OUT OF THE FRYING PAN INTO THE FIRE: WHAT VALUE ARE BURNT FISH BONES TO ARCHAEOLOGY?

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ABSTRACT: This paper examines both the effects on fish bone of heating to high temperatures and the potential information surviving for archaeologists after fishes have been burned.

Field and laboratory-based experiments were conducted using bones from a selection of fish species. Whole fishes were placed on fires which reached temperatures of up to 850°C; the colour of the bones and the representation of skeletal elements were examined. Bones were also heated in a muffle furnace to temperatures ranging from 200°-900°C and examined with regard to colour, strength and surface morphology, the last using the scanning electron microscope. The results were compared with archaeological material, and it is concluded that within limits the temperature which a bone reached during heating may be determined in an archaeological context.

Both experiments have important implications for the interpretation of archaeological burnt fish remains.

KEYWORDS: FISH, BONE, HEATING, ARCHAEOLOGY, TAPHONOMY

RESUMEN: El trabajo analiza tanto los efectos que sobre los huesos de peces produce la cocción a altas temperaturas como la información de potencial utilidad arqueológica que perdura una vez que los peces han sufrido tal proceso.

Experimentos de campo y de laboratorio, han sido realizados sobre una variada gama de pescados. Peces completos fueron colocados sobre hogueras en donde se registraron temperaturas de hasta 850°C; posteriormente, se examinaron las gamas de colores y los patrones de representatividad esquelética que presentaban las osamentas analizadas. Otros huesos fueron calentados en hornos cerrados a temperaturas que oscilaron entre los 200°-900°C calibrándose posteriormente su color, resistencia y morfología en superficie para lo cual se utilizó un microscopio electrónico de barrido. Los resultados se compararon con materiales arqueológicos concluyendo que, dentro de ciertos límites, resulta posible determinar en contextos arqueológicos la temperatura alcanzada por un hueso sometido a un proceso de calentamiento. Ambos experimentos poseen importantes connotaciones de cara a la interpretación de restos arqueológicos quemados de peces.

PALABRAS CLAVE: PEZ, HUESO, COCCION, ARQUEOLOGIA, TAFONOMIA

INTRODUCTION

Burnt bone is a common but little studied component of many archaeological sites. In some sites, where organic material is not preserved, it represents the sole evidence of animal bone (e.g. Castell Henlys; Gilchrist & Mytum, 1986). While many studies have examined the results of burning human and other large mammal bones, largely because of an interest in human cremation (e.g. Baby, 1954; Binford, 1963; Parker, 1985; McKinley, 1989) to date little attention has been paid to the effects of heating small mammal, bird and fish bones. Notable exceptions include the work of Richter (1986) who looked at the effects of cooking on fish bone collagen, and Spennemann & Colley (1989) who undertook limited field experiments.

In most archaeological instances burnt bone represents the direct exploitation of fish by man as food. Bone displaying evidence of heating is unlikely to have become incorporated into archaeological deposits by "natural" events. In most cases burnt bone probably originated either intentionally, as a result of rubbish disposal of unpleasant objects, or accidentally, during cooking.

This paper presents the results of field and laboratory experiments looking at the effects of burning bone in a natural, variable environment and under more controlled and carefully monitored conditions in the laboratory. The experiments were designed to compare the effects of burning on skeletons from a selection of animals, including mammals, bird and fish, as well as between carcasses subjected to different methods of preparation, for example filleting, boiling and baking. Only the results of burning fish bones are presented in this paper. The work formed part of a more general investigation into the effects of a range of pre-depositional processes on animal remains (Nicholson, 1991). Within this taphonomic framework explanations are sought for variability within the archaeological record.

The major questions which this paper addresses are:

1. How much variation is there in the state of combustion of animal remains within a fire?

2. How much of the skeleton survives after burning? Do certain elements predictably survive or fail to survive?

3. Does the condition of the body before burning affect the way in which the bone will burn, and so can the state of the body be determined from the burnt remains?

4. Are the bones of different species differently affected by burning?

5. How well does the colour/temperature scale proposed for human and other large mammal remains apply to fish remains?

6. Can the temperature of burning be established from the surface morphology of fish bones, as is proposed for mammal bone?

7. What implications are there for the survival of heated bone?

METHODS AND MATERIALS

A. Field Experiments

Three fires were built, each in a shallow (200-300 mm deep) scoop of 1 m^2 area. The bases were lined with locally available sandstone slabs, and six glass marbles were placed at the base of each fire, one in each corner and two in the centre. These were used as a very crude guide to the temperature at the base of the fire, as glass begins to melt at 500°-550°C (Spennemann & Colley, 1989). A more precise indication of the fire temperature was obtained by a digital readout thermometer, the probe of which was placed approximately in the centre of each fire. The wood used on the fires was from a variety of sources, and from a wide range of tree species; much of the wood was driftwood, and some had been treated with preservative. All the fires were lit when the air temperature was 19°C and there was a slight breeze.

A variety of fish and fish remains were used; for a list of species and treatments see Table 1. Three fires (here referred to as Fire 1, 2 and 3) were used in order to keep separate individuals of the same species which had been prepared differently. With the exception of a complete haddock *Melanogrammus aeglefinus* all the fish and fish bones were thrown in after the fire had been alight for 15-20 minutes. The haddock was added after the fire had been alight for one hour. Temperatures were read every 15 minutes, although problems with the digital readout thermometer caused some readings of the Fire 1 to be missed (Figure 1).

Each fire lasted from 200-230 minutes. After the fire had cooled completely the ashes were carefully collected and sieved to 1 mm.

FIRE 1	
	One complete herring, total length 290 mm.
	One complete cod, total length 380 mm.
	One complete plaice, total length 350 mm.
	One filleted haddock frame, total length 370 mm.
	A selection of dry cod bones, from a fish of 600 mm total length, comprising: a complete cranium, one maxilla, two quadrates, two hyomandibulars, two palatines, one ectopterygoid, two ceratohyals, two epihyals, two hypohyals and one first vertebra.
FIRE 2	
	One boiled cod, total length 395 mm, boiled for 1 1/4 hours.
	One baked herring, total length 300 mm, baked at 200°C for 10 minutes.
	One filleted plaice frame, total length 360 mm.
FIRE 3	
	One filleted cod frame, total length 450 mm.
	One filleted herring frame, total length 290 mm.
	Four complete long rough dabs, total lengths 145-155 mm.
	Twenty complete whiting, total length 175-200 mm.

TABLE 1. Fish and Fish Remains Burned on Open-Air Fires.

