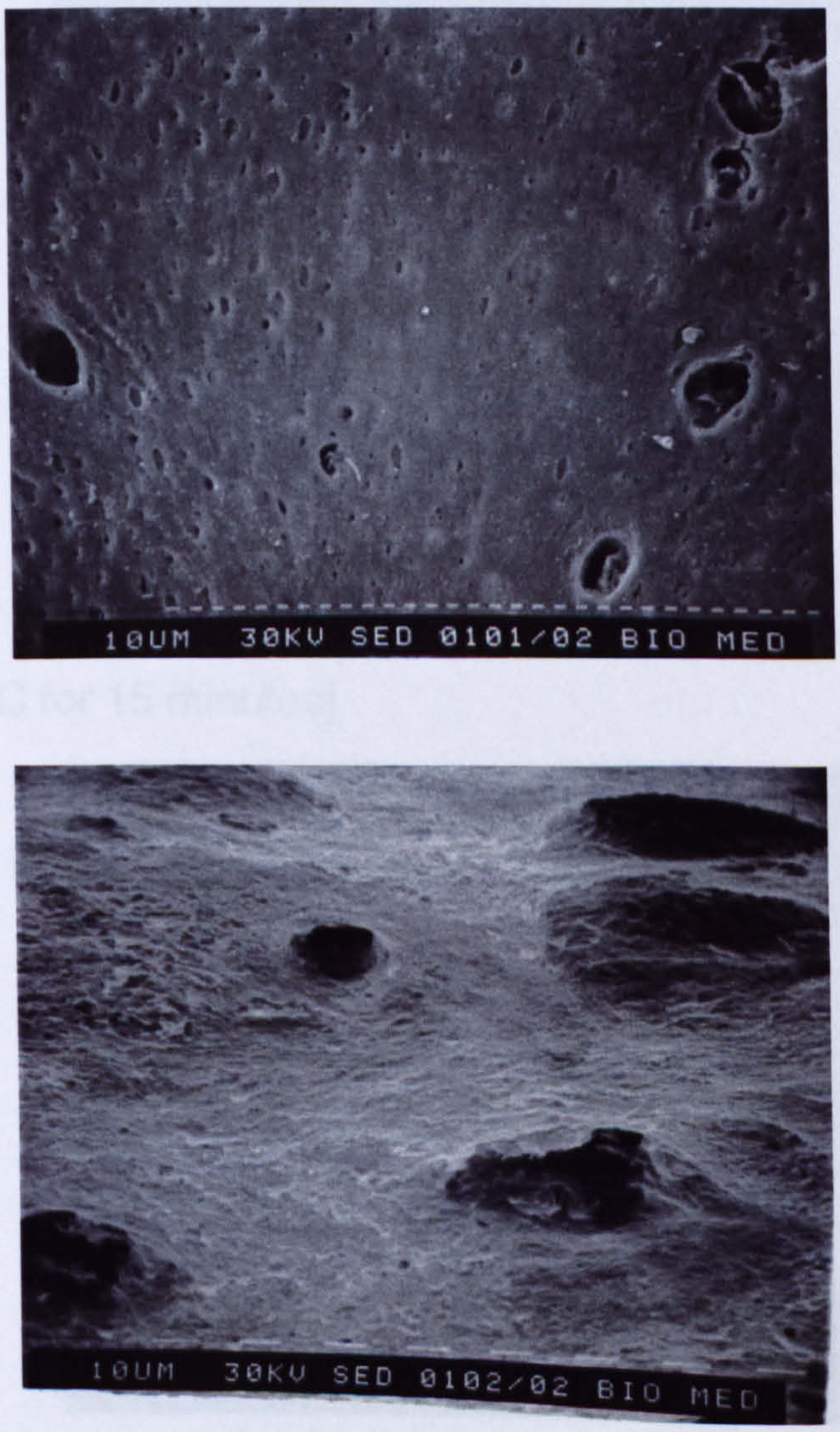


Figure 6.17 SEM image, sample pre, outer surface (upper), inner surface (lower)

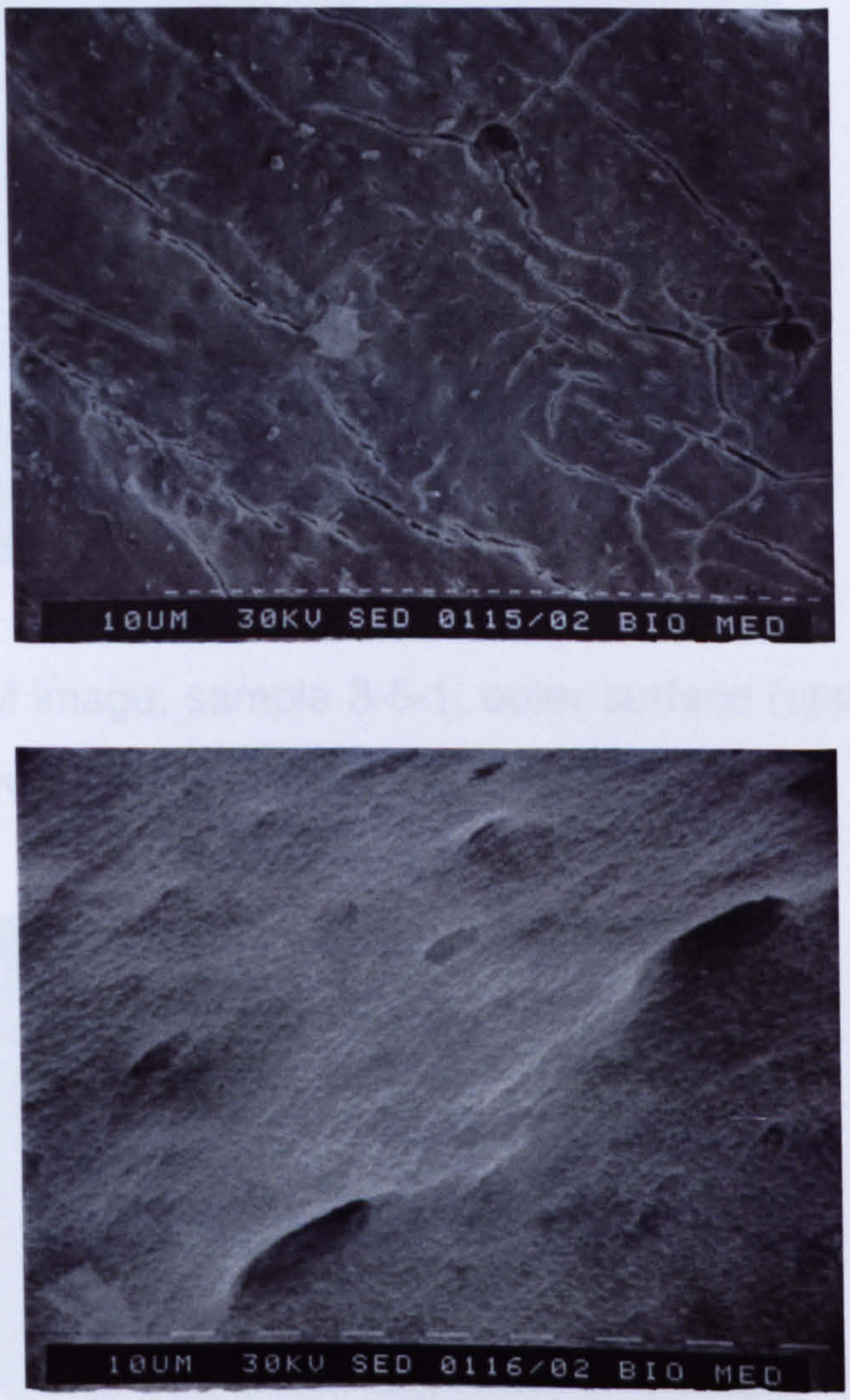


Figure 6.18 SEM image, sample 3-2-7, outer surface (upper), inner surface (lower) [500°C for 15 minutes]

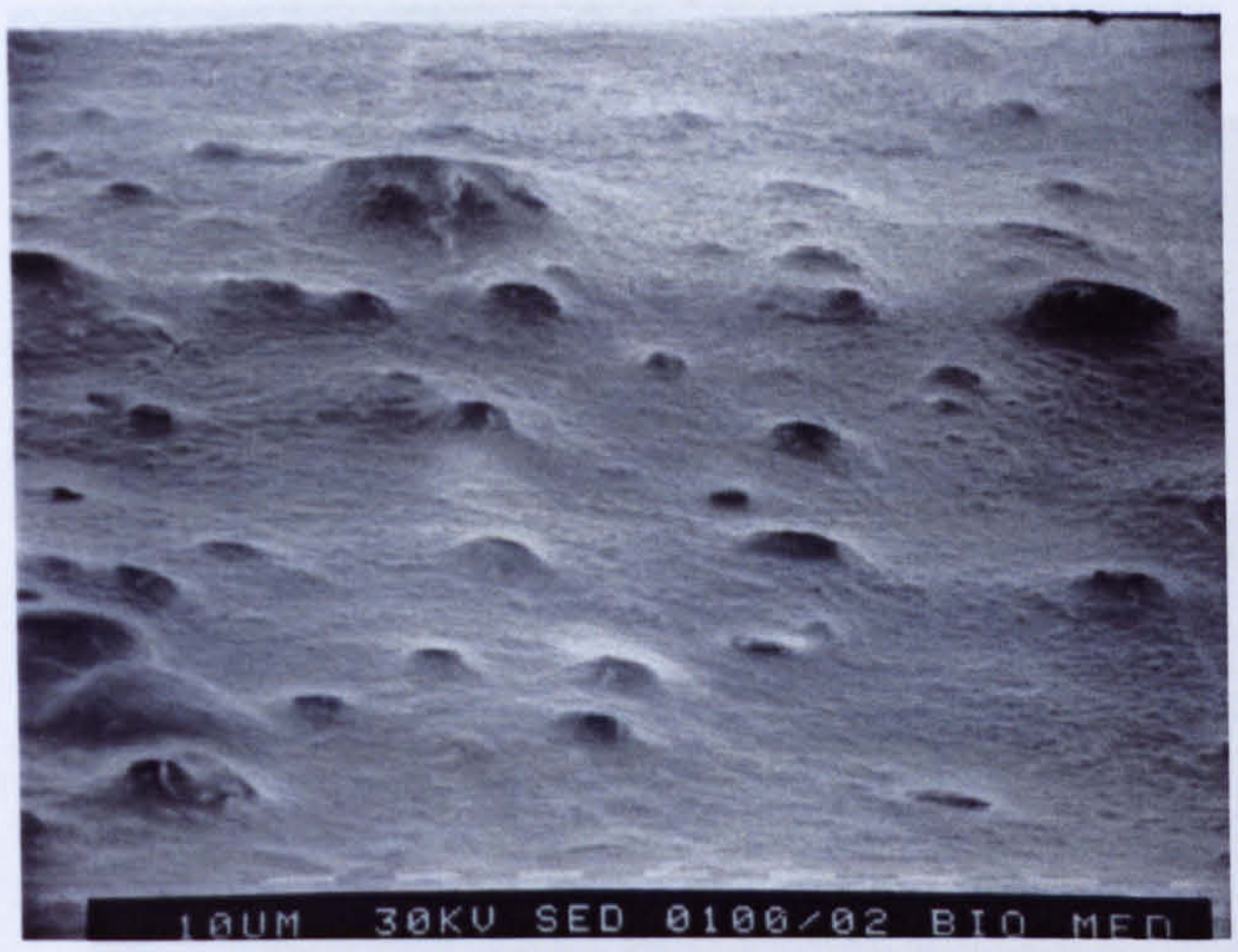


Figure 6.19 SEM image, sample 3-5-1, outer surface (upper), inner surface (lower) [500°C for 45 minutes]

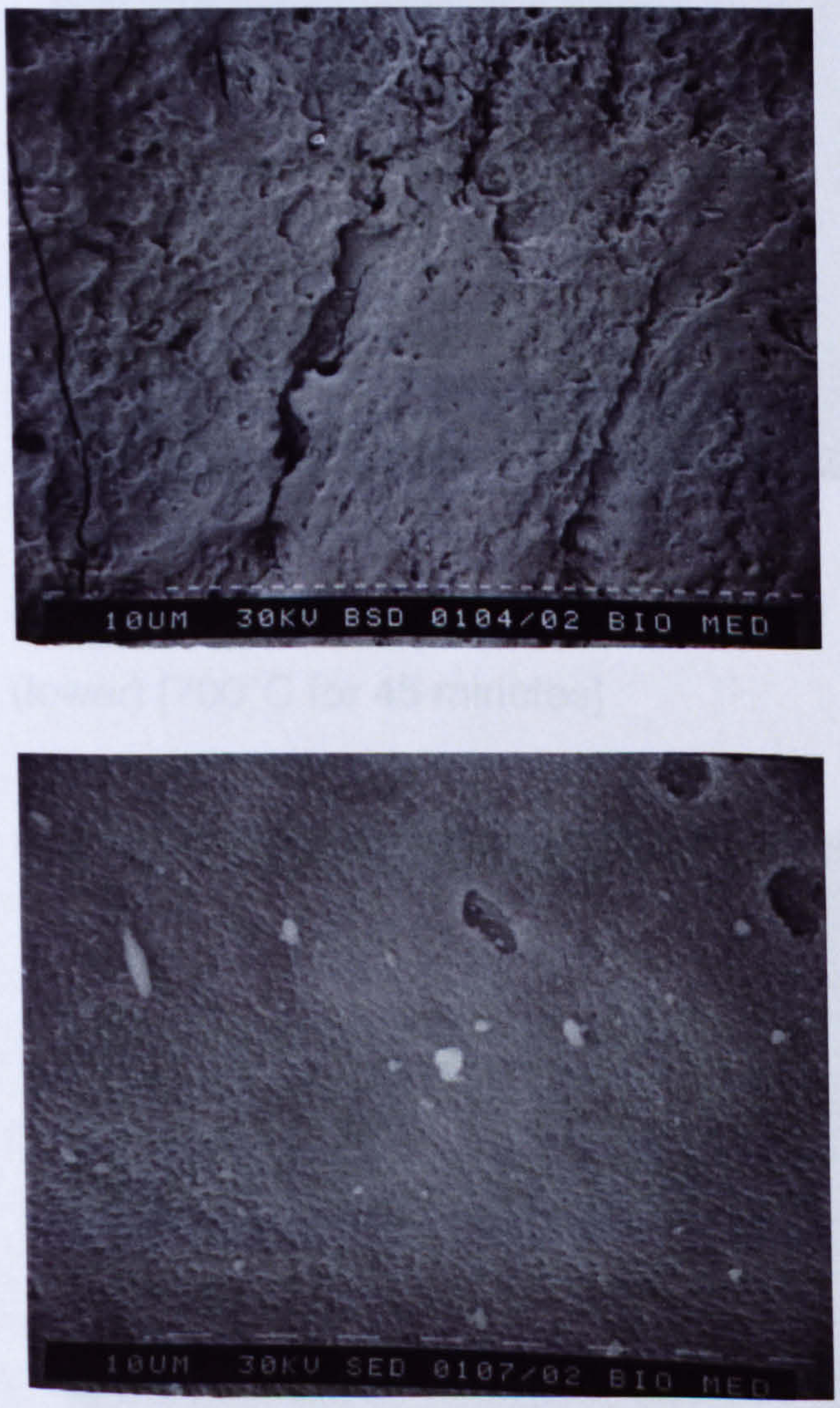


Figure 6.20 SEM image, sample 3-3-2, outer surface (upper), inner surface (lower) [700°C for 15 minutes]

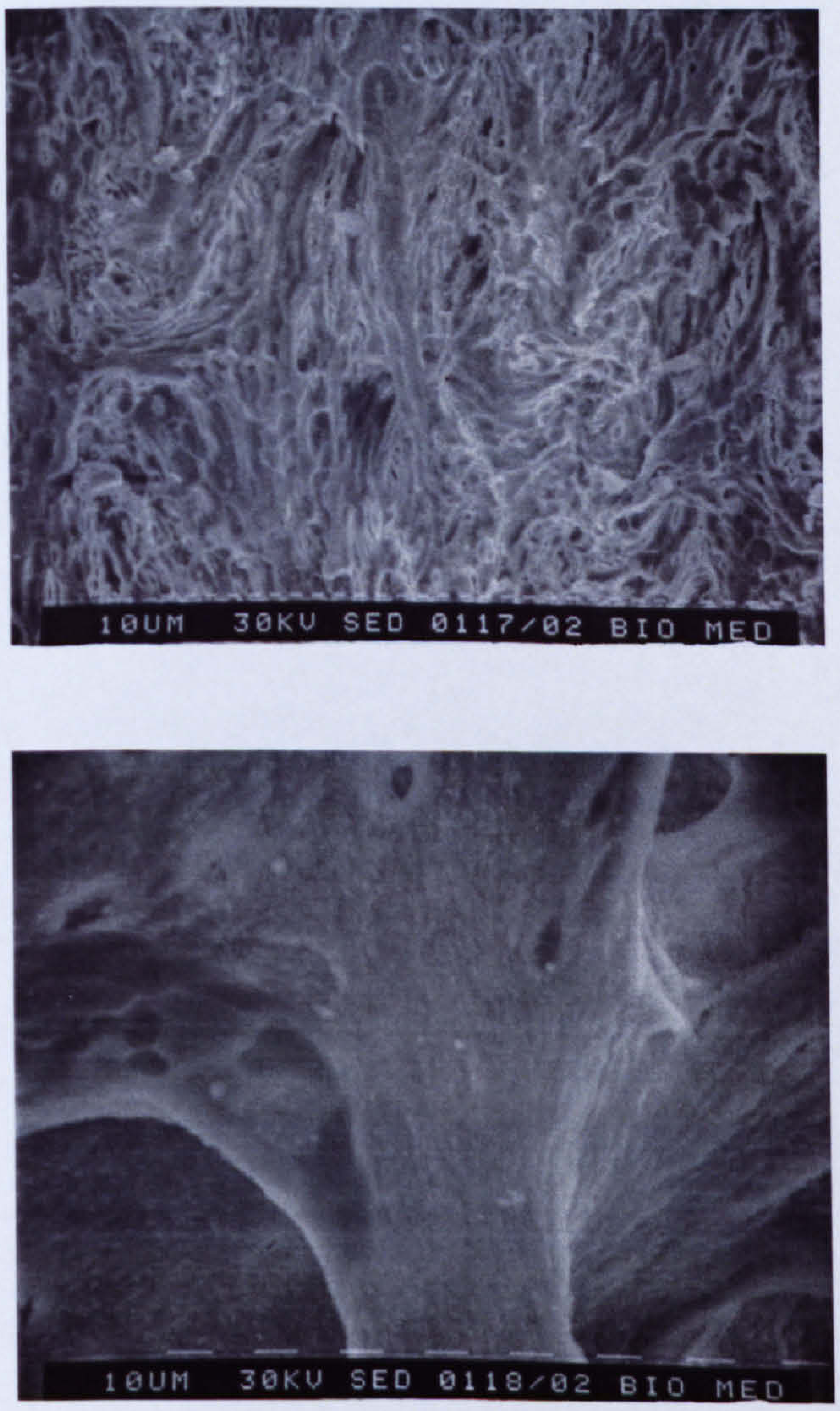


Figure 6.21 SEM image, sample 3-6-2, outer surface (upper), inner surface (lower) [700°C for 45 minutes]

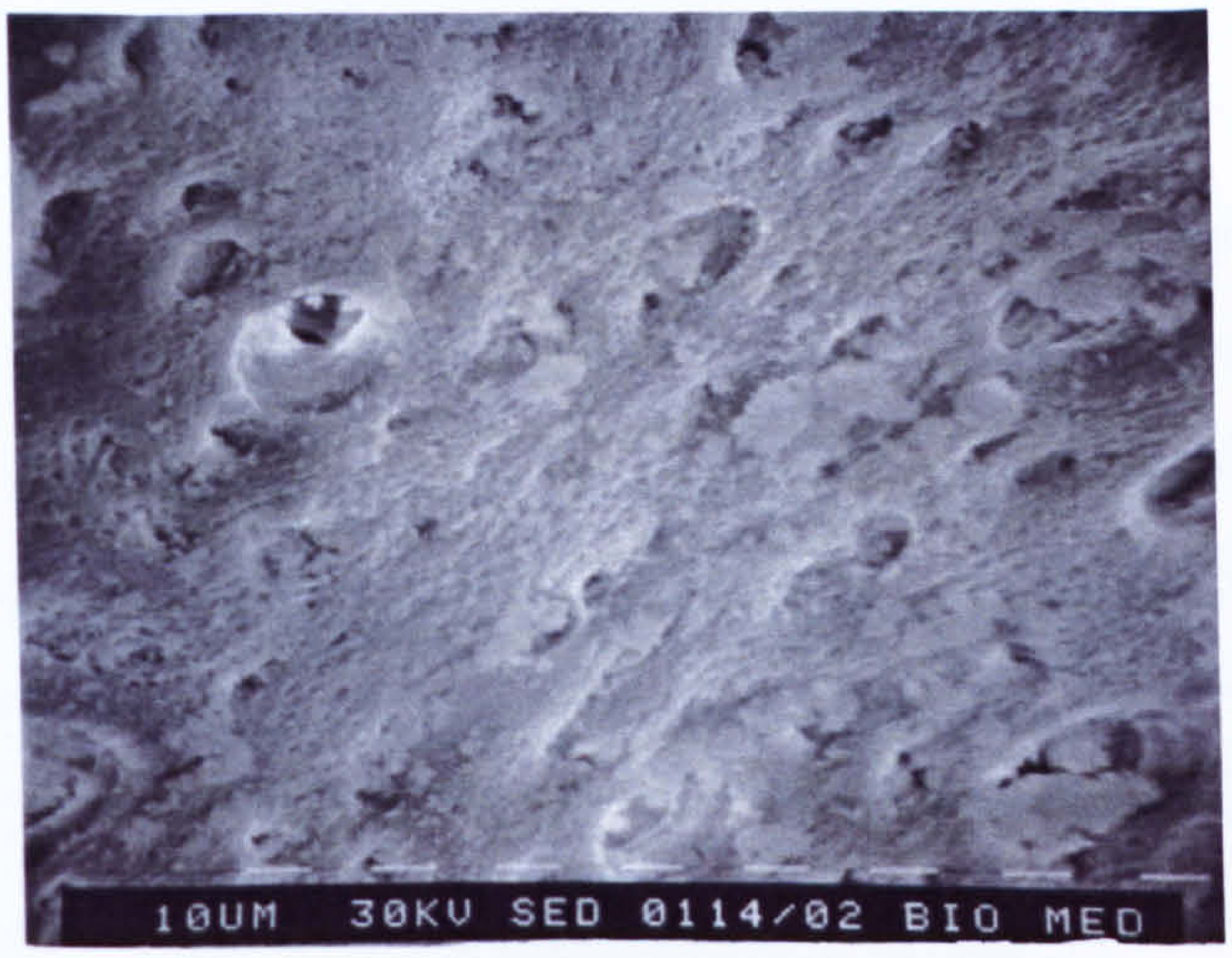


Figure 6.22 SEM image, sample 3-4-3, outer surface (upper), inner surface (lower) [900°C for 15 minutes]

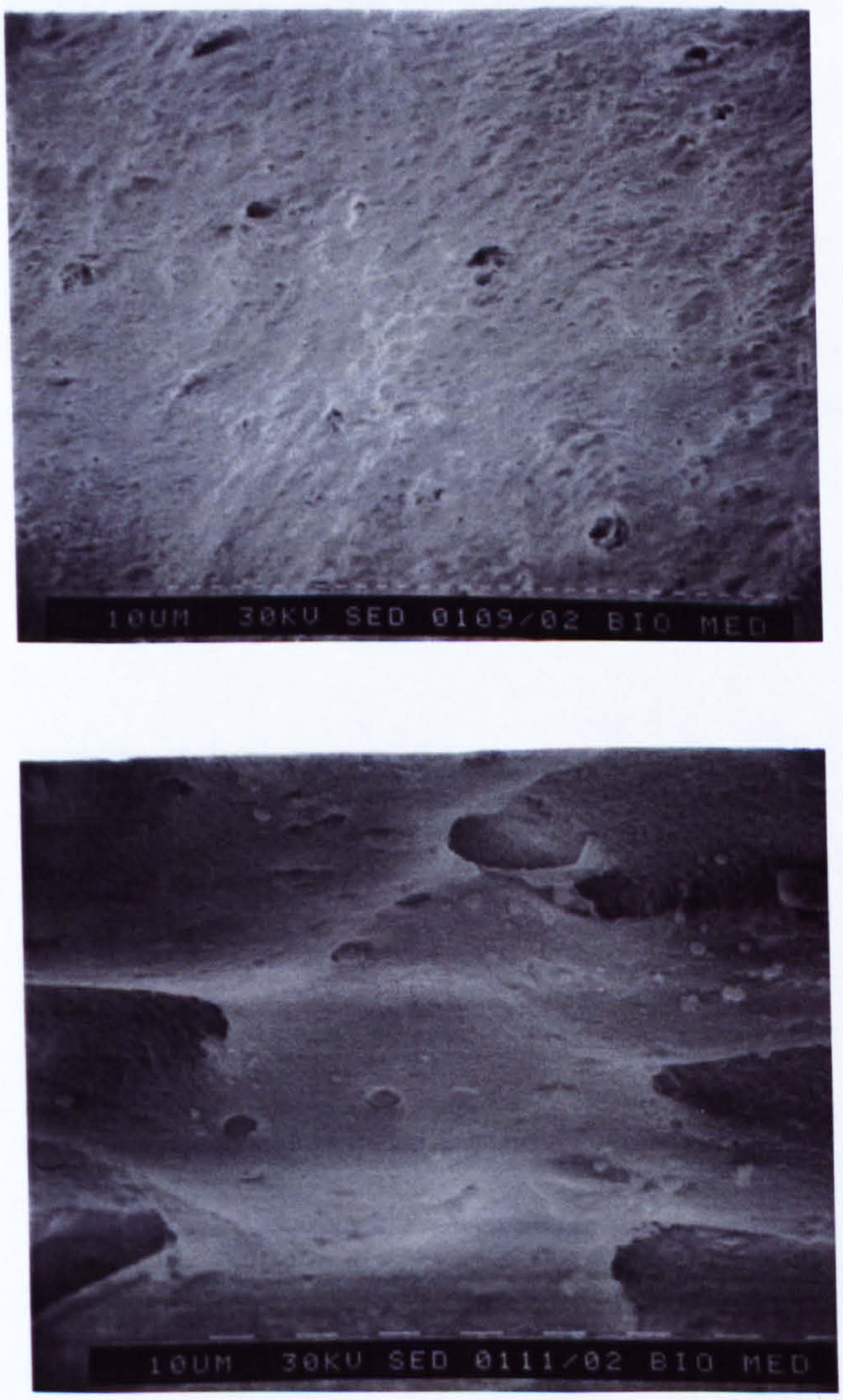


Figure 6.23 SEM image, sample 3-7-10, outer surface (upper), inner surface (lower) [900°C for 45 minutes]

SixFour Discussion

It is clear from the imaging evidence that a specific and repeating pattern exists with regard to how the bones fracture. This pattern is evident mainly from the digital photographs and radiographs (Figures 6.3 to 6.16). The scanning electron microscopy (Figures 6.17 to 6.23) focuses on the micro-scale, and it is therefore not possible to see the trend in fracturing over the whole bone. The trend in the samples used here is for thin linear fractures to appear along the long axis (metaphysis to metaphysis) of the bone (Figures 6.3, 6.11 and 6.13). As burning intensifies, these fractures become more significant in size and width. Continued burning produces smaller fractures which appear perpendicular to these long fractures. A grid-like pattern of fracture lines emerges (Figure 6.4). Again, as burning intensifies, the fracturing becomes more significant. Eventually the bone falls apart, as sections of bone come away from the shaft where the longitudinal and perpendicular fracture lines intersect (Figures 6.5, 6.12, 614 to 6.16). This explains the irregular edges of the fractured bones. The scanning electron microscopy indicates that the fractures originate from pores in the bone surface (Figure 6.18). The fractures then extend from pore to pore as burning continues (Figures 6.19 to 6.23).

The fractures exhibit this grid-like pattern because, like fracturing of any material, the cracking is occurring along lines of weakness. Initially cracks nucleate at the pores, which are points of weakness. The fractures propagate as the cracks extend from each pore, or point of weakness. The longitudinal fractures are running along lines of weakness present in the diaphysis (Turner-Walker and Parry, 1995). It is suggested that these lines of weakness are a consequence of the way in which the hard tissue is laid down during bone formation and growth. In addition high-energy fractures, such as those produced by heat, result in smooth breaks that travel along the bone indiscriminately unlike low energy fractures that appear rougher and do not pass through the osteons (Herrmann and Bennett, 1999). The fractures noted here are more similar to high-energy fractures as they appear smooth and travel through the pores of the heated bone. The fracturing itself is initiated due to the differential expansion and shrinkage of the bone shaft as a result of burning. Evidence for this differential expansion and shrinkage can be seen in Chapter 9. This expansion and shrinkage may produce tension and compression stresses (Ortner and Putschar, 1981) in the bone that cause the fractures to appear. Compression in particular can cause fracturing along the same axis as the direction of force (Ortner and Putschar, 1981). This type of fracture is referred to as a brittle fracture. The images therefore suggest that pressure is being placed on the sides of the bone diaphysis. As seen from the data in Chapter 9, shrinkage and expansion are more prevalent along this axis, and so this notion is supported. The perpendicular fractures are a result of new stresses created by the proliferation and expansion of the longitudinal fractures. Finally the bone loses its structural integrity and falls apart when the profusion of fractures means that the shaft cannot be supported any longer. The bone falls away in rectangular sections, the size of which are determined by the pattern of fractures present. The bones do not explode due to heating, either by expansion of the bony material itself or the gases within the medullary cavity.

Heating bone produces changes in crystal size and shape. This may also affect the nucleation and propagation of cracks. McKinley (1994) argues that burning induces the breakdown of the hydroxy- bonds in the apatite crystal structure that in turn causes a reduction in crystal size. In contrast however, Shipman *et al* (1984) state that heating causes an increase in crystal size. This increase could be the result of the coalescence of smaller crystals during the Fusion stage (Figure 2.1). More detailed crystal analysis by other workers have shown that crystal size increases with increased heating. This is examined further in Chapter 8. The disruption of the crystal structure during the pre-Fusion stages of burning may make the material more susceptible to cracking. This susceptibility may subsequently be reduced as the crystals fuse.

It should not be forgotten that teeth are also a form of hard tissue. It is because of this that they were also examined for patterns of heat-induced fracturing (Figures 6.6 to 6.9). The largest of the samples concerned modern adult teeth. Here, the most obvious consequence of heating was for the enamel crown to fully come away from the dentine root. Examples of the enamel crown 'popping' off can be seen in Figure 6.9 and in the results of Chandler (1987). The crowns come away from the root because of differential shrinkage and expansion. The dentine reacts more to the heating than the enamel, and so eventually the two dental layers are forcibly separated at their junction. This kind of separation is not seen in either the archaeological adult or modern juvenile dentition. This separation is not a consequence of the experimental protocol used here. Figure 6.24 gives an example of this phenomenon occurring in a modern forensic case.

Figure 6.24 Dental remains from a vehicular accident in Australia.

As can be seen from Figures 6.6 and 6.7, the modern juvenile teeth tended

As can be seen from Figures 6.6 and 6.7, the modern juvenile teeth tended to split across the enamel crown. Here the split is also caused by differential expansion and shrinkage, but in this case it is not between the crown and the root portions. Deciduous teeth lack the same root structures as permanent teeth, and so the difference in expansion and shrinkage is occurring along the medial-distal axis of the teeth. The archaeological adult teeth tend to completely fracture too. These teeth tended to completely fracture down the occlusial-apical axis of the tooth. It is clear to see why there should be a difference between the nature of fracturing of the juvenile teeth and the adult teeth. The difference between the trends in the modern and archaeological teeth is more interesting. It may be that the increased diagenesis experienced by the archaeological teeth relative to the modern teeth is the decisive factor.

One must be careful not to extrapolate the features noted from one cremation study inappropriately to all burned bone. It is entirely possible that some of the features noted here are a consequence of the experimental protocol or equipment used. To determine the likely effect of the experimental methodology on the results, two comparisons must be made. First with previous research projects, then with burned bones collected from non-experimental scenes. In the case of these fracture patterns, some confidence can be taken from the fact that the patterns here are comparable to fracture patterns noted in previous studies. Buikstra and Swegle (1989) noted that longitudinal fractures occur along the length of the bone but that transverse fractures are less frequent than in fleshed remains. They also note that both fracture types are shallow. Both fracture types are recorded here, however they are far from shallow as, at higher burning intensities, they can cause obvious and unequivocal bone fragmentation. These results are more akin to those features noted by Baby (1954), Binford (1963) and Kennedy (1996) who describe deep longitudinal splitting in burned dry bone cremations. Some caution is required when using Binford's (1963) results for comparison however, as he cooled his burned samples with water. This action, he admits, caused increased fragmentation of the bone, and it is therefore difficult to say whether all of the features, and the severity of their presence, are due to burning or due to rapid cooling. Thurman and Willmore's (1981) experimental study also noted longitudinal and perpendicular fractures and they highlighted the presence of checking. Although they do not make the points themselves, examination of the low magnification scanning electron microscopy images produced by Herrmann (1977) and Bradtmiller and Buikstra (1984) indicate that fracturing occurs from the pore spaces and spreads from pore to pore. The data collected here concurs with this.

The fracture patterns that are found on these experimentally burned bones do not match those noted on fleshed skeletons from either experimental or non-experimental burnings. The photographs produced by Bohnert *et al* (1998) indicate that the fractures found on previously fleshed skeletons are more curved and less linear, and do not form in a grid-like network. This supports the observations of others who have argued that the fracture patterns of fleshed remains are less linear, less regular and with frequent elliptical cracking (Baby, 1954; Binford, 1963; McKinley, 2000; Mayne Correia, 1997; Thurman and Willmore, 1981). It is clear that the soft tissue cover is affecting the nature of the fracturing of the skeleton. This is happening in two ways. First, the bones are remaining in their natural state for longer. That is, maintaining normal levels of water and collagen at the time of burning. These are significant variables not present in dry bones. Second and more significantly, the soft tissue cover is itself succumbing to the heat and is contracting. This is causing deformation of the enveloped bone. This in turn may lead to the initiation of another form of fracture, creep. Creep occurs when materials are heated to high temperatures and are then subjected to sustained stress which causes permanent deformation of the material (Courtney, 1990). In this case, bone would be the deforming material and the contracting muscle, or even the tough fibrous periosteal collagen sheath, would be providing the constant stress. However, stating that bone deforms due to muscle contraction is not enough. What is significant is not that the muscle is shrinking *per se*, but that this shrinking muscle is subjecting the fleshed bone to different stresses than are experienced by defleshed bone: torsion rather than tension and compression witnessed in dry bones. It is argued that this difference in stresses results in the formation of the different fracture patterns noted by previous workers.

Another factor to consider is the specimen recovery protocol. Great care was taken here when removing the burned bone from the furnace and therefore it is expected that, fragment size would be larger here than in non-experimental situations and that the bone shaft would maintain structural integrity for longer and more frequently. This would explain why greater degrees of fragmentation have been recorded elsewhere (for example, Johanson and Saldeen, 1969; McKinley, 1993). Related to this is the influence of post-interment fracturing (Gejvall, 1969). Fragmentation of the weak burned bone due to burial may be misinterpreted as being the result of heat-induced fracturing. This would affect those who use fragment size to determine skeletal completeness (Drusini *et al*, 1997). Distinguishing the two origins of fractures from each other will be easier as heat-induced cracks, as can be seen from this and other experiments, consistently produce the same fracture patterns. It is likely that any fractures produced by burial would differ from those produced by burning because of the different stresses and forces applied to the tissue by each of these processes.

The digital images clearly show the progression of fracture patterns from the initial thin longitudinal fractures to the grid-like network of lines. The radiographs however, are of more use in this respect. In addition to showing the progression of the fractures they allow one to view the progression of fracture lines across the whole bone, and not just on the aspect visible to the camera. Radiographs also allow statements to be made regarding the change in internal structure of the bone. Care must be taken when creating radiographs however, and each image must be taken with the same settings to permit thorough comparison of films. Although digital photography does not allow one to view the internal structure of the bone, it does allow one to view the external structure. Unlike with radiographs, comments can be made regarding surface morphology and colour, which are of particular interest in cremation studies. Although scanning electron microscopy can not provide information regarding the spread of fracture lines across the whole bone, it can provide great detail about microscopic fracturing and the origins of fractures, which the other two imaging methods cannot. It should be clear then that, as discussed above, a holistic approach to cremation studies would provide the most complete understanding of the effects of burning on bone.

SixFive Conclusions

One of the more interesting and useful consequences of the examination of heat-induced fracture patterns is the prediction of whether bones were fleshed or defleshed at the time of burning. The patterns recorded in this study support those noted by other workers on bones that were also defleshed when burned. It would appear then that the fracture patterns of bones that are burned defleshed are characterised by long deep longitudinal cracks, which at higher burning intensities are joined by shorter perpendicular cracks to create a grid-like pattern of fractures. Fleshed bone, although not tested here, would seem to have less regular cracking, and are particularly characterised by 'U'-shaped cracks along the bone diaphysis (see Section 6.4). Further research using a large sample such as this one should be directed towards examining the fracture patterns of fleshed and recently defleshed bones to confirm these statements and the influence of the soft tissues on propagation and proliferation of fracture patterns.

Burning of hard tissues produces distinct fracture patterns. As mentioned above, the grid-like network of fracture lines recorded here concurs with a number of previous studies for dry bone. Thus a reassessment of the existing literature in light of recent work and the results of this large sample weaken Mayne Correia's (1997) argument that the literature is contradictory. Rather, the majority of the literature supports itself. Variations in fracture patterning are to be expected given the range of variables at work, such as differences in experimental methodology and the state of preservation of the material.

The production of fractures due to heating will also have clear implications for the mechanical strength of the bone. This is examined in detail in the next chapter.

Seven The Examination of Heat-induced Changes in Mechanical Strength

SevenOne Introduction

Change in the mechanical strength of bone as a consequence of burning is one of the three categories of heat-induced change noted in Chapter 2. Any change in strength is likely to be closely related to the heat-induced proliferation of fracture lines that are examined and discussed in the previous chapter. In addition, the causes of the changes in strength will be the result of transformation at the microstructural level. This is discussed further in Chapter 8. Nonetheless the examination of heat-induced changes in mechanical strength deserves individual consideration because of the underlying importance of the loss of the water and organic material from the bone. In addition it will allow comparison with the work of other anthropologists who have specifically examined this feature.

The primary-level change that most influences the heat-induced changes in the mechanical strength of bone is the removal of the water and organic components from the osseous structure. Therefore the eviction of these components was also examined in addition to the change in actual mechanical strength of the bone.

SevenOneOne Mechanical Strength in Unburned Bone

Bone is a composite material. It is composed of an intimately linked biomineral (a carbonate-containing hydroxyapatite) and an organic matrix (a mass of cross-linked collagen fibres, mucopolysaccharides and amino acids) (Mayne Correia, 1997; Turner-Walker and Parry, 1995). It is argued that the mechanical strength resulting from the association of these two phases of bone is undermined by the presence of Haversian canal systems. It is not yet known whether this weakening is the result of the reduced amount of bone tissue itself or of the reduction in bone mineral concentration (Turner-Walker and Parry, 1995).

Bone is adapted to withstand a variety of stresses (Stiner *et al*, 1995). With regard to tension forces, bone most effectively resists applied force in the direction parallel to the orientation of the long axis of the bone (Turner-Walker and Parry, 1995). There is some disagreement regarding this anisotropic feature of bone. Turner-Walker and Parry (1995) argue that it is because the structural components of the bone (the collagen fibres and associated inorganic crystals) run approximately parallel to the long axis, thereby providing strength in that direction. Most current models however seem to suggest that the collagen fibres within the lamellar bone are aligned at an oblique angle to the long axis of the bone. Collagen fibres provide the bone with the ability to withstand tensile forces while the inorganic mineral matrix allows the bone to withstand compressional forces (Turner-Walker and Parry, 1995). The experiments of Turner-Walker and Parry (1995) have demonstrated that the tensile strength of bone decreases with decreasing bulk density (calculated by dividing mass by volume of bone sample). In other words as the bone loses mass it becomes weaker. A loss of mass could be the result of normal diagenesis, which is the subject of Turner-Walker and Parry's (1995) examinations, but could also be the product of the action of burning.

