Teeth, age at death, and archaeology: the application of tooth histology as a means of determining age at death for human remains.

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Abstract.

Dental tissue has, in the past, been examined by forensic scientists as a means of determining the age at death for individuals. Although established in the realm of forensic science these methods have not yet seen any widespread use by archaeologists. This dissertation critically examines the age determination methods of Gustafson, Johanson and Bang and Ramm, and attempts to derive some statistically valid means of using multiple age determinations made by these techniques. The means developed are then applied to some ancient, archaeological specimens. Finally a model for the formation of sclerotic dentine is developed, using both original data, and data published in the literature.

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Chapter One: Introduction

1.01 Why is knowing age at death important?

Science's inability to accurately determine the age at death of an individual is a matter of concern in two areas of research: forensic science in cases where a body's age at death is required for subsequent identification of that body, and in the study of past populations where age at death is needed in the study of pathological process and where age at death is needed in the study of the demography of a past population.

It is particularly in the latter, palaeodemography, that an accurate estimation of the age at death is both difficult and important. Ascadi and Nemeskeri (1980:p.100) consider knowing the age at death of an individual of more importance than knowing the sex. This point is debatable, but it remains that age and sex are two fundamental biological characteristics of people (Ascadi & Nemeskeri, 1980:p.100) which are vital to the demographic reconstruction of past human populations.

1.02 Existing methods of age determination.

Skeletally based methods of age determination are broadly split into two major groups: those which are based upon developmental changes in young individuals, and those which are based upon degenerative changes for individuals which have reached full skeletal and dental maturity.

For individuals who died before full maturity was reached several different methods exist based upon the developmental sequence of the skeleton. McKern and Stewart (1957 as cited in Bass, 1987.p.18-19) used epiphyseal union of the major long bones to estimate age of males in the 18-24 year age band. Anderson et.al. (1964 as cited in Bass, 1987.p.237) used the lengths of long bones from children to draw up tables of mean lengths for ages in the 1-18 year range using one year age increments. Ubelaker (1978) produced a chart describing dental eruption which is considered (Bass, 1987.p.289) as the most accurate method of determining the age of a young individual.

The major problem with these means of ageing is with sex. Generally females mature by some two to three years ahead of males. As determining the sex of a sub-adult individual is nearly impossible with any confidence then there will always be some error in any technique. However the overall picture for age estimation for young individuals is satisfactory, with good precision and reliability (see Figure 1).

Figure 1. Relative precision of various ageing techniques.

Precision for age band methods of age determination estimated, however this graph does show
how precision varies with age, and the general lowering of precision with increasing age of the skeletally based methods. The same is not true for adult age at death determination. Because juveniles undergo relatively large changes in a short space of time age determination is easy as small fluctuations and variations in the development sequence are going to make little difference to the resultant age. By contrast degenerative changes in adult human skeletons are slow. This means that a small amount of variability in the ageing criteria is going to make a large inferred age difference. Also the main causal factor in determining the rate of growth of a person is their biological nature. Nutrition can play a major part, but as long as an individual is not at the extremes of nutritional deficiency then their bodies will develop at more or less the same rate as those who are biologically similar. With adult ageing more factors come into play. Metabolism, although biologically determined, varies greatly from individual to individual within a given human population. This has the effect that a short, plump, highly stressed fast maturer can look some ten to twenty years older than their chronological age, and a slim, low stressed, slow maturer can look five to fifteen years younger than their chronological age (Angel, 1984). Again living circumstances can lead to a greater variability. Dietary deficiency in someone forty years old has had forty years in which to make it's impact on the human skeleton, compared to someone who has not had that deficiency then there will be increasing divergence with time in any affected skeletal property. Lastly is the tendency of the human body to cease systematic change, changes becoming in effect random, at about the age of fifty (Ortner, pers.comm.) (see Figure 1).

All these factors are reflected in the standard skeletal methods of age at death determination.

In their re-evaluation of Todd's method of age determination (1920,1921, as cited in Katz & Suchey,1986); Katz and Suchey used pubic bone morphology as a means of predicting age of death. Using Katz and Suchey's (1986) tables it is possible to see the increase in variability (Katz & Suchey,1986: Table 5) with increase in age, this is reflected as increasing standard deviation. It becomes impossible to discriminate between individuals of different ages who are older than fifty. Similarly Gilbert and McKern's (1973) attempt to extend Todd's (1920,1921) ageing method to females found large variability in the method, again the variability increases with age, and yet again distinguishing between individuals of different ages was not possible beyond the mid-fifties.

Reliable estimates have been claimed for a method developed by Lovejoy et.al. (1985), who developed a technique based upon the morphological characteristics of the auricular surface of the ileum. This method seems to give consistent variability across the age ranges, and is extendible up to the age of sixty

Other methods of age determination from the skeleton exist: sternal end of rib ossification (Iscan et.al.1984,1985), cranial suture closure (Ascadi & Nemeskeri,1980); although the population used to develop this method (reference population) is felt to have unreliable age at death data. These all suffer from very much the same problems as pubic morphology and auricular surface in that they are all based upon broad banded phases of development, the morphological traits of which are not very distinct from one phase to another. Means for dealing with this have been suggested (Lovejoy et.al. 1985), and usually revolve around modifying the age estimate in the light of secondary morphological characteristics; this leads to the suggestion of subjectivity playing a major part in
skeletally based methods of determining age at death (Konigsberg & Frankenberg, 1992).

1.03 Criticisms of palaeodemography and skeletally based methods of age determination.

Since early use at Lerna by Angel (Angel, 1969) the life table, whilst becoming increasingly sophisticated (Williams, 1992), has risen to become one of the most important conceptual tools in palaeodemography (Moore et al., 1975). The idea behind a life-table is to assume a stable population (Moore et al., 1975), that is a population that does not increase significantly in size; assign, based upon the age at death, cohorts, or age categories, and from there be able to estimate fertility of the population, morbidity, health or otherwise, and other demographic factors (Wood et al., 1992).

The criticisms of Weiss (1975) refer mainly to preservation and representation in the skeletal record, but are still pertinent to inaccuracy in ageing; namely that fluctuating populations and infant under-enumeration would grossly distort the life-table. This has largely been answered by Moore et al. (1975), who demonstrated that perturbations in the infant population would not be reflected in later age cohorts.

The major recent criticism of palaeodemography has been made by Bocquet-Appel and Masset (1982), basing their work on graveyard populations as a guide for some European, American and Asian mortality tables. What they said was that the age structures of ancient populations tended to resemble the age structures of their (modern) reference populations; and if the biological ageing factor has a correlation of 0.90, or less, any conclusions derived from that age structure would be statistically untenable, as perceived fluctuations in the age structure would amount to little more than stochastic fluctuations. They (Bocquet-Appel & Masset, 1982) called for new forensic standards to be applied to archaeological remains.

A reply to Bocquet-Appel and Masset's (1982) criticisms came from Van Gerven and Armelagos (1983), who used their own work on the Nubian skeletal populations from Wadi Halfa and Kulubnarti to demonstrate that the age structures did not resemble their reference populations. The second contention, that perceivable fluctuations in age structure amounted to little more than stochastic fluctuation, was answered by criticising Bocquet-Appel and Masset's method for comparing mortality amongst the !Kung to that of a modern graveyard population.

Although it is conceivable for some age structures of ancient populations to reflect that of their reference populations by mere chance. Van Gerven and Armelagos (1983) have demonstrated that it is by no means a fault inherent to the methodology. However the uncomfortable fact remains that lack of precision in the age determination can lead to palaeodemographic perturbations which look as though they have a population based cause, but are really stochastic in origin.

Hedges' (1982) work on the skeletal population of the Neolithic chambered tomb of Isbister neatly illustrates how age structure can affect social interpretation. Hedges starts by compiling a life-table for excavated material from Isbister. From the life-table he deduces that life-expectancy
was small, even for individuals in their mid-teens, he says that few survived beyond the age of forty. It is this short life expectancy that leads Hedges to suggest social problems with the handing on of specialist knowledge, and problems with sustaining population. Hedges makes it explicit that this is a tentative interpretation, and it is probably for the sake of arriving at a more interesting conclusion that he overlooks the rather mundane possibility that only a limited age range of people might have been buried in the chambered tomb; but it is also possible that the ageing techniques used to determine the age at death for individuals in the population were consistently under-ageing. Whatever criticisms there can be of Hedges' methodology it is a brave attempt to extract social meaning from skeletal remains.

From these arguments (above) it is apparent that age at death determination from the physical remains of past peoples is important if social reconstruction is to have any rigorously applied meaning, and that currently there are limitations to the abilities of palaeoosteologists to determine that age at death.
1.04 The problem with the assumption of uniform process

The work of Meindl et.al. (1983) highlights another problem with skeletally based techniques of ageing. Their work attempted to combine ages for the Hamann-Todd Collection using five ageing methods multi-varietally. Their first surprising finding was that techniques involving auricular surface and pubic symphysis consistently predicted the age of an individual as being lower than the known historical age. The reason why they found that their predicted ages were systematically biased in the first instance was not because the original techniques of pubic symphysis and auricular surface were incorrectly stated, but that their population (target population) was just not biologically the same as the reference populations. This is not just a methodological problem with ageing techniques, but one of the deeper theoretical problems.

We cannot assume that because people have certain age related phenomena now that the same phenomena operated in exactly the same way in the past. With different modern peoples we are in a position to verify, or refute, this assumption, but the past presents a greater problem (in fact as archaeologists it is one of the things in which we are interested). Howell (1976: p.27) cites Silberbauer (1965: pp.15-17) on the modern Naron speaking San people, who live only a few hundred miles from the !Kung speaking San people whom Howell (1976) studied.

'Bushmen age rapidly in their appearance and an individual who, one is quite certain, could not possibly be less than seventy years old, proves to be no more than 40. ... Life expectancy among Reverse Bushmen is difficult to calculate, but I do not believe that many live beyond 45.'

Silberbauer,1965 (in Howell,1976)

The San !Kung manifest none of the rapid ageing seen in the Naron. Strangely Howell (1976) goes on to argue for the assumption of uniform process, not because it is necessarily believable, but because it is a convenient way of looking at past demographic processes. The problem with this argument is that, from Howell's (1976) evidence human populations have clearly not been the same throughout time, and in any case one of the objectives of studying the past is to see how different, and in what ways, the past is from the present. Otherwise there is little point in studying the past at all.

One way in which this could be tackled is by testing our age determination techniques against the disinterred remains of people of known age from the past. However, this has the problem that epigraphic information does not necessarily reflect the 'true' population. For example, the many Roman graves found throughout Western Europe have a disproportionate frequency of individuals dying at five year intervals, the ages of legal maturity and one hundred again having large numbers of deaths associated with them. This is due to deliberate rounding up of the age at death, either because the individuals 'true age' was not known, or to these ages being somehow important (Ascadi & Nemeskeri,1980: p.69). This means we can have little reliable knowledge of past populations 'true
age’ at death with which to judge whether our methods of predicting age at death are going to work at the same rate for people in the past as for the modern individuals from which those methods are derived.

1.05 Chronological age versus biological age.

All the arguments (above) beg the question: why do we need chronological age at death at all? Why not just have biological age at death?

Archaeologists and social anthropologists primary aim is to develop a sense of the societies with which they deal. To do this they try to arrive at an emic sense of meanings for that society, that is meanings which mean something in the terms (mental constructs) of the people with which they deal. In some societies chronological age has no meaning. In many Tropical African census researchers had difficulties in recording ages because the people of those societies did not know their age, and were not 'fundamentally interested in knowing them'; people in those societies belonged to those age sets in which they appeared to belong (van de Walle,1968. as cited in Konigsberg & Frankenberg,1992). If this is so then why should age be of importance to Western palaeodemographers, why not just apparent (biological) age.