B. Laboratory Experiments

Experiments were conducted in the laboratory, using a muffle furnace. In human bone work a colour/temperature scale, in which the colour of bone is related to the temperature at which it was cremated, has been generally accepted by, for example Baby (1954), Binford (1963) and Ubelaker (1978) and this scale was later verified experimentally for sheep bones by Shipman and colleagues in 1984. The scale describes the colour of bones with exposure to increasing temperatures, through brown to black at 250°-300°C, blue, grey, bluish grey, and finally white at temperatures of over 700°C. The colour achieved reflects the chemical changes which have taken place in the bone, an important determinant of which is the time of exposure to the maximum temperature.

To investigate whether the colour/temperature scale was applicable to non-mammal remains, and if so whether there was any variation in response between different types of bone, a range of skeletal elements were heated in a muffle furnace to temperatures between 200°C and 900°C, at 100 degree intervals. The tested bones included an articular, hyomandibular, opercular and 8-10 vertebrae from cod *Gadus morhua*, plaice *Pleuronectes platessa,* haddock *Melanogrammus aeglefinus,* herring *Clupea harengus* and salmon *Salmo salar*, as well as calcified vertebral centra from the dogfish *Scyliorhinus canicula.* The bones were heated for a total of two and a half hours, from cold, at which point previous trial experiments indicated that the remains had reached the maximum colour change which would be achieved at a given temperature.

To examine the effect of heating bones when oxygen was limited, similar groups of bones were heated under 30 mm of silver sand in a crucible with a fitting lid. The same temperatures were used as above, and two sets of experiments were run; the first heating the remains for two and a half hours, the second to five hours.

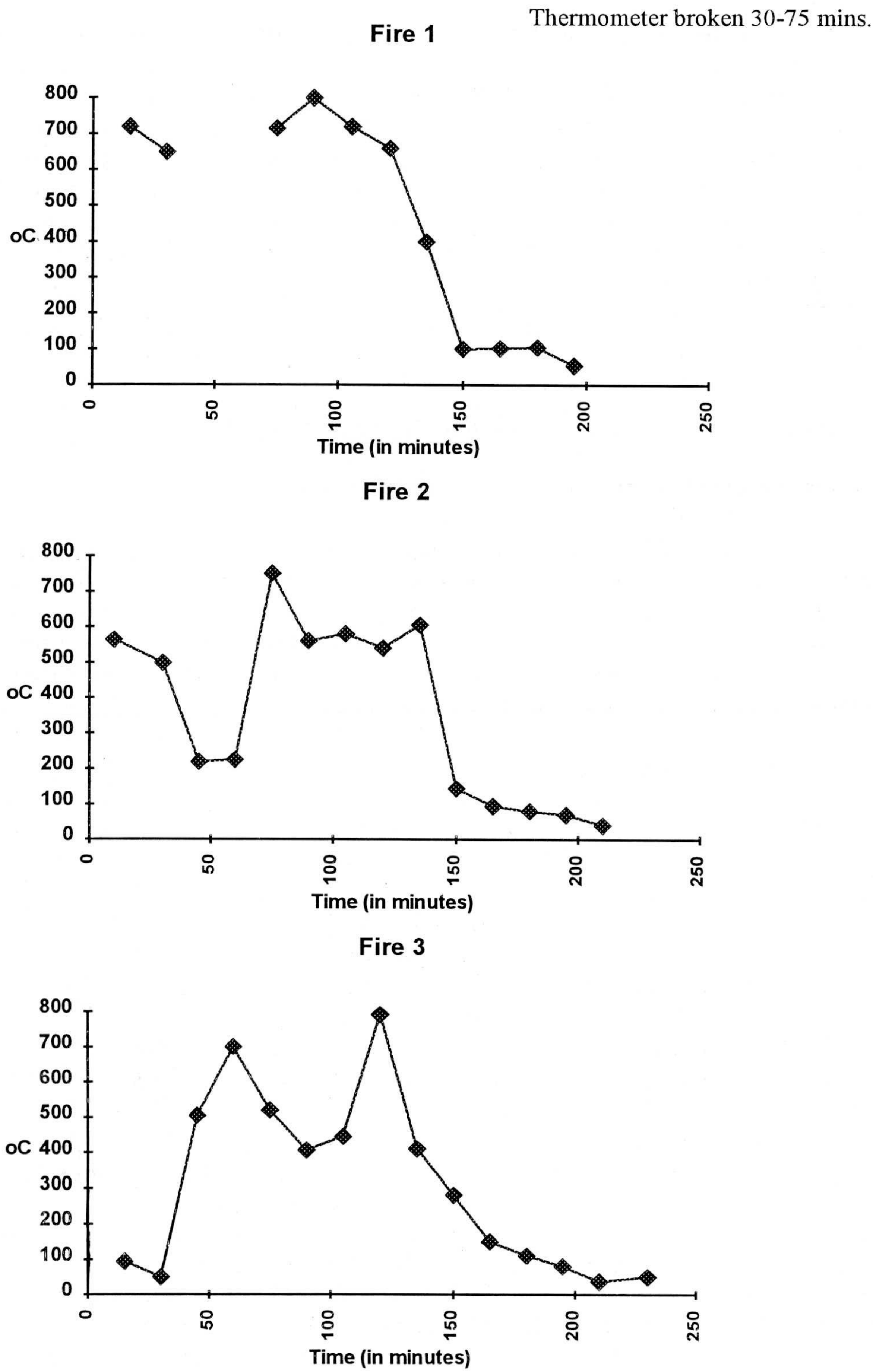


FIGURE 1. Fire temperatures.

Specimens were prepared for examination using the scanning electron microscope (S.E.M.) by cleaning with mild detergent in an ultrasonic tank, followed by brushing with alcohol and acetone, as recommended by Shipman *et al.* (1984). Fresh bones and bones heated to below 600°C were also shaken in a 1:2 mixture of methanol:chloroform for at least 12 hours to remove the extensive surface grease. Specimens were mounted on stubs and coated with gold in a Polaron coating unit to make them conductive, and viewed under the S.E.M. at magnifications from 25X to 15000X. The most useful magnifications were found to be between 1000X and 10000X. Archaeological samples from the Late Norse site of Freswick, in Caithness, Scotland (Batey, 1987) were cleaned in sodium pyrophosphate in an ultrasonic tank for ten minutes to remove adhering soil particles, and were then similarly mounted and examined.

RESULTS AND DISCUSSION

A. The Experimental Fires

i. Temperature

The temperatures for Fires 1-3 are given in Figure 1; mean readings are given, as the temperature could vary by up to 100°C during a very short space of time, depending on the movement of the flames. The maximum temperature reached by all the fires was in the range 750°C-825°C, although this temperature was not sustained for more than 15 minutes in any case. Only the glass marbles from the centre of Fire 3 showed evidence of surface melting, indicating that in all other cases temperatures at the base of the fires were never, or only briefly, in excess of 550°C.

ii. Skeletal Element Representation

The bones recovered were identified to skeletal element and species (terminology after Wheeler & Jones, 1989) and the numbers of bones recovered were compared with the number of bones in the fresh fish. Ribs, spines and rays were not counted, as identification to species is frequently very difficult or impossible. Figure 2 shows the relative abundance of skeletal elements recovered from the 20 whiting *Merlangius merlangus* and 4 long rough dab *Hippoglossoides platessoides* after burning on Fire 3, based on the expected numbers of bones. Table 2 details the recovered skeletal remains for the cod, haddock, plaice and herrings as well as for the whiting and long rough dab.