SevenOneTwo Mechanical Strength in Burned Bone

The loss of mechanical strength due to burning is well noted in the literature (McKinley, 1993; McKinley, 1994; Mayne Correia, 1997). Stiner *et al*'s (1995) experimental studies demonstrated how mechanical strength varied as a function of the extent to which the bones were burned. The water is removed from the bone first. The most easily removed water is that which is loosely attracted to the crystal surface (Mayne Correia, 1997). The eviction of the water is followed by the pyrolysis of the organic phase. It is here that the bone is the most mechanically weakened. Specifically, the removal of the collagen occurs when the bone tissue becomes isotropic (Mayne Correia, 1997). Following the heat-induced removal of the organic phase, the carbonates are lost. One may then expect, with the onset of the Fusion stage, that the mechanical strength of the bone will increase. This would be a consequence of the infilling of the pores left by the evicted water and organic phase by the newly fluid inorganic component.

Rogers and Daniels (2002) note that up to 1200°C the elastic modulus of bone increases with temperature as a direct consequence of the loss of bone matrix. This allows burned bone greater compressive strength in addition to increased brittleness. (Rogers and Daniels, 2002).

It is not a simple case of burning reducing the mechanical strength of bone by destroying the organic component. The close relationship between the collagen and the inorganic matter means that the mineral phase protects the organic phase (Bonar and Glimcher, 1970). Fortification of the organic phase is offered by the physical penetration of the collagen by the inorganic minerals themselves (Bonar and Glimcher, 1970). This protection of the organic phase may delay the onset of the Decomposition stage of heat-induced bone degradation from what one would expect for collagen alone.

Heat-induced weight loss is fairly simple to explain. It occurs in two stages. First as the water is removed, a small degree of weight loss would be expected. This would not be as significant as the weight loss associated with the removal of the organic phase. Progression into the Fusion stage of degradation would not be expected to cause an increase in weight as no materials are added to the bony matrix. That said, it has been reported that elements located within the burning environment have been incorporated into the bone during heating (Grupe and Hummel, 1991). It is unlikely that these elemental additions would cause a noticeable increase in weight however.

SevenTwo Methodology

SevenTwoOne Experimental Burning

The methodology of relevance to the examination of changes in mechanical strength and bone weight concern the actual burning of the osteological material. The details of the protocol for the burning of the bony material are presented in Chapter 4.

As stated in Chapter 4 a number of measurements were recorded before and after the burning event. With regard to the examination of heat-induced changes in mechanical strength the weight of the bones were recorded using a digital scale precise to 0.01 grams. The post-burning weight of the bone was taken five minutes after removal from the furnace to allow for the bones to cool.

Statistical analysis on the results of the changes in mechanical strength and bone weight was performed using SPSS Version 10 for Windows on a PC.

SevenThree Results

Figure 7.1 shows the number of dimensional measurements that could be recorded from the burned bone before the bone fragmented and could no longer be measured. Table 7.2 and 7.3 present the results of the analyses of heat-induced weight loss. Tables 7.1 and 7.4 have been devised to help answer questions regarding heat-induced changes in mechanical strength.

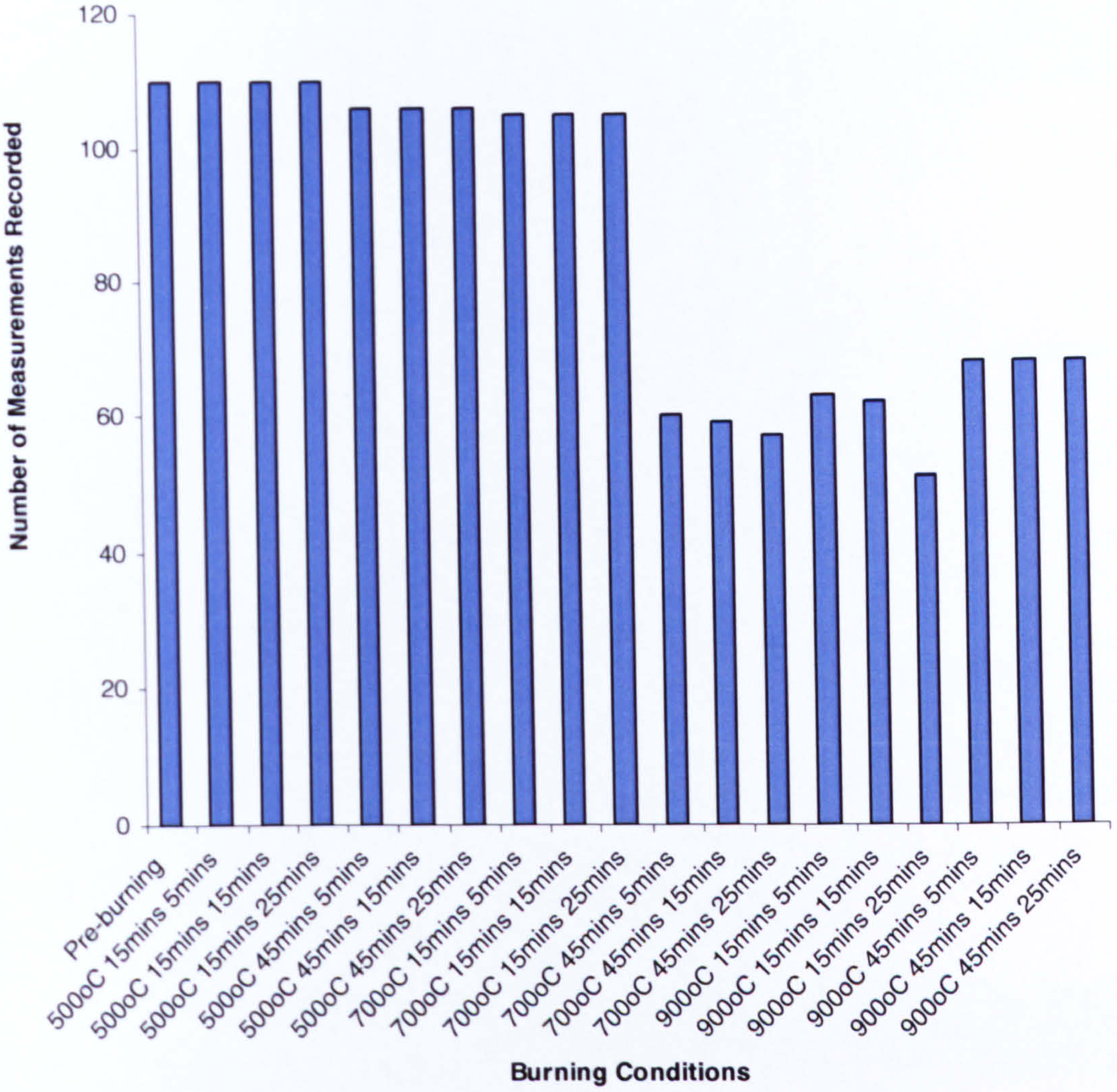


Figure 7.1 The frequency of recording before bone fragmentation during data retrieval [Note: on the *x*-axis, *a* °C *b* mins *c* mins = temperature of burning, duration of burning and time since removal from furnace]

	Removal of Water	Removal of Organic Phase	Fusion
Statistical Significance	0.083	0.007	0.109

Table 7.1 Results of Wilcoxan Rank Tests for Evidence of Heat-induced Bone Degradation

	500°C, 15 mins	500°C, 45 mins	700°C, 15 mins	700°C, 45 mins	900°C, 15 mins	900°C, 45 mins
Sample Size	10	10	10	5	4	8
Pre-burning Weight Range (g)	42.89	75.20	51.10	12.80	36.80	48.80
Pre-burning Weight Mean (g)	41.44	63.86	66.34	18.56	52.45	31.83
Pre-burning Weight Standard Deviation (g)	15.20	31.54	19.22	5.65	16.27	16.62
Post-burning Weight Range (g)	25.62	28.30	34.10	8.20	17.20	24.60
Post-burning Weight Mean (g)	29.18	32.32	21.57	11.50	27.33	16.33
Post-burning Weight Standard Deviation (g)	8.63	13.16	12.75	3.59	7.55	8.62
Percentage Shrinkage Range	34.08	16.07	34.46	1.95	4.97	17.77
Percentage Shrinkage Mean	27.10	46.90	36.15	38.19	47.56	49.08
Percentage Shrinkage Standard Deviation	11.57	6.10	10.01	0.80	2.37	6.35

Table 7.2 Descriptive Statistics of Weight Loss Data

	500°C, 15 mins	500°C, 45 mins	700°C, 15 mins	700°C, 45 mins	900°C, 15 mins	900°C, 45 mins
Significance of Pre- and Post-burning Differences (Paired T-test)	0.001	0.000	0.001	0.002	0.011	0.001
R-value of Relationship Between pre-burning weight and % Shrinkage (Linear Regression)	0.933	0.988	0.950	1	0.990	0.982

Table 7.3 Statistical Analyses of the Weight Loss Data

	Principal Component 1	Principal Component 2	Principal Component 3
Temperature	-0.237	0.952	-0.087
Duration	-0.330	-0.004	0.942
Pre-burning Weight	0.938	-0.056	-0.163
Post-burned Weight	0.864	-0.283	-0.109
% Weight Loss	0.257	0.740	0.621
Number of Measurements Recorded	0.546	-0.768	-0.147

Table 7.4 Rotated Component Matrix Resulting from Principal Component Analysis of the Influences on Mechanical Strength

SevenFour Discussion

Counting the number of times that dimensional measurements can be recorded before the analytical destruction of the bone is a rather simplistic method of examining mechanical strength. In reality it is a measure of the degree to which the burned bone can withstand stresses up to its breaking point. However as can be seen from Figure 7.1 this method of examination can show very clearly the increasing degree of fragmentation, and (by inference) loss of mechanical strength as a consequence of burning. The first reduction in recording frequency occurs after burning the bone for five minutes at 545°C. This is a slight decrease in frequency and corresponds to the eviction of water from the bone during the Dehydration Stage of Figure 2.1. The most impressive decrease in frequency occurs after burning the bone for five minutes at 745°C. This is situated towards the end of the Decomposition stage of Figure 2.1. Mayne Correia (1997) argues that it is during this stage that burned bone is at its weakest, and Figure 7.1 confirms this notion. There is a very slight increase in recording frequency after burning at 945°C. This likely represents the increased mechanical strength associated with the commencement of the Fusion stage of Figure 2.1 and the fusion and coalescing of the inorganic crystals. It should be noted again that this increase is minor and not entirely convincing.

Although the changes in the frequency of recording are often only slight, some statistical significance is present. Wilcoxan Rank tests of the recorded frequency before and after the suspected loss of water, organic materials and the onset of fusion were performed. Wilcoxan Rank tests were used because the data lacks Gaussian normality, that is, the data is non-parametric. Only the difference occurring between frequency recordings divided at 715°C and 745°C was statistically significant. The lack of statistical significance in the other two tests is likely due to the subtlety of the frequency differences and the very small samples sizes of those two particular tests. The statistical significance seen clearly coincides with the Decomposition stage detailed in Figure 2.1.

It can be seen from Tables 7.2 and 7.3 that the experimentally burned bone suffered a reduction in weight as a consequence of burning. Table 7.2 shows that in all cases, burning will cause a loss in weight, and will cause a reduction in the range and standard deviation of weights for a given sample. In addition, it can be seen that with the exception of 500°C for 45 minutes, there is a steady increase in the percentage weight loss associated with increased burning intensity. This is expected and it demonstrates that the bones progress through the heat-induced degradation stages of Figure 2.1. In all of the six burning conditions examined, a statistical significance was noted between the weight of the bones before and after burning. It is perhaps surprising that with burning for 45 minutes at 700°C and for 15 minutes at 900°C the statistical significance of the weight difference decreases (Table 7.3). This discrepancy is likely to be the result of the reduction in sample size due to heat-induced fragmentation (Table 7.2). Reconstruction was not attempted due to the fragile nature of the burned hard tissues and the fact that any adhesive used would have biased the results by adding non-bony weight to the sample. The results of the linear regression detailed in Table 7.3 show that there is a relationship between the pre-burning weight of the bone and the percentage weight shrinkage that the bone undergoes. In four cases this relationship is statistically significant. This relationship simply means that heavier bones suffer greater weight loss than lighter bones. This relationship would not exist if heating caused the same percentage loss of organic matter regardless of the bone's size, for example if a bone of 40g and 70g both lost 35 percent of their weight. Therefore in order for there to be a relationship like this, one of two situations must exist. Either it must be that a greater proportion of larger bones is composed of water and organic material than in smaller bones, or that the water and organic material in larger bones is easier to remove by heating. Both situations would allow for there to be an increase in percentage shrinkage with increased mass, which is what the regression analysis implies.

Principal component analysis was performed in order to determine whether there are any underlying associations in the data collected to examine the changes in mechanical strength. The results are presented in Table 7.4. Only three principal components were created which had eigenvalues above 1. Principal component 1 had an eigenvalue of 3.158, principal component 2 a value of 1.398 and principal component 3 a value of 1.068. Together they account for 93.73 percent of the sample variance. The results in Table 7.4 indicate that there are three main influences in the data. The first corresponds with principal component 1 and suggests that the pre- and post-burning weights are strongly associated and frequency of recorded measurements marginally so. The second principal component suggests that the temperature of burning and the percentage weight loss are strongly associated and frequency of recorded measurements is negatively correlated with these variables. The third principal component suggests that there is a relationship between the duration of burning and the percentage weight loss, although this is weaker than the relationship between percentage weight loss and temperature. As would be expected there is a strong underlying relationship connecting the pre- and post-burning weights that accounts for 52.63 percent of the variation in the sample. More interesting are the associations between the temperature and duration of burning and the degree of weight loss. The results here support the notion that bones will lose greater weight with increased burning intensity. Finally it is important to highlight the presence of frequency of recorded measurements. Table 7.4 suggests that the number of measurements recorded from an osseous element, which is a proxy for mechanical strength, is associated with the underlying influences of weight of the bone and the temperature of burning. Furthermore it is apparent that increased bone weight results in a greater number of measurements being taken but that increased temperature and loss of weight results in decreased measurement recording. From the data presented in Figure 7.4 it cannot be said that duration of burning has a strong influence on the number of measurements recorded. Therefore it can be argued that heat-induced changes in mechanical strength are determined mostly by the nature of the bony material being burned, but also by the conditions of burning itself.

Turner-Walker and Parry (1995) argue that the reduction in the mechanical strength of bone as a consequence of normal diagenesis during interment can be attributed to two phenomena. First, there is an initial loss of strength due to the hydrolysis of the collagen fibres. Without the collagen fibres the bone is less well equipped to resist applied pressure. Second, there is the further weakening of the bone as micro-organisms that devour the protein of the bone create microscopic tunnels. The tunnels increase the porosity of the bone, which as discussed above and in Chapter 8, causes a weakening of the bone. With regard to burned bone the first phenomenon can be seen. Burning acts in a very similar way to diagenesis, indeed it is often an experimental proxy for it, and the heating of the bone will also cause the collagen to hydrolyse. The second phenomenon will not occur in burned bone. If the bone is burned there is not time for the micro-organisms to act before the organic phase is removed. If any micro-organisms were present they would be destroyed. The presence of the first phenomenon can be seen by noting that the reduction in mechanical strength seen in Figure 7.1 occurs at 745°C, which falls into the Decomposition Stage of Figure 2.1. It is at this stage that the organic component of the bone, including the collagen, begins to degrade and acts to weaken the bone.

SevenFive Conclusions

Figure 7.1 and Tables 7.1 to 7.4 demonstrate how burning influences the mechanical strength of bone. Recording frequency when used as a proxy for mechanical strength shows a statistically significant decrease after burning at 745°C. This coincides with the Decomposition Stage of heat-induced bone degradation forwarded by Mayne Correia (1997) and Thompson (1999). Tables 7.2 and 7.3 support the recording frequency and mass spectrometry data by demonstrating that the reduction of bone weight due to the loss of water and organic materials can be statistically significant.

The loss of components of bone when heated will not only affect the mechanical strength of the bone, but also the microstructural architecture. Chapter 8 builds upon the data and conclusions presented here and discusses this feature further.

Eight The Examination of Microscopic Bone Architecture

EightOne Introduction

The focus of this chapter is not the gross manifestations of the effects of burning on bone. The previous three chapters have examined the macroscopic alterations that result from heating osseous material. These alterations can be termed 'secondary-level changes'. As important as these changes are, and as well studied as they are, they do not explain how these changes occur or what initiates them. They are merely the result and manifestation of other more fundamental changes in bone. These underlying heat-induced changes can be termed 'primary-level changes' and they take place at the micro- or nanoscopic scale. Unfortunately observations at the nanoscopic scale were beyond the scope of this project.

A series of techniques was employed in order to allow for a better understanding of these primary-level microscopic changes on which the more frequently studied changes in colour, mechanical strength and dimensions depend.

EightOneOne The Microscopic Architecture of Unburned Bone

The proportions of water, organic material and mineral in bone are determined by species, age, and by bone type (whether compact of cancellous) (Nielsen-Marsh *et al*, 2000). Ninety percent of the organic component is composed of Type I collagen, which comprises three stretched helical amino acid chains twisted into a triple helix (Nielsen-Marsh *et al*, 2000). These triple-helices are grouped into fibril bundles which in turn are grouped into collagen fibres (Nielsen-Marsh *et al*, 2000). The bone mineral is comprised of small crystals of hydroxyapatite. The small size of these crystals results in a high surface area for the inorganic phase (Nielsen-Marsh *et al*, 2000). This in conjunction with the isomorphous nature of the hydroxyapatite (Nielsen-Marsh *et al*, 2000) allows for a great deal of elemental interaction and activity within the inorganic phase. Complete ionic substitution can occur without a change in the material's structure (Nielsen-Marsh *et al*, 2000). For example, Ca^{2+} can be completely replaced with Sr^{2+}, Ba^{2+}, Pb^{2+}, Cd^{2+} or Sn^{2+} or partially so with Zn^{2+}, Cu^{2+}, Co^{2+}, Ni^{2+} and Mn^{2+} (Nielsen-Marsh *et al*, 2000). The organic and inorganic phases are physically and intrinsically linked (Nielsen-Marsh *et al*, 2000; White, 2000) with each phase influencing the nature of the other.

Bone can be divided into compact and cancellous forms. The compact bone is dense and punctuated by the Haversian system of canals through which blood, lymphatic fluid and nerve fibres pass (White, 2000). These Haversian canals, which run parallel to the long axis of the bone, are linked along their perpendicular axis by smaller channels known as Volkmann's canals (White, 2000). Extremely small channels called canaliculi radiate from the central canal to provide nutrients to the osteocytes which are harboured in the lacunae of the surrounding lamellar bone (White, 2000). This nutrient supplying network is not present in the cancellous bone since this bone receives nutrients directly from blood vessels situated in the surrounding marrow space (White, 2000). In human bone each Haversian system, or osteon, measures approximately 300 μm in diameter and are about 3 to 5 millimetres in length (White, 2000).

EightOneTwo Heat-induced Changes to Microscopic Bone Architecture

Heat-induced changes to microscopic bone architecture are discussed in great detail in Chapter 2, but it would be useful to mention some of the main points again within the context of microscopic bone architecture.

Alterations of the microscopic bone architecture commonly seen in archaeological and paleaentological bone include molecular loss and substitution, crystalline reorganisation and porosity and microstructural changes (Nielsen-Marsh and Hedges, 2000a). Usually these are seen as a consequence of diagenesis, but similar changes can be expected as a result of burning and cremation. For example, crystal size increases are a function of normal diagenesis (Nielsen-Marsh and Hedges, 2000a) and have also been noted in burned bone (Holden *et al*, 1995a; Rogers and Daniels, 2002). Rogers and Daniels (2002) argue that there has been little examination of the heat-induced crystallographic and microstructural changes in bone. However this statement is an example of the lack of inter-discipline awareness and literature bias that Thompson (1999) discusses. Rogers and Daniels (2002) refer to the medical literature surrounding human bone operations, and are seemingly oblivious to the archaeological and forensic literature that has discussed these very same heat-induced changes.

Hummel and Schutkowski (1993) argue that considerable heat-induced alterations will occur on the bone surface, but nonetheless that the microstructural aspect of bone is usually preserved. The most significant heat-induced structural changes occur between 600°C and 800°C (Rogers and Daniels, 2002). This corresponds to the Decomposition Stage of heat-induced bone degradation (Figure 2.1), and suggests that the removal of the organic phase may be important to further architectural change. The results of Rogers and Daniels (2002) X-ray diffraction experiments suggest that there is an increase in crystal size with an increase in the burning temperature. That is the crystals transform from their small but highly anisotropic state to one with a significantly larger equidimensionality (Rogers and Daniels, 2002). They place the key transformation section point at around 800°C (Rogers and Daniels, 2002). This is in agreement with Holden *et al* (1995a) whose experiments placed this key period between 600°C and 1000°C. They then argued that the fusion of the inorganic crystals would begin between 1000°C and 1400°C (Holden *et al*, 1995a). Along side the heat-induced change in crystal size is a change in crystal shape. Large highly ordered crystals produce higher splitting factors than small disordered crystals (Roberts *et al*, 2002; Stiner *et al*, 1995). This was noted by Stiner *et al* (1995) in their experimental studies.

The role of collagen in the heat-induced alterations of microscopic bone architecture is complex. Heat-induced changes to the bone mineral are likely to adversely influence the stabilising effect of the inorganic phase with regard to collagen denaturing while simultaneously the eventual removal of the collagen network will influence crystal size, morphology and their stoichiometry (Rogers and Daniels, 2002). Roberts *et al* (2002) argue that the removal of collagen from the bone by both diagenesis and boiling occurs due to a process of chemically-mediated hydrolysis. This is not the same for burning which removes collagen by oxidation. Experiments have shown that the loss of collagen is more rapid at higher temperatures (Roberts *et al*, 2002).

It has long been suggested that the burning of bone produces tricalcium phosphate (Holden *et al*, 1995b; Newesely, 1988; Posner, 1969). Other studies have interestingly failed to identify any such conversion (Shipman *et al*, 1984; Rogers and Daniels, 2002). Rogers and Daniels (2002) argue that the presence of tricalcium phosphate should not be expected at all because the crystal lattice network as transformed by heating supports the exclusion of carbonates and substituted ions. This implies that burning bone forces a change to a 'purer' crystalline matrix that does not allow for anything but the presence of hydroxyapatite. In addition they suggest that the presence of tricalcium phosphate or lack thereof can be explained with reference to bone sampling (Rogers and Daniels, 2002). It is argued that non-human mammalian bone will produce tricalcium phosphate while human bone will not due to the lower Ca/P ratios and greater amounts of HPO_4 and Mg in faunal bones. That is, experiments using faunal samples will detect the presence of tricalcium phosphate whereas those using human remains will not. This notion is not entirely supported by the results collated Table 8.1. A greater number of human and faunal tissue-based studies will need to examine the presence of tricalcium phosphate before any firm conclusions can be put forward. It has also been stated that tricalcium phosphate forms only at higher temperatures. This notion is consistent with the data in Table 8.1 however more experiments are required before any conclusion can be reached with confidence.

Study	Sample	Tricalcium Phosphate?	Max Temp of Experiment
Holden *et al*, 1995b	Human	Yes	1600°C
Newesely, 1988	Human	Yes	1000°C
Posner, 1969	Human	Yes	800°C
Rogers and Daniels, 2002	Human	No	700°C
Shipman *et al*, 1984	Faunal	No	940°C
Stiner *et al*, 1995	Faunal	Yes	-

Table 8.1 The relationship between presence of tricalcium phosphate and origin of sample material.

It would appear that the age of an individual has an affect on the reaction of their bone to heating. Both Holden *et al* (1995) and Rogers and Daniels (2002) noted that older bone is more resistant to heat-induced change. This is likely to be due to the increased thermodynamic instability of newer bone resulting from its greater amorphous quality and its lower degree of mineralisation (Holden et al, 1995a).

EightTwo Methodology

EightTwoOne Scanning Electron Microscopy

The technique of scanning electron microscopy is discussed fully in Chapter 6 within the context of the proliferation of fracture lines. The nature of the technique does not change however with a simple change in application, therefore it will not be repeated here.

Scanning electron microscopy has been used to great effect in the examination of the microscopic architecture of bone from both forensic and archaeological contexts. It has three main benefits over other methods of examining osseous microstructure. First, the method is relatively less financially expensive per sample when compared to other analytical techniques such as porosimetry, small-angle x-ray scattering and so forth. Second, access to scanning electron microscopy equipment for anthropologists is greater than for other analytical equipment. Third, the technique of scanning electron microscopy produces actual images of the sample being examined. These are arguably easier to comprehend and interpret by more anthropologists than a collection of numbers and graphs of the type produced by, for example, mercury-intrusion porosimetry or small-angle X-ray scattering.

As with the discussion of the nature of the technique, the methodology of the scanning electron microscopy is detailed in Chapter 6. For ease of comparison and discussion, the results of the scanning electron microscopy are reproduced from Section 6.3 in Section 8.3.

EightTwoTwo Mercury-intrusion Porosimetry

Bone has a very high internal surface area and is highly porous (Nielsen-Marsh and Hedges, 1999). It therefore seems worthwhile investigating the importance of changes in this aspect of internal structure. It has been suggested that the study of bone porosity may reveal more about diagenetic alteration than the use of more traditional techniques such as protein content, infrared splitting factor and histology (Nielsen-Marsh and Hedges, 1999). In addition porosity results are direct evidence for a reorganisation of the bone microstructure (Nielsen-Marsh and Hedges, 1999). Porosity analyses have therefore been used by archaeologists to study diagenetic change in ancient bone, recent examples of which have been conducted by Nielsen-Marsh and Hedges (1999; 2000a; 2000b), Roberts *et al* (2002) and Smith *et al* (2002). Changes in the porosity of bone necessarily relate to changes in the physical structure, incorporating both the organic and inorganic components, of that bone (Nielsen-Marsh and Hedges, 2000a). Since the technique has been so helpful in the investigation of diagenesis, it was thought that it might have much to offer those examining the influence of burning on the microstructure of osseous material. For the first time therefore this technique was used to investigate burned bone.

The technique of porosimetry was developed in soil science (Nielsen-Marsh and Hedges, 1999). The first method measured porosity in terms of water sorption (Nielsen-Marsh and Hedges, 2000b) where assessment of pore size distribution is based on measuring the mass change of a sample equilibrating between atmospheres of given humidities (Nielsen-Marsh and Hedges, 1999). The technique used in this research is not water-based, but mercury-based. This is because the water method cannot distinguish between water held in the sample due to chemical affinity and that held by surface tension. The technique is based upon the assumption that the sample being examined has cylindrical pores and that liquid penetration into the small pores is therefore governed by the capillary law (Nielsen-Marsh and Hedges, 1999). The technique functions by forcing liquid mercury into the sample at known pressures. The volume of pores with a certain pore throat diameter can be estimated since pressure can be shown to be inversely proportional to the throat diameter of filled pores (Nielsen-Marsh and Hedges, 1999).

Cell Number	Sample Number
3-2	7
3-3	2
3-4	3
3-5	1
3-6	2
3-7	10

Table 8.2 Details of Burned Bone Samples sent to the Postgraduate Institute for Fossil Fuels and Environmental Geochemistry, University of Newcastle for Mercury-intrusion Porosimetry Analysis

The samples of burned bone and unburned control were sent to the Postgraduate Institute for Fossil Fuels and Environmental Geochemistry, University of Newcastle for analysis. The technique and initial analyses were performed by Miranda Jans, Dr Colin Smith and Dr Matthew Collins. A Micrometrics Autopore II 9220 mercury-intrusion porosimetry machine was used. The technique is destructive and requires bone samples of one centimetre in length. Table 8.2 details the samples that were subjected to mercury-intrusion porosimetry.

EightTwoThree X-ray Diffraction

X-ray diffraction studies of bulk samples have demonstrated changes in bone mineral (Rogers and Daniels, 2002). X-ray diffraction has been used by previous by workers to examine the changes due to burning of the microscopic architecture of bone (Holden *et al*, 1995; Newesely, 1988; Rogers and Daniels, 2002; Shipman *et al*, 1984; Stiner *et al*, 1995) and it has been shown to have a great deal to offer the study of bone microstructure. The technique works because all matter has the ability to scatter X-rays (Wess *et al*, 2001). This feature can be used by anthropologists because the fluctuations in the electron density of material, such as at the interface between molecules, give rise to characteristic scattering patterns (Wess *et al*, 2001) which can be used to examine the microscopic structure of these materials. Scattering patterns from fresh bone samples can be compared with those from bone undergoing diagenesis, and statements can be made regarding the nature of this diagenetic change. The effect of post-mortem change in bone, such as by normal diagenesis or burning, results in deviations in mean crystal thickness of the modified bone compared to the fresh bone (Wess *et al*, 2001). This deviation often results in larger crystal sizes (Wess *et al*, 2001). The technique does have weaknesses however. Rogers and Daniels (2002) argue that X-ray diffraction data are generally subject to high uncertainties due to overlapped diffraction peaks resulting from broad diffraction maxima and relatively low crystal symmetry. In addition the line profiles created from this raw data only provide weighted spatial averages of crystal size estimates. Thus apparent changes may be due to alterations in crystal size distribution rather than simple crystal size – with an example relevant to cremation studies being the resorption of small crystals being interpreted as crystal growth (Rogers and Daniels, 2002).

The conclusions of the X-ray diffraction studies and their place within the larger debate of heat-induced changes in bone structure are discussed above. In general it can be said that the results of these experiments have shown that when heated up to approximately 1000°C, the inorganic component of bone becomes more crystalline or 'perfect' in structure. Beyond the temperature of 1000°C new mineral phases can be detected (Holden et al, 1995b; Newesely, 1988; Posner, 1969). It has been argued however that subtle heat-induced changes to the microstructure of bone can be difficult to detect using X-ray diffraction alone (Holden *et al*, 1995). In the last few years, a new technique for discerning subtle changes to bone nanostructure has been developed (Hiller *et al*, in press). This new technique, small-angle X-ray scattering (SAXS) has been shown to accurately detect changes to crystal size, shape and orientation within bone independent of crystal lattice perfection (Wess *et al*, 2001). This last point is of great benefit to those studying diagenetic change in archaeological bone (Wess *et al*, 2001). It has already been stated that burning is very similar in its degradation of bone to natural diagenesis and as such this new analytical technique could prove extremely useful to those studying cremated osseous material. Small-angle X-ray scattering is also less subjective than electron microscopy and does not rely on factors such as the degree of crystallinity which can affect the results of standard X-ray diffraction (Wess *et al*, 2001). For the reasons stated above the first attempt to use SAXS on burned bone was successfully initiated.

Burned bone and unburned bone control samples (detailed in Table 8.3) were sent to Dr Tim Wess and Jen Hiller of the Department of Biological Sciences, University of Stirling for examination. Wide-angle X-ray scattering was performed in order to assess any heat-induced changes to crystal shape. Small-angle X-ray scattering was performed in order to quantify heat-induced changes in crystal thickness. The samples were first ground into a fine powder using an agate mortar and pestle and subsequently stored in micro-test tubes. A NanoSTAR (Bruker AXS, Karlsruhe) X-ray facility was used for the analysis. The powdered samples were loaded into a sample carriage between two mica sheets and mounted in the vacuum chamber of the NanoSTAR. Scattering profiles were taken over three or nine hour exposures using sample-detector distances of 22.5 centimetres for wide-carriage between two mica sheets and mounted in the vacuum chamber of the NanoSTAR. Scattering profiles were taken over three or nine hour exposures using sample-detector distances of 22.5 centimetres for wide-angle x-ray scattering and 1.25 metres for small-angle X-ray scattering. Post-scattering procedures included the correction of collected data for camera distortions, the subtraction of a background image, analysis using Department of Biological Sciences in-house software and the conversion of the two-dimensional detector output into one-dimensional spherically-averaged profiles.

Cell Number	Sample Number
3-2	5
3-2	7
3-3	2
3-3	6
3-4	3
3-4	5
3-5	1
3-5	5
3-6	1
3-6	2
3-7	2
3-7	10

Table 8.3 Details of Burned Bone Samples sent to the Department of Biological Sciences, University of Stirling for XRD Analysis

EightThree Results

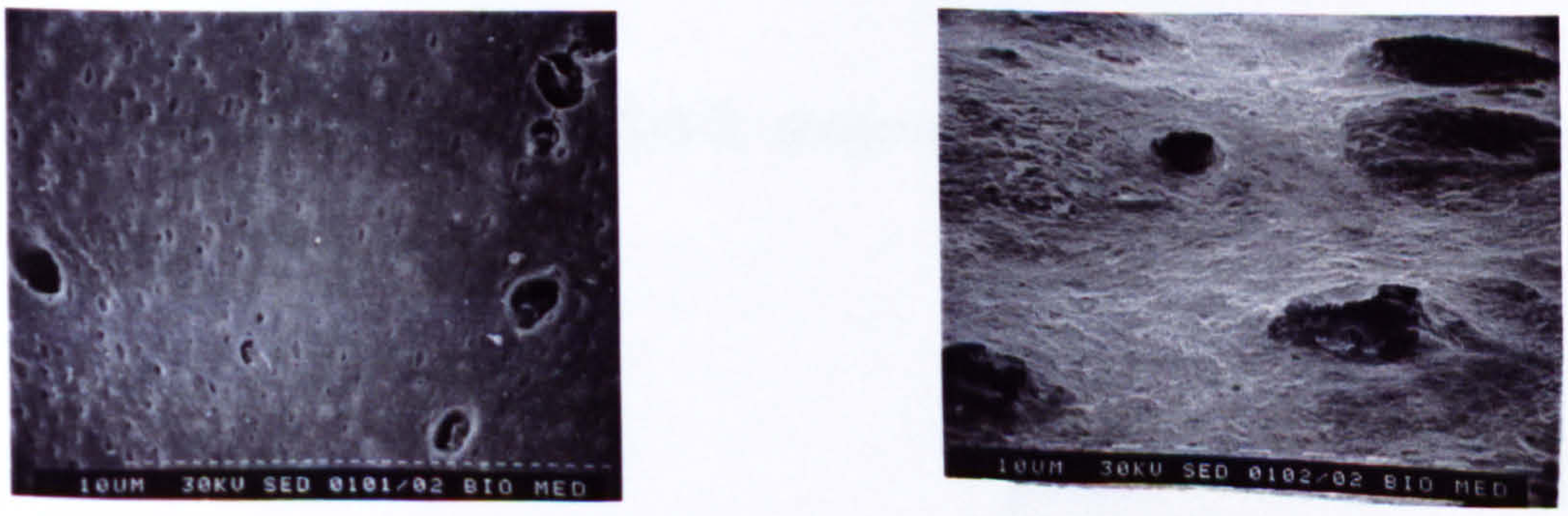


Figure 6.17 SEM image, sample pre, outer surface x (l), inner surface x (r)

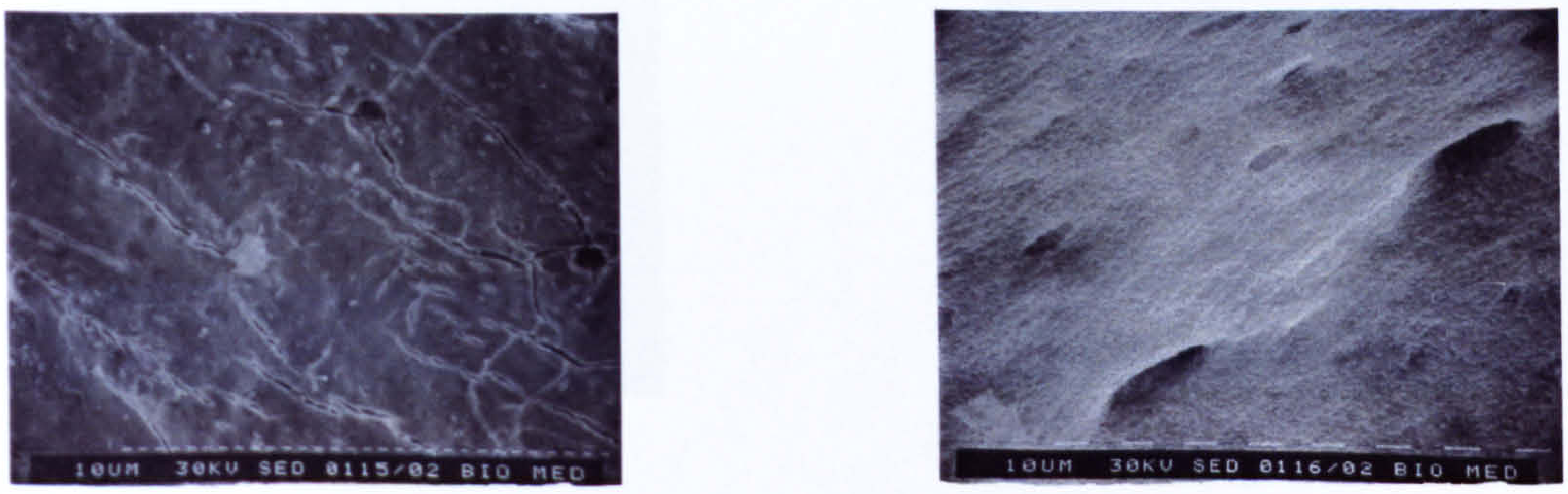


Figure 6.18 SEM image, sample 3-2-7, outer surface x (l), inner surface x (r)

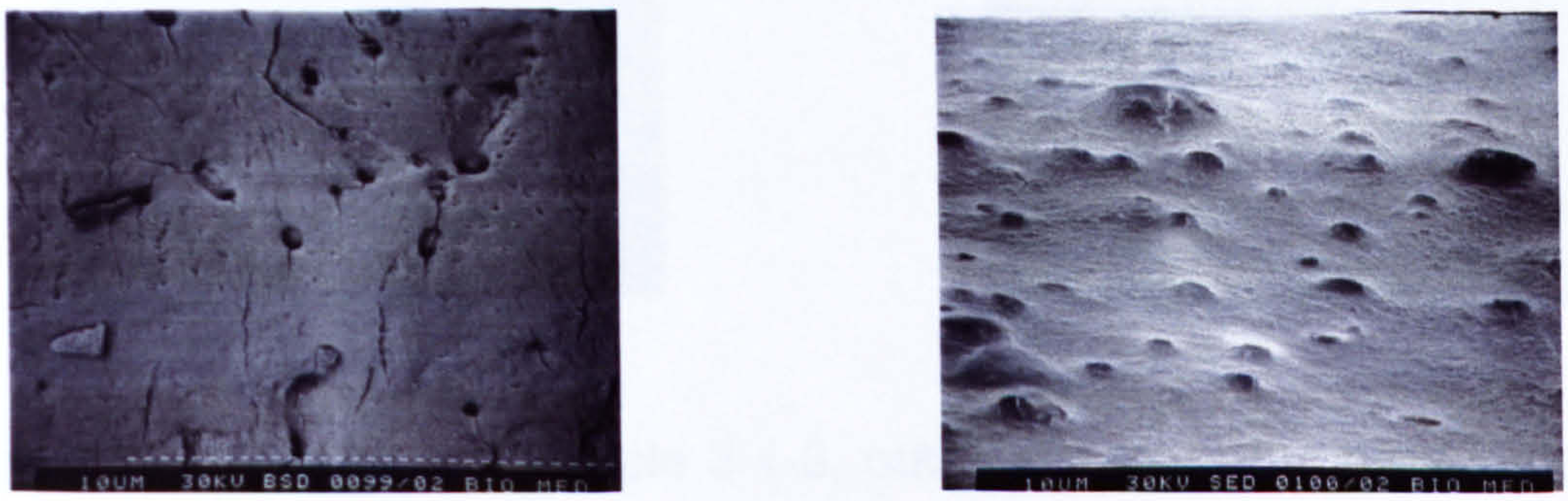


Figure 6.19 SEM image, sample 3-5-1, outer surface x (l), inner surface x (r)