One of the problems with biological age is it's ephemeral nature. As has been shown in the work of Meindl et.al. (1983, cited above) some ageing techniques were consistent, others were not. This implies that for some populations some ageing characteristics 'age faster' than others. This means that there is no one fixed biological 'age' for any human being, but many different biological ages for different parts of that individual.

Archaeologists and social anthropologists are also interested in comparing societies. This can be done on a basis examining differences in social roles between various age sets, but only by having some external assessment of age can they really come to some understanding of what a social age set means between differing societies. The same argument applies to medical historians. It might appear that they are interested in what diseases occur at which ages (despite current difficulties in determining age/disease relationships from a skeletal population), and that only biological ages are really important, but what is also of interest to a medical historian is if a biological age varies systematically from population to population. This can only be determined by reference to an independent outside age, which would have to correlate systematically with chronological age.

1.06 Other criticisms of palaeodemography and skeletally based methods of age at death determination.
One of the problems with transferring skeletally derived ages to life-tables is that the age categories given in the ageing method are larger than the age categories in the life table. For example the age categories given for the iliac auricular suture method (Lovejoy et.al. 1985) start with five year gaps for those under twenty, and end with a thirty-five to fifty year age group. For a palaeodemographic life-table the requirement is one of evenly spaced groups, usually either five or ten years. Recently new statistical methods have been brought to bear on this problem (Konigsberg & Frankenberg, 1992), principally to overcome some of the problems with 'age mimicry' stated by Bouquet-Appel and Masset. However two problems still exist. The first is that the age probability cannot be considered to be continuously distributed, and secondly there is a 'loss of resolution' in the age groups. The problem with non-continuous age distributions is that it is difficult to compare population fluctuations in younger age groups, for which narrow age ranges exist, with similar fluctuations in older age groups, where broader age ranges predominate. This has been overcome to some extent by Konigsberg and Frankenberg (1992) calculating maximum likelihood for any given age. The 'loss of resolution' is a problem because any fluctuations in 'real age' will be masked by the smoothing effects of the statistical procedures designed to remove stochastic fluctuation; that is, any real perturbations will be indistinguishable from stochastic fluctuation. The only solution to this problem is to implement new forensic techniques and standards. Konigsberg and Frankenberg (1992) consider it more important that ageing criteria are used in palaeodemography which will give a certain uniformity throughout humanity and time, rather than being precise. The drawback to low resolution in archaeological age structures is that all archaeological populations will start to look the same, in that it would no longer be valid to examine the detail of mortality as any perceivable changes, no matter how biologically well founded, might merely be an artifice of the methods used to arrive at the ages at death.

1.07 Summary.

It is clear that whilst determining the age at death for a child or sub-adult, methods in use today are both accurate and precise; not so for those techniques used to tell the age at death for an adult. The main problems seem to be inaccuracy, lack of precision, bias, and confusion over statistical treatment of a probabilistic determination of age. Even were the problems involved overcome by new forensic standards for age at death determination then it is unlikely that the new techniques could be upheld for all humanity, throughout all time.
Chapter two: Teeth and age at death.

2.01 A brief history of age determination using teeth.

The earliest attempt to deduce age from dentition was in 1836 when Thompson said that if the first permanent molar had not erupted then a child could not possibly be above their seventh year (Miles, 1963). Thompson's main concern as a medico-legal expert was that under British law at the time a child under the age of seven was incapable of committing a criminal act. It was again legislation which a year later led to a method for distinguishing children between nine and thirteen. The factory act of 1833 forbade children between the ages of nine and thirteen from working more than nine hours per day. The criteria for determining age was that the child should be of normal strength, and this obviously led to widespread evasion of the provisions of the act. In 1837 Edwin Saunders put before both houses of Parliament a means by which the ages of children could be assessed by relatively untrained people (Miles, 1963).

This line of research has been developed up to the present day with common usage of tables in archaeology, anthropology and forensic science outlining dental development such as those by Schour and Massler (1941) and Gustafson and Koch (1974: as cited in Hillson 1986a).

The earliest use of macro-structural traits was by Bodecker (1925: as cited in Costa, 1986) who studied secondary dentine formation in relation to age. The earliest systematic attempt to use macro-structural change was Gustafson's (1950) method (see later). Improvements to Gustafson's method came from Johanson (1971), a student of Gustafson, who used essentially the same criteria as Gustafson but a different statistical treatment of change. Successful attempts have been made to use other methods. Bang and Ramm (1970) used transparent length as a basis for the estimation of age.

More recently methods based upon the chemical properties have been devised, for example Bada (1976) used amino acid racemisation, although there are doubts about its applicability for archaeological specimens (Gillard et al. 1990).

Strangely enough, despite the uptake by forensic scientists of these techniques, and the better precision than skeletally based methods claimed for both the Gustafson method and the root-transparency method, little attempt has been made to apply them to archaeological material. This is because for routine skeletal reports resources and expertise are limited, and such resources that exist are channelled away from dental work (Hillson pers.comm.). The only published work to date being Hillson (1986a), who determined the age of an individual from Doukanet El Khoutifa, Tunisia, as 81±5 years.

2.02 The degenerative changes in teeth with age.
Once a human tooth is fully formed and has reached the occlusal plane there are six major changes which are seen with increasing age.

Secondary dentine: Bodecker (1925, as cited in Costa, 1986) noted that the deposition of secondary dentine in the pulpal chamber grew with increasing age. Gustafson (1950) used the apposition of secondary dentine as one of his six criteria for age determination. Johanson (1971) thought that deposition of secondary dentine on the walls of the pulpal chamber was more related to age (see Plate 2 in Appendix 4), the deposition on that part of the pulpal chamber closest to the occlusal surfaces being partially as a response to attrition, therefore pathological in origin. Secondary dentine deposition is only loosely correlated with age, there being high inter-individual variability (Johanson, 1971).

Cementum build-up: Zander and Hurzeler (1958) studied sectioned teeth from fifty-four people under twenty, and seventy teeth from those in the fifty-one to seventy-six year age band, and found that the cementum thickness tripled. Attempts by Zander and Hurzeler to resolve this more closely found a large inter-individual variability, and this was confirmed by Johanson (1971), who found a low correlation with age and thought that independently it was a very poor indicator of age. Stott, Sis and Levy (1982: as cited in Hillson, 1986b: p.198) found that in hibernating mammals cementum is laid down in annual rings. They examined this possibility for three human cadavers, achieving the impressive accuracy of no more than four years deviation from the true age. Hillson points out (Hillson, 1986b: p.198) that although it offers potential, the variable quality of preservation of cementum is likely to obscure fine details such as cementum rings (see Plate 2 in Appendix 4).

Recession of the gingiva: In teeth with healthy attachment to the alveolar bone the gingiva will be attached at a point near the cemento-enamel junction. As age increases then the likelihood of an individual having had an episode of inflammation of the gingiva, leading to a minor peridontosis, increases (see Plate 2 and 3 in Appendix 4). This means that the point of attachment to the alveolar bone, hence the extent of minor remodelling of the tooth which is in contact with the alveolar bone, will travel down the tooth with increasing age (Johanson, 1971). Costa (1986) says that this is population dependent. In European and modern American populations periodontal disease is rampant, to the extent that it is responsible for tooth loss; but in other populations this is not so. Again Johanson (1971) found that there was a very poor correlation between recession of the gingiva and age.

Root resorption: Resorption of the roots in deciduous teeth during formation of permanent teeth is part of the dental development process. Resorption of the apical end of the root in permanent teeth is considered pathological (Costa, 1986). There is some debate about the sequence of resorption, Johanson (1971) says that resorption starts from discrete areas on the cement and can be seen as pitting, even on young individuals; on older individuals the number of resorbed areas increases, as does the amount of material resorbed. Costa (1986) says that resorption rarely occurs
below the age of fifty, thus is only useful in older individuals. Both are agreed that there is a poor correlation with age, and difficulties in measurement of resorbed root.

**Attrition:** Once a tooth has reached the occlusal plane it begins to wear out. The normal processes of mastication of food and contact between opposing teeth first wear the enamel down, then the dentine (see Plates 2 and 5 in Appendix 4). Once this stage is reached the rate of wear is increased, some teeth being worn down as far as the pulpal chamber. Brothwell (1981) devised an ageing method based on the pattern of dentine exposure on the cusps of molars based upon his work on Neolithic and Medieval skeletal material from Britain. This method had the drawbacks that it used ten year age ranges, and its upper age limit was forty-five. One of the problems with dental attrition is that it is diet, hence population dependent. Miles (1963), in order to overcome this, used Anglo-Saxon skeletons from Breedon-on-the-Hill to built up an internally calibrated series for that population. What he did was to assume a period of six years between the first and second molars coming into the occlusal plane. By noting the difference in the attrition between the two, Miles was able to estimate age by examination of the third molar which comes into occlusion some six years after the second. Hillson (1986b: p.197) points to some criticisms of Miles' method, namely that there is variability in the ages at which various teeth come into the occlusal plane, and the assumption of uniform wear between teeth. Hillson (1986b: p.197) suggests that the former could be accounted for by examination of the internal microstructure.

**Figure 2. Schematic tooth section displaying no transparency.**

**µ Transparency:** Transparency is a change in the macrostructural detail of the dentine. The matrix of dentine comprises a 'felt' like structure of highly calcified tissue. The major gross macrostructural element of dentinal matrix is the tubule, which contain the odontoblastic process of the living dentine forming cells. These run radially from the dental pulp to the enamel-dentine junction (Jenkins, 1966: p.153) (see Figures: 2 and 3). As an individual grows older calcium salts are deposited into the tubules nearest to the root, causing those tubules to have the same refractive index as the material surrounding them (peritubular dentine), hence they become transparent to transmitted light (Nalbandian *et al*. 1960: as cited in Jenkins 1966: p.178). The effect is that there is a transparent zone of dentine running from the apex of the tooth some way up the tooth, increasing in extent with age (see Plates 1, 2, 3 and 5 in Appendix 4). This will be dealt with in more detail later but has been found to have the highest correlation to age (Costa, 1966: Johanson, 1971).

**µ Figure 3. Schematic tooth section displaying transparency**

Other changes in teeth include: discoloration, teeth tend to turn more yellow, or brown, with age. This is due to the build-up of secondary dentine, itself darker than primary dentine, the greater transparency of primary dentine, and the adsorption of metallic ions into the surface of the enamel (Costa, 1986). Also cementum tends to get less permeable as age increases, this is thought to be due to a layer of calcium salts forming in the outermost layers of the cementum during later life (Jenkins, 1966: p.181).

The hardness and density of all three main dental tissues increases with age. Kani (1954: as
cited in Costa, 1986) measured the specific gravity of teeth and found that it increased slightly with age. Kato (1956: as cited in Costa 1986) found that teeth became more brittle with age. This effect concurs with the generally more heavily mineralised aspect of older teeth.

There is also an accumulation of heavy metals in the dentine which can be related to age. The concentrations of lead have been found to be highest in dentine and lowest in enamel from a sample of individuals in Strasbourg (Frank et al. 1988).

2.03 Gustafson's technique.

\[\text{Figure 4. Gustafson's points for a young tooth.}\]

Gustafson (1950) used the six major criteria outlined above. Gustafson realised that no single age related process was highly correlated with age, so he used them together in a crude multi-variate system. Each of the six changes were divided into four separate stages of development. Attrition was awarded one point when the enamel had been worn away through half its thickness, two points when the dentine was showing, three when it had been worn through to the pulp. Secondary dentine was awarded one point if present, two if the pulpal chamber was half full, and three if the pulpal chamber was completely full of dentine. Periodontal changes were given one point for a small change in the position relative to the cemento-enamel junction, two were remodelling in evidence along the first third of the root, and three for two-thirds of the root. Resorption had one point awarded for a small amount of pitting, two for greater loss, and three for some damage to the underlying dentine. Cementum build-up was awarded one point for a small increase in cement thickness, two for a noticeable increase, and three for a heavy layer being present. Transparency was denoted as one point for a perceivable area of light transmitting dentine, two when the sclerotic zone extends over the apical third of the root, and three if the apical two-thirds to be sclerotic (see Figures 4 and 5). Figure 5. Gustafson's points for an older individual.