It is evident that a similar selection of skeletal elements are commonly represented in the burnt assemblages, irrespective of species or treatment of the corpse. The bones most well represented after burning were vertebrae in all cases. Bones also commonly recovered from all but the herrings were the jaw bones and jaw supports (the dentary, premaxilla, quadrate, and articular), and to a lesser degree the preopercular and post-temporal. The supracleithrum, ceratohyal, palatine and ectopterygoid were also recovered in small numbers from the gadid fish. The complete haddock (Fire 2) was added to the centre of the fire later than the other fish, after one hour, when the temperature had dropped, in a deliberate attempt to investigate the effect on the skeleton of incomplete incineration; as a result the head did not burn completely and was left as a black charred mass; however the spine was cremated entirely and most vertebrae were blue, grey or white with the paler colours found on bones towards the caudal peduncle. Some other fish were also incompletely burned;

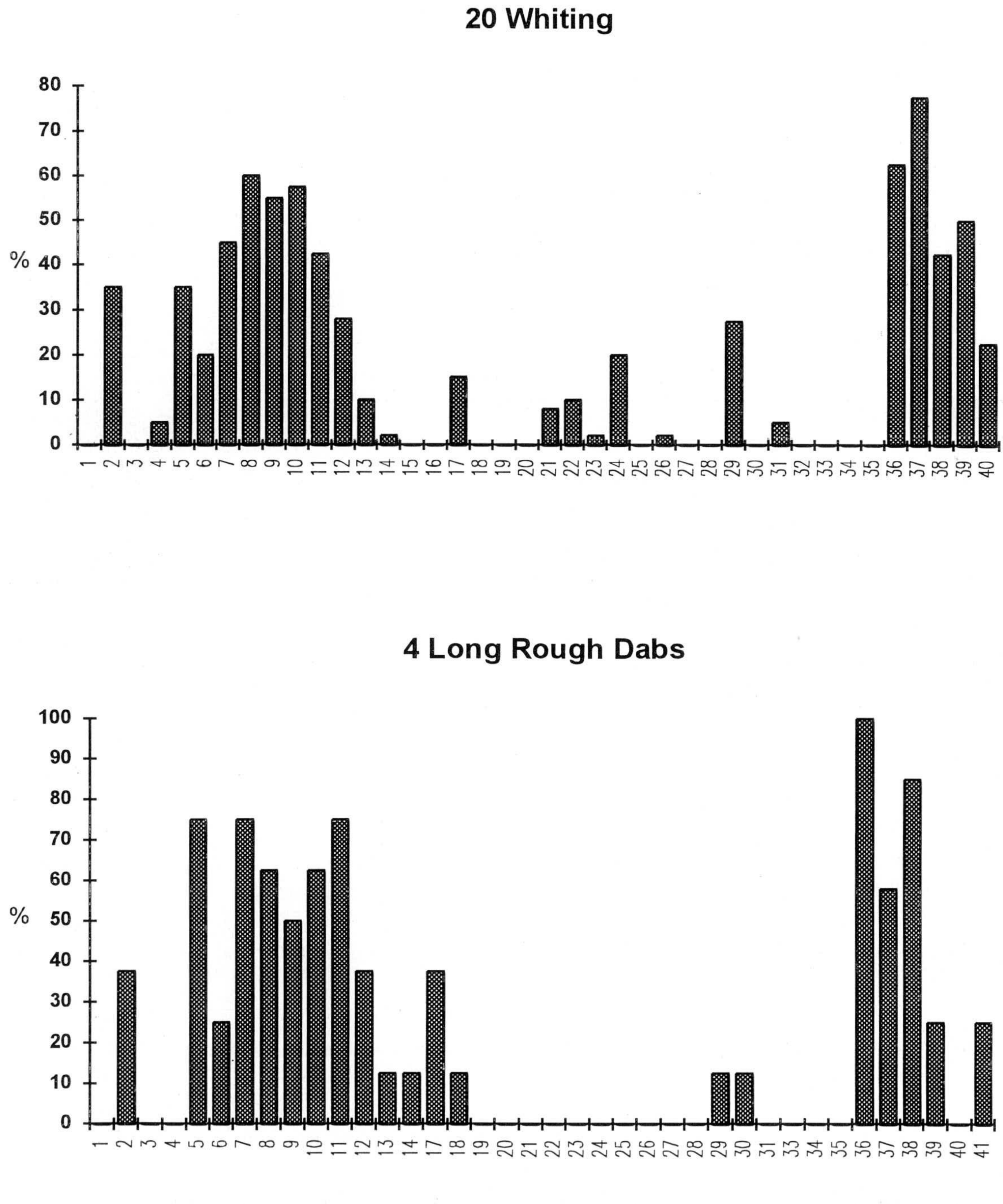


FIGURE 2. Percentage Relative Abundance of Skeletal Elements from 20 Whiting and 4 Long Rough Dab, after Burning on an Open-Air Fire. 1: Ethmoid; 2: Frontal; 3: Prefrontal; 4: Supraoccipital; 5: Prevomer; 6: Parasphenoid; 7: Basioccipital; 8: Premaxilla; 9: Maxilla; 10: Dentary; 11: Articular; 12: Quadrate; 13: Hyomandibular; 14: Symplectic; 15: Lacrimal; 16: Nasal; 17: Preopercular; 18: Opercular; 19: Subopercular; 20: Interopercular; 21: Palatine; 22: Ectopterygoid; 23: Epihyal; 24: Ceratohyal; 25: Hypohyal; 26: Infrapharyngeal; 27: Suprapharyngeal; 28: Urohyal; 29: Post-temporal; 30: Cleithrum; 31: Supracleithrum; 32: Postcleithrum; 33: Scapula; 34: Coracoid; 35: Basipterygium; 36: First vertebra (atlas); 37: Abdominal vertebra; 38: Caudal vertebra; 39: Hypural; 40: Otolith; 41: Anal pterygiophore