Figure 6.20 SEM image, sample 3-3-2, outer surface x (l), inner surface x (r)

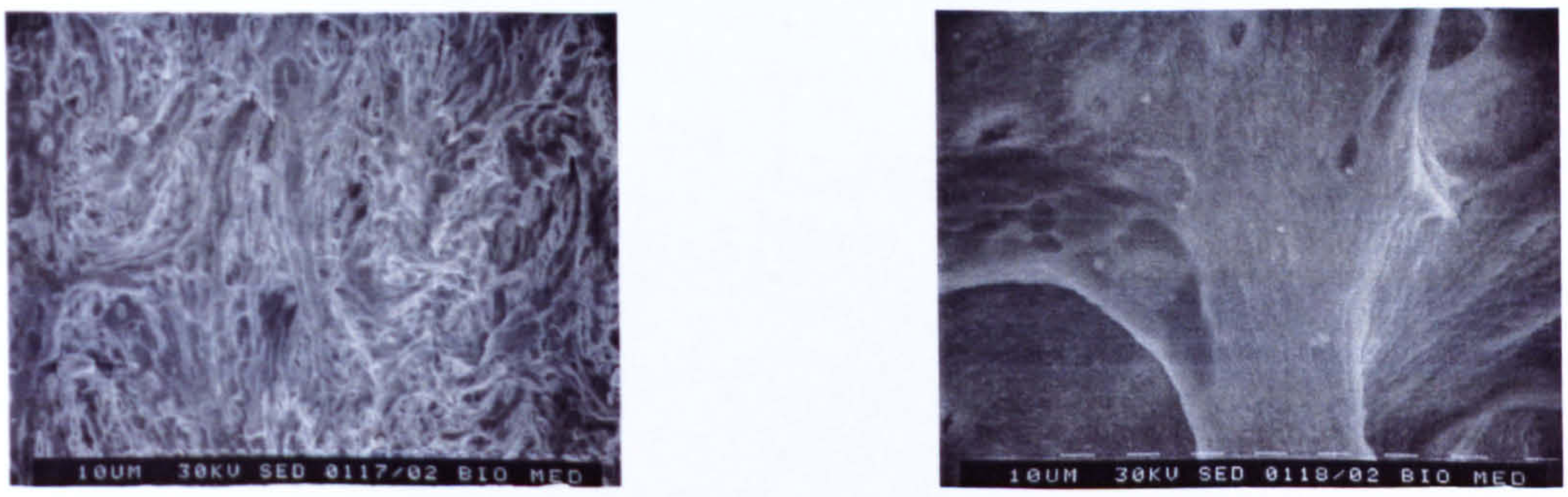


Figure 6.21 SEM image, sample 3-6-2, outer surface x (l), inner surface x (r)

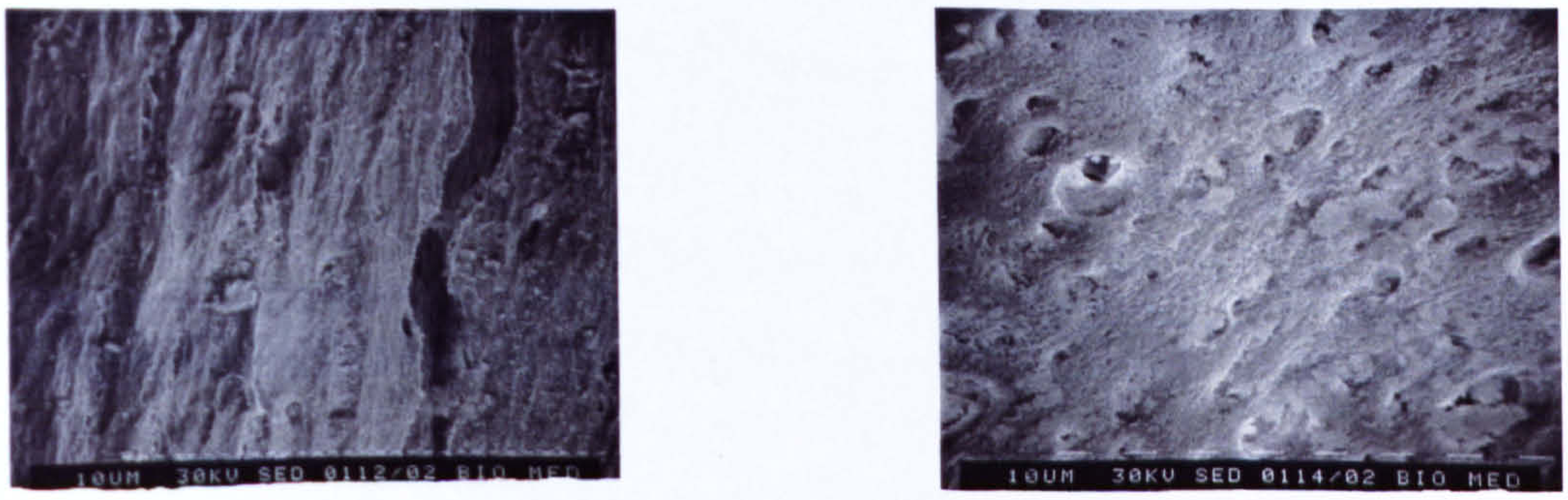


Figure 6.22 SEM image, sample 3-4-3, outer surface x (l), inner surface x (r)

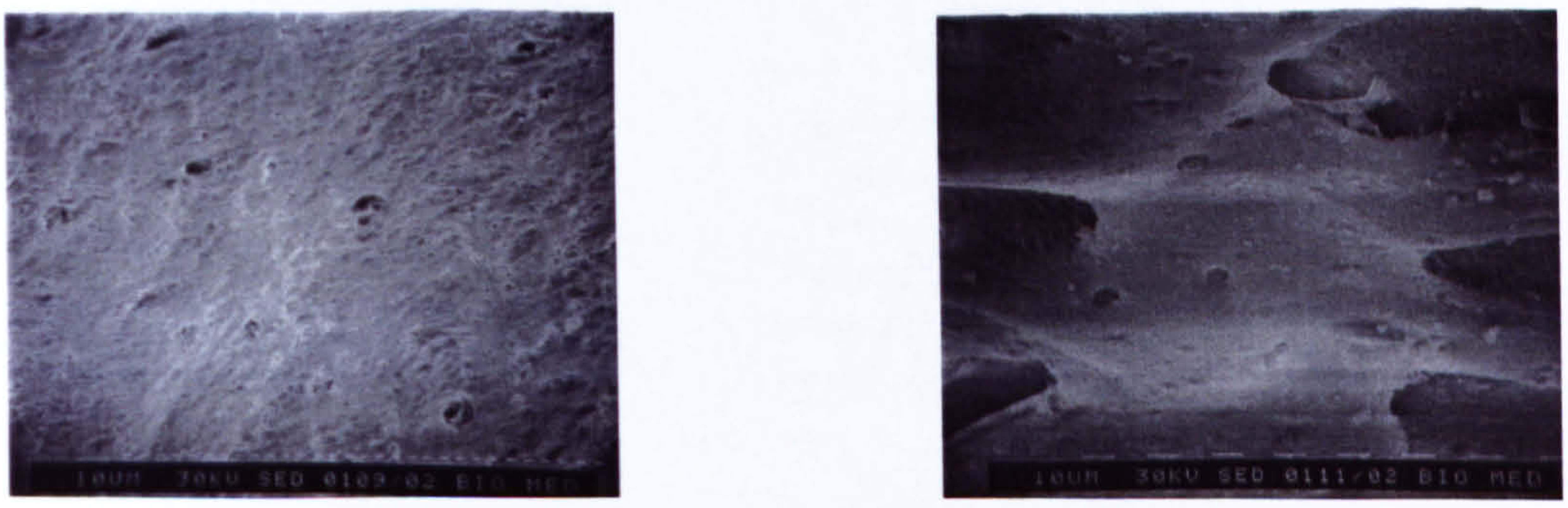
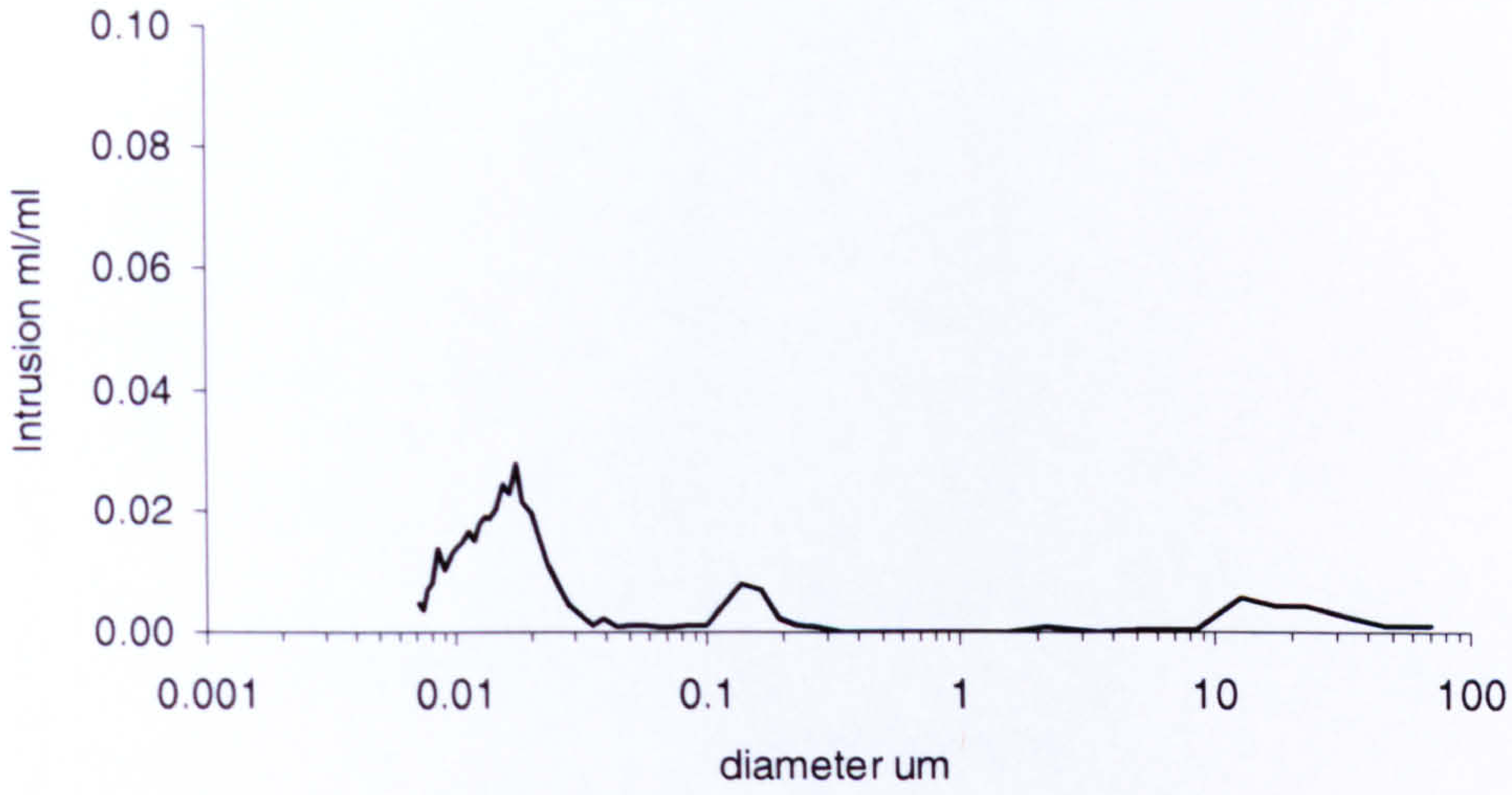


Figure 6.23 SEM image, sample 3-7-10, outer surface x (l), inner surface x (r)



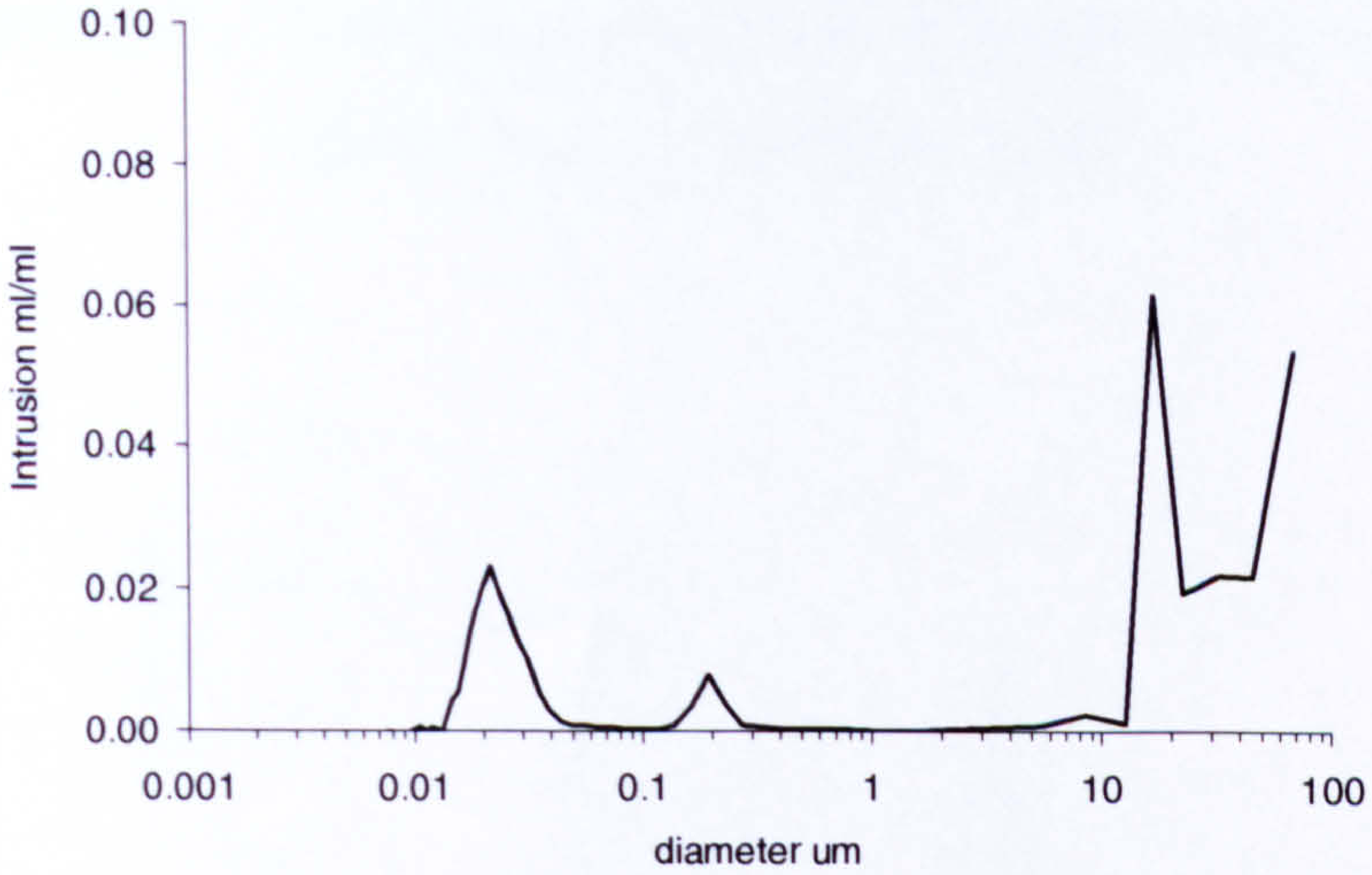
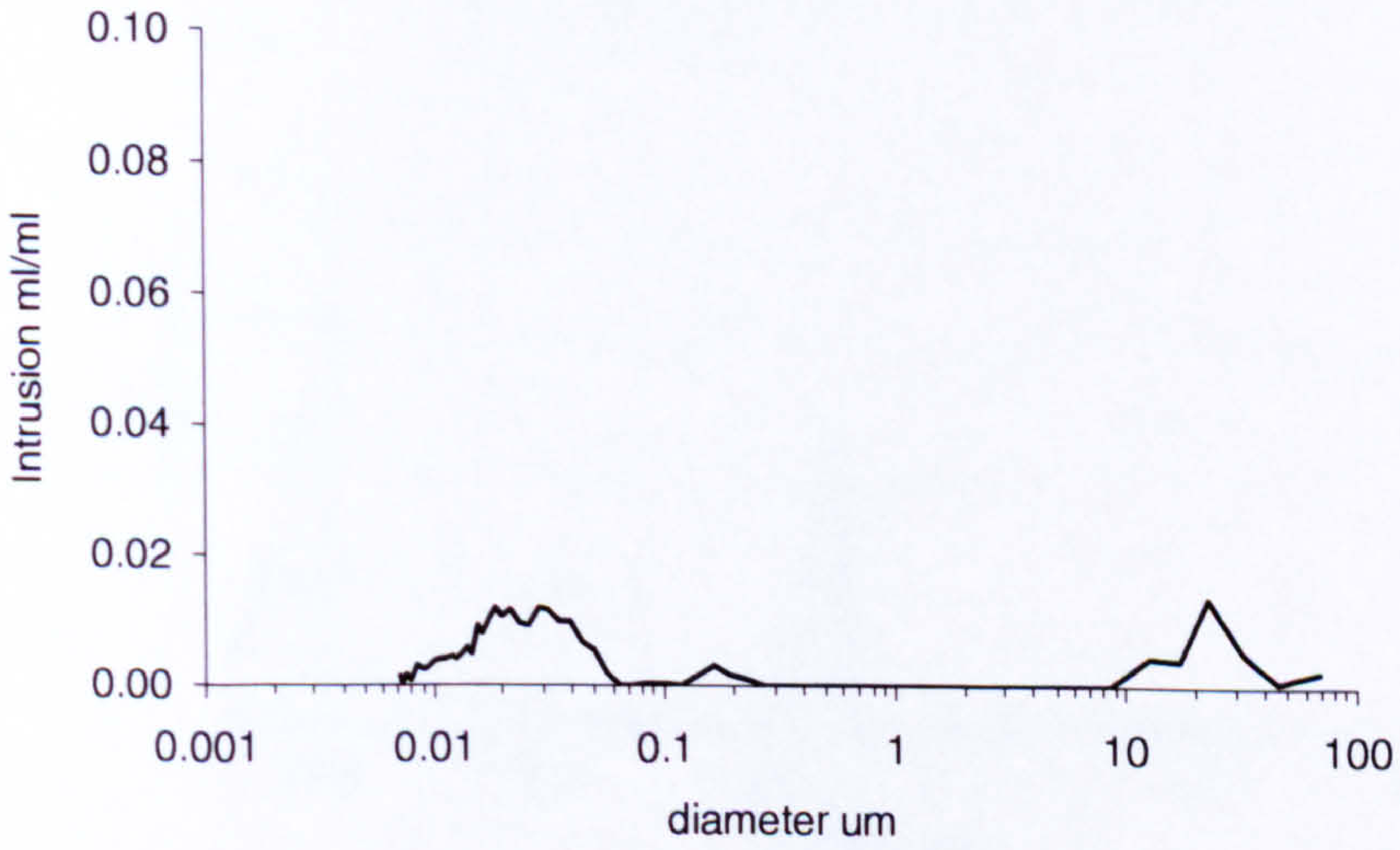


Figure 8.1 Heat-induced porosity changes in bone, 500°C for 15 minutes (upper) and 45 minutes (lower)



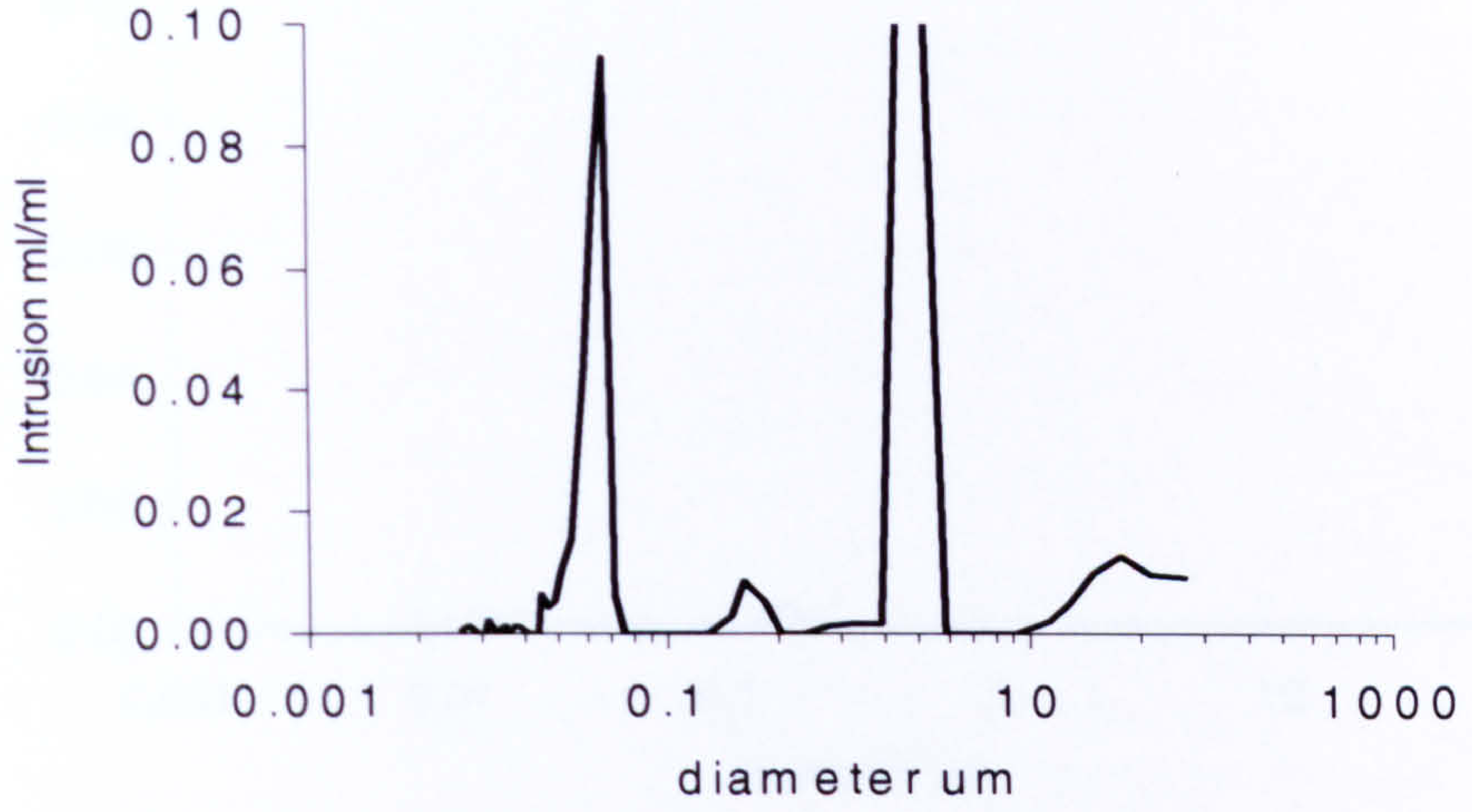
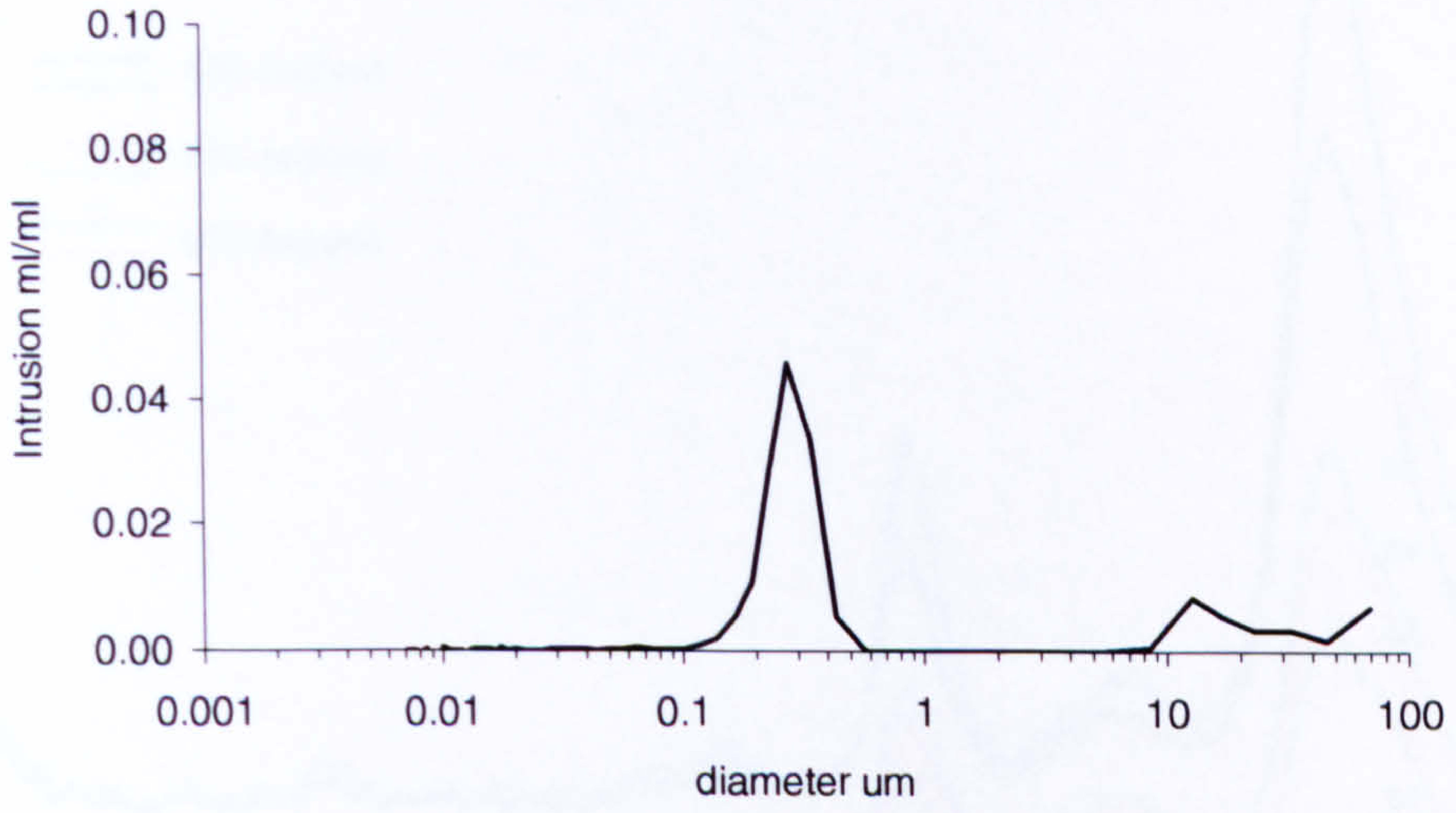


Figure 8.2 Heat-induced porosity changes in bone, 700°C for 15 minutes (upper) and 45 minutes (lower)



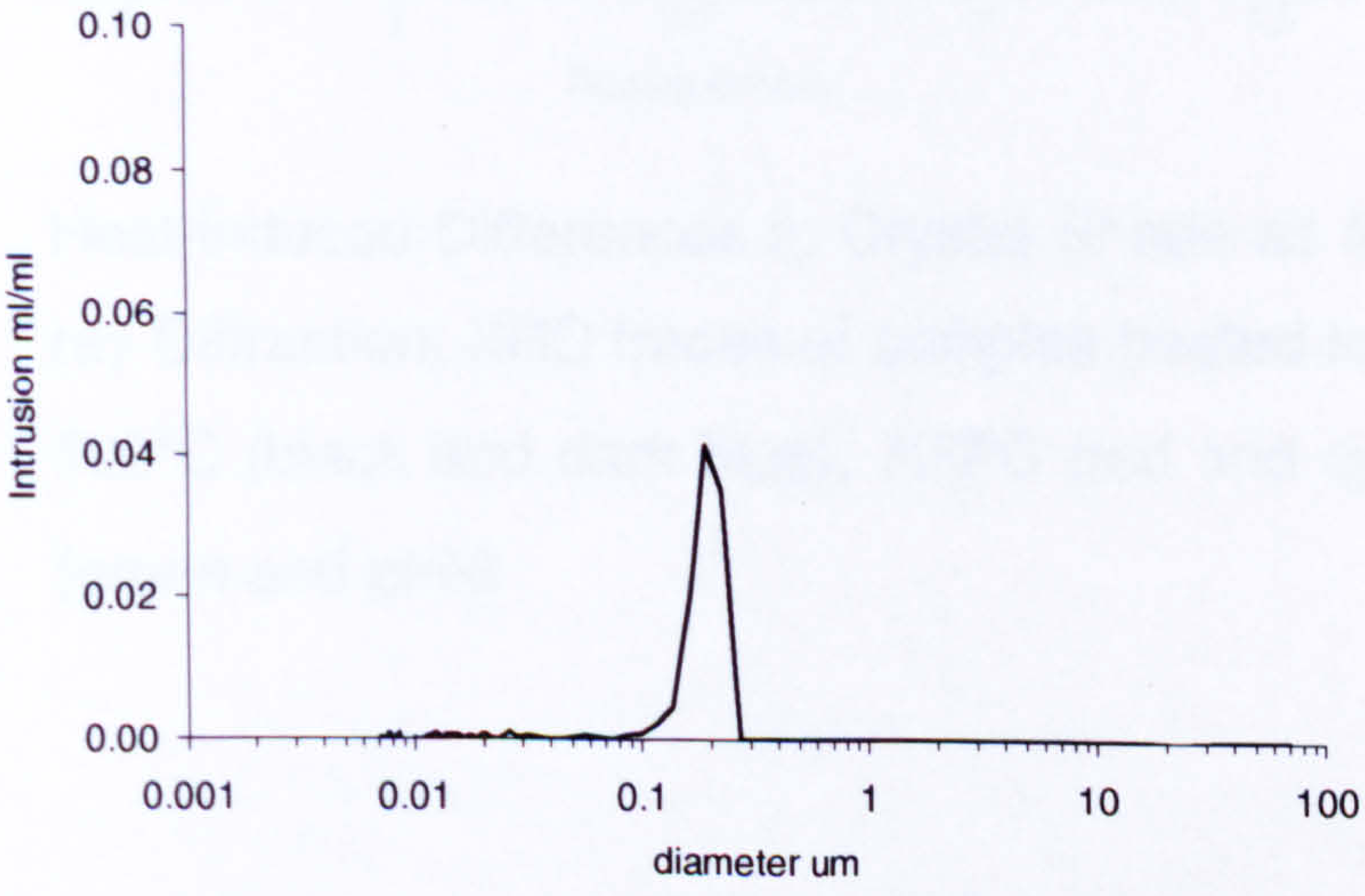


Figure 8.3 Heat-induced porosity changes in bone, 900°C for 15 minutes (upper) and 45 minutes (lower)

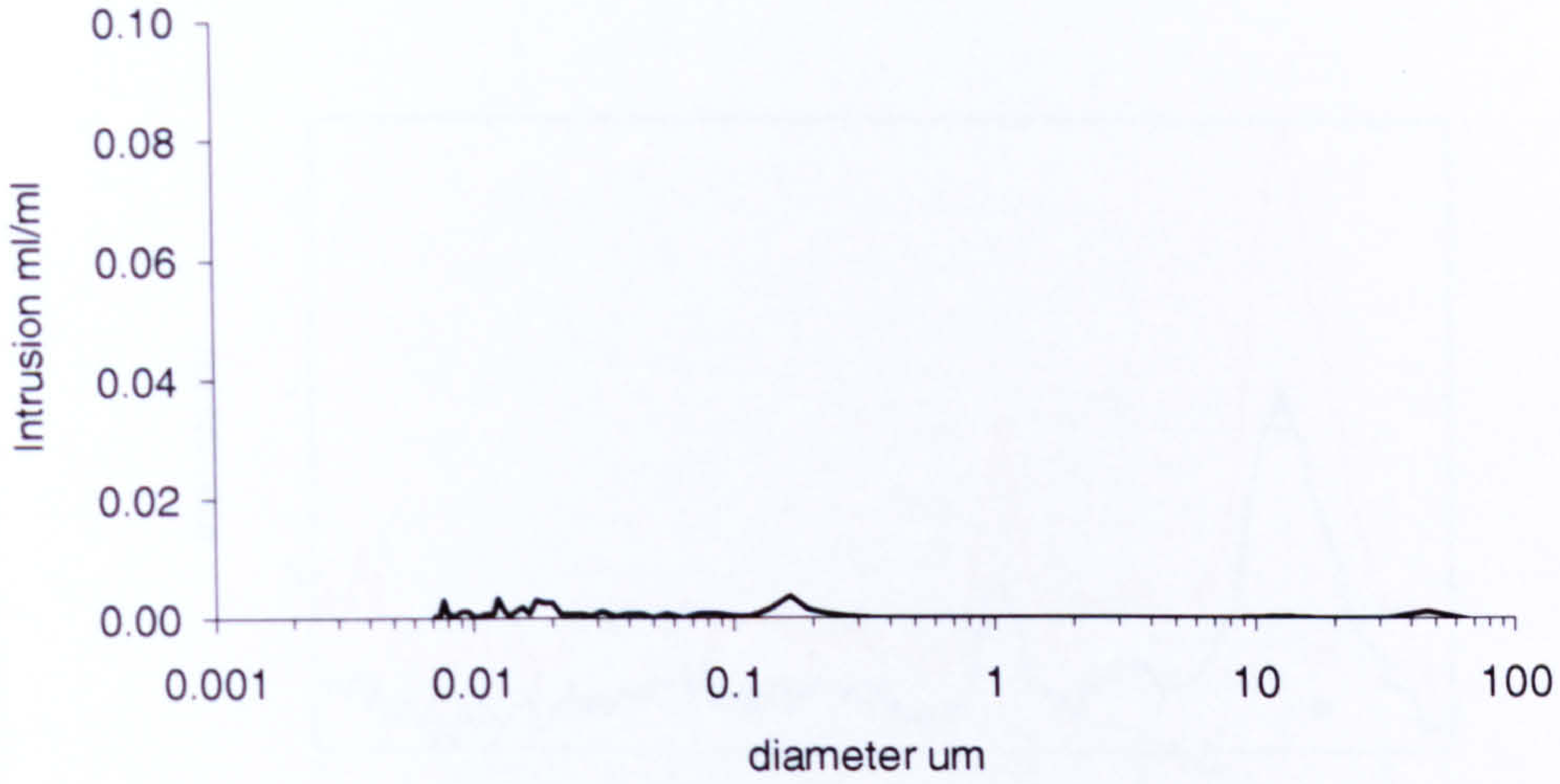


Figure 8.4 Porosity in unburned sheep bone

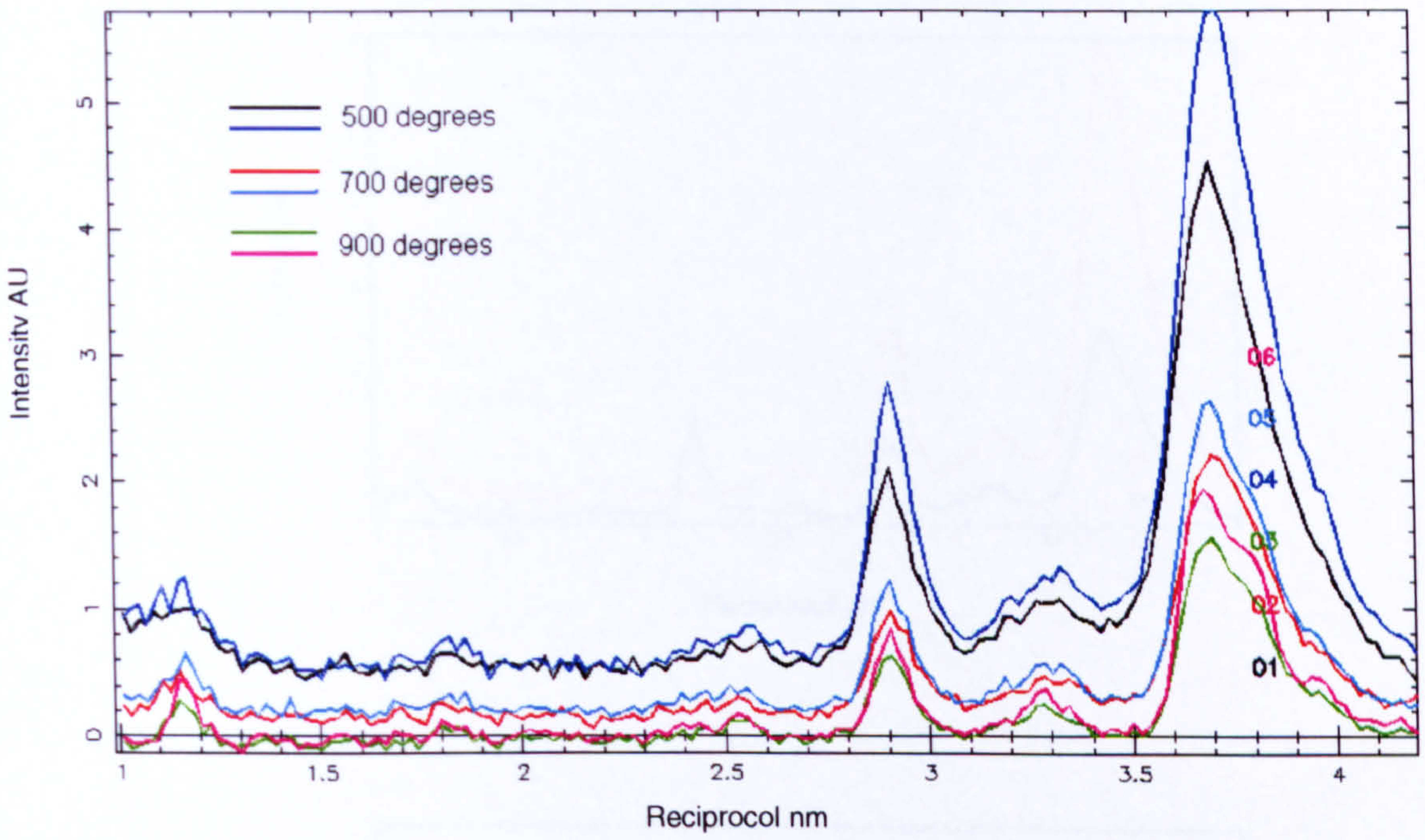
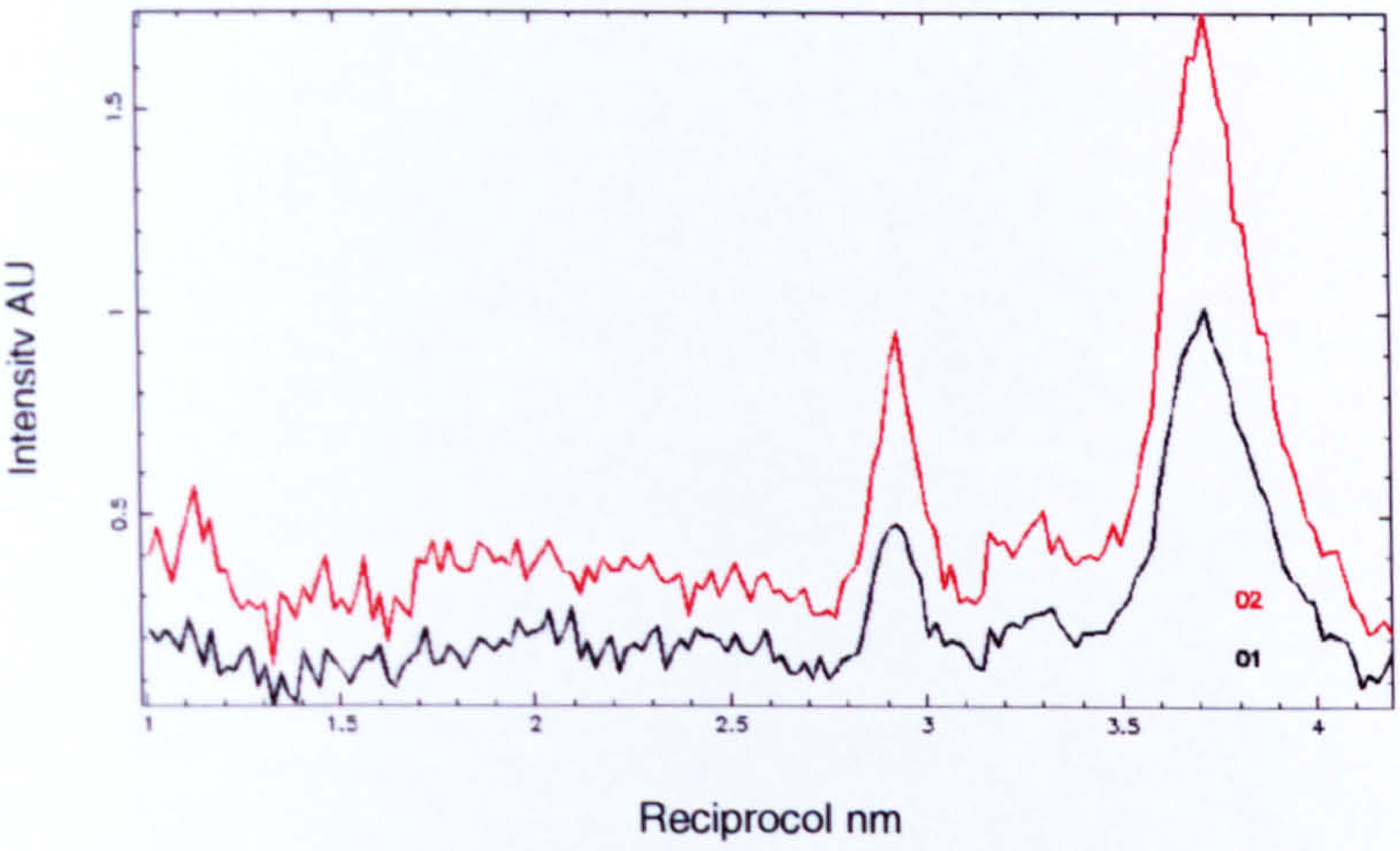