Gustafson examined some nineteen teeth, adding their point scores and then regressing the totals against known age. He then tested the technique by taking some forty-two teeth from known age individuals and calculating ages for them.

2.04 The problems with Gustafson's method.

Bang and Ramm (1970: p.29) suggested that Gustafson's age related changes, and the way in which they were measured were subjective, but this is not wholly so. Of the six criteria only cementum build-up and resorption are not measurable, the rest are fairly well defined in terms of the relative geometry of the tooth, thus giving an objectivity to the measurement and the method.

Most of the problems referred to in the literature cite Gustafson's errors as being in doubt. Gustafson claimed the errors were 3.6 years at one standard deviation, although this has been a point of some controversy. Other workers have been unable to replicate this figure. Bang and Ramm said (1970: p.29) that they were unable to achieve 3.6 years, but that they got 7.2 years. However if Gustafson's results are actually examined it appears that the errors are in fact 7.2 years, the 3.6 year error coming from the first sample of nineteen specimens. In fact no subsequent work has been able
to support Gustafson's initial error of 3.6 years (Pilz, 1959: as cited in Costa, 1986) (Nalbandian et al., 1960; Miles, 1963). Lately it has been found (Maples & Rice, 1979) that Gustafson used the original batch of nineteen, from which he derived his calibration curve, in amongst the batch of forty-two teeth to test the method; although Gustafson in the early paper (Gustafson, 1950: p.51) clearly states this was the case, and that the said teeth were examined blind. This might have been the explanation behind the anomalously low errors of Gustafson's original paper.

2.05 Johanson's modification of Gustafson's method.

Johanson (1971) used Gustafson's four point system with the additional increments of half points to account for changes in the tooth which were half-way between Gustafson's very widely spaced states. Johanson used multi-regression to construct a new set of calibration lines for the method, noting that cementum apposition and transparent dentine were the highest correlated to age.

Interestingly Johanson found that ages could be predicted more precisely for females than males, and that ages for either could be predicted more accurately than both. This demonstrated some sex dependence of the method (Johanson, 1971).

In some ways, although the half points do add resolution to the method, they make it less objective. However if one of the criteria, for example attrition, is between its one and two state, that is it displays more wear than half of the enamel but is not worn down to the dentine, then using single point notation we have a measurement error of half a point. If a half point is introduced, and it is incorrectly applied, were the whole points correctly applied, then the maximum measurement error is still half a point. In practice it is difficult to misapply points as the changes are fairly clear, and nothing is lost. So having a system which use half points can gain in resolution, whilst potentially losing nothing.

2.06 Bang and Ramm's Method.

Bang and Ramm (1970) used root dentine transparency as the basis for their ageing method. They used 1013 teeth from 201 individuals, and of these 87 teeth were unusable for their purposes. Bang and Ramm first studied a random 510 single rooted teeth to construct calibrations for transparency versus age, and later used 168 teeth to test their models. Problems were encountered when the transparent portion of the dentine did not terminate equally on both sides of the root canal, and they treated these cases by averaging the two measurements (Bang & Ramm, 1970: p.4). From all samples they found a coefficient of determination of 0.70, and having treated each tooth in the mouth separately, errors on their calibration curves which varied from four to fifteen years, dependent on tooth. Bang and Ramm arrived at two models, one for teeth displaying less than 9mm of transparent length, a second order polynomial; and one for 9mm or greater of transparent length, a linear function. They found no sex difference in the rate at which sclerotic dentine forms (Bang &

As well as cutting 400µ longitudinal sections, they examined intact teeth. They found that they could discern the extent of the sclerotic front without having to section the tooth; however they give no method recording the details of this procedure.

Bang and Ramm measured the total length of the individual teeth, and found that there was no suggestion that the size of any tooth had any effect upon the rate of sclerotic front advancement (Bang & Ramm, 1970: p.30). They also started to measure the area of the sclerotic region, but this was discontinued for reasons unstated (Bang & Ramm, 1970: p.10).
Chapter three: Experimental aims and methods.

3.01 Experimental aims.

The three main areas of concern which form the aims of this project are:

1. Testing against known age specimens, to gain some idea of how applicable the methods devised by Gustafson, Johanson and Bang and Ramm are when used away from the population on which they are based.

2. Developing some statistically valid means of using the methods in combination with each other to obtain more accurate, more reliable predictions of age, with greater precision.

3. To attempt to throw some light on the processes leading to the formation of the phenomena of sclerotic dentine.

As many attempts have been made to devise age determination methods from teeth from essentially the same measurements, any new method is unlikely to add to the sum of knowledge about age prediction, and is unlikely to be any more successful. This project has explicitly avoided producing yet another regression equation, and has instead concentrated on evaluating existing methods and the use of new statistical treatments to existing methods of age determination.

3.02 The sample.

Some 110 extracted teeth were collected over an eight month period from the Oral Surgery Department, at St. Lukes Hospital, Bradford. Of these only thirty-three were selected for sectioning because that of the 110, 77 were from those individuals under twenty years of age, thus were not really suitable for age determination by Gustafson's, or Bang and Ramm's methods.

Eight loose teeth from four individuals were selected from Medieval Chichester's skeleton collection, curated at Bradford University, six teeth from a cremation site and one tooth from the prehistoric site of Ferrybridge. None of the historical-archaeological teeth came from known age at death individuals. Of the modern sample: 15 came from males and 18 from females (see Table 1 for rough age categories).
Table 1. Age groupings of sample used in experimental work.

<table>
<thead>
<tr>
<th>Age group</th>
<th>0-20</th>
<th>21-30</th>
<th>31-40</th>
<th>41-50</th>
<th>51-60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>3</td>
<td>12</td>
<td>15</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

These cannot be said to have an even age distribution, but the range 20-40 was evenly represented.

Molars account for about 90% of all teeth used in this project and were used because few anterior teeth are extracted in modern reparative dental practice. Molars are cited as a source of unreliability by Bang and Ramm (1970: p.19) who said that were there a choice of teeth, then the best age predictions could be made by excluding upper first pre-molars and all molars. Pilz too (1959: as cited in Johanson,1971: p.79), when reporting on an evaluation carried out by Seifert, says that molars were more variable than anterior teeth. Johanson recommends that if at all possible anterior teeth should be used (Johanson,1971: p.122).

It seems as though molars are the worst possible case in terms of their variability, but there are other considerations. Molars are often crowded in the jaw, this leads to roots that are twisted to such a degree that it is impossible to cut a single section which includes the apical foramen and crown. Fused roots, a common occurrence with molars, also make for great difficulties when both cutting sections and trying to observe the age related changes. So really the sample used in this project is in some ways the worst possible sample, and any improvements made to age at death predictions should be regarded as the least improvement which can be made.

The sample naturally divides itself into two sub-samples. The first is that sub-sample from which measurements of Gustafson-Johanson points could be made; this included the entire sample of 77 roots from 35 individuals. The second was that sub-sample for which transparency could be measured, this comprised 35 roots from 17 individuals. As for much of the comparative work in this project it was incorrect to directly compare the sub-samples because of the size difference, the two groups have for the most part been treated separately.

3.03 Experimental procedure.

The modern teeth were soaked in a 40% solution of Formaldehyde for 24 hours, 100%
methanol for 24 hours, to neutralise both hydrophilic viruses and lipophilic viruses (Rayburn, 1990) which might have been residual in the pulp chambers of the teeth (Collins, 1988). All use of formaldehyde was confined to a fume cupboard, or glove box, as Formaldehyde is now considered to be a hazard in itself (Rayburn, 1990).

Fears that the sterilisation procedure would affect the tooth structure were unfounded as Bang and Ramm had used a similar procedure for a portion of their 1970 sample. These they had left in 10% neutral formaldehyde and observed again after five years, they report that there was no structural difference.

Figure 6: attachment of specimen to microtome arm.

µ §After sterilisation the teeth were mounted in clear silicon rubber on labelled microscope slides. The advantages with silicon rubber are that it is capable of offering enough support for a tooth during sawing, it is cheap and easily available; but mostly that it can be cut away for accurate alignment of the tooth with the saw blade. Conventional embedding techniques use some hard, transparent mounting media, such as polyhydroxy-dimethacrylate resin, or acrylic resins (Stevens & Germain, 1990: pp.500-503) which will have the same hardness as the teeth, thus facilitate thin sections. However as very thin sections were not required as it was found that modern teeth were hard enough to be self supporting, the silicon rubber was present merely to hold the tooth in place on its slide. Use of conventional methods is recommended for older more friable specimens of archaeological age, or badly eroded specimens, where the section might otherwise break when being sawn.

After mounting the specimens were attached to the aluminium stage of the microtome arm by their slide, sandwiching the slide between two pieces of rubber; a length of perspex was then used to spread the pressure from the clamps across the slide (see Figure 6).

The specimens were then sawn to produce longitudinal sections of 400µ-420µ (as of Bang and Ramm 1970: p.4), using a Malvern Instruments MicroSlice II precision annular saw, with a 100mm aluminium sintered blade. The advantages with the annular saw over the peripheral saw are that, the blade, being in tension on a cupped chuck, is more ridged than a self supporting peripheral blade, gives a more consistent section thickness; the blade being more ridged for a given blade thickness, a thin blade can be used, in this case 330µ (Fynn & Powell, 1988: p.16-17). After some experimentation the best cutting speed was found to be 200 r.p.m. with a pressure of 125g. This was to compensate for the fact that teeth have completely different cutting requirements to the glass of the slide, which was also being cut through; the idea being to optimise for the teeth, but the low pressures required meant that cutting the slide was rather slow.

From an individual root two sections were taken, and this was to ensure that at least one had most of the apical foramen in it; in some cases this could mean four sections per tooth for some molars.

The freshly cut sections were then inspected under a low power binocular microscope and Gustafson and Johanson’s points were be noted. The individual sections which displayed transparency were then singled out and inspected under a video microscope with a scale attachment.
calibrated for 10mm; the length of the whole tooth and the sclerotic front could then be recorded. Images were captured using transmitted light from a standard light box via a single plane polarising filter (this was found to give best contrast) onto a *Semper 6* image analysis system. Areas were then analysed for transparency, the light transmission being compared to a standard of sclerotic dentine. The method was found to work best taking readings when the intensity top and bottom cut off had been adjusted so that the standard had an area of between 1850 pixels and 1950 pixels. It was felt that this was the most satisfactory method for the image analysis to 'recognise' sclerotic dentine. Other methods were tried, such as using a standard variety of pre-set parameters to recognise areas of light and dark, but it was found that instrument 'drift' would not allow any correspondence between readings.
Chapter Four: Analysis of data.

4.01 A note on the use of statistics.

The greater part of this work deals with known ages, termed real age, and ages derived from micro-structural attributes (described above), termed predicted ages. The fundamental question is to what extent can predicted ages be used to represent real ages.

To this question there are two sub-questions, how do the micro-structural attributes, used to deduce predicted age vary with real age, and to what extent can the extant models (e.g. Gustafson's and Bang and Ramm's, described above) describe this relationship.

The key words are accuracy and precision. Accuracy and precision are both terms used to define is how well a relationship can be used to describe an empirical reality. Accuracy is the extent to which a predictive model correctly describes the systematic relationship between two or more variables. Precision is a description of variability of an empirical reality around a systematic relationship.