SKELETAL ELEMENT	No.	FIRE 1				FIRE 2				FIRE 3			
		COD C	HADDOCK F	HERRING C	PLAICE C	COD BO	HADDOCK C	HERRING BA	PLAICE F	COD F	HERRING F	WHITING C(n=20)	L.R.Dab C(n=4)
Ethmoid	2									1			
Prefrontal	2		2										
Frontal	2			1	2	1	1					2	
Prevomer	1		1				1			1		7	3
Parasphenoid	1		1	1	1							4	1
Basioccipital	1	1	1		1	1	1			1	1	9	3
Epiotic	2		2										
Prootic	2		2										
Otolith	2					1				2		9	
Premaxilla	2	2	2				2			2		24	5
Maxilla	2	2		1	1		1		1	1		22	4
Lachrymal	2												
Dentary	2	2	2	1	2		1			2		23	5
Angular	2												
Articular	2	2	2	2		1			1		1	17	6
Quadrate	2		1		1	1				2		11	3
Hyomandibular	2				1						1	4	1
Preopercular	2	1	2		1	1						6	3
Opercular	2	1	1						1			1	1
Subopercular	2												
Interopercular	2	1											
Palatine	2	1								1		3	
Ectopterygoid	2									1		4	
Entopterygoid	2												
Metapterygoid	2												
Symplectic	2	1	1							1		2	
Interhyal	2												
Epihyal	2		2		1					1		1	
Ceratohyal	2		1			1				1		8	
Basyhyal	2												
Infrapharangeal	2		2									1	
Suprapharangeal	6		1		4				1	1			
Urohyal	1				1				1				
Post-temporal	2		2		1		1			2		11	1
Supracleithrum	2	2	2		1		2		1	2		2	
Cleithrum	2	1	1		1		1		2				1
Postcleithrum	2												
Scapula	2												
Coracoid	2												
Basipterygium	2												
First Vertebra	1	1	1	1	1	1				1		12	4
Abdominal Vertebrae	17*	16	19	29	13	17	13	22	12	14	15	270	25
Caudal Vertebrae	33*	22	18	33	25	12	24	18	21	13	22	295	99
Hypural	1											2	
Otic Bullae (Herring only,	2			2							2		
Anal Pterygiophore Flatfish only)	1				1				1				1
Cranium**	1	1		1(Back)						1			

TABLE 2. Numbers of major skeletal elements recovered from experimental fires 1-3, compared with the numbers (No.) of the same selection of skeletal elements in a fresh fish.

(*) These figures refer to cod and whiting. Haddock have 19 abdominal and 32 caudal vertebrae, plaice have 12 abdominal and 28-30 caudal vertebrae and herring have between 51 and 58 vertebrae.

(**) These records refer to charred, incompletely burnt heads or parts of heads.

C = Complete; F = Filleted; BO = Boiled; BA = Baked; n = number of individuals (n=1 unless otherwise indicated).

lumps of black charred material represented parts of the corpse in several cases. These lumps sometimes contained dark brown, oily bones, but in many instances bones within the lumps were black, fragile and extremely difficult to separate or discern from the mass of charred flesh. The charred remains of skulls were particularly difficult to recognise, and if found archaeologically would be unlikely to be identified as fish. Looking at the whiting and long rough dabs, separating the head bones by side and counting only fragments which included the articular end, gave a Minimum Number of Individuals of 14 whiting (based on the dentary) and of 4 long rough dabs (based on the first vertebrae; a MNI of 3 was obtained from the dentary, premaxilla and articular).

The only bones to show substantial cracking and warping were those of the filleted cod on Fire 3. These were also, with the exception of the dry cod bones, the largest bones used for the experiment. Whether the distortion was a result of the higher temperatures on Fire 3, or the larger bones, is unclear. The bones of the herring and small dab and whiting recovered from Fire 3 were not noticibly distorted or cracked.

iii. Colour

Table 3 gives a summary of the major colours of the bones from Fires 1-3, by species. The proportions given are percentages of the total number of recovered bones of the fish which display the major colour.

A wide range of colours were displayed by the experimentally burned bones. The colours seemed to relate more to the position of the remains within the fire than to species or treatment of the corpse. In general, all the bones in the centre of the fire tended towards white or light grey, which is the expected colour based on the maximum fire temperatures of 750°- 825°C. Experiments by Spennemann & Colley (1989) suggest that the colour of a bone is related to its shape and density, with thin head bones attaining a lighter shade than vertebrae. This trend was not apparent from this study.

	DK BROWN	BLACK	BLUE	GREY	LT BLUE	LT GREY	WHITE
FIRE 1							
Complete Cod	0	48	1	0	0	3	49
Filleted Haddock	0	0	1	24	0	26	49
Complete Herring	0	11	8	44	8	0	29
Complete Plaice	0	1	1	22	0	12	64
Dry Cod Bones	2	0	20	9	2	2	67
FIRE 2							
Boiled Cod	0	21	7	14	14	2	42
Complete Haddock	0	36	47	6	0	9	4
Baked Herring	0	10	0	0	10	7	74
Filleted Plaice	0	11	7	11	4	20	48
FIRE 3							
Filleted Cod	0	4	12	3	7	25	49
Filleted Herring	0	0	0	2	12	48	38
Complete L.R.Dab	0	2	4	10	1	35	48
Complete Whiting	1	10	1	14	1	41	32

TABLE 3. Percentages of Major Colours on Fish Bones from Experimental Fires 1-3.

Although the whiting vertebrae did seem to be generally darker in colour than their head bones, this pattern was not observed for other fish: the caudal vertebrae towards the caudal peduncle of the haddock on Fire 1 were blue/grey while the headbones were mostly black, and the vertebrae from the boiled cod were a darker hue than most of its head bones. It is likely that the differences in colour of the whiting bones can be explained by the greater covering of flesh over the spine of the fish, protecting the vertebrae from oxygen and the maximum fire temperature for longer than the thinner covering over most of the head bones. While bone density will affect the speed at which the chemical changes which produce the characteristic colours in burned bone take place, all densities of bone should eventually reach the same colour for a given temperature, assuming an initially similar chemical composition, although the presence of soft tissue, particularly fat, will encourage combustion (McKinley, 1989).

There was no clear correlation between the proportions of mottled bones from a skeleton and the treatment of the carcass prior to burning. Although it might be expected that fleshed bones would appear more mottled than defleshed bones, due to uneven rates of heating and availability of oxygen (see below) this was not supported by the evidence. Almost half of the dry cod bones were mottled after burning on Fire 1 (Nicholson, 1991), a similar proportion to the originally fleshed cod bones, also from Fire 1. Mottling seemed to be determined more by the position of the remains within the fire than by the prior treatment of the carcass. Mottling was least frequent on skeletons where the predominant colour was white, indicating complete combustion; these skeletons were more commonly those of the smaller fish and/or those found in the heart of the fire.

B. The Laboratory Experiments

i. Colour

Table 4 gives the predominant and minor colours for the bones heated in open crucibles, and those heated under sand for two and a half and five hours; colours follow the Munsell soil colour chart notation (Munsell Colour Company, 1973).