Figure 8.5 Heat-induced Differences in Crystal Shape as Measured by X-ray Diffraction; XRD traces of samples heated for 15 minutes at 500°C (black and dark blue), 700ºC (red and cyan) and 900ºC (green and pink)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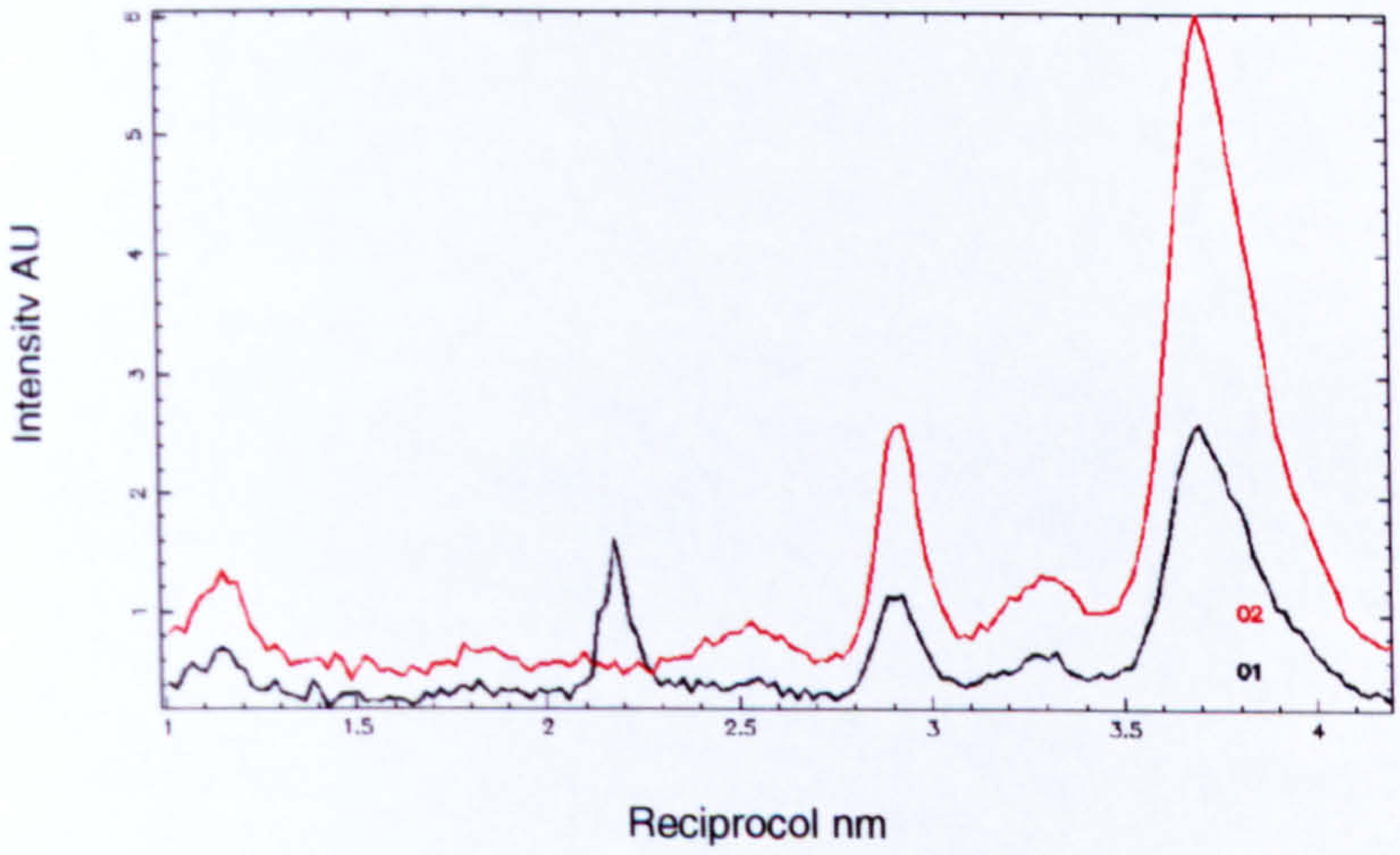
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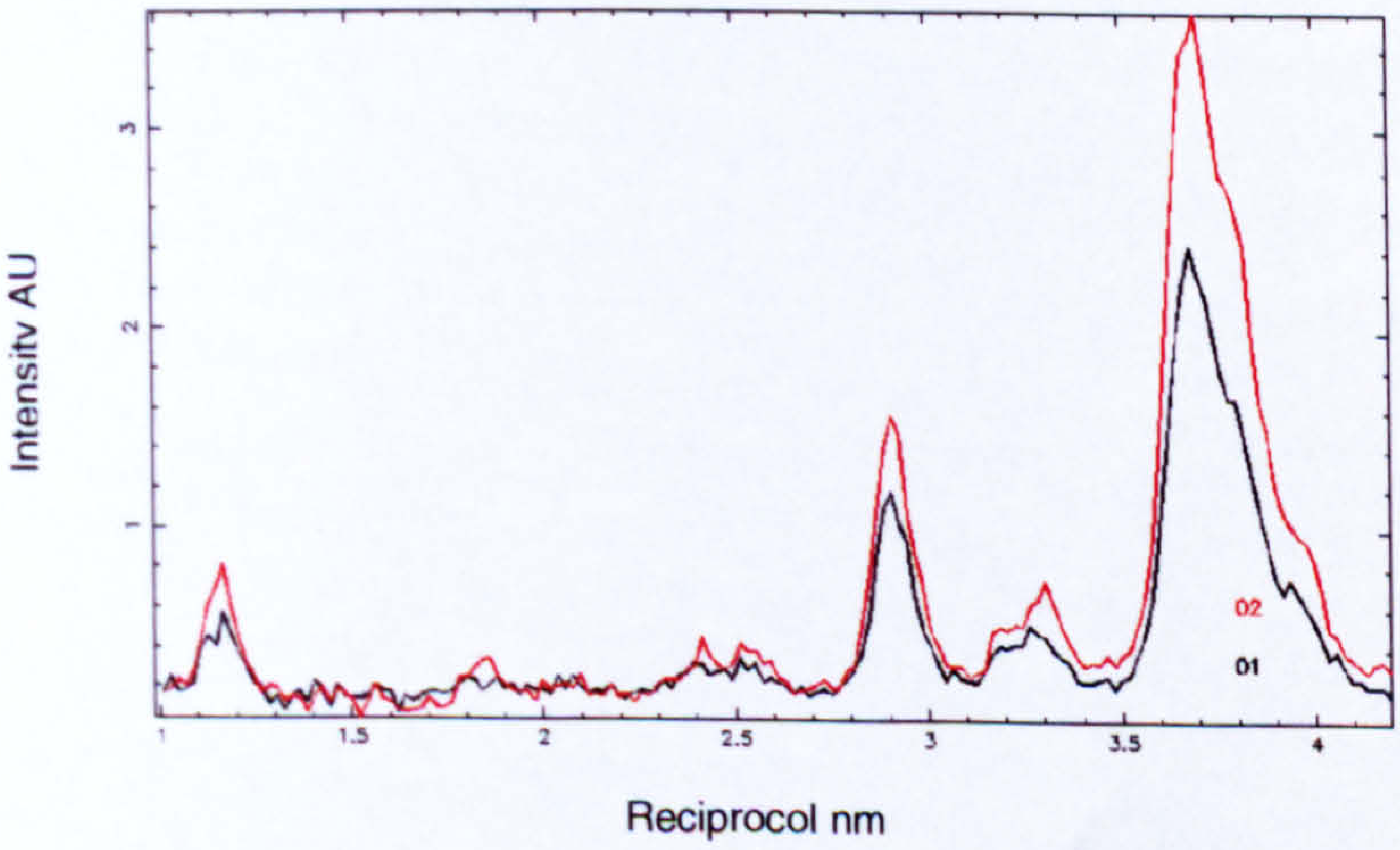
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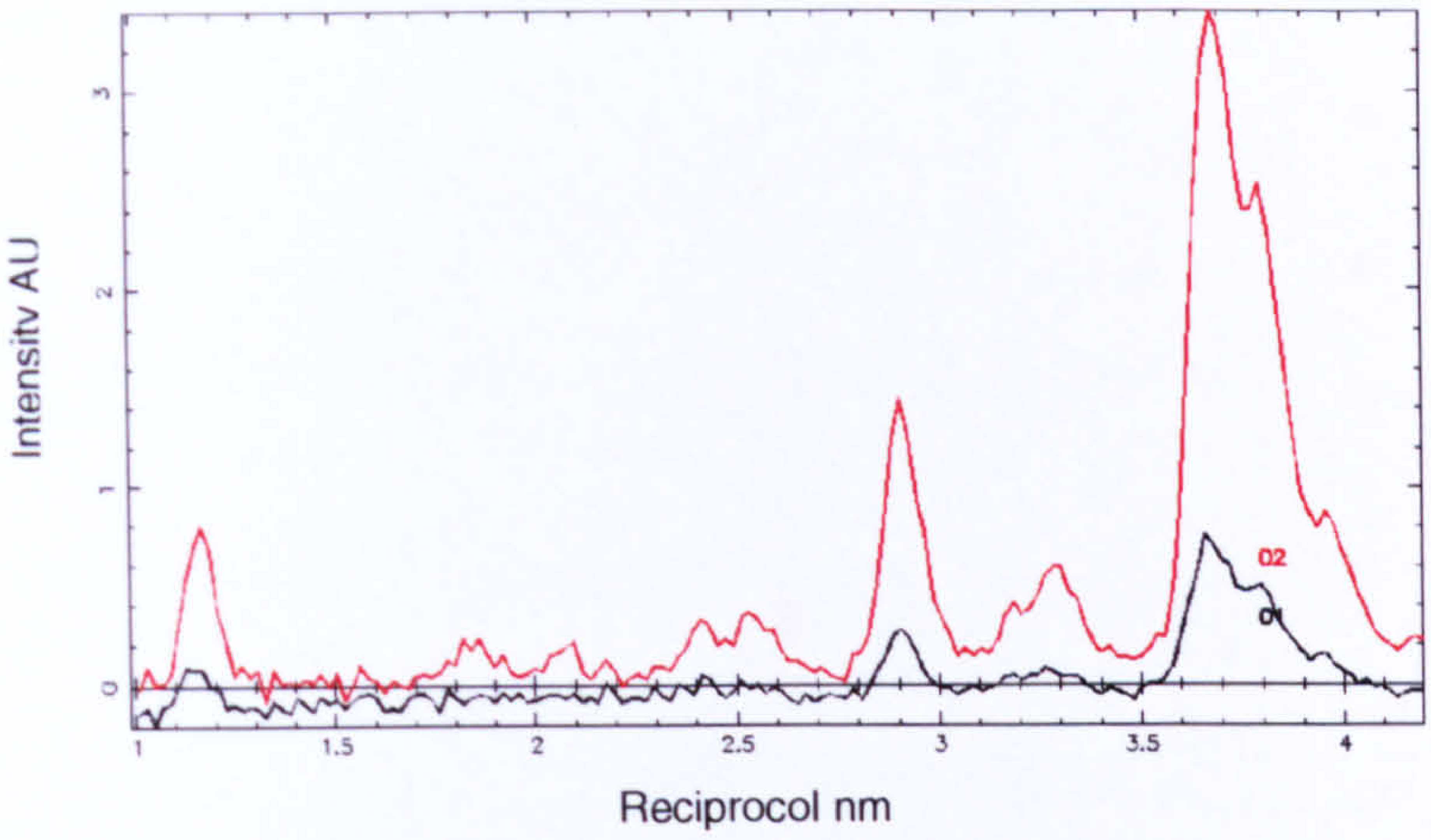

Figure 8.6 Heat-induced Differences in Crystal Shape as Measured by X-ray Diffraction; XRD traces of control samples (upper) and samples heated for 45 minutes at 500ºC (second), 700ºC (third) and 900ºC (lower) [Note: each line represents one sample]

Sample	Heating Conditions (°C, mins)	Exposure (hr)	Thickness (nm)
Control 1	Unheated	3	2.79
Control 2	Unheated	3	2.36
3-2-5	500, 15	3	5.24
3-2-7	500, 15	3	5.65
3-3-2	700, 15	3	10.37
3-3-6	700, 15	3	14.09
3-4-3	900, 15	3	17.49
3-4-5	900, 15	3	22.59
3-4-3	900, 15	9	29.39
3-4-5	900, 15	9	74.04
3-5-1	500, 45	3	7.81
3-5-5	500, 45	3	6.71
3-6-1	700, 45	3	16.11
3-6-2	700, 45	3	15.60
3-7-2	900, 45	3	31.26
3-7-10	900, 45	3	26.66
3-7-2	900, 45	9	31.83
3-7-10	900, 45	9	32.90

Table 8.4 Results of the Small-angle X-ray Scattering Analysis of Burned Bone

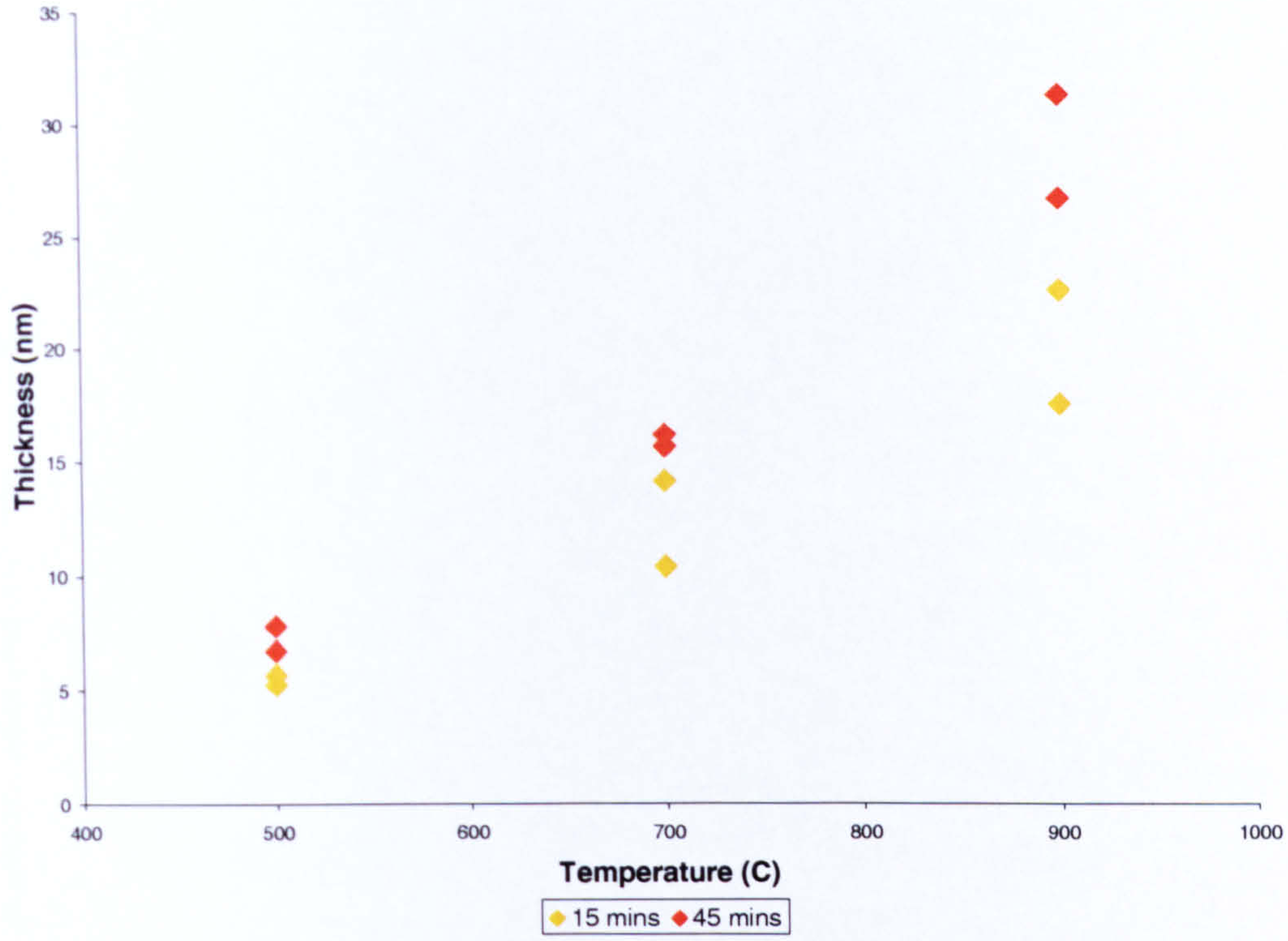

Figure 8.7 Comparison of Heat-induced Crystal Thickness (nm) in Bone Burned Under Different Conditions

EightFour Discussion

The most significant changes in bone microscopic architecture that the scanning electron microscopy images (Figures 6.3 to 6.9) detect refer to the activity of the architecture in general. Encouragingly the scanning electron micrographs of the burned sheep bone produced here are very similar to those produced by Nicholson (1993) in her study of the effects of burning on sheep bone and in the images produced by Forbes (1941). It can be seen that the unmodified natural bone of Figure 6.3 does not alter substantially due to low intensity burning of 500°C (Figures 6.4 to 6.5). With continued heating, the surface of the bone becomes roughened (Figures 6.6 and 6.8) and then highly active and deformed (Figure 6.7). The initial roughening is due to the removal of the water and the organic component of the bone, which causes an increase in bone porosity. Figure 6.6 represents the affects of burning at 700°C, which falls within the Decomposition Stage. In addition the bone architecture is being altered by the removal of the inorganic carbonates. As well as falling within the Decomposition Stage burning at 700°C is at the suggested start of the Inversion Stage. Figure 6.8 represents burning at 900°C, which is beyond the suggested range for the Decomposition Stage. It could be that the boundaries for this degradation stage need to be extended. Alternatively it could be that duration is more important than has been previously acknowledged. That is that continued burning is required before the organic phase is completely removed and Fusion Stage can be physically achieved. The activity of the bone surface in Figure 6.7 is a function of the continued removal of the organic phase and the carbonates in addition to the beginning of the Fusion Stage. Here the inorganic phase begins to become fluid resulting in the coalescing of crystal and the filling in of the pores left by the evicted bony constituents. This smooth surface, which is argued to represent evidence of fusion, is also recorded in the scanning electron micrograph produced by Nicholson (1993) of her sheep sample burned at 900°C too. Previously the commencement of the Fusion Stage has been placed at 1600°C (Mayne Correia, 1997) and then revised to 1000°C (Thompson, 1999). If Figure 6.7 does indeed show evidence of inorganic component becoming highly active, even this revised temperature may be placed too high. Evidence for the acceptance of this notion is presented in Figure 6.9. Here the outer bone surface is smooth again. This means one of two conclusions need to be accepted. Either the Fusion stage has been reached earlier than predicted and Figure 6.9 shows the product of the heat-induced activity of the inorganic phase, or there is a period of inactivity in the inorganic phase between the loss of the organic phase and carbonates and the commencement of the Fusion Stage. This last point seems unlikely and therefore the former conclusion is accepted: the Fusion Stage begins before the accepted published temperature. Revision of Figure 2.1 is therefore required.

With regard to the mercury-intrusion porosimetry, it should be noted that the *x*-axes of Figures 8.1 to 8.4 represent the diameter of the neck of the pore space, and is proportional to pressure since greater pressure results in the penetration of pores with smaller diameter necks. The *y*-axes represents intrusion, which is a function of property of the bone and can be interpreted as the volume of pore space, and is a measure of the volume of mercury forced into the bone per volume of bone. The results of the mercury-intrusion porosimetry of the bone burned at 500°C shows a slight increase in porosity (Figure 8.1). There is an increase in the pore volume between 0.007 and 0.05 µm and between 0.1 and 0.3 µm. These peaks in turn become taller and narrower with increased heating duration. The peaks between the 10 and 100 µm pore sizes can be ignored. They are unfortunate data noise, most likely a result of an increase in large pore size and numbers due to the fracturing of the burned bone from the high pressures involved in the penetration of the mercury. This is especially obvious in the sample burned to 500°C for 45 minutes (Figure 8.1). Interestingly, the samples burned to 700°C (Figure 8.2) show a reduction in height but a broadening of the peak between 0.01 and 0.06 µm. The second peak at 0.15 to 0.2 µm is now almost gone completely. This implies a reduction in the pore volume present in the material. Burning at 900°C seems to cause the most drastic change in pore size (Figure 8.3). It can be seen that these samples do not share the similar porosity curves to the samples burned at 500°C or 700°C. First there is less noise. This may suggest that for some reason, the larger pores have been removed from the sample. The samples in Figure 8.3 are now essentially uni-modal. The main peak occurs between 0.15 and 0.6 µm for the 15 minute sample and 0.1 and 0.3 µm for the 45 minutes sample. Continued heating has resulted in a smaller but narrower porosity peak. The great difference between these curves and that for the unburned sample (Figure 8.4) suggests that significant heat-induced microstructural change has occurred.

The shift in pore size diameter distribution indicated by a migration of the peaks to the right of the graph in the samples burned to a low intensity may be the result of the internal surface of the existing pores being damaged by the heat. This would increase the diameter size of these pores resulting in this peak shift. According to the experiments of Nielsen-Marsh and Hedges (1999) the pores of radii 100 nm may represent the presence of caniliculi, pores of 10000 nm are in concordance with various physiological features in bone. Increases in porosity between these sizes can be attributed to the action of micro-organisms (Nielsen-Marsh and Hedges, 1999; Smith *et al*, 2002). Although there are increases in porosity in this pore size range, the causative factor cannot be microbial action. It would seem that for some reason, micro-organisms (in the burial environment) and heat (from burning experiments) preferentially damage pores of these sizes. It may therefore be that pores of this size are the optimum size for micro-organisms and are therefore preferentially selected. This nature of these pores may also mean that heat damage occurs preferentially to them. The increase in porosity between 4 and 10 nm is attributed to the loss of collagen (Nielsen-Marsh and Hedges, 1999). This pore size range corresponds to the left peak of the samples burned to 500°C and 700°C. This increase in porosity could therefore be the result of the destruction of the collagen within the bone microstructure. More difficult to explain is the shift in pore size associated with high intensity burning. The cause here may be connected with the reorganisation of the bone microstructure rather than just the removal of certain matrix components. It may well be that the commencement of the Fusion Stage of heat-induced change in bone has resulted in the coalescing of the microscopic pores. This could be the cause of the general flatness of the graph. It would also explain the relative simplicity of the graphs as there are fewer pore spaces to cause additional peaks or roughness to the curves.

Table 8.5 compares the mercury-intrusion porosimetry readings for bone which has been burned, boiled and has undergone normal diagenesis in the burial environment. The bone samples are from either sheep (this research, see Chapter 4) or cow (Nielsen-Marsh and Hedges, 1999; Roberts *et al*, 2002). It can be seen that on the whole increasing heating intensity causes an increase in porosity. Maximum porosity occurs after burning at 700°C for 45 minutes which, as has been discussed above, is within the Decomposition Stage of heat-induced bone degradation (Figure 2.1) and therefore at the stage of peak organic phase loss. In addition continued burning to temperatures of 900°C results in a dramatic decrease in bone porosity, especially bone microporosity (pores smaller than 1 μm). This is likely due to the commencement of the Fusion Stage (Figure 2.1) and therefore the melting and coalescing of the inorganic phase. It should be noted that Bulk Density refers to the density of the bone while Skeletal Density refers to the density of the material itself. Bulk Density can be seen to decrease with increased heating up to 700°C. This is because the bone is becoming more porous and therefore less dense. Interestingly this decrease is reversed after heating to 900°C. Again this is likely to be due to the fusion of the inorganic phase filling the pores left by the evicted organic phase. This is in contrast to Skeletal Density that seems to show no discernible relationship with heating conditions. More evidence for the similarity between heating and diagenesis can be gleaned by comparing the porosity values of Nielsen-Marsh and Hedges' (1999) data and that of Roberts *et al* (2002). The range of pore size resulting from diagenetic change falls within the range resulting from boiling

Study	**Sample Conditions**	**Porosity [in pores <0.1μm]**	**Bulk DeOnsity (±0.1)**	**Skeletal Density (±0.1)**
This Research	Unburned	0.0429 [0.0335]	2.0	2.2
	Burning, 500°C, 15 mins	0.3992 [0.3570]	1.8	3
	Burning, 500°C, 45 mins	0.3673 [0.1660]	1.1	2.4
	Burning, 700°C, 15 mins	0.2213 [0.1841]	1.6	2.1
	Burning, 700°C, 45 mins	0.5468 [0.3000]	1.3	2.9
	Burning, 900°C, 15 mins	0.1643 [0.0013]	2.0	2.4
	Burning, 900°C, 45 mins	0.11 [0.0073]	1.8	2.1
Roberts *et al*, 2002	Boiling, 3 hours	0.1272 [0.0713]	1.8	2.2
	Boiling, 9 hours	0.1303 [0.0582]	1.8	2.1
	Boiling, 27 hours	0.3133 [0.2357]	1.4	2.2
	Boiling, 81 hours	0.3958 [0.3171]	1.3	2.2
Nielsen-Marsh and Hedges, 1999	Diagenesis, burial	0.1773	-	-
	Diagenesis, burial	0.2100	-	-
	Diagenesis, burial	0.3185	-	-

Table 8.5 Comparison of the Porosities of Bone as measured by Mercury-intrusion Porosimetry

for longer than nine hours but less than eighty-one hours and some low intensity burning.

The results of Nielsen-Marsh and Hedges' (1999; 2000a) experiments suggest that porosity changes are related to protein loss, and that this is not at all surprising considering that protein occupies forty percent of total bone volume. This would suggest that peak porosity change would be expected to fall within the Decomposition Stage of heat-induced bone degradation (Figure 2.1). Although considerable change to the bone porosity is observed here (Figures 8.1 to 8.2), the changes are essentially exaggerations of the curves seen in unburned bone (Figure 8.4). That is, there is mainly an increase in the number and a slight enlarging of the existing pores. It is not until the occurrence of burning that corresponds to the Fusion Stage that the curves take on a significantly different shape to that of unburned bone. This is due to the commencement of inorganic recrystallisation.

An increase in macroporosity and a decrease in microporosity are characteristic of normal diagenetic change in bone (Nielsen-Marsh and Hedges, 1999; Nielsen-Marsh and Hedges, 2000b). The results presented here suggest that the same is occurring in burned bone too. In diagenesis in the burial environment macroporosity can be accentuated by the action of micro-organisms (Nielsen-Marsh and Hedges, 2000a). This is not likely in burned bone as the focus of the microbial attack, the organic phase, will probably have been destroyed. In addition diagenetic alteration may be assisted by changes in pore size distributions within the bone (Nielsen-Marsh and Hedges, 1999). Roberts *et al* (2002) argue that boiling disrupts the mineral-organic interface and increases porosity thereby influencing bone survival and condition when discovered by archaeologists, but that this is entirely dependent on boiling duration. The same can therefore be said for burned bone. The disruption of the mineral-organic interface, or the 'loosening' of the bone matrix may facilitate more efficient mineral alteration and microbial attack (Roberts *et al*, 2002).

Figures 8.5 to 8.6 show the results of the X-ray Diffraction analyses of the burned bone samples. Figure 8.6 shows the profiles for the unburned bone samples. The two broad peaks in this profile, at 2.9 nm^{-1} and 3.6 to 3.9 nm^{-1}, correspond to the major peaks for apatite (Holden *et al*, 1995b; Roger and Daniels, 2002; Shipman *et al*, 1985). Low duration burning produced only slight changes in the profiles (Figure 8.5). There is some narrowing in the 3.6 to 3.9 nm^{-1} peak in the 700°C and 900°C samples, otherwise these samples correspond to those for poorly crystalline hydroxyapatite (Rogers and Daniels, 2002). The narrowing and separation of the peaks in the 500°C, 700°C and 900°C samples of Figures 8.5 and 8.6 indicate a move toward a more crystalline hydroxyapatite. No new mineral phases were detected, implying that even after intense burning, hydroxyapatite remains the predominant mineral phase. No tricalcium phosphate is therefore present. This heat-induced trend towards a more perfect crystal structure and lack of other mineral phases supports the previous X-ray diffraction literature (Holden *et al*, 1995b; Rogers and Daniels, 2002; Shipman *et al*, 1984). When compared to the results collected in Table 8.1, a clearer picture of the causes of tricalcium phosphate is still not reached.

Rogers and Daniels (2002) X-ray diffraction study suggests that crystal size may increase threefold as a consequence of burning. The SAXS data presented in Table 8.5 supports this conclusion. However it should be noted that Rogers and Daniels (2002) do not state how much burning is required to cause a threefold increase in crystal size. Would this increase be expected after burning of 500°C, 700°C or 900°C and for 15 or 45 minutes? Table 8.5 shows that an increase in crystal size is recorded after even low intensity burning of 500°C for 15 minutes. This temperature for an increase in crystal size is lower than the 600°C suggested by Holden *et al* (1995a). However it is not until the bone has been burned at 700°C that the threefold increase occurs. This can be seen more clearly in Table 8.5, which shows how much the crystals have increased in size due to burning. It is clear to see that increased burning intensity produces increased inorganic crystal enlargement. Table 8.4 and Figure 8.7 also show that as well as causing increased crystal enlargement, increased burning intensity causes an increase in the range of modified crystal sizes. It is interesting to note that there is no overlap in modified crystal size between samples. It cannot be said whether this is always the case without a substantial increase in sample size.

	Burning for 15 mins	Burning for 45 mins
Burning at 500°C	2.13	2.84
Burning at 700°C	4.78	6.20
Burning at 900°C	7.83	11.31

Table 8.6 Mean proportional increases in crystal size (nm) after 3 hrs exposure, due to burning

The samples burned for 900°C were exposed to a nine hour dose of X-ray radiation as well as the standard three hours. This was because there was some concern that the substantial increase in crystal size (Table 8.5) may have prevented suitable penetration by the X-rays thus not allowing for the generation of a scattering signal. After exposure for nine hours the 900°C samples produced new data indicating that crystal size increase was even greater than previously thought (Table 8.7). The results for the second sample burned at 900°C for 15 minutes is anomalous however as SAXS can only determine crystal thickness up to 50 nanometres (Fratzl *et al*, 1996). This anomalous result has occurred because the increases in crystal size causes the sample material to begin to absorb the X-rays rather than scatter them thus producing weaker and less informative scattering profiles.

Crystal size increases are one of the defining features of the Fusion Stage of heat-induced bone degradation. It can be seen from Tables 8.5 and 8.6 and from Figure 8.7 that these increases are beginning long before the accepted 1000°C start to the Fusion Stage is being reached. In addition, Figure 8.7 and Table 8.5 make it clear that the enlargement of crystal size begins

	Burning for 15 mins	Burning for 45 mins
Burning at 900°C; all data	20.20	12.64
Burning at 900°C; without anomalous data	11.48	12.64

1000°C start to the Fusion Stage is being reached. In addition, Figure 8.7 and Table 8.5 make it clear that the enlargement of crystal size begins

	Burning for 15 mins	Burning for 45 mins
Burning at 900°C; all data	20.20	12.64
Burning at 900°C; without anomalous data	11.48	12.64

Table 8.7 Mean proportional increases in crystal size (nm) after 9 hrs exposure, due to burning

slightly and increases in severity with continued heating. As with the scanning electron micrographs, the SAXS data is suggesting a revision of Figure 2.1.

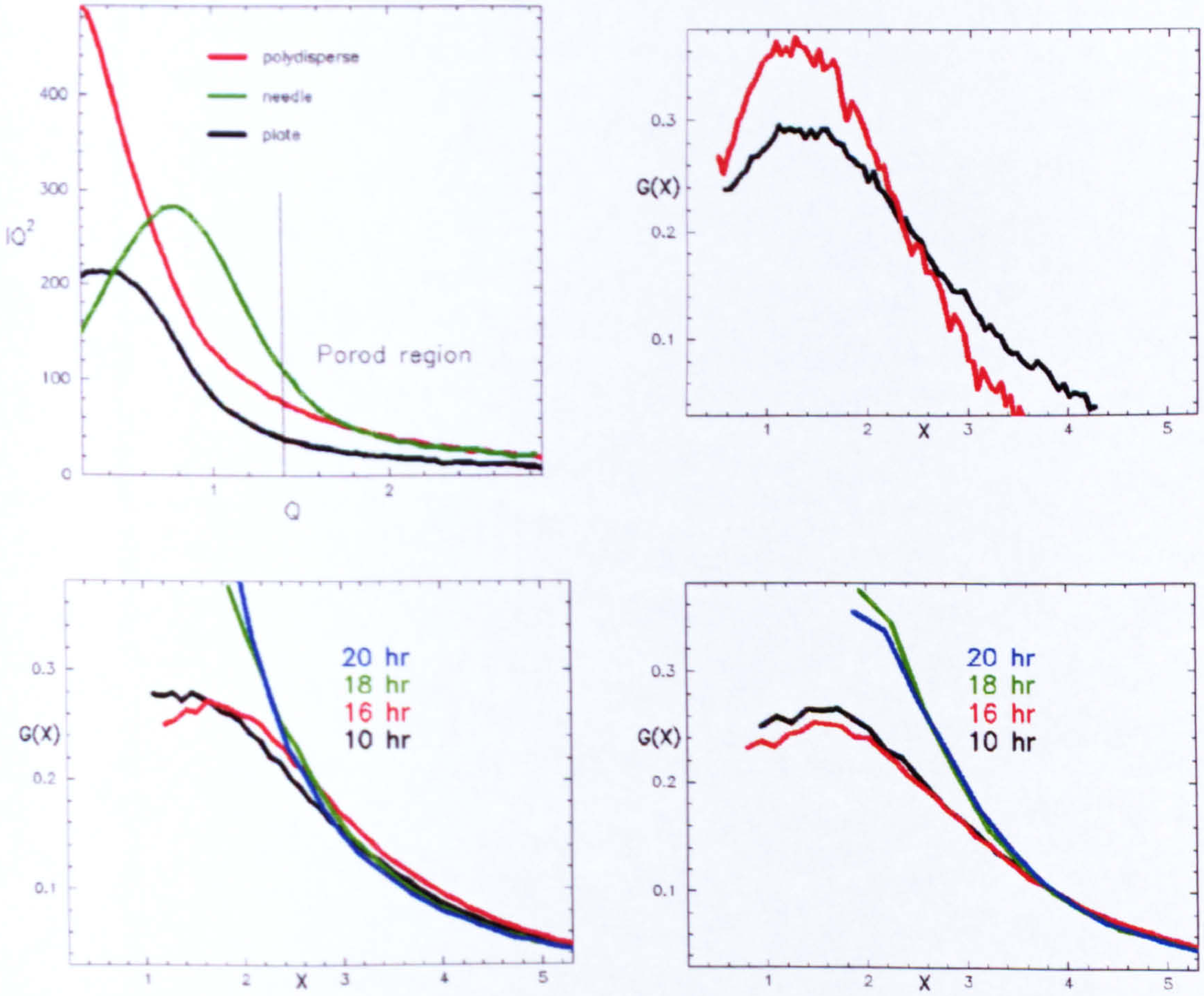

Figure 8.8 An example plot showing the three morphologies of crystallites commonly found in bone (left; after Wess *et al*, 2001) and plots illustrating needlelike morphology in control with form factor plots for pairs of samples heated for 15 mins (left) 45 minutes (right) at 500º C (red and black) or 700º C (blue and green).

Figures 8.9 to the theoretical graph in Figure 8.8 that burning causes the crystals to become more plate-like, rather than needle-like as in the unburned control samples, progressing then towards a polydisperse crystal shape. It is possible that the polydisperse readings are a consequence of the difficulty in calculating crystal shape of large-sized crystals rather than a heat-induced phenomenon.

EightFive Conclusions

The results from the scanning electron microscopy, mercury-intrusion porosimetry and the wide and small angle X-ray scattering techniques all clearly demonstrate that the heating and burning of bone causes significant alterations to occur within the microscopic bony architecture. In addition, these heat-induced changes are occurring on both the bone surface and in the microscopic architecture. The data supports the previously documented arguments for a distinct process of inorganic crystal fusion that occurs after the loss of the water and the organic phase. However it would appear that the previously documented temperature for the commencement of this stage of heat-induced bone degradation has been over-estimated. Experimental evidence collected here suggests that this stage is well underway by 900°C, and has begun by 700°C if not tentatively by 500°C. A complete redesigning of Figure 2.1 is therefore required to take into account this new appreciation of heat-induced change to bone microstructure.

In addition the examination of heat-induced change in microscopic bone architecture has resulted in a clearer understanding of the nature of the secondary-level, macroscopic changes in bone due to heating (such as changes in colour, mechanical strength and dimension). This is discussed further in Chapter 10 after the examination of dimensional change is discussed in Chapter 9.

Nine The Examination of Heat-induced Dimensional Change

NineOne Introduction

The final heat-induced transformation to be examined is the change in hard tissue dimensions. Two types of dimensional change have been recorded, that of shrinkage and warping. The study of dimensional change is extremely important, as any change that occurs in the bone as a result of heating will directly affect the outcome of any anthropological technique applied to that bone. An understanding of these dimensional changes is therefore required so that suitable corrections can be applied to any anthropological techniques used on burned human or faunal material. In this respect, shrinkage is the more dangerous of the two forms of dimensional change as it is the more subtle and difficult to detect. Warping should be obvious by the naked eye to those with an appreciation of the unmodified skeleton.