In the following analysis accuracy and precision merge to some extent. A models ability to predict one variable, given knowledge of the other variable(s), will be limited by the spread of empirical points around the systematic relationship, i.e. precision. In other words it is how precisely any attribute varies with age which limits the accuracy with which predictions can be made using that attribute. When examining the way in which attributes relate to age it is precision, the expected spread of points about a model, which is important. When examining how existing models can be used to predict age it is accuracy which is significant.

The most useful visual tool will be the bi-variate plot when examining both the relationship between attribute and age, and predicted age and real age. For the former the best single statistic is the coefficient of determination (R) which is defined (Shennan,1988: p.129) as the correlation coefficient squared (i.e. r^2), which is:
Correlation coefficient $r$:

$$\mu \frac{\$}{\mu}$$

Where:
- $x_i =$ real age of individual $i$
- $x =$ mean average of ages for all individuals in sample
- $y_i =$ value of attribute for individual $i$
- $y =$ mean average of values for attribute for all individuals in sample

The coefficient of determination is a measure of the spread of points about a regression line and is a measure of precision. That is, to what extent knowledge of one variable can be relied upon to provide knowledge of another variable. If the two variables are highly correlated, that is if knowledge of one produces a high certainty of the other falling into a narrow range of values, then the coefficient of determination will tend to unity; on the other hand if the two variables are poorly correlated, that is knowledge of one produces a low certainty of the other being in a certain predicted range of values, then the coefficient of determination will tend towards zero. So the coefficient of determination gives a measure of how highly correlated an attribute is, or attributes are, to age; thus is a measure of how well models derived from these attributes will predict age.

For testing already existing models of age determination accuracy is the most significant factor. Strictly speaking when applying a model to unknown specimens to deduce age the accuracy cannot be known. However, here we deal with teeth where the age of the individual was known before extraction, therefore accuracy can be known. To explore the accuracy of the various models (outlined above) a twofold approach is taken. Firstly average deviation shall be used as a measure of accuracy, that is it is the mean average difference between any predicted age and the real age (Cohen & Holliday, 1982: p.42).

Average deviation.

$$\mu \frac{\$}{\mu}$$

Where: $N =$ sample size

This has been preferred over standard deviation because it gives a measure of how far any single prediction can be expected to be from its corresponding true value, which is of more interest when testing predictive models. It also cannot be confused with standard deviation, or error, which is used here as a measure of precision; also there is no compelling statistical reason to use standard deviation.

The other important aspect of age determination is how well the standard errors predict what the actual errors are. It is useless being able to predict age with a quoted standard error derived from
other populations of, for example, ± 3 years if the real error of an applied model (average deviation) is 4 years. This aspect becomes very significant when pooling estimations of age are dealt with (later), and although standard ways of dealing with this have been described, it shall be dealt with by simply finding what proportion of the sample population have ages predicted for them which are further away from their true ages than their standard error (for this work 68%, or 1 standard error, shall be used). This has been favoured because statistics which involve how far a predicted age deviates from its 'true age' will be dominated by a few large deviations, where what we are really interested in is 'how many' from a given sample will deviate by more than a predicted amount, not 'by how far' which is to some extent dealt with by average deviation.

Most of this chapter will compare predictions made by the three main methods of determining age at death by macro-structural changes in the teeth. The three main means of comparison will be the coefficient of determination (R-value), which is closely related to precision, the average deviation which, when applied to modern specimens, can be interpreted as accuracy, and how well the standard means of error estimation predict what the real errors in an ageing technique in terms of the percentage of predicted ages which fall within one quoted standard deviation of their real age, which will be a measure of whether the quoted errors for the technique are reasonable.
4.02 How well the Gustafson-Johanson points and lengths of transparency correlate with age.

Points were noted according to the Gustafson-Johanson criteria (Johanson, 1971) for 77 roots from 35 individuals, and plotted against real age for those individual roots (Figure 7). Transparent length was measured for 35 roots from 17 individuals for whom transparency was apparent, and plotted against the real age for those roots (Figure 8). The reason why, at this stage, individual roots are being used, is that for any one individual there are several roots, any one of which might be the 'definitive root' for that individual. As there is no mechanism by which the 'definitive root' can be known then all roots have for the moment been treated as separate observations. Later, mean and pooled ages shall be discussed.

As can be seen in Figures 7 and 8, Johanson-Gustafson points seem to be more correlated to age than transparent length in apparent contradiction to the findings of Johanson (1971) (R-values of 0.80 and 0.72 respectively). However this is probably due to sample difference as can be seen in figure 9, where Gustafson-Johanson points are plotted against real age for those same individuals in Figure 8.

*Figure 7. Plot of Johanson-Gustafson points against real age for 77 roots.*
Figure 8. Plot of transparent length against real age for 35 roots.

Figure 9. Plot of Gustafson-Johanson points against real age for those same individuals in figure 8.
All correlation models are second order polynomial, as used by Bang and Ramm (1970). These are chosen to maximise correlation (R), not because there is any theoretical expectation that the various phenomena ought to obey polynomial relationships, but that there is no theoretically derived expectation of any model, thus no reason to assume a linear model. What is interesting is how in Figure 9 the second order polynomial approximates to a linear relationship, this could be due to the absence of a large number of relatively young individuals from the group, but is more likely to be due to balanced outliers either side of the regression line (A.M. Pollard pers.comm.).
4.03 The assumption of normality.

Figure 10. Bar chart of Gustafson-Johanson points against frequency for ten individuals aged 28 and 29.

With all dental based methods of determining age it is assumed that the various traits upon which predictions of age are based are normally distributed about a mean (for example, Bang & Ramm, 1970: p.10); but this has never been demonstrated to be the case. It would be possible to examine the distribution of known residuals from any regression line, and this could be used to examine uniform skew distributions but could not detect autocorrelation and heteroscedastic distributions (Shennan, 1988: p.140). Here the assumption of normality has been tested by using roots from a sub-sample of ten, 28 and 29 year olds. Plotting the Johanson-Gustafson points against the frequency with which they occurred (Figure 10) seems to give a bi-modal distribution centred around 3.5 points; this bi-modality might be due to the small sample size, or, might be expected as the normal distribution would be broadened somewhat as the age range for the sample is two years. A two year age range translates to about $\frac{1}{2}$ a point, which is smaller than the observed gap between the two distributions, making the most likely explanation for the observed distribution one of small sample size.
Figure 11. Plot of Log10 of cumulative frequency against Gustafson-Johanson points for ten, 28 and 29 year olds.

Figure 11 is a plot of the Log10 of the cumulative frequency against Gustafson-Johanson points. This should approximate to a straight line because the normal distribution is asymptotic (i.e. tends to zero at infinity) (Shennan, 1988: p.108), but does not. This is probably due to small sample size rather than any systematic variation in the data and the slight expected broadening of the peak mentioned earlier.

A problem with this is that although a skewed distribution can be ruled out for the errors, autocorrelation and heteroscedasticity cannot by these means. To obviate the possibility of a heteroscedastic distribution it would be necessary to compare the errors from sub-samples from across the whole age range; the same is true of autocorrelation.

A $\chi^2$ value of 0.3216 (4 degrees freedom, area under $\chi^2$ distribution at 0.95 = 0.7107) would suggest that the distribution in figure 10 can be considered normal at the 5% level of significance, making it reasonable to proceed on the basis that errors for the Gustafson-Johanson points system are normally distributed about their mean.

It was intended to use this sub-sample to test transparent length. However, as few of the 28 and 29 year olds manifested any sclerotic dentine, in keeping with Johanson's (1971) observation, that transparency was rare in those below thirty, this was deemed impossible.
4.04 Predictions of age based upon Gustafson-Johanson points and transparent length.

Ages were calculated according to Gustafson's (1950) regression equation and Johanson's (1971) regression equation, on the basis of points observed for 77 roots from 35 individuals. The predicted ages were then plotted against the real ages and average deviations calculated (see Figures 12, 13 and 14).

*Figure 12. Plot of predicted ages calculated by Gustafson's method against real age.*

*Figure 13. Plot of predicted ages calculated by Johanson's method against real age.*

From Figures 12 and 13 can be seen that the R-value is 0.74 for predictions made using Gustafson's method. It can be seen that these are slightly less well correlated with true age than predictions made by Johanson's method. However the average deviation is about 0.3 years less for Gustafson's method, that is that the predicted ages are slightly more accurate. The increase in quoted precision of Johanson's method over that of Gustafson's method, 5.16 years for Johanson's method as opposed to Gustafson's 7.03 years, is not really reflected in the increase of 0.01 difference between the respective R-values. Despite this, 73% of Johanson's predictions are within Johanson's quoted error and 84% of Gustafson's. This would indicate that the errors on Johanson's method are more realistic for one standard error, and that Johanson is right in quoting 5.16 years, despite the increase in correlation between the two methods not being significant Also to be noted is the tendency of Gustafson's model to systematically predict an individuals age as younger than that individual's real age, this will be examined in more detail in section 4.6.

*Figure 14. Plot of ages predicted by Bang and Ramm's method for 35 roots from 17 individuals against real age.*

Figure 14 displays a systematic error which was ascribed to the operator measuring the cementum, or part of the cementum, as transparent dentine, an error likely to occur and recognised by Bang and Ramm (1970). For the purposes of this project an adherence as far as possible to the original predictive models and errors was necessary, so this systematic error was corrected by applying a corrective constant of -12 years (see Figure 15).
To compare this method with Gustafson's and Johanson's on the basis of comparative figures from these plots is unrealistic and unfair. Figures 16 and 17 show plots of the same sub-group of 35 roots and 17 individuals that display transparency (as used in Figure 15).

The quoted errors on Bang and Ramm's method average at about ten years. This is an unrealistic precision as 82% of predictions actually fit within 1 standard error; the figure is 68% for both Gustafson's and Johanson's methods. The average deviation (accuracy) is 6.4 years for ages predicted for Bang and Ramm's method, 5.23 for Gustafson's method and 5.0 for Johanson's. The correlation for all the predicted ages with real age is R=0.64.
Table 2. Summary information from Figures 12 and 13.

Figure 17 Ages predicted by Johanson's method for the same group as used in Figure 15.

<table>
<thead>
<tr>
<th>Method</th>
<th>Standard error</th>
<th>Average deviation</th>
<th>% of predictions within 1 S.E of true age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gustafson's method</td>
<td>7.03</td>
<td>3.60</td>
<td>84%</td>
</tr>
<tr>
<td>Johanson's method</td>
<td>5.16</td>
<td>3.92</td>
<td>73%</td>
</tr>
<tr>
<td>Bang &amp; Ramm's method</td>
<td>» 10.00</td>
<td>6.40</td>
<td>82%</td>
</tr>
</tbody>
</table>
Table 3. Summary information from Figures 15, 16 and 17.
4.05 Summary.

On the basis of the age predictions presented in Figures 12-17 it is possible to say that in terms of accuracy (low average deviation) age predictions made using Gustafson's method will be as accurate as those made using Johanson's technique (see Tables 2 and 3). The predictions made using Bang and Ramm's method falling short of either of the other two. However, Gustafson's quoted errors of 7.03 years are rather large for the first group of 35 individuals, 84% of predicted ages actually being within one standard error of their 'true age'. The quoted error for Johanson's method, 5.16 years, is far more realistic for both groups of specimens. As the standard error on Johanson's technique is lower, and it is a reasonable error (68% or greater within 1 S.E of true age), the technique being no less accurate, then if single roots are being examined Johanson's method would give the best compromise of accuracy and low quoted error.

The reasons why predictions made using Bang and Ramm's method are worse than predictions made using the other techniques probably relates to the systematic error encountered in the first instance (Figure 14).
4.06 Age related bias in the age predictions.