While the results confirm that the colour/temperature scale obtained for mammal bone is broadly applicable to fish and bird bone, it was interesting that there were some differences in the colours achieved by the bones from the various animal groups. In particular, the colours achieved by fish bones at 400°C-600°C were consistently darker than the colours of mammal and bird bones heated in the same experiments, even though the fish bones were smaller and appeared to be more porous (Nicholson, 1991: 104-105). The dogfish mineralised vertebral centra crumbled on touch when heated to 700°C and above, but all other bones remained intact. There were no major differences in the colours achieved by the various skeletal elements from each species, suggesting that colour differences had more to do with the chemical composition of the bone - possibly with the amount of fat within the bone - than with differences in bone "density" or shape.

Turning to the bones heated in a reduced air supply, there was little difference in colour between the bones heated in open crucibles for two and a half hours and those heated for five hours under sand. Greater mottling occurred on those bones heated for two and a half hours under sand however, and at temperatures between 500°C and 700°C most bones were a darker hue. Presumably these bones had either not reached the maximum temperature all over or had had insufficient oxygen available to enable the chemical reactions to take place. In the complete absence of oxygen no combustion can occur. Conditions in nature are unlikely to be completely anaerobic, however, and a covering of 30 mm sand should approximate to naturally reducing conditions. In this situation, given

BONES HEATED IN OPEN CRUCIBLES FOR TWO AND A HALF HOURS		
Temperature	**Predominant Colour**	**Minor Colours**
Salmon		
200°C	Strong Brown 7.YR 5/8	7.5YR 5/6, 2.5YR 5/8, 5YR 3/4, N2
300°C	Black N2	5YR 3/2,3/3, 5B 6/1
400°C	Black N2	
500°C	Black N2	10YR 3/2, 4/2, 6/2, 5YR 3/3, 5B 5/1, N4, N5
600°C	Black N2	10YR 3/2,5/2,3/1,4/2,5/1, 5B 6/1,7/1, N6, N7
700°C	Grey 2.5Y 6/0	5Y 3/1,6/1, 5B 7/1, N5, N8
800°C	White N8	
900°C	White N8	10R 6/3
Cod		
200°C	Yellowish Red 5YR 5/8	7.5YR 5/8, 2.5Y 8/2, 10YR 7/6
300°C	Black N2	
400°C	Black N2	
500°C	Black N2	10YR 3/1,4/2,5/1, 5YR 3/2, 5B 6/1
600°C	Very Dark Grey N4	10YR 3/2,4/2, N2, N5, N6, N7
700°C	White N8	N4, N5, N6, 5B 6/1, 7/1
800°C	White N8	
900°C	White N8	10R 6/3, 5G 7/2
Haddock		
200°C	Yellowish Red 5Y 5/8	5YR 4/6,3/3,3/6, N2, 10YR 6/8
300°C	Black N2	
400°C	Black N2	
500°C	Black N2	5YR 3/3, 2.5/1, 10 YR 7/2,4/1, 5B 7/1,
600°C	Dark Greyish Brown 10YR 4/2	10YR 3/1,3/3,4/1,4/3, N5, N6, N8, 5B 6/1,7/1
700°C	White 2.5Y 8/1	N6,N7, 5B 6/1,7/1
800°C	White N8	
900°C	White N8	
Plaice		
200°C	Brownish Yellow 10YR 6/6	5YR 3/2, N2, 10YR 5/8, 2.5YR 2.5/4
300°C	Black N2	
400°C	Black N2	
500°C	Black N2	10YR 3/3,4/1, 5YR 3/4,2.5/2
600°C	Black 10YR 2/1	10YR 2/2,3/1, N2, N4, N6, N8, 5B 6/1, 7/1
700°C	White 2.5Y 8/0	5B 6/1, 7/1, N6, N7, 5Y 4/1
800°C	White N8	
900°C	White N8	
Herring		
200°C	Very Pale Brown 10YR 7/3	10YR 7/6, 5YR 2/1,4/4, 2.5YR 3/6
300°C	Black 5YR 2/1	
400°C	Black N2	2.5YR 3/6
500°C	Very Pale Brown 10YR 8/4	10YR 7/3,6/2,4/3,4/4,2/2,3/2
600°C	Dark Greyish Brown 10YR 4/2	10YR 4/1,3/2,2/1, N8, 5B 6/1
700°C	White 5Y 8/1	5Y 6/1, 7/1
800°C	White N8	
900°C	White N8	
Dogfish		
200°C	Yellow 10YR 7/6	5YR 4/4, 2.5YR 2.5/2,2/0,3/4
300°C	Black N2	5Y 3/2
400°C	Black N2	
500°C	Black N2	5YR 3/4, N7, 5B 7/1
600°C	Dark Greyish Brown 10YR 4/2	N2, N8, 5B 7/1
700°C	White 2.5Y 8/0	N6,N7

TABLE 4. Major and Minor Colours for Fish Bones Heated in the Muffle Furnace. (Colours identified using the Munsell Soil Colour Chart in daylight).

Temperature	BONES HEATED UNDER SAND FOR TWO AND A HALF HOURS Predominant Colour	Minor Colours	BONES HEATED UNDER SAND FOR FIVE HOURS Predominant Colour	Minor Colours
Salmon				
200°C	Yellowish Red 5YR 4/6	5YR 3/3, 2.5/1	Yellowish Red 5YR4/6	5YR 2.5/1
300°C	Black N2		Black N2	
400°C	Black N2		Black N2	
500°C	Grey 5YR 5/1	5YR 4/1, 5/3, N2, 5B 7/1	Grey 10YR 5/1	10YR 4/1, 5B 7/1, N8
600°C	Grey N5	5YR 2.5/1,5B4/1 6/1, 7/1, N4	Bluish Grey 5B 6/1	N6,N5,5B 5/1 N8
700°C	White N8	5B 5/1, 6/1, 4/1, 5YR 2.5/1	White N8	10YR 5/1
800°C	White N8	N6, N7	White N8	
900°C	White N8		White N8	
Cod				
200°C	Dark Reddish Brown 5YR 3/2	5YR 2.5/2, N2	Dark Reddish Brown 5YR 3/2	5YR 2.5/1
300°C	Black N2		Black N2	
400°C	Black N2		Black N2	
500°C	Dark Grey 5YR 4/1	5YR 2.5/1, 2.5/2	Dark Grey N4	5YR 2.5/2
600°C	Dark Grey 5YR 4/1	5B 4/1	Grey N5	5B 5/1,6/1,7/1,N4,N8
700°C	Dark Bluish Grey 5B 4/1	5B 5/1,6/1,7/1,N8	Light Bluish Grey 5B 7/1	5B 6/1,N8 N7, N6
800°C	Bluish Grey 5B 5/1	5B 6/1,7/1,N8,5Y5/1	White N8	5B 7/1, 6/1
900°C	White N8		White N8	
Haddock				
200°C	Dark Reddish Brown 5YR 3/2	5YR 2.5/2, N2	Dark Reddish Brown 5YR 3/2	5YR 2.5/1
300°C	Black N2		Black 5YR 2.5/1	
400°C	Black N2		Black N2	
500°C	Dark Grey 5YR 4/1	5YR 2.5/2, 2.5/1	Dark Grey N4	10YR 2.5/2
600°C	Dark Grey 5YR 4/1	5B 5/1, 5YR 2.5/1	Grey N5	N4,10YR 5/1,5B 6/1
700°C	Dark Bluish Grey 5B 4/1	5B 5/1, 5YR 2.5/1	Bluish Grey 5B 6/1	5B7/1,N8
800°C	Bluish Grey 5B 5/1	N8, 5Y 5/1	White N8	
900°C	White N8		White N8	