NineTwoOne The Nature of Heat-induced Dimensional Change in Bone

Arguably the clearest form of dimensional change to be caused by burning is that of warping. Two key and widely accepted statements have been made in the literature regarding this phenomenon. First it has been claimed that heat-induced warping is more apparent in bone that was fleshed at the time of burning (Binford, 1963; Kennedy, 1996), and this necessarily implies that the heat-induced contraction of the muscle fibres pulls and twists the bone away from its natural shape. Second that the heat-induced expansion of the air within the medullary cavity will also cause dimensional change (Spennemann and Colley, 1989). The likely manifestation of this will be an increase in the size of the bony dimensions of the diaphysis and particularly the epiphyses. In areas of dense bone with little cavity heat-induced warping should be very limited. There are however fundamental problems with both statements. The first is that both are speculative and are not substantiated by quantitative data. It is also unlikely that contracting muscles would have the strength to cause the bone itself to bend or reduce in size. In addition the porous nature of bone would make it extremely improbable that air expanded by heating would remain trapped within the medullary cavity under such pressures as to cause warping. This notion of air expansion cannot explain the limited warping noted in space-rich femoral and humeral heads by Wells (1960). Therefore another explanation is required, one that focuses more on the bone itself. It could be that either contraction of the periosteum or anisotropy in the collagen distribution within the bone cortex are responsible. Clearly a less anecdotal approach to the examination of heat-induced warping is required. It should not be forgotten that teeth will also warp when burned. Chandler (1987) noted how teeth curl towards the hotter areas of the furnace when heated. This is a result of the nature of the furnace but the influence of natural tooth curvature cannot be ignored (Chandler, 1987).

Wells (1960), based on his experience of examining archaeological cremations, argues that a sample of a given bone will tend to distort and shrink in a fairly constant manner. He claims that this is to be expected given that the internal structure, disposition of the trabeculae, the relative amounts of compact or spongy bone, the density of the tissues and their relationship with other structures will be fairly constant (Wells, 1960). This can only be true if the burning conditions are similar however. When burning conditions vary, the amount of shrinkage can be expected to vary accordingly. Shipman *et al* (1984) argue that their data shows that the degree of heat-induced shrinkage is directly correlated to the temperature of burning. This statement has subsequently been supported by many other workers (McKinley, 2000), although not necessarily with the same degree of conviction. McKinley (2000) also adds that variability can be expected between different individuals and different skeletal elements.

It has been noted that there seems to be a critical temperature at which the degree of shrinkage caused by burning significantly increases. This temperature has been set at around 800°C (Buikstra and Swegle, 1989;

Eckert *et al*, 1988; Holden *et al*, 1995a; Holland, 1989; Kennedy, 1996; Reinhard and Fink, 1994; Spennemann and Colley, 1989). Dehydration and the removal of the organics from the bone are important but as the cause of much of the heat-induced shrinkage is due to changes in crystal structure (McKinley, 2000), it is likely that much of this difference in degree of shrinkage is also related to changes to the crystal structure. Indeed examination of Figure 2.1 shows that this 800°C dividing point falls near the beginning of the Fusion Stage of Heat-induced bone degradation. It is in this stage that the inorganic phase begins to coalesce and fill the pores left by the evicted water and organic phase resulting in a reduction in bone size. Another potential control on the degree of shrinkage is the proportion of spongy to compact bone relative to the plane of measurement (Gilchrist and Mytum, 1986; Shipman *et al*, 1984). Both Gilchrist and Mytum (1986) and Shipman *et al* (1984) neglect to explain why the differences in bone type are influential. However Gejvall's earlier work (1969) highlights that the design of spongy bone is such that it can withstand pressures from multiple directions and as such may shrink only slightly as a consequence of burning yet retain its original shape. In addition there is some confusion in the literature as to which is the more influential bone type with regard to heat-induced shrinkage. Gejvall (1969) and Gilchrist and Mytum (1986) argue that the compact bone will shrink the most while McKinley (1994) and Van Vark (1970) argue that the spongy bone will shrink the greater amount. It could be however that all workers are correct. It may be that the spongy bone shrinks the greater amount with regard to actual measurement, but it could be that compact bone shrinks the most with regard to its own pre-burning thickness. That is to say relative versus absolute shrinkage. For example, a 5mm reduction in spongy bone size is greater than a 2mm reduction in compact bone thickness, however if the area of compact bone is only 4mm thick while the area of spongy bone is 20mm thick, the compact bone will have shrunk by fifty percent to the spongy bone's twenty-five percent. Another control that has been discussed with regard to the degree of shrinkage is the biological age of the bony tissue, which has been demonstrated as being significant because older bone contains a greater amount of collagen cross-linking which restricts shrinkage (Holden *et al*, 1995a). Regardless of how supportive the collagen cross-linking is, it can only be influential up until the point that the collagen is destroyed by heating. The presence of flesh on the bone before burning was proved to have a negligible influence (Buikstra and Swegle, 1989). It should also be borne in mind that Holland's (1989) experimental work led him to state that the amount of shrinkage produced by low-level burning (under 700°C) will be less than the intra-observer error produced when remeasuring the same bone samples

Shrinkage of dentition has also been discussed in the literature. Shipman *et al* (1984) state that they expect teeth to disintegrate rather than shrink, but this has been disproved by Chandler's (1987) limited experimental work.

NineTwo Methodology

NineTwoOne Experimental Burning

The detailed specifics with regard to the heating regimes used to burn the bone samples have been discussed in Chapter 4 and will not be repeated again here. The raw data collected can be seen in the Appendix.

NineThree Results

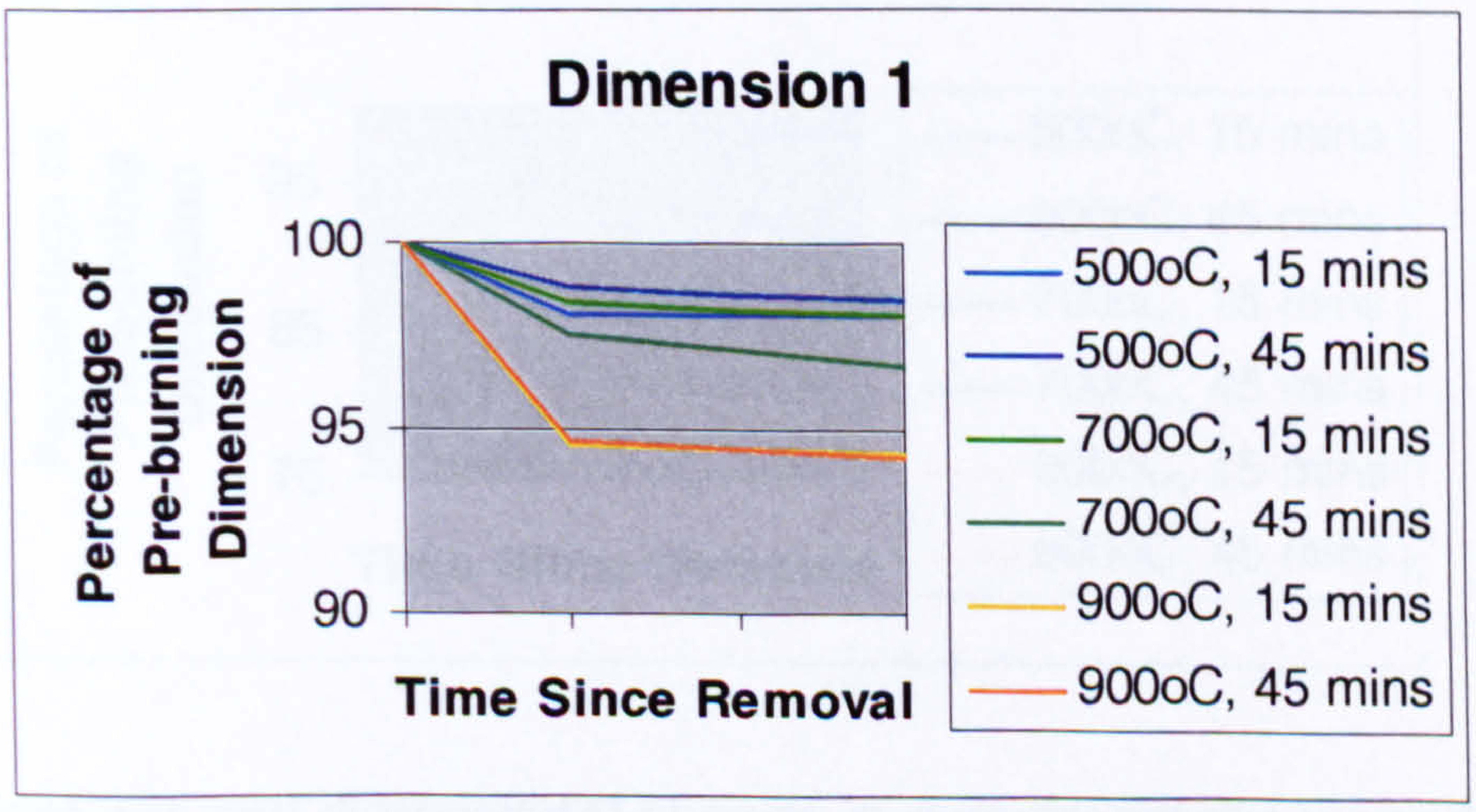

Figure 9.1 Heat-induced dimensional change in experimentally-burned bone

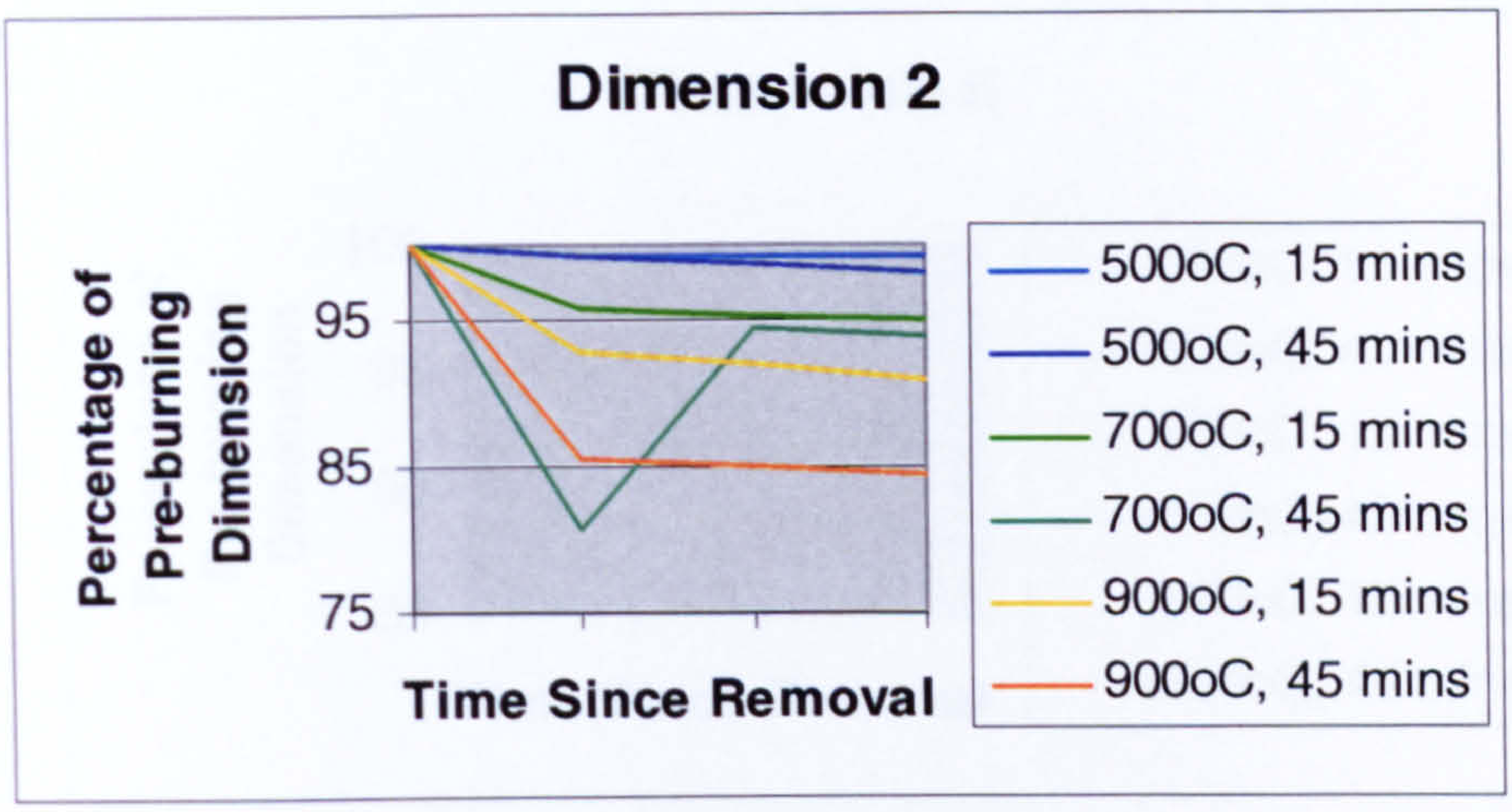

Figure 9.2 Heat-induced dimensional change in experimentally-burned bone

Figure 9.3 Heat-induced dimensional change in experimentally-burned bone

Figure 9.4 Heat-induced dimensional change in experimentally-burned bone

Figure 9.5 Heat-induced dimensional change in experimentally-burned bone

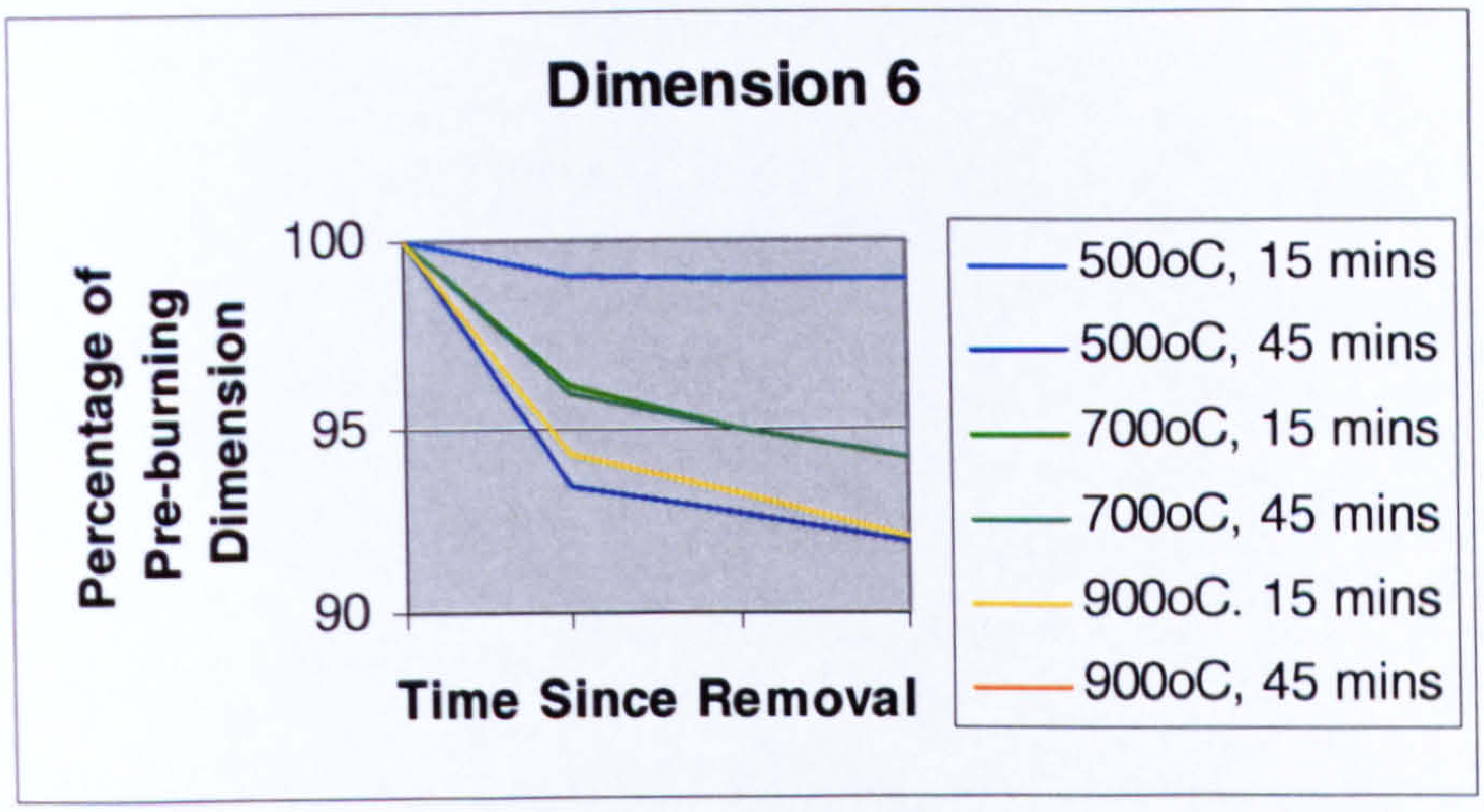

Figure 9.6 Heat-induced dimensional change in experimentally-burned bone

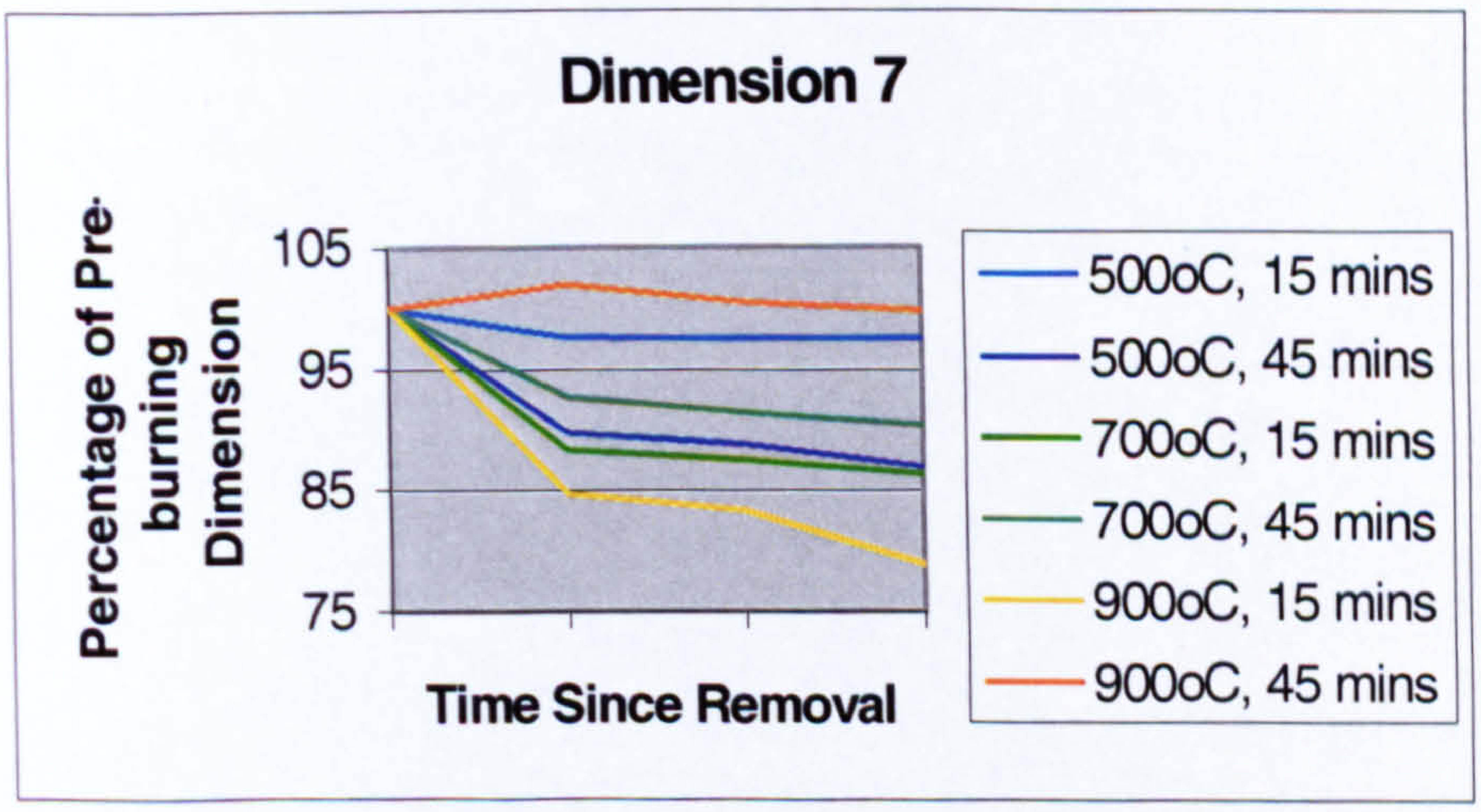

Figure 9.7 Heat-induced dimensional change in experimentally-burned bone

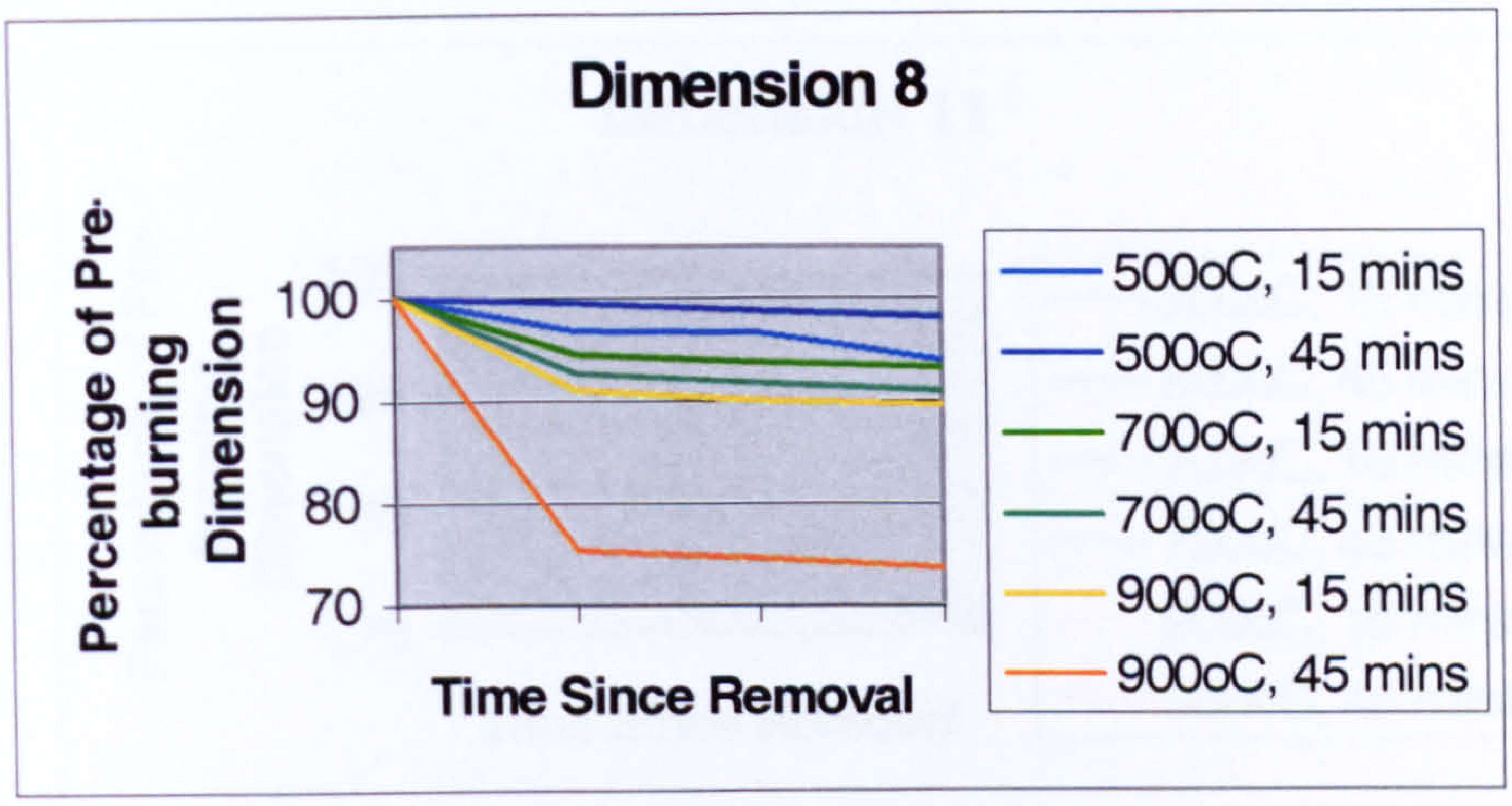

Figure 9.8 Heat-induced dimensional change in experimentally-burned bone

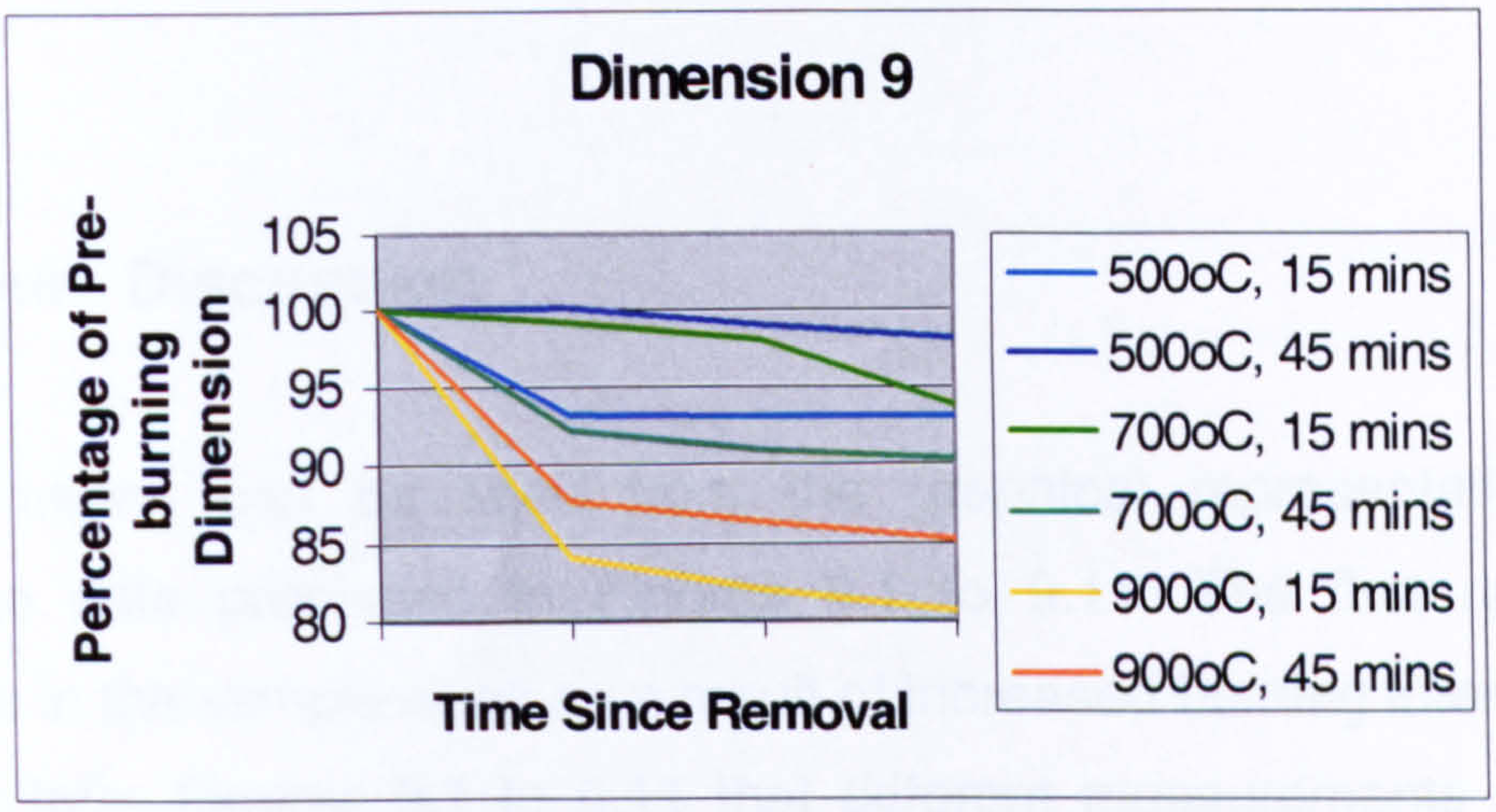

Figure 9.9 Heat-induced dimensional change in experimentally-burned bone

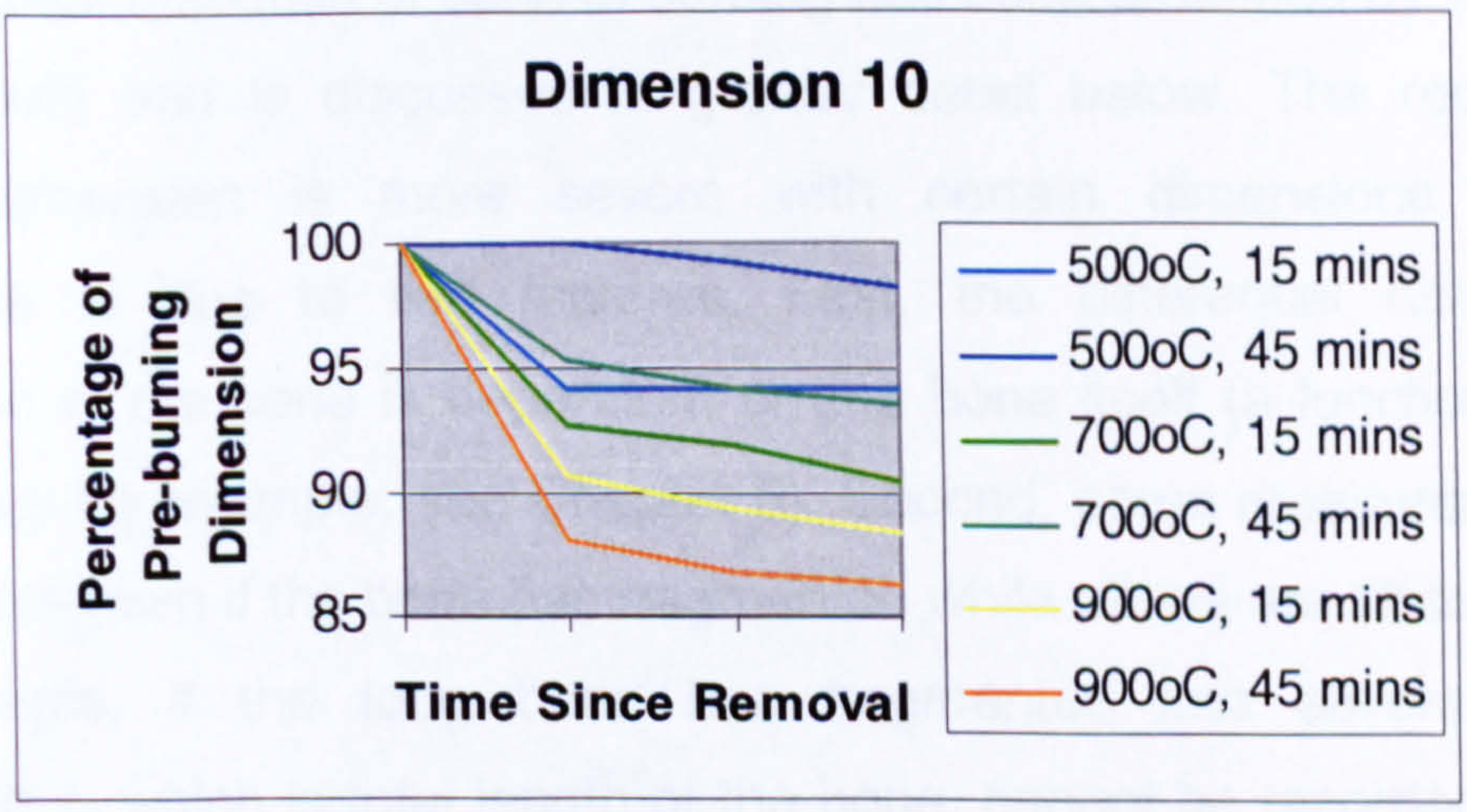

Figure 9.10 Heat-induced dimensional change in experimentally-burned bone

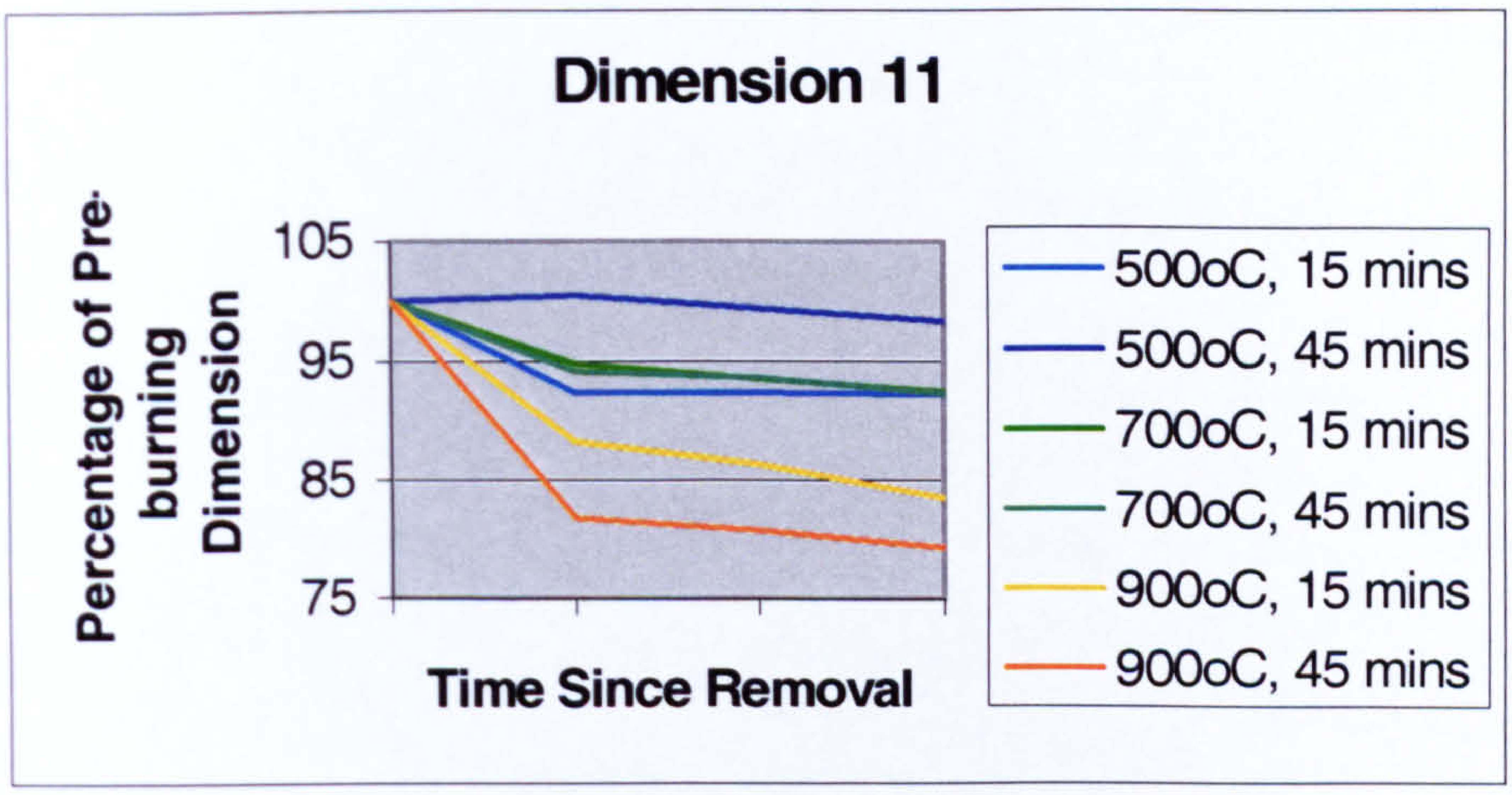

Figure 9.11 Heat-induced dimensional change in experimentally-burned bone

NineFour Discussion

Several trends can be seen from the graphical representation of the shrinkage data presented in Figures 9.1 to 9.11. The first regards the decrease in the sample sizes as a result of increased burning intensity. It can be seen from Figures 9.1 to 9.11 that different measurements respond in different ways to burning. In essence this simply means that different parts of the bone will respond differently to each other when heated. This notion of the differential response of bone to burning has been broached by Thompson (1999; 2002) and is discussed in greater detail below. The reduction in sample dimension is more severe with certain dimensions and this occurrence is due to two features. First, the differential heat-induced destruction of the bone is dependent on the bone itself (a function of bone morphology for example; see Chapter 6). Second, some measurements are still possible even if the bone has fragmented while others are absolutely not. For example, if the long bone has fragmented into several chunks, Dimension 1, which is total length of the bone, cannot be recorded whereas the dimensions across the epiphyses may well be possible. Therefore Dimension 1 would have a smaller sample size than the epiphyseal dimensions (Dimensions 2 to 7).

The second main trend seen in Figures 9.1 to 9.11 concerns the mean measurement values themselves. In most cases with most dimensions the mean measurement value decreases in size from five to fifteen to twenty-five minutes after removal from the furnace. Clearly this temporal influence means that heat-induced shrinkage is more dynamic than has been previously realised. The continued reduction in bone size even after removal from the heating device has clear implications for experimental cremation methodology. Researchers must now be aware of the fact that the length of time after removal from the heating source will influence the amount of heat-induced dimensional change recorded. However on a number of measurements (for example in Figures 9.3, 9.5 and 9.11) the difference between the measurement before burning and that at five minutes after removal from the furnace was not a reduction but an increase. This implies that the bones are increasing in size as a consequence of burning, and are then reducing in size as the material cools. The mean values for the percentage shrinkage of each sample are presented in Figures 9.1 to 9.11. Further reinvisioning and manipulation of Figures 9.1 to 9.11 will aid interpretation.

Table 9.1 summarises the percentage shrinkage values displayed in Figures 9.1 to 9.11. There is a debate in the literature (see Chapter 2 for discussion of this debate) with regard to the expected degree of heat-induced shrinkage that one should expect from burned bones. Table 9.1 highlights the samples that have experienced shrinkage of over ten percent. At times the amount of shrinkage exceeds thirty percent. Table 9.1, in conjunction with the results of Thompson (1999; 2002) can therefore finally lay to rest the argument that heat-induced shrinkage will not be recorded above five percent.