*Figure 19. Plot of real error against known age for age predictions made by Johanson's method (77 roots from 35 individuals).*

Figure 18. Plot of real error against known age for age predictions made by Gustafson's method (77 roots from 35 individuals). In Figure 12 some age related bias noted. It seemed as though the technique was consistently under-predicting for the older age categories. It was decided to examine systematic age related bias in the ageing systems by plotting the residual (that is the difference between the real age and predicted age) against real age for all three methods. In the following over prediction is where the model predicts an age which is older than the real age of the individual, and under-prediction is where the model predicts an age which is younger than the real age.
As can be seen (Figures 18, 19) there is a tendency for Gustafson's method to under-predict for the older age categories. This is not apparent in Johanson's method. This seems puzzling because the points counted for both Gustafson's method and Johanson's method are exactly the same for each individual, it could be that the attributes which are given high coefficients in Johanson's (1971) equation are those which start later in life, such as transparency. As Gustafson (1950) gave equal weighting to all attributes then any which start to become more important later in life will have less of an influence upon the predicted age, relative to the same attribute in Johanson's equation.

The systematic error in the predictions made by the Bang and Ramm method have already been accounted for, but not for age related systematic error. Figure 20 shows the real errors plotted against real age for predictions made by the Bang and Ramm method.

*Figure 20. Plot of real errors against real age for age predictions made*

by Bang & Ramm's method (35 roots from 17 individuals).

As can be seen from figure 20 Bang and Ramm's predictive model has no systematic age related bias, except for the already accounted for -12 year correction factor.
4.07 Improvements to prediction: the combination of multiple teeth and roots.

Errors (δ) on Gustafson's, Johanson's and Bang and Ramm's ageing techniques are empirically defined, and are in effect the standard deviations of their empirical data. This is defined:

**Standard deviation:**

\[
\mu = \bar{x} \\
\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N}
\]

Where:
- \( x_i \) = predicted age for individual i
- \( x \) = real age for individual i
- \( N \) = number of individuals in sample

However, according to the *central limit theorem*, if several measurements are made of a quantity their average will tend towards the 'true' measurement. It is not necessarily true that this average will be nearer to the true measurement than any single measurement. If the measurements, thus predictions, of age made by the Gustafson-Johanson or Bang and Ramm's models are independent measurements of the same quantity, then if several measurements can be made of the same quantity, then it follows that their average will tend towards the true measurement, and the precision with which this measurement can be made will be greater.

In the previous predictions of age in this work single roots have been treated as independent individuals. Obviously, in order to predict an age that would be useful in palaeodemography it is necessary to predict an age for an individual, not just separate predictions for that individual's tooth roots. This could be used to give a more precise estimate of the true age for any given individual.

One method given by Gustafson (1950) is to average the predictions and divide the empirically derived standard error of the mean for one prediction, by the square root of the number of predictions. Johanson (1971) does not consider multiple measurements. Bang and Ramm (1970) have empirically derived error estimations which are different for each type of tooth examined. They give a method for the combination of errors which is very much the same as Gustafson's, that is they divide the square root of the mean average of error estimations by the number of measurements.
From Gustafson:

\[ \mu \]  

From Bang and Ramm:

\[ \mu \]  

Where:

\( \text{Age} \) = new estimate of age based on multiple age estimations  
\( \text{age}_i \) = individual age estimate  
\( N \) = number of individual age estimates  
\( \delta \) = new estimate of error  
\( \delta_i \) = error estimate for any single age estimate  
\( C \) = an empirically derived correction factor

However Ward and Wilson (Ward & Wilson, 1978: Wilson & Ward, 1981) criticise this second method. Because the 'true age', the age for which the separate predicted ages from individual roots are a part of, is a normal distribution, and predicted ages are described by a normal distribution; then the mean of this 'real age' distribution is not merely the mean average of the separate distributions. If one of the predicted distributions has a smaller standard deviation than another, then the mean of the distribution from which they both come from must be proportionately closer to the one with the smaller standard deviation so that the probability (area) of each separate distribution is equal. Gustafson's method for combining different distributions is fine so long as the standard deviations of the separate distributions are equal; otherwise a method using pooled means and errors on those pooled means must be used (as described in Ward & Wilson, 1978).
According to Ward and Wilson (1979),

\[ \mu \leq \sigma \]

And:

\[ \mu \leq \sigma \]

Ward and Wilson (1979, 1981) also describe a means of detecting outliers by using a \( \chi^2 \) statistic based upon the distance between the means of the separate distributions of predicted ages and their standard deviations.

Where:

\[ \mu \leq \sigma \]

As several roots, and usually several teeth were sampled for the group of specimens for which transparency measurements were possible, then these seem to be the ideal specimens to test the methods of combining different ages and errors.

As predictions made for Johanson's method are logically correlated with those predictions made for Gustafson's method then it is incorrect to attempt to combine these two, and an age predicted from transparency will be correlated in both Gustafson's and Johanson's methods, as both of these methods use transparency. It was decided to recalibrate, using Gustafson's (1950) published data a new calibration that excluded transparency so ages derived from Gustafson's model could be combined safely with those derived from transparency.

The modified predicted ages were then pooled according to Ward and Wilson (1979, 1981) with ages calculated in accord with Bang and Ramm's predictive model for all roots for an individual, with the explicit assumption that separate roots could be treated as independent observations.

All ages predicted by Johanson's method were pooled for the same group of specimens, and new errors were calculated (see Figures 21 and 22).

*Figure 21 Plot of pooled mean predicted ages, and errors, for the modified Gustafson and Bang and Ramm methods, against real age.*

*Figure 22 Plot of pooled mean predicted ages, and errors, for Johanson’s method, with real age.*
As can be seen from Figures 21 and 22, the improvement to quoted precision on the pooled mean predicted ages for a combination of Gustafson's technique (minus transparency) and transparency, is about three years, giving a quotable precision of 4.58 years, and real average deviation of 4.64 years, 70% of all predicted ages being within one quoted error. These errors are entirely reasonable and consistent, being an improvement in both precision and accuracy over the use of just one tooth root.

By contrast the averaged means and errors of predicted ages by Johanson's method have an unrealistic quotable error of 3.34 years. The accuracy is lower than for the above pooled means, an average deviation of 4.99 years and only 52% of the averaged predicted ages being within one quoted error of the real age. This of course could be due to assuming that all roots can be regarded as independent observations; this would be at odds with the findings above.

To test this proposition average means and errors were again calculated regarding only teeth as independent observations. Roots from the same tooth had their ages and errors averaged. Figure 23 shows the result.

*Figure 23 Plot of pooled means and errors of predicted ages calculated by Johanson's method, regarding only different teeth from the same individual as independent observations, against real age.*

From Figure 23, the average deviation (accuracy) has increased to 5.11 years, the quoted error 4.58 years, and only 53% of predicted ages lie within one quoted error of their corresponding true ages.
4.08 The relationship between error on pooled means and the chi-squared value.

Ward and Wilson (1979, 1981) say that if a chi-squared value is above a certain critical value defined by an arbitrary probability (usually 5% significance), the differences between the distributions of the individual age predictions are too great for it to be probable that the individual predictions can be described by the same normal distribution. However in this situation it has, by necessity, to be the case that all values have to belong to the same normal distribution, as all roots came from the same person. Therefore a concern should be the identification of, and suitable treatment of, outliers in different age estimates for the same individual.

Figure 24. Plot of chi-squared value against magnitude of real error on pooled means.

Deciding upon a value of the chi-squared statistic which could be used to discriminate between those pooled means with components which are unlikely to be part of the same distribution, and those which are, is difficult; any attempt to do so would be arbitrary. So it was decided to plot the chi-squared value (amount of disagreement between the component distributions) and the real error on the pooled mean (see Figure 24).

As can be seen outliers have chi-squared values above 2.5-3. The one exception has very good agreement within itself, and in reality does look a great deal older than it really is, possibly due to pathological processes (see Chapter 6).

It is recommended that those individuals whose chi-squared value for the pooled mean of their predicted ages comes to more than three should be re-examined with a view to determining age by some other method, or, weighting the error on the pooled mean to account for the additional uncertainty.

4.09 Summary and conclusions.

Whilst it is true that trying to obtain an age from one root alone Johanson's method has the best precision and accuracy. It appears that when several roots are available then the best, most reliable, and most precise estimation of age can be made with a combination of Gustafson's method and Bang and Ramm's method, the transparency component having been removed from the former. For this it appears that it is reasonable to treat all roots as being independent observations of the same value.

Pooling the predicted ages (as above) for roots treated as independent measurements of the same value resulted in a small improvement in accuracy and precision over any of the techniques used singly or on one root. Quotable precisions for the pooled mean predicted ages (variable dependent upon teeth used, number of observations etc.) were ≈ 4.58 years with accuracy ≈ 4.64
years; this compares favourably with the best method of single root determination (i.e. Johanson's), which can quote a precision of 5.16 years and accuracy of 5 years. Both methods achieve ≈ 70% of predictions within one quoted error of the real age.

It has to be borne in mind that the predicted ages made using Bang and Ramm's method contained a systematic error, and that these ages were one of the components of the pooled mean predicted ages. So were the Bang and Ramm method to be used without the errors encountered here, then it might be that the errors on the pooled mean age predictions could reasonably come down yet further.

The reason why Johanson's method might have failed in this second part is because the predictive model was quite a finely tuned affair with small quoted errors. The problem with this is that the model then becomes very dependent upon it's source population, but this is not so for Gustafson's model, or Bang and Ramm's model, which quote fairly liberal errors. It also has to be borne in mind that by using molars, as discussed before, the models are being tested against the worst of all possible worlds.

Finally, by examining the degree of agreement between the predicted ages for the real ages, an idea might be obtained of the likely real error (Figure 24). Any individuals getting chi-squared values above three should be re-examined.
Chapter five: application to archaeological specimens.

It has been demonstrated (Chapter 4) that degenerative dental micro-structural change can be used as a means of accurately determining the age at death for an individual if given suitable statistical treatment. As pointed out in Chapter 1, this could be of use to the forensic scientist who, when faced with an unknown cadaver, wishes to narrow the range of possibilities down prior to a more formal identification; or to the palaeopathologist who is currently unable to determine accurately the age at death for ancient skeletons.

This chapter examines dental based age determination techniques applied to archaeological specimens and the problems unique to archaeological material.

5.01 Ferrybridge.

The excavation of a Bronze Age burial mound at Ferrybridge in advance of pipeline construction in 1992 yielded little in the way of skeletal material (Thornton, 1992); this was due to a very aggressive, hostile, burial environment, a soil rich in magnesian limestone. The only skeletal remains to be consistently found there were the teeth of those buried there. With kind permission of Francis Thornton (Department of Archaeological Sciences, University of Bradford) it was decided to section two of those teeth to see whether or not any of the macroscopic features were still visible. The selected teeth were a second left upper molar, and a lateral lower incisor, both of which displayed considerable external erosion, being a chalky white with heavy pitting on both crown and root; this gave rise to suspicions that there might not be any preserved internal macro-structure. Of the two teeth the incisor seemed to be the best preserved, being far less eroded about it’s root, so it was decided to section this; the decision for the molar pending results from the incisor.

Inspection of the section confirmed the observation made from the external appearance, there was little of the macro-structure left. The pulp chamber, root canal and apical foramen were enlarged; the apical foramen was now some 1½ mm across and the dentine looked as though it had suffered almost complete recrystallisation, as it was now white and of a chalky texture. However, there were what looked to be the remains of the original dentine structure adjacent to the dentine-enamel junction.

It proved impossible to see any of the distinguishing attributes that might have lead to a determination of the age at death for the individual concerned.
5.02 The cremations from Bootle.

The contents of a cremation urn were examined by Rebecca Wiggins (Department of Archaeological Sciences, University of Bradford) (Wiggins, 1992). The urn was of a mid to late Bronze age type, and one of three features excavated to the south-west of Bootle village, Cumbria, in advance of gas pipeline construction. The other two features were pits for the deposition of similar cremations.

