

Technological Examination of Neolithic–Bronze Age Pottery from Central and Southeast Europe and from the Near East

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Scanning electron microscopy is used to examine sequences of pottery sherds from central and southeast Europe, Greece and the Near East spanning the period from the Neolithic to the Bronze Age, in order to obtain information on the ceramic technologies employed in antiquity. On the basis of the vitrification observed and the chemical composition, the types of clay and firing procedures (temperature and atmosphere) employed in the manufacture of the pottery are defined. Two underlying trends in the associated ceramic technologies are thus identified. The first is based on the use of non-calcareous or “unstable” calcareous clays fired in a reducing atmosphere at temperatures below 800 °C and the second on the use of “stable” calcareous clays fired in an oxidizing atmosphere at temperatures in excess of 800 °C.

Keywords: POTTERY, FIRING TEMPERATURE, FIRING ATMOSPHERE, CALCAREROUS CLAY, SCANNING ELECTRON MICROSCOPE, X-RAY DIFFRACTION, X-RAY FLUORESCENCE, VITRIFICATION, BLOATING, NEOLITHIC, CHALCOLITHIC, BRONZE AGE, GREECE, EGYPT, JERICHO, SERVIA, BALKANS.

Introduction

Sequences of pottery sherds from central and southeast Europe (Czechoslovakia, Hungary, Yugoslavia, Bulgaria, Romania, southwest Russia and Greece), Servia (Macedonia), Anatolia, Jericho and Egypt spanning the period from the Neolithic to the Bronze Age were examined principally using the scanning electron microscope (SEM) in order to obtain information on the type of clay and firing procedures used in their manufacture.

Freshly fractured surfaces in the pottery were examined in the SEM (Cambridge S600), both in the as-received state and after refiring at known temperatures in oxidizing and reducing atmospheres in a laboratory furnace. The oxidizing atmosphere was achieved by maintaining a flow of air over the pottery samples during refiring and the reducing atmosphere by maintaining a flow of nitrogen with the samples buried in

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flour. Semi-quantitative analysis for the major and minor elements (Si, Al, K, Fe, Mg, Ca and Ti) was undertaken using the energy-dispersive X-ray fluorescence spectrometer attachment to the SEM and the mineral phases present in the pottery were identified by means of X-ray diffraction with Debye-Scherrer powder cameras. The texture of the pottery fabric was assessed by examination of a fracture surface under an optical microscope ($\times 10$ magnification).

The SEM examination of the pottery in the as-received state provided information on the internal morphology developed during the original firing in antiquity and in particular, on the extent of vitrification (the glassy phase) and the pore structure (Kingery, 1974; Tite & Maniatis, 1975; Maniatis & Tite, 1978). From the re-examination of the pottery after refiring at known temperatures, it was possible to follow the subsequent development of vitrification. Using these data, together with those from X-ray fluorescence analysis and X-ray diffraction, the different types of clay used to make the pottery were distinguished and the approximate firing temperatures and firing atmospheres employed in its production were established (see next section). Results for the various sequences of pottery under consideration are presented and the conclusions regarding the different ceramic technologies, as defined in terms of the type of clay and firing procedures, are discussed.

Development of Vitrification

Semi-quantitative analysis undertaken using the X-ray fluorescence spectrometer attachment to the SEM showed that both non-calcareous and calcareous clays were used in the manufacture of the pottery under consideration, the calcium oxide concentrations being in the range 1–38%.

The examination of the pottery in the SEM, both in the as-received state and after refiring at known temperatures, established that the first stage in the development of