Of note here in Table 9.1 are the samples that have, even after twenty-five minutes of cooling, demonstrated heat-induced expansion. Seventeen cases of overall heat-induced expansion out of a possible 198 does not seem particularly monumental, indeed it is just 8.6 percent. However when one highlights the samples that demonstrated heat-induced expansion in at least

Dimension		500oC 15mins	500oC 45mins	700oC 15mins	700oC 45mins	900oC 15mins	900oC 45mins
D1	5 Minutes	1.94	1.2	1.64	2.44	5.52	5.35
	15 Minutes	1.96	1.39	1.81	2.92	5.56	5.57
	25 Minutes	1.96	1.5	1.95	3.34	5.69	5.76
D2	5 Minutes	0.9	0.88	4.25	19.33	7.29	14.45
	15 Minutes	0.86	1.47	4.86	5.58	8.03	15.16
	25 Minutes	0.87	1.83	5.23	6.24	9.1	15.71
D3	5 Minutes	0.79	-4.53	-1.72	3.07	6.52	36.18
	15 Minutes	10.13	-3.84	-1.1	4.4	7.4	37.06
	25 Minutes	0.84	-3.19	-0.37	5.22	8.73	37.68
D4	5 Minutes	-1.59	1.15	14.09	5.24	19.15	14.62
	15 Minutes	-1.59	1.15	14.6	6.88	20.54	16.2
	25 Minutes	-1.46	2.06	15.68	8.67	21.55	16.47
D5	5 Minutes	2.67	3.04	7.02	6.02	10.62	4.96
	15 Minutes	2.7	3.61	7.57	6.88	11.59	10.39
	25 Minutes	2.73	4.14	8.29	7.26	13.58	10.79
D6	5 Minutes	0.93	6.57	3.88	4.1	5.67	-3.92
	15 Minutes	1.06	7.35	5.1	5.06	6.77	-2.71
	25 Minutes	1.06	8.04	5.82	5.85	7.94	-1.93
D7	5 Minutes	2.34	10.15	11.64	7.32	15.26	-2.04
	15 Minutes	2.4	11.16	12.45	8.53	16.64	-0.6
	25 Minutes	2.4	13.04	13.59	9.57	21.12	0.15
D8	5 Minutes	3.28	0.47	5.51	7.42	9	24.57
	15 Minutes	3.35	1.28	6.25	8.32	10.04	25.4
	25 Minutes	6.13	1.82	6.77	9.1	10.43	26.23
D9	5 Minutes	6.83	-0.12	0.85	7.81	15.86	12.32
	15 Minutes	6.94	0.98	1.97	9.12	17.99	13.66
	25 Minutes	6.97	1.86	6.24	9.66	19.35	14.8
D10	5 Minutes	5.79	-0.07	7.27	4.62	9.43	11.98
	15 Minutes	5.84	0.83	8.02	5.74	10.63	13.17
	25 Minutes	5.77	1.72	9.52	6.47	11.66	13.76
D11	5 Minutes	7.65	-0.45	5.24	5.92	11.81	18.18
	15 Minutes	7.65	0.64	6.5	6.38	13.68	19.17
	25 Minutes	7.75	1.68	7.61	7.7	16.5	20.66

Table 9.1 Percentage shrinkage due to heating [Note: samples experiencing high degrees of shrinkage (blocked in grey), heat-induced expansion (overall expansion and some expansion) and location of bone measurement (shades of grey) are highlighted]

one of their ten bone specimens (Table 9.1) it can be seen that heat-induced expansion is an extremely common phenomenon. The high presence of heat-induced expansion suggests that this is not all attributable to heat-induced warping. Rather this is the never-before recorded presence of heat-induced expansion of a non-warping origin. Thompson (1999; 2002) in his preliminary experiments on the influence of burning on the assessment of sex of the pelvis noted the presence of expansion or negative shrinkage on a number of his dimension measurements. This was attributed to the warping of the bone. However, in retrospect some of this dimensional change may now be attributable to heat-induced expansion. Another factor suggesting the preference of heat-induced expansion over expansion due to heat-induced warping is the reduction of expected warping due to the careful placement and removal of the bone material from the furnace. Table 9.1 also shows that heat-induced expansion is predominantly a low intensity burning phenomenon. This is likely due to the more influential heat-induced shrinkage over-riding the expansion at higher burning intensities. This also suggests that without the occurrence of heat-induced expansion, the degree of heat-induced shrinkage would be more substantial.

There is a further pattern in the heat-induced expansion and shrinkage data that requires explanation. Table 9.1 divides the eleven measurements into regions of bone. As detailed in Chapter 4, Dimension 1 is the total length of the bone, Dimensions 2 to 7 are measurements across the bone epiphyses and Dimensions 8 to 11 are measurements across the bone diaphysis. It can be seen that the greatest occurrence of heat-induced expansion across the bone as a whole occurs in the epiphyses. In addition the severest degree of heat-induced shrinkage is also witnessed in the epiphyses. Both of these features are due to the nature of the bone in the epiphyses compared to the diaphysis. At first glance it would appear that spongy bone is the more flexible of the two forms of bone. It is however, designed to be rigid and to absorb forces from multiple directions and sources. It may be then that spongy bone has more random collagen orientation than compact bone and hence is offered less structural support. This would only be true until the collagen was destroyed by heating, although the random orientation of the remaining spaces may be structurally weaker than the collagen free compact bone.

This conclusion tends to support McKinley (1994) and Van Vark (1970) who argue that spongy bone is more influential on post-burning dimensional size than compact bone rather than Gejvall (1969) and Gilchrist and Mytum (1986) who concluded the reverse. The notion that trabecular bone is less subject to distortion than compact bone is important with regard to our understanding of not only the nature of bony material but also the nature of the processes of distortion. None of these authors suggest why this is so however.

Table 9.2 displays the statistical significance using t-tests of the percentage dimensional changes displayed in Tables 9.1 to 9.11. Within Table 9.2 very strong ($p \leq 0.01$), strong ($p \leq 0.05$) and moderate ($p \leq 0.1$) statistical significance are highlighted to ease tabular interpretation. It can be seen that the majority of statistical significance occurs due to heat-induced dimensional change at medium to high burning intensities. This should be no surprise as it is not until these situations that the Fusion stage can begin. As described in Chapter 2, the Fusion stage of degradation is the period when significant heat-induced shrinkage will occur. What is also clear is that the very strong statistical significance is focussed on the column representing burning at 700°C for fifteen minutes. Burning beyond this temperature seems to produce weaker statistical significance in contrary to what is expected. This can be explained by the fact that as the bones burn, they progress through the Decomposition stage and the Inversion Stage to the Fusion Stage of heat-induced degradation. It is suggested that as the bones travel through the Decomposition stage they experience peak fragility (Chapter 7) and begin to fragment in the furnace thus reducing sample size. The weaker statistical significance at higher burning intensities can be attributed to this reduction in sample size. Table 9.2 also confirms the preliminary statements made by Thompson (1999; 2002) who claimed that heat-induced shrinkage could indeed be statistically significant.

Dimension		500oC 15mins	500oC 45mins	700oC 15mins	700oC 45mins	900oC 15mins	900oC 45mins
D1	Pre - Post 5mins	0.074	0.11	0.012	0.028	0.18	0.043
	Pre - Post 15mins	0.074	0.066	0.012	0.043	~	0.043
	Pre - Post 25mins	0.074	0.038	0.012	0.109	~	0.043
D2	Pre - Post 5mins	0.161	0.332	0.005	0.028	0.028	0.018
	Pre - Post 15mins	0.16	0.185	0.005	0.027	0.028	0.018
	Pre - Post 25mins	0.161	0.137	0.005	0.028	0.043	0.018
D3	Pre - Post 5mins	0.415	0.61	0.475	0.043	0.075	0.043
	Pre - Post 15mins	0.083	0.309	0.61	0.043	0.075	0.043
	Pre - Post 25mins	0.415	0.185	0.878	0.043	0.08	0.043
D4	Pre - Post 5mins	0.838	0.475	0.05	0.091	0.068	0.042
	Pre - Post 15mins	0.838	0.475	0.05	0.091	0.068	0.043
	Pre - Post 25mins	0.838	0.333	0.05	0.041	0.068	0.042
D5	Pre - Post 5mins	0.169	0.038	0.005	0.018	0.012	0.16
	Pre - Post 15mins	0.169	0.02	0.005	0.018	0.012	0.012
	Pre - Post 25mins	0.153	0.011	0.005	0.018	0.028	0.012
D6	Pre - Post 5mins	0.221	0.138	0.012	0.018	0.017	0.54
	Pre - Post 15mins	0.221	0.059	0.005	0.018	0.017	0.444
	Pre - Post 25mins	0.221	0.066	0.005	0.018	0.028	0.444
D7	Pre - Post 5mins	0.507	0.066	0.005	0.058	0.012	0.953
	Pre - Post 15mins	0.475	0.028	0.005	0.036	0.012	1
	Pre - Post 25mins	0.475	0.014	0.005	0.028	0.027	0.906
D8	Pre - Post 5mins	0.185	0.477	0.051	0.068	0.068	0.18
	Pre - Post 15mins	0.139	0.362	0.025	0.068	0.068	0.18
	Pre - Post 25mins	0.093	0.214	0.011	0.068	0.068	0.18
D9	Pre - Post 5mins	0.007	0.726	0.721	0.109	0.066	0.109
	Pre - Post 15mins	0.007	0.477	0.26	0.109	0.066	0.109

	Pre - Post 25mins	0.007	0.26	0.047	0.109	0.068	0.109
D10	Pre - Post 5mins	0.007	0.838	0.011	0.109	0.028	0.043
	Pre - Post 15mins	0.008	0.541	0.012	0.068	0.018	0.043
	Pre - Post 25mins	0.008	0.313	0.008	0.068	0.043	0.043
D11	Pre - Post 5mins	0.005	0.553	0.373	0.109	0.027	0.043
	Pre - Post 15mins	0.005	0.573	0.373	0.109	0.027	0.043
	Pre - Post 25mins	0.005	0.086	0.373	0.109	0.027	0.042

Table 9.2 Summary of the statistical significance (2-tailed) of the heat-induced percentage dimension changes [Note: very strong ($p \leq 0.01$), strong ($p \leq 0.05$) and moderate ($p \leq 0.1$) significance highlighted]

It is important to compare the dimensional change values recorded by this research with those of previous studies to determine whether these results have experimental comparability and validity. Heat-induced shrinkage from a number of studies have been compared in Figure 6.1 of Thompson, 1999. It can been concluded from this comparison that the range of shrinkage values noted here are similar to those found by the faunal studies of Gilchrist and Mytum (1986) and Shipman *et al* (1984). Both of these works noted large ranges in the amount of shrinkage recorded beginning at under five percent and reaching as much as forty-five percent. This data compares less favourably with the work of Buikstra and Swegle (1989), Holland (1989) and Spennemann and Colley (1989) who found heat-induced shrinkage was never greater than three percent. These differences are likely due to differences in experimental protocol. Figure 6.1 (Thompson, 1999) shows that this study, as with Thompson's previous work (1999; 2002), has clear comparability with other published data. The values recorded in this research should not therefore be treated as erroneous.

NineFive Conclusions

Discussion of heat-induced dimensional change can no longer just focus on the extent of heat-induced shrinkage. Figures 9.1 to 9.11 and Tables 9.1 and 9.2 clearly demonstrate that shrinkage due to burning can statistically reduce the size of a bone. However, these same Tables also show that both temperature and duration of burning are highly influential on the extent of this shrinkage that is recorded, as are the location of the plane of measurement and the period of time since removal from the heating source. Heat-induced shrinkage is a much more multi-faceted feature than has been fully acknowledged previously. In addition the clear presence of heat-induced expansion adds a further complication. So much so that the phrase 'heat-induced shrinkage' is no longer appropriate and should instead be replaced by 'heat-induced dimensional change'. As with heat-induced shrinkage, heat-induced expansion is influenced by burning temperature, duration, plane of measurement and time since removal from the heating source.

Within the greater discussion of Chapter 10, an attempt is made to state how the greater awareness and understanding of dimensional change achieved due to this research will affect the practice of biological anthropology on burned remains.

Ten Implications for the Examination and Analysis of Burned Human Skeletal Remains

TenOne Introduction

The aim of this chapter is to collate the results and discussions from the previous chapters and to examine them in relation to the wider context of our understanding of the influence of burning on both the human body and on the practice of biological anthropology in the forensic and archaeological arenas. This is done by discussing how this research has modified our understanding of heat-induced change and determined the influence of these heat-induced changes on anthropological techniques.

TenTwo Our Changing Understanding of Heat-induced Osteological Transformations

The benefit of adopting a holistic approach to experimental work is that it is possible to achieve a fuller appreciation of the problem being investigated. With respect to this research it was not enough merely to attempt to grapple with the causes and influences of heat-induced changes in human hard tissues by simply examining one of the macroscopic changes themselves. Previous studies have focussed on heat-induced colour change or the heat-induced propagation of fracture patterns but in doing so not only neglect to establish the interconnectivity of these heat-induced phenomena but also overlook the underlying causes of these features. This is seen as a fundamental flaw of many of the previous studies and has thus been strenuously avoided here. As such a large body of data has been collected on all macroscopic secondary-level and selected microscopic primary-level heat-induced changes. Effective discussion is now possible on the principal changes in bone as a consequence of heating as well as their more commonly recognised physical manifestations.

It is difficult to link together the secondary-level heat-induced changes in bone. There are no real cause and effect relationships. This is especially true of the changes in tissue colour. These changes are not related to the propagation of fracture patterns or the alteration in mechanical strength. Such associations can be made between these last two features however. The increase in number and severity of fracture lines is clearly going to result in a detrimental effect on mechanical strength. Examination of these three features cannot aid in determining the causes of the change in colour, the instigator of the fracture patterns or the reported increase in mechanical strength. Other more significant heat-induced changes in hard tissue must be at the heart of the secondary-level changes, as they themselves do not explain their origins.

It would appear from the results, discussions and conclusions presented in the previous five chapters that heating will affect bone in a fairly specific way, although a gradient of severity does exist. There are two fundamental changes that occur in bone when it is heated that will be the most significant with regard to the secondary-level features seen in burned bone. The first is the eviction of the aqueous and organic component of the bone. The second is the recrystallisation of the inorganic component. These two processes can be used to explain the presence of all other heat-induced features. Table 10.1 summarises this notion and brings together the conclusions of Chapters 5, 6, 7, 8 and 9. It is clear from Table 10.1 that those workers that ignore the microscopic heat-induced events by virtue ignore a whole other level of understanding.

The relationships between all of the heat-induced transformations in bone hinted at in Table 10.1 are shown in Figure 10.1. Again it can be seen that the two most significant heat-induced features are the loss of the organic

Heat-induced Feature	Cause		Evidence	Thesis Chapter
Colour Change	Removal of Organic Phase	- Specifically the removal of carbon	Colour change [Munsell colour chart]	5
Occurance of Fracture Patterns	Removal of Organic Phase	- Results in dehydration and increased bone weakness	Fracture patterns [visual, X-ray and SEM]	6
Reduction in Mechanical Strength	Removal of Organic Phase	- Results in dehydration and increased bone weakness	Weaker bone [weight loss]	7
Increase in Mechanical Strength	Recrystallisation of Inorganic Phase	- Melting crystals fill empty pore spaces and closer packing in crystal atomic structure increases strength	Stronger bone	7
Reduction in Dimensions	Recrystallisation of Inorganic Phase	- Melting crystals fill empty pore spaces and closer packing in crystal atomic structure reduces bone size	Smaller bone [measurements]	9
Increase in Dimensions	Application of Heat	- Excited particles occupy more structural (solids) or microscopic void (gases) space	Larger bone [measurements]	9
Changes in Porosity	Removal of Organic Phase and Recrystallisation of Inorganic Phase	- Removal of organics increases porosity while melting inorganics reduces porosity	Hg-IP	8
Increase in Crystal Size	Recrystallisation of Inorganic Phase	- Melting crystals allow larger crystals to grow at expense of smaller ones	XRD and SAXS	8

Table 10.1 The Causes of Heat-induced Changes in Bone

component (represented by the loss of weight) and the recrystallisation of the inorganic component. Again the benefits of a holistic approach to experimental cremation studies can be seen as without this approach these relationships could not have been recorded. It may then be possible to use Figure 10.1 to make basic statements regarding what should be expected in a bone if another heat-induced feature has been seen. For example, if a burned bone has experienced some colour change it will be possible to relationships in Figure 10.1 and say that some weight loss would be expected as well.

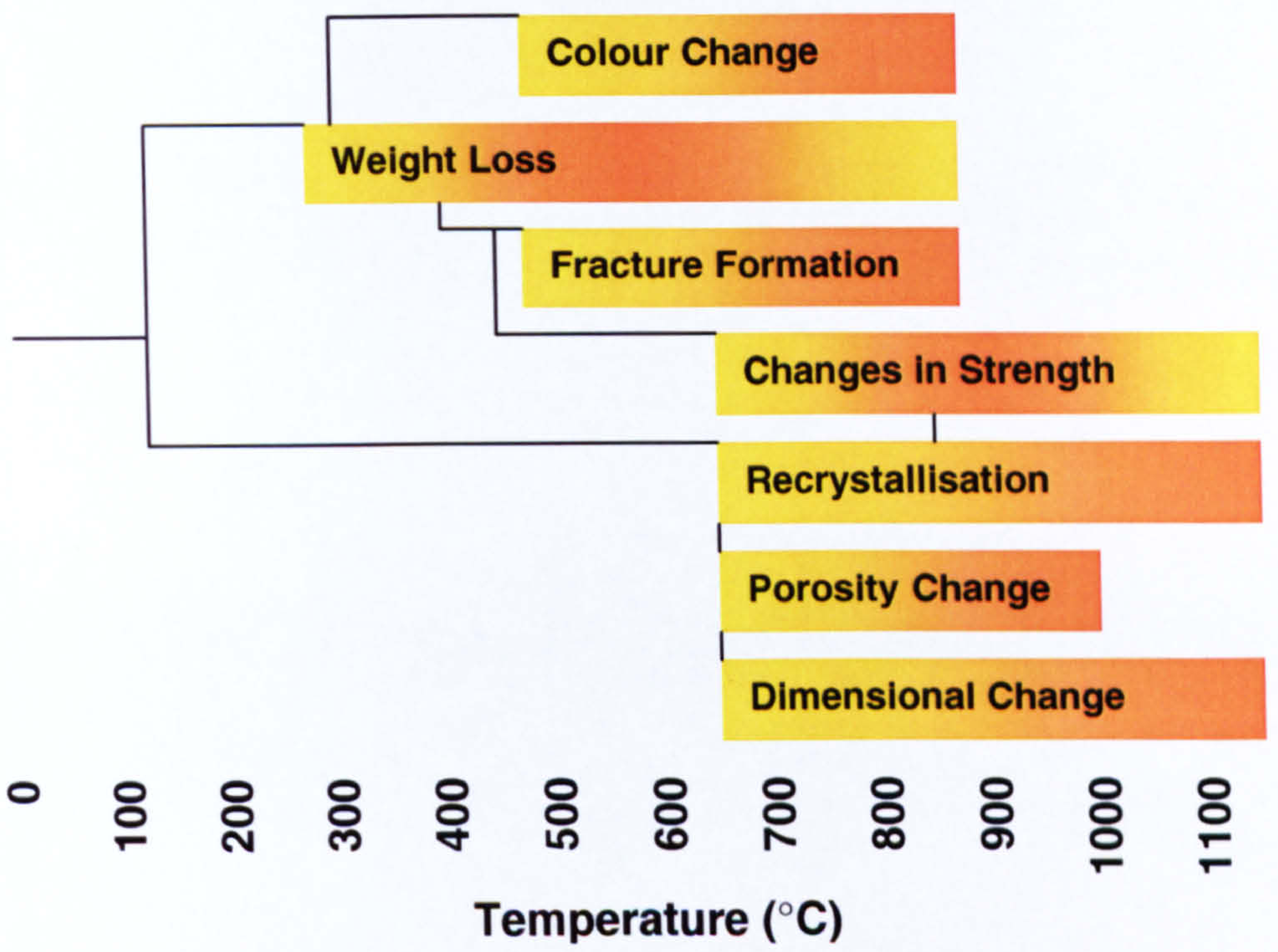

Figure 10.1 The Relationships Between the Heat-induced Changes in Bone. [Note: darker shading indicates more intense activity]

The results and conclusions delivered in Chapters 5 to 9 support Table 2.1. All four stages of heat-induced degradation suggested and put forth by Mayne Correia (1997) and revised by Thompson (1999) can be interpreted from the data collected here. This is the first time that an attempt has been made to support the existence of these generally accepted, yet essentially theoretical, Stages of heat-induced transformation. Table 10.2 demonstrates the support this research provides Figure 2.1. However two revisions of the Table are necessary before it can be fully accepted once more. First the phrase 'Stages of heat-induced degradation' should be replaced with 'Stages of heat-induced transformation'. This is because the term 'degradation' is value-laden and implies a progression to a simpler state. This is not true with burned hard tissue as the final state of bone after burning is simply different from its original state and in no way less useful, informative, or revealing. The second revision concerns the temperatures at which each stage placed at lower temperatures. Table 10.3 details how the data collected in this research suggests this particular revision.

Stage of Transformation	Evidence
Dehydration	Fracture patterns; Weight loss
Decomposition	Colour change; Weight loss; Reduction in Mechanical Strength; Changes in Porosity
Inversion	Increase in Crystal Size
Fusion	Increase in Mechanical Strength; Reduction in Dimensions; Increase in Crystal Size; Changes in Porosity

Table 10.2 Support for the Four Stages of Heat-induced Transformation in Bone

Stage of Transformation	Commencement	Revised Commencement	Evidence for Revision
Dehydration	100°C	100°C	-
Decomposition	500°C	<500°C	Weight loss by 500°C
Inversion	700°C	500°C	Recrystallisation at 500°C
Fusion	1000°C	700°C	Significant shrinkage from 700°C; crystal size increase at 700°C

Table 10.3 Evidence for a Reduction in the Commencement Temperatures of the Four Stages of Heat-induced Transformation of Bone

The revisions suggested in Table 10.3 result from the research conducted here. As such, it is not possible to fully revise the commencing temperatures for the Dehydration and Decomposition Stages since the temperatures investigated here do not descend as low as the beginnings of these Stages. Comment cannot be made regarding a new commencing temperature for the Dehydration Stage, however the fact that evidence for the Decomposition Stage is seen by 500°C strongly indicates that the commencement of that Stage is earlier than the 500°C suggested previously (Table 10.3). Here a commencing temperature as low as 300°C may seem reasonable. Figure 10.2 shows that modified version of Figure 2.1 clearly still has a place within the cremation literature, therefore Figure 2.1 has been reproduced, revised and presented in Figure 10.2. Perhaps one of the most significant impacts of these revisions concerns the use of anthropological techniques. As has been discussed previously (Chapter 9) these techniques are going to be severely commences. these revisions concerns the use of anthropological techniques. As has been discussed previously (Chapter 9) these techniques are going to be severely affected by any heat-induced dimensional change that results from the occurance of the Fusion Stage of transformation. Previously the beginning of this Stage was thought to be high enough not to be experienced in most house fires and other forensic situations. Now that this commencement temperature has been lowered, it is clear that one should expect to see anthropological technique-influencing heat-induced dimensional change at temperatures consistent with house fires, mass disaster incidents and in archaeological funerary pyres. All cremated and burned human hard tissue from every context must now be treated with analytical caution.

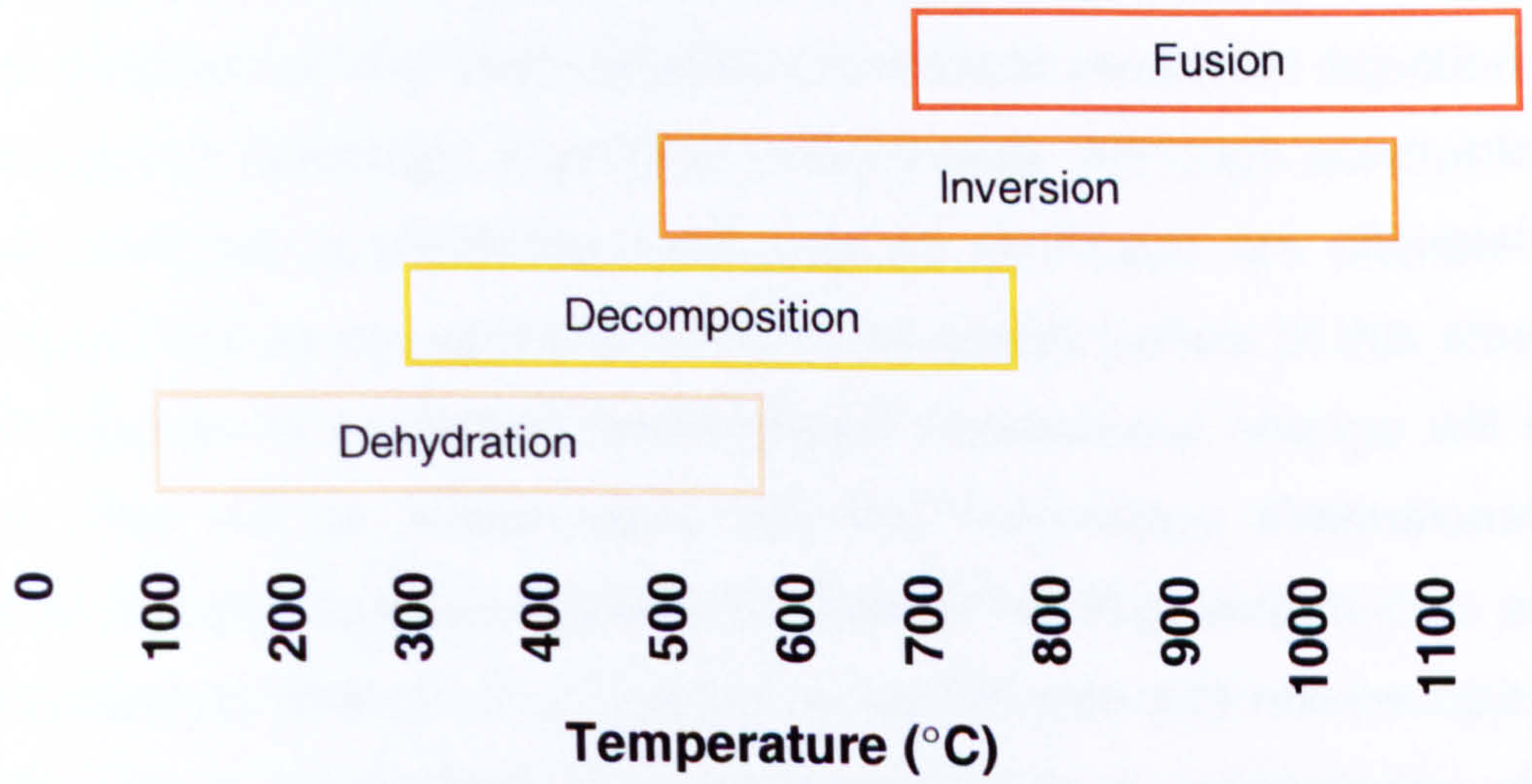

Figure 10.2 Revised Stages of Heat-induced Bone Transformation

In discussions regarding our changing understanding of the effects of heating on bone, it should not be forgotten that similar revisions of our understanding of the effects of heating on teeth will also occur. Chapters 5 and 6 in particular show how the changes experienced by bone are also experienced by teeth. Colour changes and fracture patterns are recorded but unfortunately microstructural analyses were not conducted on the teeth samples. Although teeth are structurally different from bone, there is no reason to doubt that they experience the same four stages of heat-induced transformation and associated heat-induced features. There is however likely

TenThree Predicting Heat-induced Dimensional Change

The analysis of samples is very interesting and extremely useful in attempting to understand the processes of heat-induced change. However the purpose of this has to be to make comments on all burned and cremated bones, that is on the entire population of burned bones. To date only two attempts have been made to extrapolate from experimental samples to the wider population. This is in keeping with the generally poor use of statistics in studies of burned bone (Thompson, 1999) and to an extent throughout much of the early forensic anthropology research (Giles and Klepinger, 1988). Thompson (1999; 2002) extended his experimentally-gained percentage shrinkage values to incorporate the burned pelves not included in his study while Shipman *et al* (1984) created a non-linear prediction equation, also for heat-induced shrinkage, from their primary data. Although admirable, both of these attempts at predicting heat-induced shrinkage are ultimately flawed because they do not appreciate the multivariable nature of this shrinkage. A fresh attempt at predicting heat-induced dimensional change will be made here. This will be based upon, not just percentage dimensional change values and temperature, but also duration of heating, weight loss, alterations in mechanical strength and changes in crystal size and microscopic porosity. Before this is undertaken, it is important to gain an appreciation of which of these variable are related to each other. Principal component analysis will be used for this assessment, and the results are presented in Table 10.4.

It can be seen from Table 10.4 that five principal components exist in the data derived from this investigation into heat-induced transformations in bone. These five components, each of which has an initial eigenvalue of greater than one, explain one hundred percent of the sample variance. The underlying causes of these five associations are difficult to explain. The first

	Principal Component				
	1	**2**	**3**	**4**	**5**
Temperature	0.392	0.565	**0.669**	0.233	0.161
Duration	-0.506	0.332	-0.099	-0.196	**0.765**
% Weight loss	**-0.832**	0.190	0.438	0.280	0.033

Number of Measurements	-0.138	**-0.890**	-0.209	-0.357	-0.132
Crystal Size	0.257	0.517	0.533	0.210	**0.582**
Skeletal Density	0.020	0.091	**-0.940**	0.300	-0.133
Bulk Density	**0.676**	-0.071	0.371	**0.642**	-0.158
Microporosity	0.103	-0.223	**-0.921**	-0.269	-0.136
Mesoporosity	0.096	**0.934**	-0.145	0.240	0.202
Macroporosity	**-0.952**	-0.116	-0.104	-0.241	-0.105
D1 % Change	-0.321	**0.686**	0.178	0.018	**0.628**
D2 % Change	0.448	0.342	**0.689**	-0.015	0.455
D3 % Change	**0.766**	0.182	0.248	0.153	0.544
D4 % Change	**0.985**	0.094	0.123	0.068	-0.032
D5 % Change	-0.304	**0.849**	0.346	-0.259	0.023
D6 % Change	**-.0941**	-0.113	0.173	-0.193	0.188
D7 % Change	**-0.876**	0.297	-0.132	-0.356	0.036
D8 % Change	0.148	0.091	0.355	0.194	**0.898**
D9 % Change	0.351	0.075	0.199	**0.911**	0.034
D10 % Change	**0.680**	-0.230	0.381	-0.427	0.397
D11 % Change	0.025	0.376	-0.267	**0.865**	0.196

Table 10.4 Rotated Component Matrix Resulting from Principal Component Analysis of the Influences on Heat-induced Transformation in Bone. [Note: Major associations (>0.550, <-0.550) are highlighted]

component, as it associates weight loss, bulk density and macroporosity must be the loss of the organic phase. This must also be true of the second component since it concerns the number of measurements and mesoporosity. These five variables are all influenced greatest by the removal of the organic phase from the bone and seem to explain the heat-induced changes in of Dimensions 1, 3, 4, 5, 6, 7, and 10. This concerns all bar one of the epiphyseal dimensions yet only one of the four diaphyseal dimensions. The strong association between temperature, skeletal density and microporosity implies the involvement of the recrystallisation of the inorganic phase. These first three principal components explain 83.77 percent of the variation in the sample, and the fact that they are attributable to the removal of the organic phase and the recrystallisation of the inorganic phase adds considerable weight to the fundamental importance of these two singular features as discussed in Section 10.2. The fourth component associates bulk density with a degree of dimensional change thereby implying the influence of the changing microscopic porosity of the bone. The final component associates duration of heating with crystal size and two dimensions witnessing heat-induced change. It is unclear what the underlying force of this association is, but the alteration of crystal size would be consistent with the data. Of interest is the fact that changes in crystal size are only moderately associated with one variable. This statement negates the fact however that changes in crystal size has a moderate association with the second, third and fifth principal components. Since crystal size can only alter during recrystallisation of the inorganic phase, and not during the removal of the organic phase, this suggests that the underlying associations of components 2 and 5 may not be entirely that of the loss of the organic phase.

The simplest method of predicting heat-induced changes in bone using sample data is through the creation of linear regression equations. Table 10.5 displays the results of equations generated using the experimental burnings of this research. It should be noted that the method of linear regression creation used here is termed 'Stepwise'. During this process an equation is generated by layering independent variables upon each other until the optimum equation has been formed. This is in contrast to the standard method of linear regression creation, which simply uses all of the independent variables of interest. This therefore allows for efficient equations to be created which only use the most relevant variables instead of using all of them unnecessarily.

To some extent the notion of creating prediction equations for heat-induced change is nonsensical. There are simply too many variables and currently too little knowledge regarding them to create reliable formulae. However a distinct benefit of the 'Stepwise' method of linear regression creation is that it allows one to determine the most influential variables, which in turn provides valuable information regarding the process of heat-induced change in bone.

Dependent Variable	**Equation (using most appropriate variables)**	**R^2 Value**
D1 % Change	-	
D2 % Change	-15.564 + 1.5 (Crystal Size)	0.848
D3 % Change	25.726 - 468.258 (Macroporosity)	0.757
D4 % Change	25.208 – 311.342 (Macroporosity)	0.950
D5 % Change	-	

D6 % Change	-1.750 + 242.815 (Macroporosity)	0.842
D7 % Change	6.948 + 184.843 (Macroporosity)	0.751
D8 % Change	-10.615 + 1.426 (Crystal Size)	0.837
D9 % Change	-34.544 + 27.957 (Bulk Density)	0.737
D10 % Change	-	
D11 % Change	-	
Temperature	207.015 + 31.850 (Crystal Size)	0.704
Duration	-	
D1 % Change	-1.023 + 0.131 (Duration)	0.789
D1 % Change	-6.273 + 0.131 (Duration) + 0.0075 (Temperature)	0.928
D1 % Change	5.606 + 0.138 (Duration) – 0.0607 (Number of Measurements) – 1.092 (Skeletal Density) + 0.01354 (% Weight Loss)	1.000

Table 10.5 Linear Regression Equations Used to Predict the Influence of Heating on Certain Variables. [Note: dash indicates an equation could not be created]

Perhaps then, the most important point to make regarding the linear regression equations in Table 10.5 is the fact that the most useful independent variables to use as predictors of dimensional change involve those connected with the heat-induced changes in microstructure. This is important for two reasons. First it again highlights the importance of the recrystallisation of the inorganic phase in changing the dimensional properties of bone. Second it highlights the fact that the use of temperature as a predictor is inaccurate, and that the equations of Shipman *et al* (1984) and the like should be treated with much caution. Comparison of the equation published by Shipman *et al* (1984) and those created here (Table 10.5) clearly demonstrates the increased imprecision of simply attempting prediction using just a single independent variable. In addition it should also be noted that using this research it was not possible to create an equation using just temperature data as Shipman *et al* (1984) did.

Dependent Variable	Prediction Equation	R^2 Value
D1 % Change	Shipman *et al* (1984) $0.302X^3 + 0.0000826x^2 + 0.0000000704x – 0.688$	0.775
D1 % Change	This Research -1.023 + 0.131 (Duration)	0.789
D1 % Change	This Research -6.273 + 0.131 (Duration) + 0.0075 (Temperature)	0.928

Table 10.6 Comparison of Published Heat-induced Shrinkage Linear Regression Equations

One of the aims of this research was to indicate the multivariable nature of the causes of heat-induced change. Table 10.6 clearly shows how the addition of extra variables to a linear regression attempting to predict dimensional change will increase the appropriateness of that equation. The R^2 value (which is a description of how well the regression line fits the data) of the linear regression equations created to describe dimensional change increases from 0.789 to 0.928 and then to 1 with the addition of extra variables. Further research into the heat-induced transformation of bone is required before more appropriate prediction equations can be created, tested and adopted by practitioners. However it can now be said that the simple concept of absolute temperature influencing dimensional change is no longer a valid model.

TenFour Correcting for Heat-induced Influences on Anthropological Techniques

There are two main reasons for studying the effects of burning on bone and teeth. The first is simply to understand the process of heat-induced change. This has been the thrust of many studies (see Chapter 2) and a respectable body of knowledge is being amassed. The second reason is to provide a means of correcting all anthropological techniques that are applied to burned bone. Anthropological techniques rely on unmodified bone dimensions for their accuracy and as has been discussed in great detail, heating and burning will cause substantial changes to occur in the hard tissues. It is therefore of great concern that this second issue has not been investigated with any vigor. Little has been published regarding the influences of burning on the results of anthropological techniques. Thompson (1999; 2002) discussed the effect of heat-induced shrinkage on uni- and bi-variate metric method of sex assessment. He stated that significant misclassification of sex could be achieved when using metric sex assessment methods as a result of the changing relationship between the variables of measurement. This sentiment was also reiterated by McKinley (2000). Although discussing sex assessment formulae derived for the pelvis, Thompson's (1999; 2002) conclusions can be applied to all uni- and bi-variate methods of osteological analysis.

Since it has already been shown that heat-induced features do not mimic pathology and trauma (Mayne Correia and Beattie, 2002) the osteological techniques of concern are those that assess biological sex, age at death, stature and ancestry. Techniques for these assessments are either viewed as morphological or metric depending on whether they use shape and form or discrete measurements to estimate the feature of interest. While some heat-induced change in bone will affect both of these types of technique, other changes will not. Table 10.7 displays the influence of heat-induced change on these two types of anthropological technique.

It can be seen from Table 10.7 that both morphological and metric methods of osteological analysis can be affected by heat-induced changes in bone. Techniques can either be affected directly or indirectly if the heat-induced change witnessed is indicative of another more rudimentary change. For example colour change will not affect the results of anthropological techniques itself but the cause of the colour change, the removal of the organic fraction, will affect the techniques being used. The most influential heat-induced events with regard to the altering of the results of anthropological techniques are the removal of the organic phase and the recrystallisation of the inorganic phase. These two heat-induced features account for all of the heat-induced changes detailed in Table 10.7 and are therefore the fundamental causes of any inaccuracy in anthropological method due to burning.

Heat-induced Change	Technique Affected	Cause of Effect
Colour Change	Metric	Indirectly: Colour change implies loss of organics which causes shrinkage
Weight Loss	Metric	Indirectly: Weight loss implies loss of organics which causes shrinkage
Fracture Formation	Morphological and Metric	Directly: Increased

		fragmentation reduces likelihood of technique application
Changes in Strength	Morphological and Metric	Indirectly: Weaker bone increases fragmentation which reduces likelihood of technique application
Recrystallisation	Morphological and Metric	Directly: Changes in microstructure may affect shape and will affect dimensions.
Porosity Change	Metric	Indirectly: Implies loss of organics and reorganisation of microstructure.
Dimensional Change	Morphological and Metric	Directly: Differential size changes may affect shape and will affect dimensions.

Table 10.7 The Influence of Heat-induced Change on Anthropological Techniques

Using Table 10.3 it can be argued that all burned skeletal remains that an anthropologist will be asked to examine will have undergone some form of heat-induced transformation. Using Table 10.7 it can be argued that all forms of heat-induced change will affect all types of anthropological technique. Therefore all anthropological analyses conducted on burned remains will be wholly and fundamentally inaccurate. It is likely that the metric techniques will be more adversely affected than the morphological ones. This is because the heat-induced changes outlined in Table 10.7 affect metric techniques more often than morphological techniques. In addition, the recrystallisation of the inorganic phase will cause changes in bone that are subtle and undetectable since the pre-burning dimensions are unknown. Any changes that would affect the morphological techniques are more likely to be detectable before application of the technique begins. The next important issue to determine then, is just how inaccurate the results of these analyses will be.

It is difficult to assess the level of inaccuracy generated due to heat-induced changes in burned bone. However the level will depend on both the extent of the heat-induced changes and the nature of the anthropological technique. In general the more severe the burning the greater the degree of heat-induced change which in turn will increase the level of inaccuracy in the technique. Thompson (1999; 2002) demonstrated how increased shrinkage could theoretically cause greater misclassification of biological sex when using metric sex assessment techniques. With regard to the nature of the technique itself uni-variate, bi-variate and multi-variate techniques react differently depending on the influence of the heat-induced dimensional change on the component variables of the metric technique. Table 10.8 further summarizes Thompson's (1999) findings and reiterates the problematical nature of the influence of heat-induced change on the accuracy of anthropological techniques. Thompson's (1999; 2002) discussions on the complications of using metric sex assessment techniques focussed on the influence of heat-induced shrinkage. These complications are further compounded now that the presence of heat-induced expansion has been noted.

Nature of Metric Technique	**Algebraic Expression Example**	**Consequence of Heat-induced Change**
Uni-variate	$y = a * k$	If: a decreases, y decreases
Bi-variate	$y = (a * k) / b$	If: a decreases more than b, y decreases; b decreases more than a, y increases
Multivariate	$y = (a / b) + c - k$	If: b decreases more than a and c, y decreases; a or c decreases more than b, y increases

Table 10.8 Summary of Thompson's (1999) Observations of the Influence of Heat-induced Change on the Results of Anthropological Techniques

Correcting for the influence of heat-induced change can occur in one of two ways. First, in order to compensate for the heat-induced dimensional changes the techniques themselves can be modified, for example by changing the constants or increasing the error margins. Second, the measurements recorded can be modified so that the anthropological techniques of analysis are used on the estimated pre-burning dimensions of the bone rather than on the dimensions suffering heat-induced change. McKinley (2000) states that most standard skeletal indices cannot be calculated on burned bone and Thompson (1999; 2002) advocates the use of extreme caution. However attempts have been made to employ the former solution when analysing burned remains. Both Gejvall (1969) and Van Vark (1974; 1975) provided specific anthropological techniques with suitably broad error margins. There is a very specific problem with this approach to minimising the effects of heat-induced change on anthropological techniques. Either every anthropological technique needs to be examined and modified in isolation or new techniques need to be created to replace the many techniques currently being used on unmodified non-burned skeletal remains. These comments, in conjunction with the mathematical complexities highlighted in Table 10.8, show that it this would be a very complicated and time-consuming task indeed. However, if one makes the assumption that all human bone will fundamentally act in a fairly uniform manner when burned, with explicit heat-induced transformations only varying in speed and severity based on external variables, it will be possible to predict the pre-burning conditions of the bone. An appreciation of every single variable acting on bone is not required just as long as it is possible to say how far from the norm the burned bone has diverged. For example, how much larger have the inorganic crystals become or by how much has the micro-porosity reduced? These sorts of heat-induced transformations are possible to measure in the laboratory, and with a substantial body of experimental research it will be possible to create regression equations that will predict pre-burning conditions with reasonable accuracy. In turn existing anthropological techniques will be applicable to these pre-burning bony dimensions and values. To recapitulate it would therefore be possible to alter each measurement from every cremation using one of a limited suite of equations rather than having to mathematically correct every metric anthropological technique one wished to employ.