The burned teeth were in poor condition and their external appearance, as with the Ferrybridge teeth, was white and chalky. It was again anticipated that little in the way of internal structure would be present.

Six incisors and one molar were examined (the shapes being so distorted by heating that it was impossible to give more precise descriptions of them) and sections were taken.

Much to the observer's surprise, although all of the dentine was white and chalky, internal features were discernible. The inside of the pulp chamber was charred black, and there seemed to be a distinct, sharp, border, where what was interpreted as secondary dentine was deposited. The cementum layer was clearly visible as a faint line. For some reason on all these teeth the crowns were missing (see Plate 4 in Appendix 4).

As on two of the teeth there was a considerable build-up of cementum, and supposed secondary dentine, it was hypothesised that there were the remains of at least two people in the urn, one older than the other. It was impossible to give any clearer idea of just how old these people were as too few of the diagnostic criteria were present.

This hypothesis is entirely consistent with the report of the excavator, Richard Holbrey (pers. comm.), who said that in the two pits there had been much charcoal, but the urn had:

"... by far the greatest mass of bone material of all the cremations, very little charcoal was similarly contained. This suggests that the bone was selected for inclusion into the urn prior to the burial rite."

R. Holbrey, 1992

5.03 The Chichester specimens.

Four skeletons were sampled from the Medieval Chichester collection, with the permission of Dr. C. Roberts (Department of Archaeological Sciences, University of Bradford). The individual skeletons were selected on the basis of their having both a loose incisor and molar which could act as specimens without actually having to extract any teeth from either the mandible or maxilla, thus avoiding unnecessary damage to the skeleton.

Externally, all the teeth appeared to be in excellent condition, and sections were taken for two roots on the molars and the single root on the incisors. However, when the sections were examined it was found that transparency was undetectable in all but two teeth (see Plates 4 and 5 in Appendix 4). What appeared instead was a chalky, pinkish, re-crystallisation of the dentine, which appeared to
have started in the pulpal chamber and expanded outwards towards the cementum and enamel (see Plate 6 in Appendix 4). At first this generated great excitement as it was thought that this might be the first archaeological report of 'pink teeth' (van Wyk, 1987), even though the appearance looked more like a re-crystallisation front.

**Figure 25. Outline diagram of the hypothesised uptake of groundwater by the tooth**

Some of the 'pink' dentine was examined by means of an EDAX micro-probe to test for the accumulation of blood characteristic of the 'pink' dentine (van Wyk, 1987); as it was thought that iron would be present. It was found that iron was not in fact present in any quantity above minimum detectable level, and that the only unexpected elements were bromine and aluminium. So far any explanation of the 'pink' dentine has been elusive, but it is possible that once the living matter has disappeared from the alveolar bone and the root canal, the apical foramen acts as a capillary taking up any surrounding groundwater and dissolved elements (see Figure 25), which over the course of time produces recrystallisation of the dentine from the pulp chamber outwards. This is of course reliant on episodes of waterlogging in the area surrounding the root and root canal, and the apical foramen not being blocked in any way; this could explain the variation seen in the teeth from Chichester, where the two teeth which did not display any evidence of recrystallisation, or 'pink' dentine, manifested extremely clear ageing attributes, including a sclerotic front which was very well delimited (see Plate 5 in Appendix 4). It is not possible at this point to utterly preclude the possibility that the 'pink' dentine was the result of bleeding into the root canal, but it would be necessary to suggest re-crystallisation as a secondary process to explain the full range of phenomena.

Given the absence of transparency for most of the roots it seemed in this case that the best ageing technique would be the modified Gustafson method, that treats transparency as having been obliterated. The results are as follows (Table 4).
<table>
<thead>
<tr>
<th>Specimen</th>
<th>Tooth</th>
<th>Root</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH86</td>
<td>+6</td>
<td>mesial</td>
<td>37.64 ± 7.53</td>
</tr>
<tr>
<td>S20</td>
<td>distal</td>
<td></td>
<td>40.03 ± 7.53</td>
</tr>
<tr>
<td>male 30-40</td>
<td>1-</td>
<td></td>
<td>44.81 ± 7.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>CH86</td>
<td>+7</td>
<td>mesial</td>
<td>47.20 ± 7.53</td>
</tr>
<tr>
<td>S42</td>
<td>distal</td>
<td>44.81 ± 7.53</td>
<td></td>
</tr>
<tr>
<td>female</td>
<td>-2</td>
<td></td>
<td>51.98 ± 7.53</td>
</tr>
<tr>
<td>CH86</td>
<td>7+</td>
<td>mesial</td>
<td>42.42 ± 7.53</td>
</tr>
<tr>
<td>S74</td>
<td>distal</td>
<td>42.46 ± 7.53</td>
<td></td>
</tr>
<tr>
<td>male</td>
<td>+1</td>
<td></td>
<td>47.20 ± 7.53</td>
</tr>
</tbody>
</table>
Table 4. Ages for skeletons from Chichester
with substantial internal re-crystallisation

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Tooth</th>
<th>Root</th>
<th>Age by Johanson's method</th>
<th>Age by Gustafson's method</th>
<th>Gustafson's age without transparency</th>
<th>Age by Bang &amp; Ram's method</th>
<th>Pooled mean age</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH86</td>
<td>7-mesial</td>
<td></td>
<td>40.21 ± 5.16</td>
<td>45.36 ± 7.03</td>
<td>47.20 ± 7.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S108</td>
<td>distal</td>
<td></td>
<td>40.43 ± 5.16</td>
<td>45.88 ± 7.03</td>
<td>47.44 ± 7.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>male</td>
<td>+1</td>
<td></td>
<td>58.17 ± 5.16</td>
<td>51.77 ± 7.03</td>
<td>42.42 ± 7.53</td>
<td>53.40 ± 11.03</td>
<td>45.91 ± 6.21 $\chi^2 = 0.0759$</td>
</tr>
</tbody>
</table>

For the remaining skeleton, which had a tooth which displayed transparency, a full range of ages were available (also see Plate 5 in Appendix 4).

Table 5. Ages for the skeleton from Chichester for which a full range of measurements were possible.
5.04 Discussion of more general points and conclusions.

A certain amount of information can be obtained from the study of cremated bone, but age determination is often limited to discrimination between adult and sub-adult/child (McKinley, 1989). Using dental histology it is possible to discriminate between young and old adult, as seen with the Bootle material (see Section 5.02). Also dental histology, as with the Bootle cremations, gives another means by which multiple burial can be identified, besides the observation of duplicated bone fragments (McKinley, 1989).

Whether teeth can be of use as a means of age determination in archaeology is very much dependent upon the local burial micro-environment. We have seen that even teeth (such as those from Chichester) with excellent external appearances can display considerable internal erosion. It is not true to say that teeth, because of their hard calcified exterior, preserve well, as erosion and deterioration come from within, possibly via the apical foramen. The processes of post-depositional decay of teeth need to be understood in more detail. Because the external appearance of teeth has usually been good it has been said that teeth preserve best of all the tissues of the human body, this can now be seen to be variable and dependent upon purpose, i.e. if dental disease is being examined then external morphology is probably more important than internal micro-structure (Hillson, 1986b: pp.119,156,166). However, for the purpose of determining age at death by internal macro-structural change, the external appearance has been misleading, and in reality teeth are preserved little better than the rest of the skeleton, dependent on conditions.

One problem which has been observed, particularly on the Bootle material and Chichester specimens, has been missing values. If a set of values is taken for a tooth, and one is missing, then there is no knowledge of what that value was; in the case of much of the Bootle material transparency was not discernible, it looked as though any transparency might have been obliterated, but there might not have been any in the first place. In this case it was justified to examine ages for either contingency. In the case of the Bootle cremations only two attributes were present; from such poor information it would be difficult to determine age; but if just the crown and apex had been missing, giving attrition and root resorption as missing values, there would have been the possibility of determining age. Given the nature of archaeological materials in which it is most often the case where information is incomplete, some attention needs to be given to how to treat missing values if these age determination techniques are to be used in the future.

A more general argument is the fact that sectioning archaeological teeth is destructive. Although some hope lies in age determinations made by the use of intact teeth (Bang & Ramm, 1970: Drusini et al. 1991). However, without sections to confirm that no re-crystallisation of the dentine structure has occurred these methods must be considered unreliable. More pertinent is the question of whether the information gain is worth the artefactual loss (more shall be said about...
the possible information gain in Chapter 6). Is it worthwhile to be able to determine age at death fairly reliably to a ten year span when probabilistic treatments of palaeodemographic data are claimed to accurately reconstruct a population profile (Konigsberg & Frankenberg, 1992). A possible niche in archaeology exists in circumstances where a cemetery population is too small to reconstruct age profiles with any statistical validity, or in special circumstances where accurate age at death determination for a historically known individual, where the age at death is not historically recorded, and would be of public interest (e.g. the Robin Hoods or King Arthurs of this world). Or possibly more systematic use of the techniques on those individual skeletons where conventional age at death determinations are too vague, such as those which by their skeletal age are classified as over forty.

There is the question of effort. As well as being destructive of skeletal materials the sectioning of teeth requires expensive equipment and expertise. It only takes as long to determine the age at death for an individual as by conventional means, but this time would always be in addition to, rather than a substitute for, age determination by skeletal methods. In effect it would double the processing time required for skeletal remains. As presently most processing of skeletal remains is done by a single individual with minimal budget, time and resources, dental based age determination could only be properly done in the larger laboratories, probably with a small team of expert specialists; this would mean quite a large institutional shift in the way routine work was carried out on skeletal material. It might be felt that this point is overstated, but the current (1993) price of the necessary equipment of about £10,000 - £15,000 would preclude smaller operators from this type of work.

Even were dental based methods of age determination considered worthwhile and became routine, there would be statistical problems with composition of life-tables. The problem here being that from a sample for which age determinations are pooled means of ages derived from a combination of Gustafson's method and transparency, all the individual probability distributions are going to be different dependant on how many, and which roots are used. This problem has been addressed, in theory, by Konigsberg and Frankenberg (1992) who devised statistical methods for continuously distributed age determinations; unfortunately they were unable to apply their methods as no data then existed.
Chapter six: other measurements of transparency.

As sclerotic dentine is a visible phenomena there should be other measurements, and other ways of measuring it, than cutting longitudinal sections through teeth and using length. One approach has been to use transmitted light through intact (not sectioned) teeth, and try to measure the transparent length that way. Another measurement has been that of area. This chapter examines both these possibilities and goes further in an attempt to explain the formation mechanisms behind sclerotic dentine.

6.01 Intact sections.

According to Bang and Ramm (1970) it is possible to measure transparency without taking a section through the tooth. On the face of it this seems an ideal non-destructive method for delicate archaeological specimens which section cutting would otherwise irreparably destroy. Bang and Ramm measured transparency on intact teeth prior to taking sections, the details of the procedure they used being unstated. They found that their measurements of transparency had coefficients of determination between 0.68 and 0.51; this compares well to 0.73 for the roots sampled earlier (Figure 8). However, it has to be borne in mind that the sample in Figure 8 was primarily of molars and that Bang and Ramm quote an R-value of 0.83 for right lateral upper incisors for longitudinal sections, having quoted an R-value of 0.68 for intact sections for the same tooth.

The next published work dealing with intact sections was in a paper by Drusini et.al. (1991). They used intact teeth and a high intensity light source and from this measured the apparent transparent length by means of vernier callipers, and evaluated the transparent area using an image analysis system. Their quoted coefficients of determination are similar to Bang and Ramm's for the transparent length measurements against real age, 0.70, and for area an R-value of 0.65 was cited, although the area measurements did include an element of transparent length measurement.

Drusini et.al. (1991) also looked at some buried material, but most of this was relatively recent, dating from 1890-1930. How far the use of intact teeth could be extended to samples such as Chichester, where extensive deterioration has taken place remains to be seen.
6.02 Transparent area and proportional transparent length.