TABLE 4 cont.

sufficient time all bones should eventually reach the same temperature related colour as bones freely supplied with oxygen.

The mottling seen on the bones burnt under sand for two and a half hours is similar to that seen on some of the bones from the experimental fires, and also on many archaeological bones. In these situations the mottling may occur because the bones were covered by ash, or flesh, which promoted uneven conditions of heat and oxygen supply, or because the uneven and sporadic nature of the heat within a fire had resulted in uneven exposure to temperature.

ii. Surface Morphology

As the colour of bone may be altered in the soil, for example by manganese staining, iron oxide staining or deposition of other minerals within the bone (Franchet, 1933) it is useful to be able to determine burning by other means. The use of the scanning electron microscope (S.E.M.) to observe changes in surface micromorphology on bone after heating was first documented by Shipman *et al.* (1984) who looked at modern sheep and goat bones and teeth, and concluded that temperature of burning could be established from a study of the surfaces micromorphology of bone and dentine.

Temperature	Macroscopic appearance and Microscopic Appearance through the light microscope	Microscopic Appearance - through the S.E.M. (vertebrae only)
Stage 1 20°C	The surfaces of all bones were gently undulating and continuous.	The surfaces of all bones were gently undulating and continuous.
200°C	The surfaces of the bones were similar to fresh bone. The flat areas of the head bones were brittle and cracked.	The surfaces of the bones were undulating and continuous, and very similar to fresh bone.
Stage 2 < 300°C > 400°C	The surfaces of all bones were covered with a black peeling char, which was particularly thick and bubbly on the articular surfaces.	The surfaces of all the vertebrae were obscured by peeling char which formed an undulating, sometimes cracked layer on all the surfaces, even after cleaning. Beneath this layer the plaice, herring and salmon bone surfaces were undulating, but were less regular than on fresh bone. No areas beneath the char could be viewed on the other species, as even after cleaning the layer was continuous.
Stage 3 < 500°C < 700°C	Most bone surfaces were extensively cracked. The subchondral surfaces of the articular and opercular bones were, where not covered in char (generally at temperatures above 500°C) extensively cracked. All but the herring bones exhibited radial cracks. On all vertebrae not covered in bubbly char the growth rings were clearly visible.	It is difficult to categorise the range of surface forms observed on the bones in this stage, due to the variability in form between specimens. In general, the surfaces of the vertebrae were continuous and rather lumpy, or particulate. Some of the variation appears to be related to species; while the surfaces of the salmon vertebrae appeared lichen-like, those of cod and haddock were lumpy, while herring bones had a regular undulating surface at 500°C, which became particulate by 600°C. A variety of forms were observed on the surface of the plaice vertebrae while the dogfish centra had very fissured and lumpy appearance. After heating to 600°C-700°C the examined surfaces of all the specimens appeared frothy.
Stage 4 > 700°C > 900°C	All surfaces were smooth, chalky and featureless. All but the very deep cracks have disappeared.	At these high temperatures sintering of the mineral phase of bone produced distinctive enlarged crystals, the shape of which varied between species and with condition of burning and skeletal element. In general the pattern exhibited could be decribed as nodular, although flat, polygonal plates were also observed on a salmon vertebra. Haddock and herring exhibited a regular "knitted" appearance on the specimens studied. The surfaces of plaice and dogfish fell between these two forms.

TABLE 5. Heating Stages in Bones: Fish Bone Surface Macroscopic and Microscopic Morphology.

Observations under the S.E.M. on a selection of vertebrae from cod, haddock, plaice, herring, salmon and the mineralised centra of dogfish, showed similar changes, although there was some variation within the stages particularly in samples heated to above 700°C. The stages observed on the fish vertebrae under the S.E.M. and under the light microscope are detailed in Table 5. Although in general the patterns observed are similar to those documented by Shipman *et al.* (1984), their Stage 2 (185°-<285°C) was not established with confidence on the samples I examined. At above 700°C a wide range of surface morphologies were observed. These included smooth polygonal plates, similar to the surface illustrated for sheep subchondral bone by Shipman and colleagues (*ibid.*) as well as nodular surfaces similar to Shipman's cortical bone samples, and a to-date undocumented regular "knitted" pattern. Other less regular surfaces were also observed. The surface morphologies did not appear to be species-specific, and more probably reflect variations in factors including rates of cooling, atmosphere within the heating device and shape of the bone surface. All have in common the fact of enlarged crystals, as a result of the recrystallisation of the hydroxyapatite mineral after sintering. A selection of these surfaces are illustrated in Figure 3, and are compared with archaeological samples. The dogfish centra crumbled to powder at temperatures above 700°C.

Having observed the stages on freshly burnt bone, archaeological samples were examined to see whether the same surface morphologies were present. The archaeological bones examined included a range of colours, and in general the surface morphology and the colour of the bone gave a similar picture of heating temperature (Table 6). There were exceptions, however. Some samples, although appearing burned on the basis of colour (white and black) had a surface micro-morphology resembling that expected for fresh bone. It is unclear whether this is due to diagenetic changes in the bone by staining or modifications to the surface, although the surfaces appeared to be uneroded. The two ambiguous white samples appeared to be only superficially white on examination under the light microscope, however, suggesting staining, bleaching or mineral efflorescence.