This solution to the issue of correcting the measurements of burned bone for analysis is only useful for the application of metric methods and not morphological methods. To correct for these would be much more convoluted. Theoretically it would be possible to predict the dimensional change undergone as a consequence of burning, however the sheer number of planes of measurement that would need to be calculated in order to generate a three-dimensional likeness that could have the morphological techniques applied to it is likely to be prohibitive. A potential remedy to this could be the use of three-dimensional modeling software, however a specific computer program would need to be written for this application.

TenFive Research and Experimental Limitations

Every piece of research will suffer from limitations, and those concerned with this piece of work focus mainly on one area: the bone samples. The main limitation of all previous cremation research is the small sample size used. Based on this weakness, significant statements are made regarding the nature of burned bone which are then subsequently and readily accepted throughout the discipline. This work has managed to resolve these sample size issues, but not others. It was not possible to use modern human bone in this project. As archaeological bone is wholly inappropriate due to the lack of organic components, modern sheep bone was employed. Despite the claims of Mayne (1990) it is still not fully known how well sheep bone mimics the response of human bone when burned. Further research is desperately needed to clarify this issue.

In a similar vein it is still unclear how comparable experimentally-gained data on heat-induced changes are to those experienced in actual forensic and archaeological situations. Controlled experiments are 'ideal' conditions and are unlikely to be witnessed in the field. This is especially true of studies such as Cattaneo *et al* (1999), Duffy *et al* (1991) and Holden *et al* (1995b) who burned only small segments of bone or tissue rather than the whole bone and subsequently extrapolated their results. Bohnert *et al* (1997) initially argue of the appropriateness of this transition, but then later adopt the opposing view based on this same argument (Bohnert *et al*, 1998). Comparison of experimental and real-life contexts was unfortunately beyond the scope of this study but is required promptly before a great body of research is conducted.

Although the eleven bone and three dental measurements are entirely appropriate, in retrospect an extra measurement should have been taken across the midpoint of the bony diaphysis. This would have ensured that effectively the entire bone was being examined for heat-induced dimensional change. No information has been lost because of this situation but valuable information may possibly have been gained.

It has been claimed above that the sample size of this research has resolved many of the issues and limitations concerning previous studies. However the sample sizes for the examination of porosity and crystal size are still small. This is because these techniques have never been used on burned bone before and as such an element of caution was employed. The consequence of this is that the results from these analyses should be viewed as those of a preliminary study. There is no reason to doubt their validity, but more data is required before absolute confidence can be placed in their findings.

Unfortunately there were restrictions placed upon the acquisition of appropriate sheep long bones. As such it was not possible to collect sixty identical bones. All of the bones used were long bones and taken from adult sheep, but increased comparability would have been achieved if the same long bone could have been used from sheep of exactly the same age. It is not expected that the results would have been affected to a significant degree however.

One of the more important issues raised by Thompson (1999) concerning common cremation research limitations was that of the divided nature of cremation research. He argued that there was a disparate nature to this research, which was essentially divided into two temporally-based camps, with little or no cross-collaboration or cross-referencing. Although this is still largely true four years later, this current piece of research has managed to combine the previous work of both the archaeological and forensic workers to produce a more coherent and cohesive understanding of the nature of heat-induced change.

It is unfortunate that again one of the limitations raised by Thompson (1999) still exists: that of literature bias. Although there are now a number of very good article review papers (such as Mayne Correia, 1997, McKinley, 2000 and Thompson, 1999) this research still suffers from a lack of inclusion of a number of foreign language papers. Many cremation papers are in German and unless they have been incorporated into the likes of Mayne Correia (1997) and McKinley (2000) they have not been included. This bias is not expected to be a major experimental limitation, but nonetheless its presence will be felt.

TenSix The Direction of Future Research

Although this piece of research has resulted in a significant step forward in our understanding of the influence of burning on the human body, there are obviously still many more questions to answer. Perhaps the most significant of these focus on the changes to the microstructure of the bone and teeth. It has become very clear that this area of change needs to be fully understood since all other changes and effects descend from transformations at this primary-level. In essence the mercury-intrusion porosimetry and small-angle x-ray scattering were preliminary investigations with small sample sizes which need to be repeated with a larger number of burned bones and teeth. The exciting and revealing initial results desperately need expanding upon.

In addition to collecting new and more reliable data regarding the effects of burning and cremation on the human skeleton, the existing information retrieved from animal analogue studies requires verification. As stated above, there is still uncertainty in the literature concerning just how similar the changes seen in sheep bone are to those seen in human bone. This verification will prove difficult in the current research climate of restricted access to modern fresh human material. Archaeological human material is of limited use since the important and influential organic component will have decayed away decades ago. To compliment the experimental testing of the appropriateness of using animal analogues in cremation studies is a need to examine more actual archaeological and forensic case studies to confirm that experimental results can be confidently applied to real-life situations.

The final focus of future research should be the refining and modification of anthropological techniques of human identification. There are hundreds of techniques now in existence and although it is not necessary to test them all, research into the important and popular methods is absolutely vital. Until this is complete, the unfortunate situation is that all osteological profiles based on burned and cremated remains should be treated with an extensive amount of caution.

The most important feature of future cremation research must be integration. It is vital for the success of future cremation work and for a fuller understanding of the nature of heat-induced change that subsequent studies integrate their research questions with those that have been asked both before and concurrently. Arguably part of the success of this project has been that it has built directly upon previous work (Thompson, 1999). The disarticulated nature of the majority of the previous research is directly attributable to the scarcity of knowledge that is present today, even though research on burned and cremated human material has been performed for over forty years. To date it has been possible to integrate the work of two undergraduate dissertations with the conclusions of Thompson (1999) and this piece of research. James Mabbitt (2003) of the Department of Archaeology, University of Sheffield used the improved understanding of heat-induced colour change to help interpret the burned faunal remains recovered from the Palace of Nestor, Pylos, Greece, while Michelle Clarke (2003) of the University of Central Lancashire used the same improved understanding to interpret experimentally burned animal bones. Of greater note is the utilisation of the new body of knowledge regarding the microscopic changes in bone by Lisa Bhayro (2003) in her attempt to distinguish human from non-human burned bone based on histological analysis.

It has now been established throughout the previous chapters of this thesis the nature of heat-induced change in the human body and the boundaries of our understanding of this change. It is now vital that we take a slight intellectual side-step to examine the legal and ethical consequences of researching into this arena. The consequence of this will be to allow the placement of all previous, current and proposed future work into an appropriate context.

Eleven Legal and Ethical Considerations of Burning Human Remains

ElevenOne Introduction

Anthropology does not function within a legal, ethical or social vacuum. This is true of both forensic and archaeologically-oriented workers. An awareness of the ramifications of anthropological work and research is necessary. The legal and ethical discussions fall into two sections – those concerning the actual burning of human tissue and those concerning the use of burned human tissue for research purposes.

ElevenTwo Considerations of Burning Human Remains

Human bodies can either be burned in a legal or illegal manner. From a legal perspective there is a very detailed framework regarding the cremation of a deceased individual in England. This may stem from the notion that cremation was for a long time seen as being more offensive than traditional interment. It appears that many of these legal rulings are in existence to ensure that someone is not cremated against wish. Changing attitudes towards cremating the dead make this notion and the associated rulings seem slightly antiquated. For example, it was still not lawful to cremate unidentified individuals or those who were known to have left instructions to the contrary until the Cremation Regulations, 1965 came into force (Smale, 1993). Illegal burnings and cremations tend to be as a form of homicide, whether direct (setting fire to the person) or indirect (setting fire to the building that the individual is in), or in an attempt to conceal a crime. Other laws are likely to be used to prosecute individuals who attempt or succeed in killing individuals with fire.

The Cremation Act 1902 and the subsequent Cremation Act 1952 provide the legal conditions for the establishment, running and closure of crematoria in England. Section 4 of the 1902 act states that the responsibility to provide and maintain burial grounds and cemeteries, or anything essential, ancillary or incidental relating to them lies with the burial authority (Smale, 1993). This is extended to include crematoria. The Local Government Act 1972 (Section 214 (1)) defines the burial authority as the district councils and London boroughs. Tunbridge Wells was the first local authority to attempt to acquire the power to create a crematorium in 1889, but this did not happen due to lack of interest from the Home Office (White, 1993). It was not until the Cardiff Corporation Act, 1894 that permission was given from central government to establish a crematorium with the purpose of burning human remains (White, 1993). The Cremation Acts (1902; 1952) also detail the requirements for the location of crematoria, the requirements for new crematoria and the fees that can be charged. The specifics of crematoria maintenance are covered by the Cremation Regulations, 1930. Regulation 1 states that every crematorium must by kept in good working order, provided with sufficient attendants and constantly kept in a clean and orderly condition. The standard of care expected at every crematorium is stipulated in the Federation of British Cremation Authorities Code of Cremation Practice. This is only an ethical document however and holds no legal weight.

There is no statute in existence specifying that either burial or cremation must take place (Dorries, 1999). If cremation is chosen as the means of body disposal, Smale (1993) states that the requirements for the actual burning of a body for funerary purposes are covered by the Cremation Regulations, 1930 and the revisions in the Cremation Regulations 1952, 1965 and 1979 and the Cremation (Amendment) Regulations, 1985. It is important to note that the formalities of cremation differ depending on whether an autopsy has occurred and whether an inquest is to be held (Dorries, 1999; Matthews, 2002). First and foremost, Regulation 6 of the Cremation Regulations, 1930 provides that no body can be cremated until the death has been duly registered. This is overseen by Regulations 7 and 8 that state that four forms must be duly completed before the cremation process may begin. These are: Form A – Application for Cremation, Form B – Certificate of Medical Attendant, Form C – Confirmatory Medical Certificate and Form F – Authority to Cremate. After cremation, the ashes of the deceased must be returned to the individual who requested the cremation if they so desire (Smale, 1993). If this does not happen, the Cremation Authority retains the ashes and if no special arrangement is made will inter or scatter the said ashes (Smale, 1993). Regulation 17 of the Cremation Regulations, 1930 requires the Cremation Authority to provide a Registrar who will record the details of every cremation undertaken by that Authority. Amendments were devised in the Cremation (Amendment) Regulations, 2000 to cover the cremation of body parts. This was the result of the realisation that much human tissue had been retained after removal during post-mortem investigations and that the existing regulations failed to cover body parts when the rest of the body had been disposed of (Matthews, 2002). Cremation of body parts can now occur if death has been duly registered and if the body parts have been removed during the course of a post-mortem examination (Matthews, 2002).

White (1993) presents an interesting argument regarding the legality of burning human bodies in general. He points out that the Cremation Acts refer only to the regulations regarding the cremation of human remains. The definition of the term cremation is the burning of a body in a crematorium. Therefore White (1993) asserts, the burning of a body in a non-crematorium context is not unlawful as it is not deemed to be a cremation. It was held that at common law it was not a misdemeanor to burn a body rather than burying it unless the act caused a public nuisance or impeded a Coroner's inquest (Smale, 1993; White, 1993). Section 8 (1) of the Cremation Act, 1902 makes it a punishable offence to cremate a body not in accordance to the specifics of the Act. Section 8 (2) of the Cremation Act, 1902 makes it a punishable offense to falsify the representation or certification of cremation procurement. Section 7 of the Cremation Act, 1902 concerns the falsification of the official Register of Cremation.

Although a rigorous legal framework is in existence, mistakes at the crematorium will still occur. Murray and Rose (1993) and Kennedy (1996) both detail cases in which a forensic anthropologist had to sift through the cremated remains of individuals in order to ascertain whether the remains returned to grieving families were indeed the remains of their loved ones.

ElevenThree Considerations of Researching with Burned Human Remains

Arguably very little research is conducted into the effects of burning on the human body. This does not mean however that a discussion of the legal and ethical considerations of research in this area should not begin. In actuality the considerations for the use of burned material in research are just the same as for unburned material. Even the burning process itself should not require special concern as it is arguably simply another part of the analytical process and no different than covering samples with gold for scanning electron microscopy or more accurately powdering samples for X-ray diffraction which like burning, is a destructive irreversible process. As such, many of the points mentioned below are designed with non-burned material in mind, but are equally applicable to burned tissues.

ElevenThreeOne The Collection of Burned Human Remains

In essence, research into human remains can be separated into three distinct phases. These are the collection, the analysis and the storage or post-analysis fate of the human material. Work with burned human remains is no different. The legal and ethical considerations associated with research in forensic, and to an extent, archaeological anthropology has been discussed previously in detail by Thompson (2001). This publication focuses very much on the collection of research material from modern human remains. As such, there is only limited regard to remains from antiquity. Further, the emphasis on the use of modern material has meant that the potential significance of both the Vermillion Accord (World Archaeological Congress, 1989) and the Valetta Convention (European Cultural Convention, 1992) were overlooked. Both documents were designed for application in the field of archaeology, however both papers are vague with regard to human remains and timescales. Article 1 of the Valetta Convention, which defines archaeological heritage for the purpose of the document, simply states that all remains, objects and traces of mankind from past epochs constitute heritage deserving protection. Clearly then the Valetta Convention provides international protection for the collection of human remains for research purposes. Although the Vermillion Accord specifically refers to human tissue, it like the Valetta Convention are pointedly vague with regard to the period of time that is afforded protection. It would be fairly straightforward to argue that modern material and those of antiquity were equally protected by these two items of legislation.

The first point to state before continuing is that existing English statutes do not cover all situations in which human material might be removed for research purposes. In these cases it falls to the courts to decide whether the collection of any human material can be justified at common law as being for the good of the public (Nuffield Council on Bioethics, 1995). Those situations that are covered are done so in the Human Tissue Act, 1961, the Anatomy Act, 1984, the Theft Act, 1968 and to an extent the Burial Act, 1857.

The Human Tissue Act, 1961 was devised with the purpose of regulating the emerging field of human organ transplantation. In addition it allowed, for the first time, for doctors to use every part of the human body for therapeutic, research and educative purposes while attempting to balance the concerns surrounding deceased individuals – that is the concerns of the deceased themselves, the living relatives and the state (Lanham, 1971; Thompson, 2001). The main points of relevance to those wishing to collect human material for anthropological cremation research are detailed in Sections 1 (1) and 1 (2). These two Sections state that human material may be removed for research purposes if the deceased has expressed such a desire, or if no desire has been expressed, if the deceased had not specifically stated otherwise and no surviving relative objects. The Act has a number of issues however that complicate the situation for anthropological researchers. The Act only refers to medical education and research, thus forcing anthropologists to attempt to define their research as such. The Act requires that fully registered medical practitioners alone may remove tissue, so again the anthropologist must attempt to define themselves as such. This would prove very difficult indeed as most anthropologists do not have a clinical qualification and so cannot register as medical practitioners. The Act does not specify which tissues are covered and of what age. Thus one must assume that both soft and hard tissues are covered, and human material of both modern and archaeological origin. This last point generates a new obstacle for potential researchers, that of consent. Clearly Section 1 (1) of the Act cannot be upheld being as that those individuals from antiquity could not have given permission for their bodies to be used in such a way. Indeed the question would not have even existed for it to be answered. Therefore the researcher must show that either the individual did not object, which again cannot be done as the question did not exist then for it to have been objected to, or that the surviving relatives do not object. And here lies the crux of the anthropologist's predicament: who can be defined as a surviving relative? Does this constitute the cultural descendents of the ancient remains? And what of the Act's demands that a reasonable enquiry should be made to find the surviving relatives? What is a reasonable enquiry? And does it, as Thompson (2001) suggests, differ from discipline to discipline based on such things as time constraints and a sense of urgency? In addition does it even really matter if the surviving relatives are consulted when it falls to the individuals in physical possession of the remains to decide their fate and as it is not actually a criminal offense not to follow the regulations set out in the Act. As can be seen, the Human Tissue Act, 1961 is riddled with uncertainties and ambiguities. These are compounded by the fact that the Act is having to be interpreted by a discipline for which it was not originally created.

The Anatomy Act, 1984 is a refurbishment of the Anatomy Act, 1832 and governs the anatomical examination of human remains. By the term 'anatomical examination' the Act means dissection. It requires that a Home Office license is necessary for both the examiner and the location of the examination. The Act also stipulates a time-limit for the anatomical examination which is currently set at three years (Kennedy and Grubb, 2000). A Home Office license is not required for every individual who examines human bodies so long as permission is received from a suitably licensed practitioner. This allows for human dissection to be used as a teaching tool. Although it is a clear criminal offense to flout the Act, it is undermined slightly by two points. First it does not cover material collected before the implementation of the Act. This is of use to many anthropologists who research with archaeological material. Second the Act states that Section 1 (1) of the Human Tissue Act, 1961 takes precedence over the Anatomy Act, 1984. Therefore any material donated to medical research by the deceased is not protected by the less-ambiguous and more consequential regulations of the Anatomy Act, 1984.

The importance of the Theft Act, 1968 with regard to the collection of human material for research is that it helps to define how human tissues can be viewed as property. Traditionally the law does not regard the human body as property (Cookson, 2000; Mason and McCall Smith, 1999; Murphy and Stockdale, 2001; Skegg, 1977), but recently this has been modified to mean the human body in its natural unmodified state (Cookson, 2000; Davies, 1998; Grubb, 1998; Mason and McCall Smith, 1999; Murphy and Stockdale, 2001). Modification that transforms the body into property is the application of skill to the remains. However there is now the issue of defining what constitutes the application of skill. Grubb (1998) suggests that in the future it will not be the application of skill that confers property-status to human tissue but the significance of the tissues beyond their simple existence, that is what the intended use for the material is. Organ transplantation and use as an exhibit in a trial are two examples (Grubb, 1998), but teaching and research aids may also be included too (Thompson, 2001).

The Burial Act, 1857 governs the removal of human remains from their place of burial, and thus includes remains that are removed for research purposes. Although almost one hundred and fifty years old, the Act covers both modern and archaeological remains and makes it clear that it is a criminal offense to disregard the Act. The Act simply requires that one apply for a Home Office license to remove human material from its place of burial. This license will state who may remove the remains, where they may be stored and what will happen to them after removal. The choice of the phrase 'place of burial' is significant in that it covers cemeteries but also other locations like clandestine graves or archaeological features such as barrows. Removal of human remains from consecrated ground is governed by ecclesiastical law.

It is also possible to take human material for research from the unclaimed bodies of those who have died. This brings with it issues regarding the exploitation of vulnerable sections of society and the lack of consent from the individual or anyone with an interest in the deceased (Campbell *et al*, 1997; Jones, 2000; Thompson, 2001). However as Thompson (2001) notes, although ethically dubious the use of unclaimed bodies can be upheld by law under Section 1 (2) of the Human Tissue Act, 1961 or Section 4 (3) of the Anatomy Act, 1984.

As can be seen from the above discussion, attempting to collect human remains for research, especially from a modern context, seems a very daunting task. There are many pertinent ethical issues to deliberate. In addition there are many laws to consider and many of them are unclear as to how they fully relate to biological anthropology. It is not surprising then that many anthropologists decide to use an animal analogue. There are many ethical concerns regarding the use of animals for research, but these usually refer to live specimens. The source of tissue for anthropologists is often farmers or butchers who are in possession of faunal remains from animals that have already been killed, often for a non-research purpose such as food. It should be noted that the use of modern human dentition for anthropological research is not as complicated or problematic. The main reason for this is because the sources of the teeth are still living. As such full and informed consent can be received from each tooth donor.

Of note here is the fact that the Human Tissue Act, 1961 and the Anatomy Act, 1984 are in the process of being reviewed with a view to revising the legislation concerning the collection of human tissue as a consequence of the Bristol and Alderhay enquiries. It is, as yet, unclear just how significantly the process of human tissue collection and subsequent use will be affected.

ElevenThreeTwo The Analysis of Burned Human Remains

The ethical concerns regarding the analysis of burned human remains focus on the concept of abusive research. Anthropological research can be abusive in two ways. First the research protocol itself can be abusive. Second the use of results and conclusions from unethical research can be deemed abusive.

Initially it may be difficult to see how biological anthropological research could be abusive. Thompson (2001) makes the point that if using live research subjects, then anthropological research can abuse those subjects just as any research that utilises live subjects can be abusive. However this is not really applicable here as one cannot burn the human tissue while it is still on a live research subject. If the tissue is legally removed in some way first with full informed consent, such as by amputation or some other medical procedure, then the tissue ceases to be the property of the patient and from a certain ethical standpoint its use cannot be the cause of abusive research to the live subject. In other words the extracted human tissue exists in legal and to some extent ethical, isolation from any human subject. Three further points persist with regard to abusive experimental protocol. First it is important to appreciate that uncomfortable methodology is not necessarily unethical methodology. However the distinction between the two is not always clear as different sections of society have different ethical codes, each as valid as the other. One set of ethical coding may deem a particular protocol as ethical while another may state the contrary. The solution to this problem may be discussion by all parties until a compromise or understanding can be reached. The second point is that if anthropological research does not have a clear or significant benefit, it is arguably a waste of any human tissue used. This concept of maximum benefit over minimum cost is known as consequentialism or utilitarianism, and is one of the driving ethical frameworks used by modern researchers in all disciplines. The third point is that although the dead cannot be abused, the living can, and this extends to the cultural descendents of the human remains being analysed. The accusations of abuse here do not just stem from the use of remains without permission from the cultural descendents. There are also concerns because some bodies taken are not used, information gained is often not shared with the indigenous people and the descendents are not involved in formulating or researching the questions at all (Campbell *et al*, 1997; Thompson, 2001). Currently much effort is being placed by both researchers and indigenous people to resolve these issues, and compromises are being reached (Hunt, 2001). This said, Thompson (2001) wonders whether these concerns of abuse are only concentrated on 'culturally significant' material. Most anthropological research on archaeological remains will be conducted on material held in universities and museums and are not deemed significant by ethnic groups and are therefore not subjected to cries of abuse.

The second ethical concern of the analysis of human material for research purposes is the use of results and conclusions from unethical experiments. The argument that using these results is unethical is due to the concept of moral complicity. This is the notion that those who use the results from unethical experiments are just as abusive as those who collected the data in the first place. The counter to this argument is to separate the unethical nature of the original research from the ethical intentions of the current work (Thompson, 2001). It is suggested that this can be done be accepting that valid data, even from unethical experiments, cannot be invalidated and by attempting to separate the unethical principles of the past from our modern approach (Campbell *et al*, 1997; Thompson, 2001). Hunt (2001) supports this notion, declaring that we must not discount or destroy the possibility for future knowledge in our attempts to remedy the past. As a final point, Thompson (2001) asks whether results from unethical experiments rather than be rejected outright, will instead be assessed on the severity of their abuse. This is venturing into the realm of public perception of the law and ethics, which although of some relevance here, is essentially a different issue that would be more appropriately dissected elsewhere.

ElevenThreeThree The Storage of Burned Human Remains

The main issue with the post-experimental fate of burned human material is simply what should happen to the tissue. If there is no further use for the material it arguably should be disposed of, either by returning it to its cultural descendents or by interment or cremation. A number of post-experimental uses may exist however. An anthropologist looking from the utilitarian point of view would argue that as much benefit as possible should be extracted from these burned remains. Further uses could include other research, creating teaching tools and the use of the human material in a reference collection. These last two uses are less compelling as it is possible to use other items such as casts, images and descriptive text for educative and comparative purposes. This is less preferential than using actual burned material because features such as surface texture and subtle colour change would be lost, but they would be adequate for these purposes. The storage of burned human remains is not always inappropriate, however it must always be justifiable (Thompson, 2001). While Hunt (2001) argues that emphasis should be placed on future research and new technological investigation, the storage of human tissue on the proviso that someone, someday may wish to use it is not sufficient (Jones, 2000).

It is worth briefly returning to the use of human remains as a teaching tool as it has been the focus of recent discussion (Hunt, 2001; Skegg, 1991; Thompson, 2001; in press). While Skegg (1991) examines the legal aspects of using human tissue in this role, Thompson (2001; in press) appraises the notion as to whether or not human material should be used in teaching at all. Both Skegg (1991) and a decade later Thompson (2001) highlight the fact that English law accounts for the use of human material as a teaching tool in both the Human Tissue Act, 1961 and the Anatomy Act, 1984. This will include the use of burned human remains. Thompson (2001; in press) subsequently argued that the ethical considerations of using human tissue as a teaching tool will undoubtedly include the exploitation of vulnerable population demographics, consent and the right to self-determination after death, repatriation and the indefinite storage of human remains and the utilitarian model of achieving maximum benefit to the discipline at the minimum cost to the deceased.

ElevenThreeFour Publication of Results and Conclusions

The end result of any research should be academic and public dissemination. With regard to human remains (and burned human remains are no exception) the main ethical issue is that of anonymity. That is the identity and personal details of the remains must be kept from other academics and the public. It is hard to imagine either a situation where this would not be easy to perform, or a research project that would require the publication of this sort of personal information.

ElevenFour Conclusion

The main point that needs reiterating here is that burned human remains used in anthropological research deserve no more or less respect than unburned human tissues. Therefore all of the points discussed above are equally applicable to human remains in this condition, whether or not they were burned before or as part of the experimental process. The discipline as a whole has a responsibility to ensure that all researchers who work within its remit are suitably clear on the legal and ethical elements of their work, and of the repercussions if they are not duly observed or considered.

Twelve Conclusions

It is clear that the burning of human individuals has a considerable emotional, spiritual, legal and ethical resonance throughout our modern and ancient societies. As such, burned human remains are extremely significant when processed by the forensic anthropologist and the archaeologist. Yet it is a source of concern that, to date, there are still large gaps in our understanding of this category of human remains. These gaps concern the not only effects that fire has on the tissues of the body, but also how heat-induced changes affect the ability to create an accurate osteological profile for demographic or identification purposes, how best to handle such remains and how to appropriately administer the contexts within which they appear. An examination of the literature and the contexts within which burned bodies appear indicates that there is a demand for a greater understanding of the processes of heat-induced osseous change in addition to an enhanced consideration of the consequences of analysing burned human remains. This demand emanates from both the forensic and archaeological disciplines. Furthermore, it has been shown that the study of burned human remains has many legal and ethical connotations that cannot and should not be ignored, with many of them being detailed here. All future researchers in this area must be aware of these ramifications and integrate them fully into their studies.

Changes in colour due to burning are well documented and the results here are in keeping with those earlier works. However, it is much clearer now that the determining factor regarding colour change is not temperature. The addition of a second variable in these experiments, duration, produces comparable colour change progression to the earlier single variable studies. Colour change is a function of the loss of the organic phase from the bone, which is itself dependent on many variables of which temperature is the most often cited.

The development of fracture patterns due to burning has been debated greatly in the literature. The repeatability of the linear grid-like patterning here shows that bones burned dry have a distinct and reliable pattern development that is distinctively different to those on bones that are burned fleshed. The fracture patterns of teeth are also distinctive, and this is likewise dependent upon their pre-burning conditions. The origin of heat-induced fracture lines, as revealed by scanning electron microscopic analysis of the external bone surface, can be seen to be the naturally occurring pores within the bone. It has been revealed here that fractures spread from pore to pore, increasing in length, depth and breadth until finally the structural integrity of the bone is lost, and the hard tissue falls apart.

Heat-induced changes in mechanical strength are generally regarded as the product of heat-induced weakening of bone. However this association belies the fact that after the commencement of the Fusion stage of heat-induced bone transformation, the mechanical strength of the bone can increase again. As has been shown here, both the increase and decrease in the mechanical strength of burned bone are dependent upon the state of the pore spaces within the bone. Initial burning increases the number and size of these spaces, thereby weakening the bone. However the alterations resulting from the Fusion stage essentially reverse these initial changes, resulting in fewer and smaller pore spaces, which in turn results in stronger bone. The loss of the organic phase of the bone will leave behind these spaces and this process can be measured by examining the loss of weight of bone. It has been demonstrated here that this loss is so great as to be strongly statistically significant.

Of great interest to those attempting to explain heat-induced change in bone is the state of the inorganic phase. For the first time, heat-induced changes at the microscopic scale were examined using mercury-intrusion porosimetry and small-angle X-ray scattering techniques. This revolutionary approach has allowed for an unprecedented degree of understanding to be achieved. It has now become clear just how influential the changes in the inorganic phase are. The increase in crystal size as part of the process of recrystallisation and the shifting porosity of the bone can now be seen to be highly influential in governing the response of bone to heating.

The occurrence of heat-induced dimensional change is more complex than previously ever realised. The degree of heat-induced shrinkage can clearly be extremely severe, and in addition can also be statistically significant. Furthermore heat-induced shrinkage can be seen to continue for some time after the removal of the hard tissue from the heating source. It has also been demonstrated that the type of bone is important with regard to the response to heat and subsequent shrinkage. In addition the revealing of the existence of heat-induced expansion helps to underline the complex nature of the influence of heat on the structure of bone. These new developments in understanding simply highlight the difficulties faced for those who wish to provide prediction equations and correction factors for use on existing anthropological techniques.

The results of the examination of heat-induced changes in colour, fracture patterns, mechanical strength, microstructure and dimensions have highlighted that the previously accepted notion of four stages of heat-induced transformation are still valid, but do require refinement. In essence, the commencement temperatures of all four stages (Dehydration, Decomposition, Inversion and Fusion) have been reduced. This therefore implies that there is a greater probability of an anthropologist encountering burned remains to handle bone that has undergone some significant heat-induced changes that are likely to have a strong effect on any anthropological techniques used.

An intentionally holistic approach was adopted with regard to the experimental and research philosophy of this project. Rather than simply focusing on one specific heat-induced change, every one was studied. Therefore for the first time it is now possible to plot the relationships between these changes, and to show their influences and causal factors. As such, it can now be said that there are two levels of heat-induced transformation that hard tissue will undergo when subjected to heating and burning. The secondary level changes have been the focus of the majority of the burned bone research to date. This is because this level of change is very obvious at the macroscopic scale. Secondary level changes include the alteration of colour, the propagation of fracture patterns, the modification of mechanical strength and the adjustment of dimensions. It is no longer necessary to invest such time and resources into further research of these secondary level heat-induced transformations. This is for two reasons. First, the bulk of previous work has done much to illustrate the nature and influences of these changes. Second, and more significantly, they do not truly explain the influence of burning on the hard tissues of the body. In order to do this one must focus on the causes of these secondary level macroscopic changes. The causes of these macroscopic changes occur at the microscopic scale, and can be termed primary level heat-induced transformations. These changes, which include changes in crystallinity and hydroxyapatite lattice structure and composition, are what drive the changes at the secondary level and are the most basic changes caused by heating and burning. Although considerably less attention and research has focussed here, it will only be by understanding and modeling this level of change that we will be able to fully understand the influence of heating on the hard tissues of the human body. It is only when we reach this intellectual juncture that we will be able to suitably consider the influence of burning on anthropological techniques. Subsequently, appropriate corrections and fuller interpretations of the contexts of burned human remains will be possible.

Much further work has been suggested at throughout this thesis and it is hoped that much of it will be initiated in the next few years. Of particular interest is the continued examination of the primary-level heat-induced changes using mercury-intrusion porosimetry, SAXS and histological analysis. The influence of burning on the recovery of useful DNA is also a vital area of research, especially given the clear forensic applications of this project. Once these studies have been concluded it will be possible to begin them again but using fleshed remains. This will allow for the role of the soft tissues to be examined in addition to creating a mass of data and conclusions more applicable to forensic contexts. As a result of the new approach to studying burned bones presented here, the future of research into heat-induced osteological change is now extremely exciting and has the very real possibility of changing the way all subsequent practitioners collect, analyse and store burned human remains.

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Appendix

Dimension 1

pre-burning, 500oC for 15 minutes	post-burning, 5 mins after removal, 500oC for 15 minutes	post-burning, 15 mins after removal, 500oC for 15 minutes	post-burning, 25mins after removal, 500oC for 15 minutes	percentage shrinkage, 5 mins after removal, 500oC for 15 minutes	percentage shrinkage, 15mins after removal, 500oC for 15 minutes	percentage shrinkage, 25mins after removal, 500oC for 15 minutes	pre-burning, 500oC for 45 minutes	post-burning, 5 mins after removal, 500oC for 45 minutes	post-burning, 15mins after removal, 500oC for 45 minutes	post-burning, 25mins after removal, 500oC for 45 minutes	percentage shrinkage, 5 mins after removal, 500oC for 45 minutes	percentage shrinkage, 15mins after removal, 500oC for 45 minutes	percentage shrinkage, 25mins after removal, 500oC for 45 minutes
127	126 6	126 5	126 5	0 31	0 39	0 39	184	185 5	185 1	185	-0 82	-0 6	-0 54
124 2	123	123	123	0 97	0 97	0 97	155	151 1	150 9	150 7	2 52	2 65	2 77
136 1	133	133	133	2 28	2 28	2 28	128	127 4	127 2	127	0 47	0 63	0 78
136 3	135 8	135 8	135 8	0 37	0 37	0 37	138	136 9	136 7	136 3	0 8	0 94	1 23
218 4	216 2	216	216	1 01	1 1	1 1	186	182 7	182 4	182 2	1 77	1 94	2 04
145 5	144 4	144 4	144 4	0 76	0 76	0 76	220	.	.	.	.	.	.
153	155 8	155 8	155 8	-1 83	-1 83	-1 83	219	220 8	220 5	220 2	-0 82	-0 68	-0 55
156 4	152 8	152 7	152 7	2 3	2 37	2 37	162	154 4	154 1	154	4 69	4 88	4 94
204	204 7	204 7	204 7	-0 34	-0 34	-0 34	137	136 1	135 8	135 8	0 66	0 88	0 88
162 2	140 2	140 2	140 2	13 56	13 56	13 56	127	125	124 6	124 5	1 57	1 89	1 97

Dimension 1

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage, 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal, 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage, 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
150 2	148 3	148 1	148	1 26	1 4	1 46	160	.	.	.	.		.
147 8	144 2	144	143 9	2 44	2.57	2 64	120	117 8	117 5	117 2	1 83	2 08	2 33
214	.	.	.	.	.	.	161	.	.	.		.	
206	204 4	204 2	204 1	0 78	0 87	0 92	136	.	.			.	.
180	.	.	.	.	.	.	121			.	.	.	.
181	178	177 8	176 9	1 66	1 77	2 27	100	97 2	96 8	96 5	2 8	3 2	3 5
159	157 9	157 7	157 5	0 69	0 82	0 94	134	131 5		.	1 87	.	.
108 8	107 4	107 1	107	1 29	1 56	1 65	114	113 1	112 7	.	0 79	1 14	
138 9	136 4	136 1	136	1 8	2 02	2 09	117	112 5	112 1	.	3 85	4 19	
138 8	134.3	134	133 8	3 24	3 46	3 6	100	96 5	96	95 8	3 5	4	4 2

Dimension 1

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
181	.	.	.		.	.	185		.	.	.	.	
160 5	.		.			.	186	.	.				
211	.	.	.	.		.	217	.	.	.	.	.	.
148	139 7	.	.	5 61	.	.	129	121 6	121 2	121	5 74	6 05	6 2
149	.		.	.	.	.	133	127 6	127 3	127 1	4 06	4 29	4 44
160	151 3	151 1	150 9	5 44	5 56	5 69	126	119 4	119 1	118 8	6 72	6 95	7 19
161	.	.	.		.		134	127 8	127 6	127 3	4 63	4 78	5
196	.	.		.	.	.	186	.			.	.	.
197	.	.	.	.		.	162	152 9	152 6	152 3	5 62	5 8	5 99
83 1	.	.	.	.			207	.	.	.	.	.	.

Dimension 2

pre-burning, 500oC for 15 minutes	post-burning, 5 mins after removal, 500oC for 15 minutes	post-burning, 15 mins after removal, 500oC for 15 minutes	post-burning, 25mins after removal, 500oC for 15 minutes	percentage shrinkage, 5 mins after removal, 500oC for 15 minutes	percentage shrinkage, 15mins after removal, 500oC for 15 minutes	percentage shrinkage, 25mins after removal, 500oC for 15 minutes	pre-burning, 500oC for 45 minutes	post-burning, 5 mins after removal, 500oC for 45 minutes	post-burning, 15mins after removal, 500oC for 45 minutes	post-burning, 25mins after removal, 500oC for 45 minutes	percentage shrinkage, 5 mins after removal, 500oC for 45 minutes	percentage shrinkage, 15mins after removal, 500oC for 45 minutes	percentage shrinkage, 25mins after removal, 500oC for 45 minutes
30.4	30	30	30	1.32	1.32	1.32	49.6	53	52.7	52.6	-6.85	-6.25	-6.05
27.7	25.9	25.9	26	6.5	6.5	6.14	46.6	47.1	46.9	46.8	-1.07	-0.64	-0.43
25.7	25.4	25.4	25.4	1.17	1.17	1.17	28.9	29.1	28.8	28.7	-0.69	0.35	0.69
26	25.7	25.7	25.7	1.15	1.15	1.15	27.1	26.5	26.3	26.2	2.21	2.95	3.32
45.1	44.1	44.3	44.1	2.22	1.77	2.22	52.2	49.2	49.1	48.9	5.75	5.94	6.32
25.8	25.4	25.4	25.4	1.55	1.55	1.55	46.2	46.8	46.6	46.2	-1.3	-0.87	0
44.6	47.9	47.9	47.9	-7.4	-7.4	-7.4	47	46.4	46.2	46.3	1.28	1.7	1.49
47.4	47.4	47.4	47.4	0	0	0	33.9	32	31.8	31.7	5.6	6.19	6.49
44.8	44.8	44.8	44.8	0	0	0	26.8	26.3	26.1	25.9	1.87	2.61	3.36
31.9	31.1	31.1	31.1	2.51	2.51	2.51	29.4	28.8	28.6	28.5	2.04	2.72	3.06

Dimension 2

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage, 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal, 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage, 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
47.2	45.5	45.3	45.1	3.6	4.03	4.45	37.7	35.6	35.4	35.2	5.57	6.1	6.63
45.8	41.5	41.4	41.1	9.39	9.61	10.26	30.3	29.2	29	28.9	3.63	4.29	4.62
47.6	45.8	45.6	45.2	3.78	4.2	5.04	37.8	35.7	35.5	35.4	5.56	6.08	6.35
48.4	44.1	43.8	43.8	8.88	9.5	9.5	38.2	.	.	.	.	.	.
48.2	47.2	47	46.7	2.07	2.49	3.11	30.1	29.2	29	28.8	2.99	3.65	4.32
48.9	47.8	47.5	47.4	2.25	2.86	3.07	27.8	2.2	26	25.8	92.09	6.47	7.19
34	32.4	32.1	32.1	4.71	5.59	5.59	37.7	.	.	.		.	
22.7	21.9	21.7	21.6	3.52	4.41	4.85	37.5			.	.		
23.3	22.8	22.6	22.6	2.15	3	3	37	.	.	.	.	.	.
23.7	23.2	23	22.9	2.11	2.95	3.38	27.6	25.9	25.7	25.3	6.16	6.88	8.33

Dimension 2

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
51	.	.	.	.	.		53.7	45.3	45	44.8	15.64	16.2	16.57
51.5	49.1	48.8	48.5	4.66	5.24	5.83	52.1	43.8	43.5	43.3	15.93	16.51	16.89
45.6	41.5	41.1	40.9	8.99	9.87	10.31	46.3	38.9	38.6	38.4	15.98	16.63	17.06
46.8	44.3	44		5.34	5.98		32.9	29.1	28.8	28.7	11.55	12.46	12.77
47	.	.		.	.	.	44.7	.	.		.	.	
33.4	30.2	30	29.8	9.58	10.18	10.78	29.7	27.8	27.5	27.2	6.4	7.41	8.42
33.5	30.6	30.4	30.1	8.66	9.25	10.15	28.8	25.9	25.7	25.4	10.07	10.76	11.81
25.6	.	.		.	.	.	23.9	.	.	.	.	.	.
26.1	24.4	24.1	23.9	6.51	7.66	8.43	34	25.3	25.1	25	25.59	26.18	26.47
.	.	.	.	.	.	.	42.8	.		.	.		.