As length of transparency is correlated with age, and length of transparent dentine is related to the area, and thus volume, it might be thought that the transparent area is related to age, dependent upon the processes that lead to the formation of sclerotic dentine.

It might also be thought that if transparent length is related to age, then age might be related to the proportion of the sectional length of the tooth that is transparent.

Either of these measurements might have a higher correlation to age than just transparent length. On the basis that a large tooth might develop sclerotic dentine at a faster rate than a small tooth, one of the determining factors being size in this case, or, that it is not the actual transparent length which is important, but the volume of sclerotic dentine, this means that the area of transparency would be more related to age than just length measurement.

For the 35 roots from 17 individuals which displayed transparency, both transparent area, total area, transparent length and total length were measured as described in Section 3.03.

Sections which displaying transparency were then singled out and inspected under a video microscope. Images were captured using transmitted light from a standard light box via a single plane polarising filter (this was found to give best contrast) onto a Semper 6 image analysis system. Areas were then analysed for transparency by first measuring the area in pixels of the whole tooth section. Then the transparent dentine area was measured. To ensure that what was being measured was in fact translucent dentine the light transmission was compared to a standard of sclerotic dentine. The method was found to work best taking readings when the intensity top and bottom cut off had been adjusted so that the standard had an area of between 1850 pixels and 1950 pixels. It was felt that this was the most satisfactory method for the image analysis to 'recognise' sclerotic dentine. Other methods were tried, such as using a standard variety of readings, but it was found that instrument 'drift' would not allow any correspondence between readings. Despite the care taken it was found that for a very few teeth some areas of the tooth section would transmit light as well as the recognisably sclerotic zone. As these were measured as separate areas by the image analysis program it was felt that both sets of measurements should be used, the maximum that included all areas measured by the program, and a minimum, that included only those areas of a tooth section which would be recognised as sclerotic by a human operator.

Figure 26 shows the minimum proportion of transparent area present against real age. Figure 27 shows maximum proportion of transparent area against real age. Figure 28 shows minimum transparent area against real age. Figure 29 shows maximum transparent area against real age. Figure 30 shows proportion of transparent length against real age. Figure 31 shows transparent length against real age, and is really a repeat of Figure 8.
Figure 27. Maximum proportion of transparent area against real age for 35 roots from 17 individuals.

Figure 26. Minimum proportion of transparent area against real age for 35 roots from 17 individuals.
Figure 29. Maximum transparent area against real age for 35 roots from 17 individuals.

Figure 28. Minimum transparent area against real age for 35 roots from 17 individuals.
Figure 31. Transparent length against real age for 35 roots from 17 individuals.

Figure 30. Proportion of transparent length against real age for 35 roots from 17 individuals.
As can be seen from Figures 26 and 27 the proportion of transparent area for a given root section is not highly correlated with age, nor is the absolute area (Figures 28, 29). The proportional length of the transparent zone is more correlated than the absolute areas (Figure 30), but not as highly as transparent length alone (Figure 31).

The coefficient of determination values (R-values) are very significantly different, although as can be seen in Table 6 all measurements are highly correlated to age at the 1% level (Pearson correlation coefficient), and 0.05% level (t-test); all critical values from White et al. (1988). Had the R-values been only slightly lower for area measurements than for the transparent lengths then it would have been probable that the discrepancy could be attributed to inaccuracy in the method of area measurement. As transparent length as a proportion of root length is also significantly less correlated to age than the transparent length alone, then it might seem reasonable that there really is a reason in terms of the formation of sclerotic dentine which might explain these results.

Table 6. Pearson correlation coefficients and t-tests of significance of the correlations seen in Figures 26-31.

<table>
<thead>
<tr>
<th>r²</th>
<th>r</th>
<th>v</th>
<th>t</th>
<th>critical value of t at o.05%</th>
<th>critical value of Pearson correlation coefficient at 1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>transparent length (Figure 31)</td>
<td>0.72</td>
<td>0.84</td>
<td>32</td>
<td>9.07</td>
<td>3.64</td>
</tr>
<tr>
<td>transparency as a proportion of root length (Figure 30)</td>
<td>0.6</td>
<td>0.77</td>
<td>32</td>
<td>6.92</td>
<td>3.64</td>
</tr>
<tr>
<td>minimum transparent area (Figure 28)</td>
<td>0.41</td>
<td>0.64</td>
<td>32</td>
<td>4.71</td>
<td>3.64</td>
</tr>
<tr>
<td>maximum transparent area (Figure 29)</td>
<td>0.34</td>
<td>0.58</td>
<td>32</td>
<td>4.06</td>
<td>3.64</td>
</tr>
<tr>
<td>minimum proportion of transparent area of whole tooth section (Figure 26)</td>
<td>0.48</td>
<td>0.69</td>
<td>32</td>
<td>5.43</td>
<td>3.64</td>
</tr>
<tr>
<td>maximum proportion of transparent area of whole tooth section (Figure 27)</td>
<td>0.52</td>
<td>0.72</td>
<td>32</td>
<td>5.88</td>
<td>3.64</td>
</tr>
</tbody>
</table>

Where:

\[ r^2 = \text{coefficient of determination} \]
\[ r = \text{correlation coefficient} \]
\[ \nu = \text{degrees of freedom (n-2)} \]
\[ t = \text{t-test statistic} \]
6.03 The formation of sclerotic dentine.

Jenkins (1966: p177-178) cites three ideas about the formation of sclerotic dentine. First is where the tubules become obstructed by the formation of lipid material within them. This has been discounted on the grounds that the permeability of dentine was unaffected by the removal of fat by solvents (Rushton, 1940: as cited in Jenkins, 1966: p.178). Second, that some tubules become sealed as their odontoblasts die, either spontaneously, or following the reduction in pulp chamber size by the deposition of secondary dentine (Jenkins, 1966: p.178). The mechanism here is one of secondary dentine deposition on the sides of the pulp chamber leaving no room for the odontoblasts, which gradually die off, allowing calcification of the tubules (Jenkins, 1966: p.171). This is to be discounted because in anterior teeth the major deposits of secondary dentine are at the crown-ward end of the pulp chamber, but transparency starts with the most apical tubules. The third possibility (Jenkins, 1966: p.177) is that the tubules become narrower by deposition of calcium salts upon the peritubular dentine of the walls. This leads eventually to the total occlusion of individual tubules.

Of the models cited above, only the second gives a causative mechanism for the formation of sclerotic dentine; the others are merely descriptions of how it forms and what it is. However it is the third which is most in keeping with modern observations of transparent dentine.

It is known that the diameter of dental tubules starts at \( \approx 3.2\mu \) in diameter in young individuals and decreases to \( \approx 1.5\mu \) at fifty, becoming \( \approx 1.2\mu \) at about seventy (de Jonge, 1950: as cited in Johanson 1971), and that the actual transparency is due to precipitation of minerals in the dental tubules, thus the tubules refractive index becomes the same as their surrounding matrix allowing light transmission (Pilz, 1959: as cited in Drusini et al. 1991). Pilz (1959) also showed that sclerotic dentine could be related to degenerative changes in the pulp.

So far the understanding of sclerotic dentine has been mostly descriptive, in that it is now acknowledged that sclerotic is a hyper-calcified deposit in the dental tubule, and starts as a thickening of the peritubular dentine. However little effort has been directed to the phenomena in terms of human metabolic processes.

6.04 A model for the formation of sclerotic dentine.

The poor correlation between transparent area and age, and proportional length and age would imply that sclerotic dentine forms at a certain rate regardless of the size of the tooth or the actual volume of the calcium salts deposited in the dental tubules; in fact it would be reasonable to suggest that the main focus of sclerotic dentine formation are the tubules themselves. This brings in the function of the odontoblasts, as it is not possible that the odontoblastic process is still within the tubule when a tubule has become entirely occluded with calcium salts. This indicates that the formation of sclerotic dentine is more related to the disappearance of the odontoblastic processes,
thus of the odontoblasts themselves.

Jenkins (1966) describes Fish's (1933) observations. Fish identifies two different responses of dentine to irritation. First was the 'dead-tract' response, where under the severe irritation of being partially drilled into, the odontoblasts were directly killed off. This led to the formation of reparative secondary dentine being formed on the wall of the pulp chamber adjacent to the affected tubules. The affected tubules become blocked off but not completely filled with calcium salts. Under a less severe stimulus a plug of calcium salts formed in the outer end of the tubule, which Fish termed the 'translucent zone reaction'. This response allowed communication between the still living odontoblast and the pulp chamber. It is this second 'transparent zone reaction' which is comparable to 'age related' sclerotic dentine.

Coming back to Pilz's (1959) suggestion that the circulatory system affects the formation of sclerotic dentine, Bang and Ramm (1970: p.27) observed that one of their sample, despite being a young man, displayed marked transparency. This they attributed to his having a chronic, severe, circulatory problem.

What has to be explained is how sclerotic dentine forms, why is it for the most part age related, and, what part does the circulatory system play?

The deduction that sclerotic dentine is related to the regular filling in of individual tubules in the dentine requires some causative explanation in terms of the process being a response to a long term, but not particularly severe irritation; the irritation being the attenuation of blood supply to the odontoblasts. The hypothesis is that when the odontoblasts are placed under moderate stress then their response is to shorten their odontoblastic process, filling in the redundant part of the dental tubules in which that odontoblastic process resided. The supply of blood to the odontoblasts being reduced by either a lack of supply to the tooth, as in the case where an individual has a severe blood circulation problem, or, by changes in the cells of the pulp chamber, it appears that both these changes take place with advancing age.

Morse (1991) describes how the deposition of secondary dentine and the thickening of cementum narrows the root apex, leading to severely compromised circulation and innervation in aged individuals. Other changes concern the actual cells. Fat droplet deposition within the dental pulp complex has been observed, the histologic description being that fine droplets of fatty deposits are found in the odontoblasts, nuclei of the pulp cells, and walls of pulp tissue capillaries; however, according to Morse (1991) this may be an artefact of specimen preparation. Vacuolisation of the odontoblasts is another change which might be an artefact, but has been described as the next sign of ageing. This is a process where the odontoblasts are pushed apart and separated from the dentine wall by an apparent pressure of inter-cellular accumulation of tissue fluid (Morse,1991). The next observable stage is related to the accumulation of inter-cellular fluid and reduction in the number of pulp cells, where the tissues of the pulp take on a netlike appearance; this again may be an artefact (Morse,1991). As the pulp ages then there is a great decrease in the number of pulp cells, and a corresponding decrease in the number of odontoblasts. There is an apparent increase in the number of collaginous fibres. The odontoblasts that remain become shorter and more flattened, and the number of blood capillaries decrease (Morse,1991). Hyaline degeneration is an intermediate stage in
the calcification of the pulp that takes place within the inter-cellular fibres and leads to fat replacement in the circular spaces in the tissues (Morse,1991). Other degenerative changes in the pulp complex include mucoid degeneration, calcification and metaplasia (Osborn,1981: p.101).

Even if some of the above changes are artefacts there are still sufficient real degenerative changes to make out a case for a long-term and not too severe stress upon the odontoblasts which are deprived of their connection with the full circulatory system.

The model of sclerotic dentine formation suggested here is one that involves the odontoblasts, under the not too great stress of compromised circulation and deprivation of vital fluids, gradually dying off and depositing calcium salts into the existing peritubular dentine, filling up the tubules where the odontoblastic processes formerly were. This is the same response to a stimulus of the same magnitude described by Fish (1933: as cited in Jenkins,1966) i.e. a greater stress results in the odontoblasts dying off too rapidly to allow the formation of sclerotic dentine. This model links the formation of sclerotic dentine with circulation and thus can be used to explain the great amount of transparent dentine observed by Bang and Ramm (1970). It also implies that the formation of transparent dentine is a reflection of the age related degenerative changes seen in the pulp. As such it predicts that any circulation problem suffered by an individual, where the problem would result in a deficient supply to the teeth, would result in an apparent increase in transparent dentine. This makes pathology one of the possible causes of transparent dentine and contradicts Nalbandian et.al. (1960: as cited in Johanson,1971: Gustafson,1966: p.135) who thought that transparent dentine was not related to pathology.