SITE CODE	BONE TYPE	COLOUR	APPEARANCE	INTERPRETATION
FL80 JJ 52 4 sq1	Vertebra of Molva cf. molva	Black & Dark Brown	Gently undulating, vitreous, small nodules lie on the surface	Heated to 300-400°C
FL80 JJ 52 4 sq1	Vertebra of Molva cf. molva	Black	Irregular, continuous	Uncertain if heated
FL80 JF 39 4 sq1	Gadid Vertebra	White	Enlarged needle-shaped and and nodular crystal	Heated to 700°C or above
FL80 JF 39 4 sq1	Gadid Vertebra	White	Gently undulating, continuous	Uncertain if heated
FL80 JM/R 4 sq1	Gadid Vertebra	Black	Continuous, gently undulating	Uncertain if heated
FL80 JJ 60 4 sq1	Gadid Vertebra	White & Grey	Frothy	Heated to 500-700°C
FL80 JJ 60 4 sq1	Gadid Vertebra	Grey, White, & Light Blue	Frothy	Heated to 500-700°C
FL80 JJ 56 4 sq1	Gadid Vertebra	White	Highly particulate, some areas nodular	Heated to 600-700°C
FL80 JJ 56 4 sq1	Gadid Vertebra	Brown	Gently undulating, continuous	Not heated
FL80 JJ 56 4 sq1	Gadid Vertebra	White	Enlarged, irregular crystals	Heated to 700°C or above
FL81 2ae 132 MD1	Gadid Vertebra	Black	Some areas viscous, some irregular	Heated to 300-400°C
FL80 JJ 52 4 sq1	Gadid Vertebra	Mid Blue	Particulate	Heated to 500-600°C

TABLE 6. Archaeological Samples from Freswick Links, Scotland: Surface Apperarance with the S.E.M.

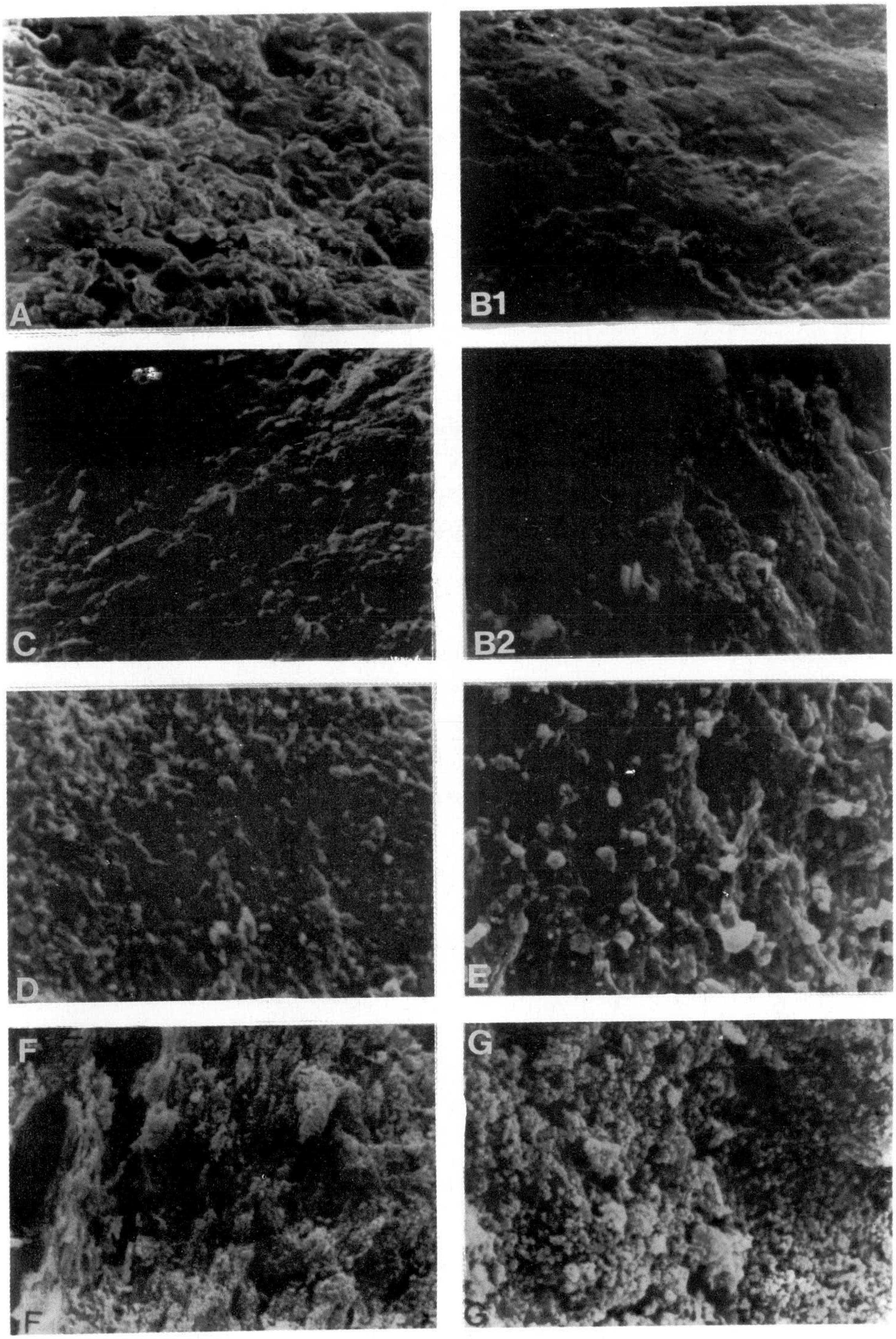
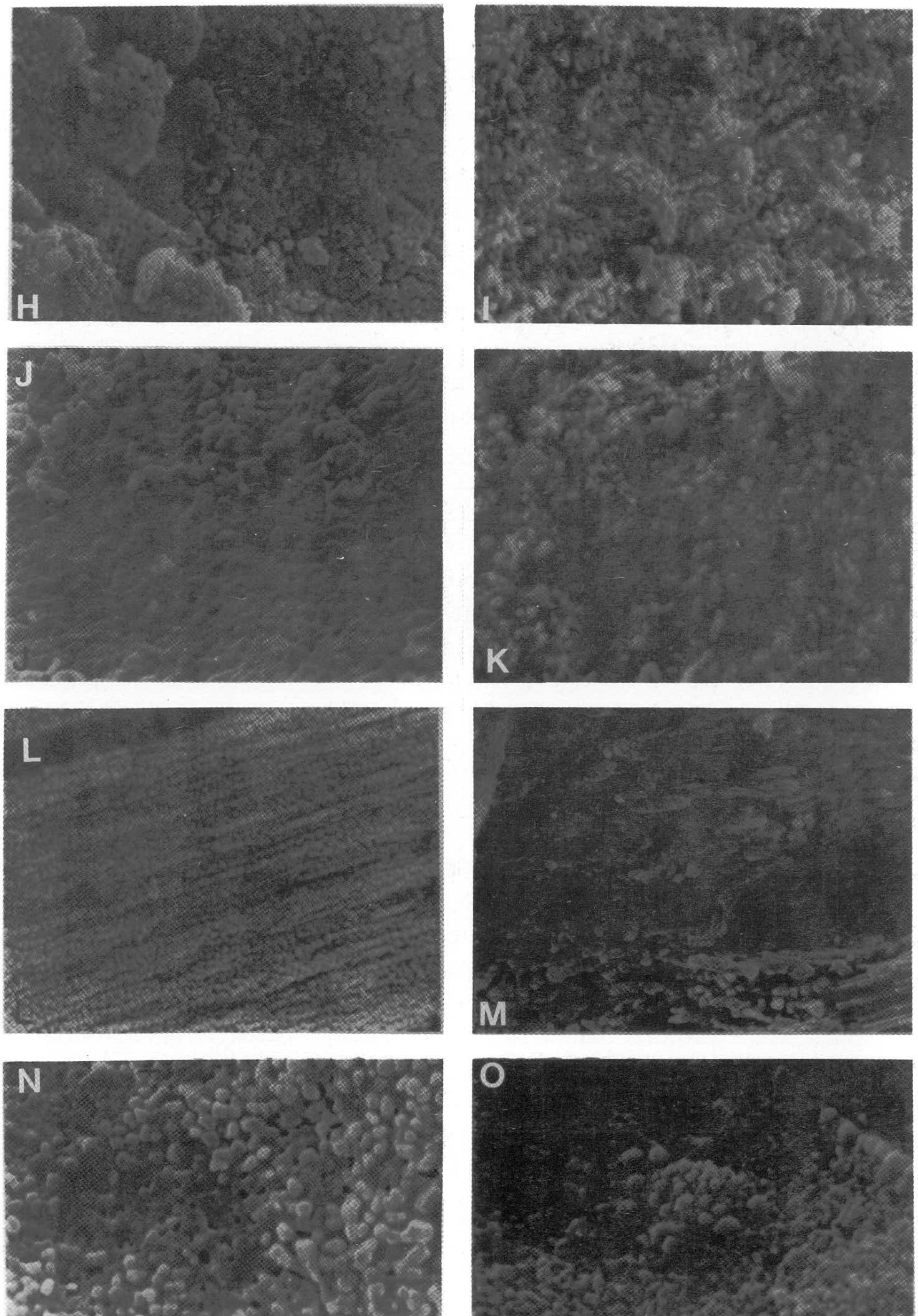