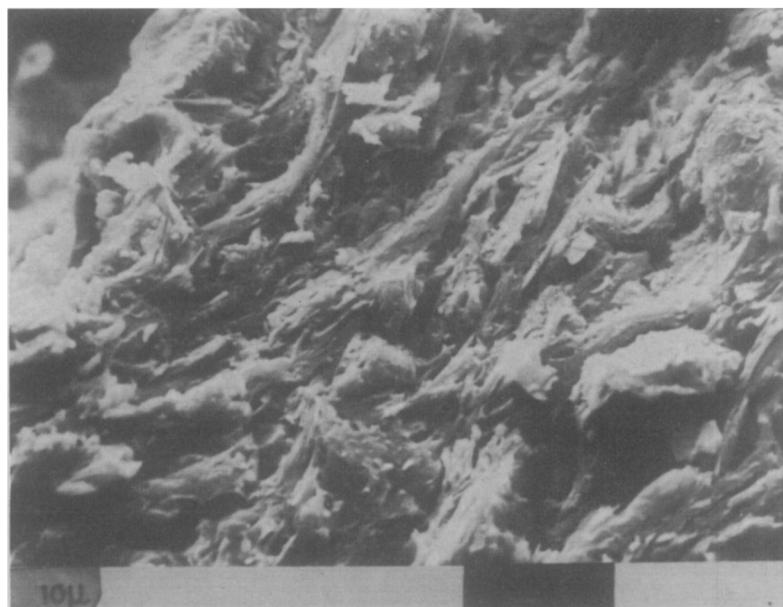


Figure 1. Initial vitrification (IV): non-calcareous clay. Yugoslavia sherd (Y3a): as received.

vitrification which could be clearly defined was the appearance of isolated smooth-surfaced areas or filaments of glass (Figure 1). This structure, which is referred to as the initial vitrification stage, was similar for both the non-calcareous and calcareous clays and was developed typically at firing temperatures in the range 800–850 °C in an oxidizing atmosphere. In some cases it was possible to recognize a slightly earlier stage in the development of vitrification in which there was no definite smooth-surfaced areas of glass but some slight buckling and rounding of the edges of the clay plates had occurred. This structure, intermediate between the no vitrification (NV) and initial vitrification (IV) stages, is represented by the symbol NV+. When the pottery was fired to higher temperatures, the amount of glass increased and high temperature crystalline phases which could be identified by X-ray diffraction were formed. At this stage, the actual vitrification structures developed depended critically on the type of clay from which the pottery was manufactured and the atmosphere in which it was fired, and there was an effectively inverse correlation between the concentration of high temperature crystalline phases formed and the development of the glass phase.

Non-calcareous clays

In the case of pottery made from non-calcareous clays (NC) which normally contained less than 6% of calcium oxide, the development of the glass phase predominated and the only high temperature crystalline phase detected was a small amount of spinel. With increasing firing temperature, the isolated areas of glass associated with the initial vitrification stage steadily increased in size (Figure 2) until they coalesced to form an essentially continuous smooth vitrified layer which was visible over the entire fracture surface (Figure 3). A temperature range of only about 150 °C separated this stage which is referred to as continuous vitrification (CV) from the initial vitrification stage (IV).

Firing in a reducing atmosphere, as compared to an oxidizing atmosphere, resulted in the lowering of the temperatures at which the various vitrification structures were formed by about 50 °C. This more rapid development of melt in a reducing atmosphere is consistent with the equilibrium phase relationships since the stable crystalline phase will in this case be fayalite which has a low melting temperature, whereas in an oxidizing atmosphere, the crystalline phases will be ferric iron-bearing spinels (e.g. magnetite) which have high melting temperatures (Muan, 1957; Naslund, 1976). In addition to lowering the vitrification temperatures, firing in a reducing atmosphere also resulted in the development of a very high concentration of fine bloating pores (0.2–4 µm diameter) (Figure 4) in conjunction with the first appearance of continuous vitrification [CV (FB)] (Maniatis & Tite, 1975). This effect was enhanced when a fast heating rate (e.g. 800 °C hour⁻¹ plus 1 min soaking time at the maximum temperature as compared to 200 °C hour⁻¹ plus 1 hour soaking time) was employed. With increasing firing temperature in a reducing atmosphere, the size of the pores increased (Figure 5) and their number decreased until a network of unconnected coarse spherical pores (10–50 µm) associated with the final vitrification stage [CV(CB)] prior to the terminal distortion of the pottery (i.e. total collapse or large-scale bloating to produce a friable and highly porous body) was formed throughout the pottery body by about 1050–1100 °C. A similar final vitrification stage (Figure 6) was observed with firing in an oxidizing atmosphere, but in this case, in addition to being reached at a higher temperature (~1150 °C), there was no prior formation of a high concentration of fine bloating pores.