However what it is unable to explain is why transparency should start from the apex of the tooth, unless as suggested by Dr.C.Knüsel (pers.comm.) that it is a functional adaptive response to maintain supplies to the crown of the tooth. It also explains why fully necrotic teeth do not continue the sclerotic process after full necrosis has occurred, as it requires the odontoblasts to still be functioning to some extent.
6.05 Tests and implications of the model.

The model described above uses innervation and partial dysfunction of the blood supply to the living teeth to explain the phenomena of sclerotic dentine. If the model is correct in its major features then a causal link between the circulatory system and the rate of formation of sclerotic dentine must be established. This could be accomplished by measuring sclerotic length for individuals (mortuary specimens) of known medical history, especially with circulatory diseases, and determining whether the length of sclerotic dentine was systematically longer, whilst controlling for age, than for individuals with no such condition.

A similar exercise could be carried out for palaeopathological specimens. However, circulatory diseases recognisable in the palaeopathological record tend to be of a type which is localised to the particular bone in which they occur. Ortner & Putschar (1981: pp. 235-244) describe several such processes. Ischemia is an attenuation of the blood supply to bone caused by osteon formation which are devoid of vascular supply, this in its turn causes localised necrosis of these areas of the bone (Ortner & Putschar,1981: p.235). Infarction is the necrosis of larger areas of the fatty bone marrow and bone trabeculae, caused by interruption of circulation. Often specific reasons for the cut-off of blood supply are not known (Ortner & Putschar,1981: p.236). Linked to Ischemia and Infarction are more specific diseases. Aseptic necrosis of the femoral head is a complication (including Perthes' disease) of trauma to the neck of the femur, the blood supply being cut off at the point of fracture; this condition may be accompanied by infarction, and leads to loss of mechanical function of the femoral head and eventual slippage of the femoral head (Ortner & Putschar,1981: p.238). Other traumas can cause other conditions. Kohler's disease and Osgood-Schlatter's disease both involve a similar, trauma induced, aseptic necrosis as Perthes' disease, only to the vault of the foot and tibia respectively (Ortner & Putschar,1981: p.242-243). Osteochondritis dissecans is an aseptic necrosis which affects the knee by producing a small piece of necrotic cartilage which is triangular in profile into the synovial joint with subsequent loss of joint function; the main diagnostic being a small area of depression on the articulator bone, the cause again seems to be mechanical stress (Ortner & Putschar,1981: p.242).

If, as the model above predicts, sclerotic dentine has its origin in compromised blood supply to the teeth, and were an individual to have either ischemia or a trauma induced aseptic necrosis of the alveolar bone, then a high degree of sclerotic dentine could be expected to form in those teeth immediately reliant upon the affected alveolar bone for their blood supply. However, this would only be localised, there could be no expectation that any individual whose mandibular teeth were affected would display the same phenomenon in their maxillary teeth.

Circulatory diseases which have a more generalised effect upon the body are in evidence in the palaeopathological record. Pulmonary osteoarthropathy is a rare condition of obscure aetiology which manifests itself in the skeleton as symmetrical deposition of periosteal bone on the long bones of the extremities. However, it is thought that the underlying causes are altered neurocirculatory reflexes (Ortner & Putschar,1981: p.245). Bone is very sensitive to closely applied
pressure by dilated arteries, this is evidenced by abnormal vascular groves on bony surfaces, and consists of erosion of the underlying bone. These aneurysms are indicative of chronic, generalised, circulatory disorders, affecting the whole body, and are common in the latter stages of venereal syphilis where the aorta is strongly affected (Ortner & Putschar, 1981: p.246).

If the linkage between transparent dentine and compromised circulation to the teeth is correct, then, unlike the more localised circulatory disorders, there is a greater chance that any individual skeleton displaying the symptoms of pulmonary osteoarthropathy and aneurysmal erosion will also have a higher rate of sclerotic dentine formation in all teeth. So another test of the model would be to examine individuals who had symptoms of long standing venereal syphilis, again with the expectation that these individuals would display a larger length of transparent dentine, when controlled for age.

6.06 Summary and conclusions.

It is the case that without understanding the processes of the skeleton, and the mechanisms responsible for change in the skeleton, no satisfactory approach to palaeopathology can be maintained. This last chapter has been an attempt to understand one of the age related changes in the human skeleton in terms of the mechanics of the human body. In short, without the understanding of the processes of human ageing, attempts to age human skeletons in both palaeopathology and forensic science will be flawed, as the limits to the ageing methods will never be realised.

If the techniques for determining age at death outlined in this dissertation become routine practice for palaeopathologists, as they are for forensic scientists, and the problems of preservation can be overcome; then the possibility of more precise and accurate age determination exists for skeletal populations, which would lend more weight to the conclusions of palaeodemographers about past populations.

In addition, were the model outlined above for the formation of sclerotic dentine to prove to have any foundation in reality, then there exists the possibility for palaeopathologists to diagnose certain circulatory disorders, or at least be aware of the known limitations on their methods for determining age at death.
Bibliography.


Todd, T.W. (1921). Age changes in the pubic bone II. The pubis of the male Negro-White hybrid. American


Appendix one: Data for the group with full Johanson-Gustafson points.

Notes:

A = Attrition.
P = Periodontosis
C = Cementum apposition
S = Secondary dentine deposition
R = Root resorption
T = Transparency

Tooth allocation is a modification of the Haurup dental sternography system, where L represents lower, mandibular tooth; U represents upper maxillal tooth; the side to which represents the side of the maxilla-mandible. The numeric componant represents which tooth is denoted.
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Appendix two: Data for the group displaying transparency.

Notes:

A = Attrition.
P = Periodontosis
C = Cementum apposition
S = Secondary dentine deposition
R = Root resorption
T = Transparency

Tooth allocation is a modification of the Haurup dental sternography system, where L represents lower, mandibular tooth; U represents upper maxillal tooth; the side to which represents the side of the maxilla-mandible. The numeric componant represents which tooth is denoted.
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Appendix three: basic program written to calculate pooled mean ages, errors on those ages, and chi-squared values.

The following code is a *Microsoft QBasic™* program designed to calculate pooled mean ages, errors on those pooled mean ages, and chi-squared values, for two or more normal distributions.
CLS
BEEP
PRINT "Calculation of Pooled mean, chi-squared values and errors on pooled"
PRINT "mean for manually input normal distributions"
PRINT
PRINT "Warning: make sure the printer is on and working, otherwise"
PRINT "the program will encounter a device error"
PRINT INPUT "press Return to continue"; R
REM
PRINT
PRINT
PRINT
100 CLS
INPUT "Individual identification ........... "; P$ 
B = 0
D = O
E = 0
F = 0
G = 0
H = 0
I = 0
J = 0
K = 0
L = 0
M = 0
N = 0
O = 0
T = 0
S% = 0
PRINT
INPUT "input number of terms in statement ..... "; A
PRINT
REDIM C(A - 1, 1)
PRINT
PRINT
FOR B = 1 TO A
PRINT "Age number .......... "; B
PRINT
INPUT "Input age .......... "; C(B - 1, 0)
INPUT "Standard deviation ... "; C(B - 1, 1)
PRINT
PRINT
NEXT B
LET B = 0
REM Pooled Age
FOR B = 1 TO A
C(B - 1, 1) = C(B - 1, 1) * C(B - 1, 1)
NEXT B
LET B = 0
FOR B = 1 TO A
E = C(B - 1, 0) / C(B - 1, 1)
T = T + E
NEXT B
LET B = 0
FOR B = 1 TO A
F = 1 / C(B - 1, 1)
G = G + F
NEXT B
T = T / G
PRINT "Pooled mean is .......... "; T
REM Chi Squared
LET B = 0
FOR B = 1 TO A
H = C(B - 1, 0) - T
I = H ^ 2
J = I / C(B - 1, 1)
K = K + J
NEXT B
PRINT "Chi Squared Value is ...... "; K
REM error on pooled mean
LET B = 0
FOR B = 1 TO A
L = 1 / C(B - 1, 1)
M = M + L
NEXT B
N = 1 / M
O = N ^ .5
PRINT "Error on pooled mean is ..."; O
REM LPRINT
REM LPRINT
REM LPRINT "Individual ....................... "; PS
REM LPRINT "Pooled mean age is ................ "; T
REM LPRINT "Chi-Squared value is ................ "; K
REM LPRINT "Error on pooled mean is ............ "; O
PRINT
PRINT
PRINT
PRINT
PRINT
INPUT "Another Pooled mean? (Rtn for Yes, 1 for No)... "; S%
BEEP
IF S% = 1 THEN GOTO 69 ELSE GOTO 100
BEEP
69 END
Appendix four: Plates.

General key:

A = Attrition.
P = Periodontosis.
C = Cementum apposition.
S = Secondary dentine deposition.
R = Root resorption.
T = Transparency.
D = Denticle (Plate 4).
RD = Recrystallised dentine (Plate 6).
ND = Normal dentine (Plate 6).
RDE = Reparative dentine (Plate 5).

Plate 1. Longitudinal section of left mandibular first molar, distal root, from a 36 year old male.

Note: Early stages of the development of translucent dentine (T). Cementum (C) appears thick due to the incident angle subtended by the section.

Plate 2. Longitudinal section of right maxillary central incisor from a 60 year old male.

Note: Formation of translucent dentine to half way up the length of the root (T). Also attrition of occlusal enamel so that the dentine is exposed (A), considerable cementum build-up (C), secondary dentine deposition (S), and recession of the gingivae (periodontosis P).

Plate 3: Longitudinal section of lower second mandibular molar, distal root, from a 37 year old female.

Note: Mid stages of formation of translucent dentine (T). Although length of translucent dentine appears too great due to angle subtended by section. Also note slight recession of the gingivae (periodontosis P).
Plate 4: Longitudinal section of a cremated premolar/molar root from Bootle.

Note: Pulp chamber and apical foramen still visible; cementum build-up (C) visible as a discoloured area around apex of root. Dentine (D) clearly discernible in the pulp chamber, and crown of tooth completely missing.
Plate 5: Longitudinal section of an incisor from a male aged 35+, from the Chichester collection.

Note: Typical length of sclerotic dentine (T) for an individual in their mid-forties. Attrition of the occlusal enamel has exposed the underlying dentine (A). Some build-up of secondary dentine on the walls of the pulp chamber (S), particularly heavy is the build-up of secondary dentine on the top of the pulp chamber directly beneath the exposed dentine (RDE).

Plate 6: Longitudinal section of maxillary incisor from a female aged 50+ from the Chichester collection.

Note: The dentine is pinkish-white due to recrystallisation whilst in the archaeological deposit. The boundaries of the recrystallised region (RD) are clearly demarked by unaffected dentine (ND) close to the cementum and enamel. Attrition has occurred on the occlusal surface (A) exposing the dentine, which is consistent with the individual being 50+ years of age.
Plate 1. Longitudinal section of left mandibular first molar, distal root, from a 36 year old male.

Plate 2. Longitudinal section of right maxillary central incisor from a 60 year old male.

Plate 3: Longitudinal section of lower second mandibular molar, distal root, from a 37 year old female

Plate 4: Longitudinal section of a cremated premolar/molar root from Bootle. Plate 5: Longitudinal section of an incisor from a male aged 35+, from the Chichester collection.

Plate 6: Longitudinal section of maxillary incisor from a female aged 50+ from Chichester.