FIGURE 3. Fish Vertebrae, Surface Morphology of the Articulating Facets, Viewed through the SEM (scale bar = 1 micron). A. Contemporary cod, unheated; B1. Mid-brown gadid, from Freswick; B2. Same sample as B1, different area; C. Contemporary cod, heated to 200°C; D. Contemporary cod, heated to 400°C; E. Black and dark brown ling *Molva cf. molva*, from Freswick; F. Contemporary salmon, heated to 700°C; G. Light blue, white and grey gadid, from Freswick;



H. Contemporary haddock, heated to 900°C; I. White gadid, from Freswick; J. Contemporary salmon, heated to 900°C; K. White gadid, from Freswick; L. Contemporary herring, heated to 900°C; M. White gadid, from Freswick; N. Contemporary cod, heated to 900°C; O. Contemporary salmon, heated to 900°C.

iii. Strength

When burnt, fish remains are extremely fragile, especially thin head bones. Even if circumstances enabled them to become buried intact, excavation and sieving may destroy them. Burned material is best removed in a block of soil and carefully disaggregated in the laboratory. Once buried, changes induced by microorganisms are likely to be minimal on completely calcined bone (heated to 600°C-700°C and above). Once completely combusted, bone comprises solely mineral material (hydroxyapatite or possibly tricalcium phosphate). Incompletely incinerated bone is brown or black and contains some organic material, hence it is much more liable to attack by bacteria and fungi than completely calcined bone. Under all but the most acidic conditions charred bone is therefore likely to degrade more rapidly than completely calcined material.

To determine the strength of mammal bone heated to temperatures between 200oC and 900oC static bending tests were performed using the Instron model 1122 table testing instrument. The results indicated that bone heated to 900oC is marginally stronger in bending than bone heated to 500oC-800oC (Nicholson, 1991, 1993). This is due to the physical expansion of the hydroxyapatite crystals after sintering or vitrification, followed by recrystallisation at temperatures of about 800oC-900oC, with a corresponding decrease in pore space. Below about 500oC organic material left in the bone increases its resilience, as the strength of bone is a product of its composite structure of collagen fibres impregnated with mineral (Currey, 1984); even thermally denatured collagen appears to lend some structural support. Subjection to purely physical force (e.g. trampling) or to internal pressures due to the addition and removal and/or freezing and thawing of water (for example in bone exposed above ground or buried in the topsoil) will result in the rapid fragmentation of calcined bone, as experiments have demonstrated (Nicholson, 1991); less well burned bone will remain intact longer under these circumstances.

CONCLUSIONS

These experiments caution against using burnt bones to infer the history of a burning event. The condition of bones after burning on small open-air fires was very variable, and depended most upon the position of the remains within the fire and the degree and duration of the maximum fire temperature. Spacial variation in fire temperature was enormous; carcasses at the centre of the fire were almost all completely calcined while those towards the periphery were commonly only charred. At the periphery of the fire, the post-cranial portion of complete fish tended to burn more vigorously than the head, probably because burning fat raised the local temperature, hence vertebrae attained a paler hue than the head bones; however this result could also derive from the positioning of the animal within the fire. As this study demonstrates, even a small "campfire" may attain temperatures sufficient to calcine bones.

Although many bones were lost, or rendered completely unidentifiable by burning, a surprising number of bones survived, even from very small fish. Breakage was more common for larger bones. Vertebrae and bones of the jaw and jaw support were particularly well represented.

Looking at the surface morphology of bone burned when fresh should enable an approximate indication of the temperature reached by the bone, and can help to distinguish between burned and unburned bone in cases where colour may be equivocal. The colour and surface morphology of individual bones can not be used to deduce the type of fire used, however, or the temperature which the fire reached. Bones from different species may not attain the same colour for a given maximum temperature, and the colour of different bones subjected to the same temperature may vary greatly depending upon the duration of the maximum temperature, size of the bone, type of the bone, and local atmospheric environment.

Because of the loss of some bone in burning, and the added complication of differential susceptibility to post-depositional destruction of bone heated to various temperatures, burnt bone clearly can not be treated in the same way as presumed unheated bone for quantification purposes. However, the preservation of even small bone after burning in a more-or-less undistorted form should allow speciation in many cases, and an approximation of fish size. In preferential circumstances of bone deposition and preservation it is possible that bone burnt in cooking may be distinguished archaeologically from bone burnt as rubbish; completely calcined bone (grey or white) would not be expected in a cooking accident, but unfortunately the reverse is not neccessarily true.

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