Dimension 3

pre-burning, 500oC for 15 minutes	post-burning, 5 mins after removal, 500oC for 15 minutes	post-burning, 15 mins after removal, 500oC for 15 minutes	post-burning, 25mins after removal, 500oC for 15 minutes	percentage shrinkage, 5 mins after removal, 500oC for 15 minutes	percentage shrinkage, 15mins after removal, 500oC for 15 minutes	percentage shrinkage, 25mins after removal, 500oC for 15 minutes	pre-burning, 500oC for 45 minutes	post-burning, 5 mins after removal, 500oC for 45 minutes	post-burning, 15mins after removal, 500oC for 45 minutes	post-burning, 25mins after removal, 500oC for 45 minutes	percentage shrinkage, 5 mins after removal, 500oC for 45 minutes	percentage shrinkage, 15mins after removal, 500oC for 45 minutes	percentage shrinkage, 25mins after removal, 500oC for 45 minutes
16.5	16.2	16.2	16.2	1.82	1.82	1.82	26.2	40.5	40.2	40.1	-54.58	-53.44	-53.05
16.3	15.9	15.9	15.9	2.45	2.45	2.45	40.5	40	39.8	39.7	1.23	1.73	1.98
16.3	16.1	16.1	16.15	1.23	1.23	0.92	17.2	16.6	16.5	16.3	3.49	4.07	5.23
16.1	16.3	16.3	16.3	-1.24	-1.24	-1.24	16.5	16.1	16	15.8	2.42	3.03	4.24
38.2	42.8	42.6	42.7	-12.04	-12.04	-11.78	41	39.9	39.7	39.5	2.68	3.17	3.66
17.1	16.9	16.6	16.8	1.17	1.75	1.75	45.6	44.9	44.7	44.5	1.97	2.4	2.84
42.9	42.5	42.5	42.5	0.93	0.93	0.93	45.2	45.7	45.5	45.4	-1.11	-0.66	-0.44
43.1	44.8	4.8	44.8	-3.94	88.86	-3.94	20.5	21.4	21.2	21.1	-4.39	-3.41	-2.93
40.7	39.1	39.1	39.1	3.93	3.93	3.93	16.5	16.3	16.2	16	1.21	1.82	3.03
24.3	21	21	21	13.58	13.58	13.58	17	16.7	16.5	16.4	1.76	2.94	3.53

Dimension 3

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage, 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal, 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage, 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
40.1	41.6	41.4	41.3	-3.74	-3.24	-2.99	36.7	.	.	.	.	.	.
40.1	39.2	39	38.9	2.24	2.74	2.99	16.5	15.8	15.6	15.5	4.24	5.45	6.06
41.8	44.6	44.5	44.1	-6.7	-6.46	-5.5	36	.	.		.	.	.
44.2	45.3	45.2	45	-2.49	-2.26	-1.61	20.1	19.1	16.9	18.7	4.98	5.97	6.97
23.8	23.2	22.9	22.8	2.52	3.78	4.2	16.1	15.9	15.6	15.5	1.24	3.11	3.73
26.3	24.8	24.8	24.4	5.7	5.7	7.22	15.9	15.8	15.5	15.3	0.63	2.52	3.77
17.1	17	16.8	16.7	0.58	1.75	2.34	19.5	.	.	.	.	.	.
21.3	21	20.9	20.7	1.41	1.68	2.82	30.2		.	.	.	.	.
10.7	12	11.9	11.8	-12.15	-11.21	-10.28	30.4	29.1	28.9	28.7	4.28	4.93	5.59
11	11.5	11.4	11.3	-4.55	-3.64	-2.73	16.1	.	.				.

Dimension 3

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
24.2	.	.	.	.	.	.	40.3	.	.		.		
23.3	22.7	22.6	22	2.58	3	5.58	39.2	20.7	20.5	20.2	47.19	47.7	48.47
42.1	43	42.9	42.6	-2.14	-1.9	-1.19	45.2	19.3	19	19	57.3	57.96	57.96
40	37.6	37.3	.	6	6.75		16.4	.	.	.		.	.
40.7	.	.	.	.	.	.	36.4	14.2	14	13.9	60.99	61.54	61.81
16.7	15.6	15.5	15.4	6.59	7.19	7.78	15.9	.	.	.	.	.	.
16.86	15.3	15.2	15	9.25	9.85	11.03	16.1	14.2	14	13.9	11.8	13.04	13.66
10.9	.	.	.	.	.		11.2	14.8	14.6	14.4	-32.14	-30.36	-28.57
11.06	9.2	8.9	8.8	16.82	19.53	20.43	21.8	10.3	10.1	10	52.75	53.67	54.13
.	.	.		.	.	.	41.2	18.4	18.2	16	55.34	55.83	56.31

Dimension 4

pre-burning, 500oC for 15 minutes	post-burning, 5 mins after removal, 500oC for 15 minutes	post-burning, 15 mins after removal, 500oC for 15 minutes	post-burning, 25mins after removal, 500oC for 15 minutes	percentage shrinkage, 5 mins after removal, 500oC for 15 minutes	percentage shrinkage, 15mins after removal, 500oC for 15 minutes	percentage shrinkage, 25mins after removal, 500oC for 15 minutes	pre-burning, 500oC for 45 minutes	post-burning, 5 mins after removal, 500oC for 45 minutes	post-burning, 15mins after removal, 500oC for 45 minutes	post-burning, 25mins after removal, 500oC for 45 minutes	percentage shrinkage, 5 mins after removal, 500oC for 45 minutes	percentage shrinkage, 15mins after removal, 500oC for 45 minutes	percentage shrinkage, 25mins after removal, 500oC for 45 minutes
18.2	14.6	14.6	14.6	19.78	19.78	19.78	26.8	35.3	35.3	35.2	-31.72	-31.72	-31.34
17.5	16.3	16.3	16.3	6.86	6.86	6.86	36.2	31.5	31.5	31.4	12.98	12.98	13.26
15.7	16.7	16.7	16.7	-6.37	-6.37	-6.37	14.3	14.8	14.8	14.7	-3.5	-3.5	-2.8
16.9	15.9	15.9	15.9	5.92	5.92	5.92	14.5	13.2	13.2	13.2	8.97	8.97	8.97
16.2	20.7	20.7	20.5	-27.78	-27.78	-26.54	37.3	32.2	32.2	32.1	13.67	13.67	13.94
13.2	13.5	13.5	13.5	-2.27	-2.27	-2.27	22.2	25	25	24.8	-12.61	-12.61	-11.71
39.2	32.2	32.2	32.2	17.86	17.86	17.86	26.2	23.6	23.6	23.3	9.92	9.92	11.07
34.1	39.1	39.1	39.1	-14.66	-14.66	-14.66	16.8	14.3	14.3	14	14.88	14.88	16.67
19.4	21.9	21.9	21.9	-12.89	-12.89	-12.89	12.9	13.8	13.8	13.5	-6.98	-6.98	-4.65
17.2	17.6	17.6	17.6	-2.33	-2.33	-2.33	15.2	14.3	14.3	14.1	5.92	5.92	7.24

Dimension 4

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage, 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal, 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage, 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
37.2	30.7	30.5	30.3	17.47	18.01	18.55	3.9	3.1	3	3	20.51	23.08	23.08
36.7	28	27.7	27.7	23.71	24.52	24.52	10.9	10	9.9	9.8	8.26	9.17	10.09
21.1	.	.	.	.	.		4.1	3.8	3.7	3.5	7.32	9.76	14.63
24.6	25.8	25.6	25.4	-4.88	-4.07	-3.25	8	7.8	7.7	7.6	2.5	3.75	5
28.9	21.7	21.5	21.4	24.91	25.61	25.95	11.1	10	9.9	9.8	9.91	10.81	11.71
28.8	21.1	20.9	20.7	26.74	27.43	28.13	4.6	5.2	5.1	5	-13.04	-10.87	-6.7
9.96	9.7	9.6	9.5	2.61	3.61	4.62	7.8	.		.	.	.	.
6.5	6	6	5.9	7.69	7.69	9.23	8	.	.		.	.	.
2.5	2.5	2.5	2.5	0	0	0	8.2	8.1	8	7.8	1.22	2.44	4.88
2.1	1.5	1.5	1.4	28.57	28.57	33.33	4.6	.	.	.	.	.	.

Dimension 4

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
25.8	.	.		.		.	39.1	25.4	25.1	25	35.04	35.81	36.06
21.2	20.8	20.4	20.2	1.89	3.77	4.72	34.4	25.4	25.1	25	26.16	27.03	27.33
23.3	20.3	20.1	19.8	12.88	13.73	15.02	23.2	.	.	.	.		.
29	.	.	.	.	.	.	15.1	12	11.8	11.7	20.53	21.85	22.52
29	.	.	.		.	.	8.6	.	.	.	.		
15.7	11.8	11.6	11.4	24.84	26.11	27.39	14.1	11.7	11.5	11.4	17.02	18.44	19.15
19.2	12.1	11.8	11.7	36.98	38.54	39.06	11.4	13.2	12.9	12.9	-15.79	-13.16	-13.16
12.2	.	.		.	.	.	13.7	13.6	13.3	13.3	0.73	2.92	2.92
13	.	.		.	.	.	16.6	13.5	13.2	13.2	18.67	20.48	20.48
.	.	.	.	.	.	.	6.8	.	.	.	.	.	.

Dimension 5

pre-burning, 500oC for 15 minutes	post-burning, 5 mins after removal, 500oC for 15 minutes	post-burning, 15 mins after removal, 500oC for 15 minutes	post-burning, 25mins after removal, 500oC for 15 minutes	percentage shrinkage, 5 mins after removal, 500oC for 15 minutes	percentage shrinkage, 15mins after removal, 500oC for 15 minutes	percentage shrinkage, 25mins after removal, 500oC for 15 minutes	pre-burning, 500oC for 45 minutes	post-burning, 5 mins after removal, 500oC for 45 minutes	post-burning, 15mins after removal, 500oC for 45 minutes	post-burning, 25mins after removal, 500oC for 45 minutes	percentage shrinkage, 5 mins after removal, 500oC for 45 minutes	percentage shrinkage, 15mins after removal, 500oC for 45 minutes	percentage shrinkage, 25mins after removal, 500oC for 45 minutes
25.3	25	25	25	1.19	1.19	1.19	53.5	48.8	48.5	48.4	8.79	9.35	9.53
24.4	24.6	24.6	24.6	-0.82	-0.82	-0.82	31.2	32.1	32	31.7	-2.88	-2.56	-1.6
22.8	23.5	23.5	23.5	-3.07	-3.07	-3.07	26	25.3	25.2	24.9	2.69	3.08	4.23
23.9	24.3	24.3	24.3	-1.67	-1.67	-1.67	24.3	23.1	22.9	22.8	4.94	5.76	6.17
29.7	29.2	29.1	29	1.68	2.02	2.36	50	49.4	49.2	49	1.2	1.6	2
22.5	21.9	21.9	21.9	2.67	2.67	2.67	31	30.2	30	30	2.58	3.23	3.23
34.1	32.9	32.9	32.9	3.52	3.52	3.52	32	30	29.8	29.7	6.25	6.88	7.19
32.6	32.7	32.7	32.7	-0.31	-0.31	-0.31	35.5	34.6	34.4	34.2	2.54	3.1	3.66
30.4	26.8	26.8	26.8	11.84	11.84	11.84	24.6	24.3	24.1	23.9	1.22	2.03	2.85
35.2	31.1	31.1	31.1	11.65	11.65	11.65	19.6	.	.	.		.	

Dimension 5

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage, 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal, 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage, 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
32.8	30.9	30.7	30.6	5.79	6.4	6.71	27.1	.	.	.	.	.	.
32.9	30.5	30.2	30	7.29	8.21	8.81	28.3	27	26.7	26.7	4.59	5.65	5.65
29	27.9	27.7	27.3	3.79	4.48	5.86	27.2	24.4	24.2	24	10.29	11.03	11.76
28.4	27.4	27.1	27.1	3.52	4.58	4.58	32.9	.	.	.	.	.	.
53.2	50	49.9	49.7	6.02	6.2	6.58	28.1	.	.	.	.	.	.
55.7	49.8	49.7	49.3	10.59	10.77	11.49	25.3	24.4	24.1	24	3.56	4.74	5.14
32	30.2	30.1	30	5.63	5.94	6.25	34	31.2	31	30.8	8.24	8.82	9.41
26.9	25.4	25.3	25	5.58	5.95	7.06	33.1	31	30.8	30.7	6.34	6.95	7.25
8.9	7.7	7.6	7.6	13.48	14.61	14.61	32.8	30.7	30.5	30.4	6.4	7.01	7.32
8.2	7.5	7.5	7.3	8.54	8.54	10.98	25.5	24.8	24.5	24.4	2.75	3.92	4.31

Dimension 5

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
51.4	46.9	46.5	.	8.75	9.53	.	49.7	47.2	46.9	46.8	5.03	5.63	5.84
52.5	47.9	47.5	47.2	8.76	9.52	10.1	49.2	43.9	43.7	43.3	10.77	11.18	11.99
30.7	28	27.6	27.4	8.79	10.1	10.75	29.2	36.4	26.1	25.9	-24.66	10.62	11.3
31	29	28.7	.	6.45	7.42	.	25.9	23.4	23.1	23	9.65	10.81	11.2
31.96	29.1	28.7	28.4	8.95	10.2	11.14	32.6	29.5	29.2	29	9.51	10.43	11.04
33.4	31.3	31.1	30.8	6.29	6.89	7.78	26.1	.	.	.	.		.
33.6	31	30.9	30.6	7.74	8.04	8.93	23.7	21.4	21.1	21.1	9.7	10.97	10.97
11.16	7.9	7.7	7.5	29.21	31	32.8	10.1	8.9	8.7	8.6	11.88	13.86	14.85
11.8	.	.	.	.	.	.	33.2	.		.	.	.	.
23.6	.	.	.	.	.	.	29.5	27.2	26.9	26.8	7.8	8.81	9.15

Dimension 6

pre-burning, 500oC for 15 minutes	post-burning, 5 mins after removal, 500oC for 15 minutes	post-burning, 15 mins after removal, 500oC for 15 minutes	post-burning, 25mins after removal, 500oC for 15 minutes	percentage shrinkage, 5 mins after removal, 500oC for 15 minutes	percentage shrinkage, 15mins after removal, 500oC for 15 minutes	percentage shrinkage, 25mins after removal, 500oC for 15 minutes	pre-burning, 500oC for 45 minutes	post-burning, 5 mins after removal, 500oC for 45 minutes	post-burning, 15mins after removal, 500oC for 45 minutes	post-burning, 25mins after removal, 500oC for 45 minutes	percentage shrinkage, 5 mins after removal, 500oC for 45 minutes	percentage shrinkage, 15mins after removal, 500oC for 45 minutes	percentage shrinkage, 25mins after removal, 500oC for 45 minutes
18.4	18.3	18.3	18.3	0.54	0.54	0.54	40.9	23.2	23	22.9	43.28	43.77	44.01
18.5	19	19	19	-2.7	-2.7	-2.7	27	26.5	26.3	26.1	1.85	2.59	3.33
22.5	22.3	22.3	22.3	0.89	0.89	0.89	19	18.8	18.6	18.4	1.05	2.11	3.16
23.1	22.8	22.8	22.8	1.3	1.3	1.3	22.4	22	21.9	21.7	1.79	2.23	3.13
22.1	21.5	21.2	21.2	2.71	4.07	4.07	23.1	25	24.9	24.7	-8.23	-7.79	-6.93
21.8	21.1	21.1	21.1	3.21	3.21	3.21	22.8	22.4	22.2	22.1	1.75	2.63	3.07
27.1	28.2	28.2	28.2	-4.06	-4.06	-4.06	21.3	21.6	21.4	21.3	-1.41	-0.47	0
27.4	27	27	27	1.46	1.46	1.46	18.1	18	17.8	17.7	0.55	1.66	2.21
23.1	22	22	22	4.76	4.76	4.76	22.4	22.4	22.2	22	0	0.89	1.79
17.5	17.3	17.3	17.3	1.14	1.14	1.14	25.9	19.4	19.2	19	25.1	25.87	26.64

Dimension 6

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage, 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal, 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage, 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
27.2	27	26.8	26.4	0.74	1.47	2.94	19.2		.	.	.		
27.7	27.3	27.1	26.8	1.44	2.17	3.25	19.5	17.8	17.7	17.5	8.72	9.23	10.26
21.8	21.7	21.4	21	0.46	1.83	3.67	18.4	17.6	17.5	17.4	4.35	4.89	5.43
21.9	21.5	21.3	21.2	1.83	2.74	3.2	20.5		.	.	.	.	
41.2	41	40.8	40.7	0.49	0.97	1.21	19.4				.	.	
42.2	40.6	40.3	40.2	3.79	4.5	4.74	17.7	16.9	16.6	16.3	4.52	6.21	7.91
15.3	13.9	13.7	13.6	9.15	10.46	11.11	29.4	28	27.7	27.7	4.76	5.78	5.78
16.5	16.7	16.4	16.2	-1.21	0.61	1.82	27.4	27.1	26.8	26.7	1.09	2.19	2.55
7.2	6.3	6.2	6.2	12.5	13.89	13.89	27.6	27.1	26.9	26.7	1.81	2.54	3.26
7.3	6.6	6.4	6.4	9.59	12.33	12.33	17.4	16.8	16.6	16.4	3.45	4.6	5.75

Dimension 6

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
39.1	37	36.6	.	5.37	6.39	.	25.8	37	36.7	36.6	-43.41	-42.25	-41.86
39.2	37.1	36.8	36.3	5.36	6.12	7.4	25.4	38.1	37.9	37.8	-50	-49.21	-48.82
20.7	20.5	20.2	19.8	0.97	2.42	4.35	21.3	20	19.7	19.6	6.1	7.51	7.98
27.6	26	25.8	.	5.8	6.52	.	18.4	16.2	16	15.9	11.96	13.04	13.59
26.8	25.3	25	24.9	5.6	6.72	7.09	27.1	25	24.7	24.6	7.75	8.86	9.23
21.9	18.1	17.8	17.9	17.35	18.72	18.26	18.2	19	18.7	18.7	-4.4	-2.75	-2.75
21.9	20.2	20	19.9	7.76	8.68	9.13	21.3	19.4	19.2	19.1	8.92	9.86	10.33
7	7.2	7.1	6.9	-2.86	-1.43	1.43	7.3	6.5	6.4	6.1	10.96	12.33	16.44
7.2	.	.		.	.	.	15.9	15.2	15	14.9	4.4	5.66	6.29
21.8		.		.			22.3	20.4	20.1	20	8.52	9.87	10.31

Dimension 7

pre-burning, 500oC for 15 minutes	post-burning, 5 mins after removal, 500oC for 15 minutes	post-burning, 15 mins after removal, 500oC for 15 minutes	post-burning, 25mins after removal, 500oC for 15 minutes	percentage shrinkage, 5 mins after removal, 500oC for 15 minutes	percentage shrinkage, 15mins after removal, 500oC for 15 minutes	percentage shrinkage, 25mins after removal, 500oC for 15 minutes	pre-burning, 500oC for 45 minutes	post-burning, 5 mins after removal, 500oC for 45 minutes	post-burning, 15mins after removal, 500oC for 45 minutes	post-burning, 25mins after removal, 500oC for 45 minutes	percentage shrinkage, 5 mins after removal, 500oC for 45 minutes	percentage shrinkage, 15mins after removal, 500oC for 45 minutes	percentage shrinkage, 25mins after removal, 500oC for 45 minutes
5.3	4.7	4.7	4.7	11.32	11.32	11.32	35.6	22.3	22	22	37.36	38.2	38.2
4	5.3	5.3	5.3	-32.5	-32.5	-32.5	18.8	20.3	20.1	20	-7.98	-6.91	-6.38
8.5	7	7	7	17.65	17.65	17.65	5.9	5.6	5.5	5.2	5.08	6.78	11.86
10.3	7.8	7.8	7.8	24.27	24.27	24.27	9	9	8.9	8.8	0	1.11	2.22
13.4	17.3	17.4	17.4	-29.1	-29.85	-29.85	25.6	24.7	24.5	24.4	3.52	4.3	4.69
7.5	8.6	8.5	8.5	-14.67	-13.33	-13.33	17.8	16.6	16.5	16.3	6.74	7.3	8.43
21.5	21	21	21	2.33	2.33	2.33	15.5	13.6	13.5	12.3	12.26	12.9	20.65
20.5	21	21	21	-2.44	-2.44	-2.44	12	10.9	10.8	10.6	9.17	10	11.67
16.8	15.7	15.7	15.7	6.55	6.55	6.55	8.5	7.1	7	6.9	16.47	17.65	18.82
17	10.2	10.2	10.2	40	40	40	6.9	5.6	5.5	5.5	18.84	20.29	20.29

Dimension 7

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage, 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal, 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage, 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
20.4	20	19.9	19.7	1.96	2.45	3.43	5.4	.	.	.		.	
21	19	18.8	18.7	9.52	10.48	10.95	5.8	5.6	5.6	5.5	3.45	3.45	5.17
16.6	13.6	13.3	13.2	18.07	19.88	20.48	10.7	8.1	8	7.9	24.3	25.23	26.17
15.8	15	14.8	14.7	5.06	6.33	6.96	14.3		.				
37.5	33.1	32.9	32.6	11.73	12.27	13.07	5.6	4.7	4.6	4.5	16.07	17.86	19.64
41.4	40.4	40.2	39.9	2.42	2.9	3.62	7.2	6.5	6.4	6.3	9.72	11.11	12.5
22.6	19.6	19.4	19.2	13.27	14.16	15.04	10.2	9.7	9.5	9.5	4.9	6.86	6.86
7.4	6.6	6.5	6.4	10.81	12.16	13.51	19.2	18.3	18.1	18	4.69	5.73	6.25
1.9	1.6	1.7	1.5	15.79	10.53	21.05	19	19.3	19.1	19	-1.58	-0.53	0
1.8	1.3	1.2	1.3	27.78	33.33	27.78	6.6	6.8	6.7	6.6	-3.03	-1.52	0

Dimension 7

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
36.8	35.4	35	.	3.8	4.89		27.8	28.4	28.1	28	-2.16	-1.08	-0.72
36	32.2	32	31.8	10.56	11.11	11.67	28	29.9	29.6	29.5	-6.79	-5.71	-5.36
17.6	16.1	15.9	15.5	8.52	9.66	11.93	12.4	14.7	14.5	14.4	-18.55	-16.94	-16.13
20.3	18.8	18.5		7.39	8.87	.	3	5.3	5.2	5.2	-76.67	-73.33	-73.33
20.5	18.8	18.6	18.4	8.29	9.27	10.24	20.4	18	17.8	17.6	11.76	12.75	13.73
17.2	14.9	14.6	14.6	13.37	15.12	15.12	8	.		.	.	.	.
19.2	14.6	14.3	14.1	23.96	25.52	26.56	18.5	9	8.9	8.8	51.35	51.89	52.43
7.8	4.2	4	3.8	46.15	48.72	51.28	3.3	2	2	1.9	39.39	39.39	42.42
6.7	.	.	.	.	.	.	6.5	8	7.8	7.8	-23.08	-20	-20
10.1		.		.			15.7	14.7	14.5	14.4	6.37	7.64	8.28

Dimension 6

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15 mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
24.7	26.6	26.6	26.6	-7.69	-7.69	-7.69	24	23.2	22.9	22.8	3.33	4.58	5
24.2	25	25	25	-3.31	-3.31	-3.31	32.5	31.1	31	30.7	4.31	4.62	5.54
24.5	23.9	23.8	23.9	2.45	2.86	2.45	22.2	19.6	19.4	19.4	11.71	12.61	12.61
26.8	25.8	25.8	25.8	3.73	3.73	3.73	19	19.1	19	18.8	-0.53	0	1.05
33.6	34.4	34.3	34.1	-2.38	-2.08	-1.49	22						
25.6	20	20	20	21.87	21.87	21.87	31.1	32.5	32.2	32.1	-4.5	-3.54	-3.22
30.2	30	30	30	0.66	0.66	0.66	34.5	29.6	29.4	29.2	14.2	14.78	15.36
37.2	34.6	34.6	34.6	6.99	6.99	6.99	22.9	23.2	23.1	22.8	-1.31	-0.87	0.44
36.1	35.3	35.3	28.5	2.22	2.22	20.92	14.5	18.3	18.1	18	-26.21	-24.83	-24.14
27.8	26.1	26.1	26.1	6.12	6.12	6.12	21.6	20.9	20.7	20.8	3.24	4.17	3.7

Dimension 6

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage, 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal, 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage, 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
33.8	26.3	26	26	22.19	23.08	23.08	26.4	.		.			
32.7	33	32.9	32.6	-0.92	-0.61	0.31	23.6	22.1	22	21.8	6.36	6.78	7.63
31.8	27.2	27	26.9	14.47	15.09	15.41	24		.		.		
29.8	27	26.7	26.8	9.4	10.4	10.07	23.9	.	.	.	.	.	
27.8	27.8	27.5	27.2	0	1.08	2.16	21.3	20.2	20	19.8	5.16	6.1	7.04
29.2	29.1	29	28.7	0.34	0.68	1.71	22.9	21.1	20.9	20.7	7.86	8.73	9.81
23.4	24.2	24	23.9	-3.42	-2.56	-2.14	23.2	.		.			
17.9	16.9	16.7	16.6	5.59	6.7	7.26	24.8	.			.		
25.6	24.5	24.4	24.2	4.3	4.69	5.47	23.4		.	.	.		.
25.3	24.5	24.3	24.2	3.16	3.95	4.35	22.3	20	19.7	19.6	10.31	11.66	12.11

Dimension 6

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
29	.	.	.	.	.	.	24.7	.	.			.	.
29	.	.	.	.	.	.	24	.		.		.	
31.8	.	.	.	.		.	29.4	.				.	.
33.9	.	.	.	.	.		25.9	.	.	.			.
33	.	.	.	.	.	.	31.8	.	.	.	.		
22.9	22.3	22.1	22	2.62	3.49	3.93	22.3	.	.	.	.		
25.1	22.6	22.3	22.2	9.96	11.16	11.55	21.9	18.6	18.4	18.2	15.07	15.98	16.89
28	23	22.7	22.7	17.86	18.93	18.93	27	17.8	17.6	17.4	34.07	34.81	35.56
28.8	27.2	26.9	26.7	5.56	6.6	7.29	24.9	.	.	.	.		.
.	.	.	.	.	.		28.8				.		

Dimension 9

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15 mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
14 2	14 4	14 3	14 3	-1 41	-0 7	-0 7	21 6	22	21 8	21 8	-1 85	-0 93	-0 93
14 8	14 3	14 3	14 3	3 38	3 38	3 38	18 5	17 6	17 4	17 2	4 86	5 95	7 03
15 2	14 6	14 6	14 6	3 95	3 95	3 95	11	11 8	11 7	11 5	-7 27	-6 36	-4 55
15 4	15	15	15	2 6	2 6	2 6	13 5	12 6	12 5	12 3	6 67	7 41	8 89
30 2	28 4	28 3	28 2	5 96	6 29	6 62	30 3						
14 2	13	13	13	8 45	8 45	8 45	20 8	23 3	23 1	23	-12 02	-11 06	-10 58
28	23 2	23 2	23 2	17 14	17 14	17 14	21 8	21 4	21 2	21 1	1 83	2 75	3 21
26 4	25 3	25 3	25 3	4 17	4 17	4 17	13	12 7	12 6	12 4	2 31	3 08	4 62
28 8	27 1	27 1	27 1	5 9	5 9	5 9	11 3	10 8	10 6	10 5	4 42	6 19	7 08
18 7	15 3	15 3	15 3	18 18	18 18	18 18	10 2	10 2	10 1	10	0	0 98	1 96

Dimension 9

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage, 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal, 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage, 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
22 7	21 5	21 4	21 2	5 29	5 73	6 61	18 9						
22 6	23 2	22 9	22 9	-2 65	-1 33	-1 33	13 5	13 2	13	13	2 22	3 7	3 7
26 8	23 2	23	22 8	13 43	14 18	14 93	20 4						
25 4	21 4	21 2	21 1	15 75	16 54	16 93	21 3						
24 2	24 4	24 1	23 9	-0 83	0 41	1 24	12 7	11 7	11 5	11 5	7 87	9 45	9 45
24 7	24	23 8	23 6	2 83	3 64	4 45	12	10 4	10 3	10 1	13 33	14 17	15 83
12 5	13 5	13 2	13 2	-8	-5 6	-5 6	21 5						
15 9	16	15 8	15 7	-0 63	0 63	1 26	17 2						
8 3	9 6	9 5	6 4	-15 66	-14 46	22 89	18 8						
9 6	9 7	9 6	9 5	-1 04	0	1 04	11 8						

Dimension 9

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
24							21 3						
23 4							21 6						
25 5							24 1						
20 4							14 2						
20 13							21 1						
13	10	10	9 8	23 08	23 08	24 62	12 1	11	10 8	10 7	9 09	10 74	11 57
14 3	12 2	11 9	11 8	14 69	16 78	17 48	14 1	12 3	12 1	12	12 77	14 18	14 89
9 4	8 2	7 9	7 8	12 77	15 96	17 02	10 6	9	8 9	8 7	15 09	16 04	17 92
9 3	8 1	7 8	7 6	12 9	16 13	18 28	16 1						
							25 1						

Dimension 10

pre-burning, 500oC for 15 minutes	post-burning, 5 mins after removal, 500oC for 15 minutes	post-burning, 15 mins after removal, 500oC for 15 minutes	post-burning, 25mins after removal, 500oC for 15 minutes	percentage shrinkage, 5 mins after removal, 500oC for 15 minutes	percentage shrinkage, 15mins after removal, 500oC for 15 minutes	percentage shrinkage, 25mins after removal, 500oC for 15 minutes	pre-burning, 500oC for 45 minutes	post-burning, 5 mins after removal, 500oC for 45 minutes	post-burning, 15mins after removal, 500oC for 45 minutes	post-burning, 25mins after removal, 500oC for 45 minutes	percentage shrinkage, 5 mins after removal, 500oC for 45 minutes	percentage shrinkage, 15mins after removal, 500oC for 45 minutes	percentage shrinkage, 25mins after removal, 500oC for 45 minutes
25	25	25	25	0	0	0	23.5	22.6	22.4	22.3	3.83	4.68	5.11
23.4	22.7	22.7	22.7	2.99	2.99	2.99	18.8	20	19.9	19.7	-6.11	-5.57	-4.40
22.9	20.9	20.9	20.9	8.73	8.73	8.73	17.6	18.2	18	17.9	-3.41	-2.27	-1.7
22.3	22.3	22.3	22.3	0	0	0	17.6	17.4	17.2	17	1.14	2.27	3.41
24	23.9	23.9	23.8	0.42	0.42	0.83	22.1	21.7	21.5	21.4	1.81	2.71	3.17
21.5	19.5	19.4	19.4	9.3	9.77	9.77	18.2	20.2	20.1	19.8	-10.99	-10.44	-8.79
25.9	23.3	23.3	23.3	10.04	10.04	9.81	20.1	19.2	19.1	18.8	4.48	4.98	6.47
26.2	25.2	25.2	25.2	3.82	3.82	3.82	21.5	20.3	20.2	20	5.58	6.05	6.98
24.6	23.2	23.2	23.2	5.69	5.69	5.69	17	17.4	17.1	17	-2.35	-0.59	0
27.4	25.2	25.2	25.2	8.03	8.03	8.03	17.7	16.4	16.2	16.1	7.34	8.47	9.04

Dimension 10

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage, 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage, 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
24	20	19.8	19.8	16.67	17.5	17.5	20.3						
24.6	20.5	20.3	20.2	16.67	17.48	17.89	22.1	20.6	20.4	20.2	6.79	7.69	8.6
22.6	20.8	20.5	20.3	7.96	9.29	10.18	20.8						
21.9	20	19.9	19.7	8.68	9.13	10.05	21.5						
24.3	.				.	.	21	.	.				
23.8	23.9	23.8	23.2	-0.42	0	2.52	19.9	18.5	18.3	18.2	7.04	8.04	8.54
22.6	22.1	22	21.8	2.21	2.65	3.54	20.8	.		.			
21.1	20.8	20.6	20.2	1.42	2.37	4.27	20.8				.		
6.4	5.8	5.8	5.6	9.38	9.38	12.5	19.8	19.8	19.5	19.4	0	1.52	2.02
6.9	6.7	6.6	6.4	2.9	4.35	7.25	19.3	18.4	18.2	18	4.66	5.7	6.74

Dimension 10

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage, 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage, 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
23.8	21.4	21.1		10.08	11.34	.	26.4	.	.			.	
24.3	.			.	.	.	25.5	.	.	.	.		
21.4	20.9	20.6	20.1	2.34	3.74	6.07	20.7	20.3	20.1	19.9	1.93	2.9	3.86
23.4	20.8	20.5	.	11.11	12.39	.	20.4	17.4	17.1	17	14.71	16.18	16.67
22.86	20.9	20.7	20.5	8.57	9.45	10.32	23.7	.		.	.		
24	24	23.8	23.6	0	0.83	1.67	18.4	.		.	.		.
24.6	23.5	23.4	23.1	4.47	4.88	6.1	19.3	17.6	17.4	17.2	8.81	9.84	10.88
8.5	6	5.8	5.6	29.41	31.76	34.12	8.7	7.1	7	7	18.39	19.54	19.54
8.2	.	.	.	.	.		27	.			.	.	.
17.1	.	.	.	.		.	22.4	18.8	18.5	18.4	16.07	17.41	17.86

Dimension 11

pre-burning, 900oC for 15 minutes	post-burning, 5 mins after removal, 900oC for 15 minutes	post-burning, 15 mins after removal, 900oC for 15 minutes	post-burning, 25mins after removal, 900oC for 15 minutes	percentage shrinkage 5 mins after removal, 900oC for 15 minutes	percentage shrinkage, 15mins after removal, 900oC for 15 minutes	percentage shrinkage, 25mins after removal, 900oC for 15 minutes	pre-burning, 900oC for 45 minutes	post-burning, 5 mins after removal, 900oC for 45 minutes	post-burning, 15mins after removal, 900oC for 45 minutes	post-burning, 25mins after removal, 900oC for 45 minutes	percentage shrinkage 5 mins after removal, 900oC for 45 minutes	percentage shrinkage, 15mins after removal, 900oC for 45 minutes	percentage shrinkage, 25mins after removal, 900oC for 45 minutes
18.4	18	18	18	2.17	2.17	2.17	20.5	20.2	20.1	20	1.46	1.95	2.44
18.5	17.5	17.5	17.5	5.41	5.41	5.41	16	16.7	16.5	16.3	-4.38	-3.13	-1.88
20.8	19.9	19.9	19.9	4.33	4.33	4.33	14	13.8	13.6	13.5	1.43	2.86	3.57
21.8	19.1	19.1	19	12.39	12.39	12.84	15	15.1	15	14.8	-0.67	0	1.33
18.2	16.5	16.5	16.4	9.34	9.34	9.89	20.3	20.5	20.3	20.2	-0.99	0	0.49
21	19	19	19	9.52	9.52	9.52	13.9	14.6	14.4	14.3	-5.04	-3.6	-2.88
18.5	16.4	16.4	16.4	11.35	11.35	11.35	14.2	14.6	14.4	14.2	-2.82	-1.41	0
19.8	17.7	17.7	17.7	10.61	10.61	10.61	11.2	10.8	10.6	10.4	3.57	5.36	7.14
18.4	18.2	18.2	18.2	1.09	1.09	1.09	14.2	14.2	14.1	13.9	0	0.7	2.11
15.1	13.3	13.3	13.3	11.92	11.92	11.92	13.6	13.2	13.1	13	2.94	3.68	4.41

Dimension 11

pre-burning, 700oC for 15 minutes	post-burning, 5 mins after removal, 700oC for 15 minutes	post-burning, 15mins after removal, 700oC for 15 minutes	post-burning, 25mins after removal, 700oC for 15 minutes	percentage shrinkage 5 mins after removal, 700oC for 15 minutes	percentage shrinkage, 15mins after removal, 700oC for 15 minutes	percentage shrinkage, 25mins after removal, 700oC for 15 minutes	pre-burning, 700oC for 45 minutes	post-burning, 5 mins after removal, 700oC for 45 minutes	post-burning, 15mins after removal, 700oC for 45 minutes	post-burning, 25mins after removal, 700oC for 45 minutes	percentage shrinkage 5 mins after removal, 700oC for 45 minutes	percentage shrinkage, 15mins after removal, 700oC for 45 minutes	percentage shrinkage, 25mins after removal, 700oC for 45 minutes
16.2	17.7	17.6	17.4	-9.26	-8.64	-7.41	15.1						
16	17.8	17.5	17.3	-11.25	-9.38	-8.13	14.8	13.6	13.5	13.3	8.72	9.4	10.74
17.2	16.9	16.7	16.3	1.74	2.91	5.23	14.8						
16.9	15	14.8	14.8	11.24	12.43	12.43	16.4						
22.4							15.1						
22.2	21.9	21.7	21.4	1.35	2.25	3.6	15.7	14.5	14.5	14.2	7.84	7.84	9.96
14.5	14	13.8	13.8	3.45	4.83	4.83	16.6						
13	12.5	12.3	12.2	3.85	5.38	6.15	14.4						
3.2	2.4	2.4	2.3	25	25	28.13	13.9						
3.9	3	3	3	21.88	23.08	23.08	14.5	14.1	14	13.9	1.4	2.1	2.8

Dimension 11

pre-burning, 800oC for 15 minutes	post-burning, 5 mins after removal, 800oC for 15 minutes	post-burning, 15mins after removal, 800oC for 15 minutes	post-burning, 25mins after removal, 800oC for 15 minutes	percentage shrinkage 5 mins after removal, 800oC for 15 minutes	percentage shrinkage, 15mins after removal, 800oC for 15 minutes	percentage shrinkage, 25mins after removal, 800oC for 15 minutes	pre-burning, 800oC for 45 minutes	post-burning, 5 mins after removal, 800oC for 45 minutes	post-burning, 15mins after removal, 800oC for 45 minutes	post-burning, 25mins after removal, 800oC for 45 minutes	percentage shrinkage 5 mins after removal, 800oC for 45 minutes	percentage shrinkage 15mins after removal, 800oC for 45 minutes	percentage shrinkage, 25mins after removal, 800oC for 45 minutes
21.3	19.5	19.2		8.45	9.86		24						
21.6							22.2						
17.5	15.7	15.5	15	10.29	11.43	14.29	17.4	15.2	15	14.8	12.64	13.79	14.94
16.5							14.3	11.9	11.3	11.1	16.78	20.98	22.38
16.4	14.2	14	14	13.41	14.63	14.63	15.8						
15.3	15.2	13.7	13.6	0.65	10.46	11.11	12.6						
15.1	14.3	14.1	13.9	5.3	6.62	7.95	16.8	14.5	14.3	14.2	13.69	14.88	15.48
5.5	4.2	3.9	3.6	23.64	29.09	34.55	2.7	1.7	1.7	1.6	37.04	37.04	40.74
9							15						
14.2							16.4	15.1	14.9	14.8	7.93	9.15	9.76

Stick Boy and Match Girl in Love

Stick Boy liked Match Girl,
he liked her a lot.
He liked her cute figure,
he thought she was hot.

But could a flame ever burn
for a match and a stick?
It did quite literally;
he burned up pretty quick.

Tim Burton, 'The Melancholy Death of Oyster Boy
& Other Stories', 1997