In addition to actually producing bloating, firing clays in a reducing atmosphere also created a state of "incipient" bloating. For example, when clays were refired at 900 °C in an oxidizing atmosphere after first firing at 750 °C in a reducing atmosphere, fine bloating pores were produced even though no bloating was present, either after the first

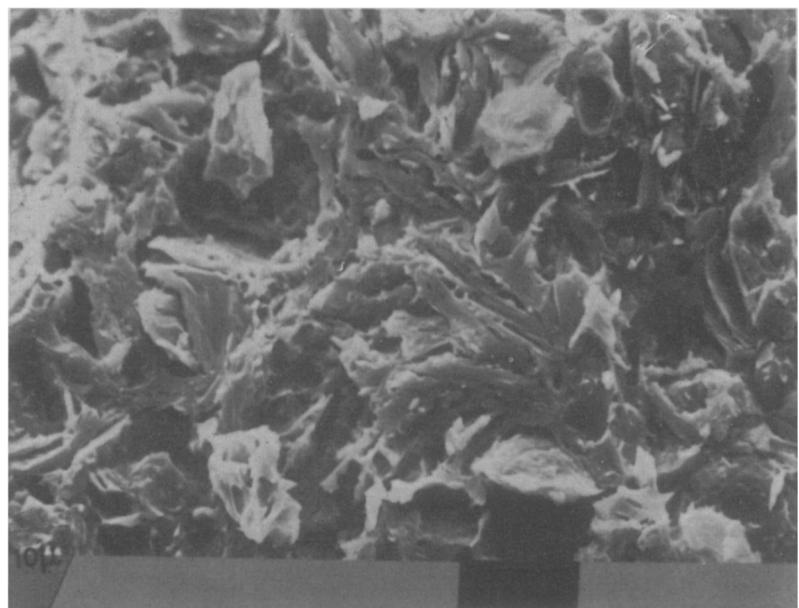


Figure 2. Extensive vitrification (V): non-calcareous clay. Romania sherd (R3a): refired at 900 °C in oxidizing atmosphere.

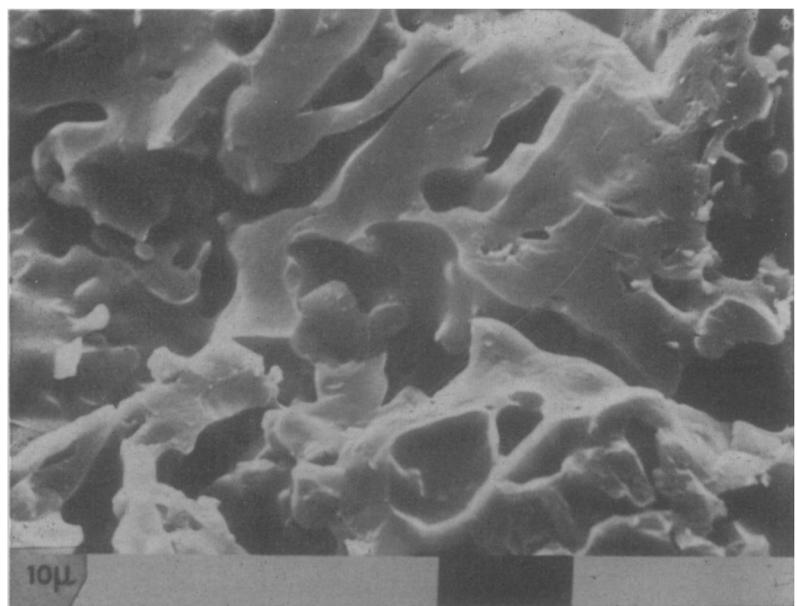


Figure 3. Continuous vitrification (CV): non-calcareous clay. Romania sherd (R3a): refired at 1020 °C in oxidizing atmosphere.

firing in a reducing atmosphere, or after firing at 900 °C in an oxidizing atmosphere without pre-firing in a reducing atmosphere. Similarly, bloating pores were produced in a few sherds when they were refired in an oxidizing atmosphere even though none were observed in the sherd in its as-received state.

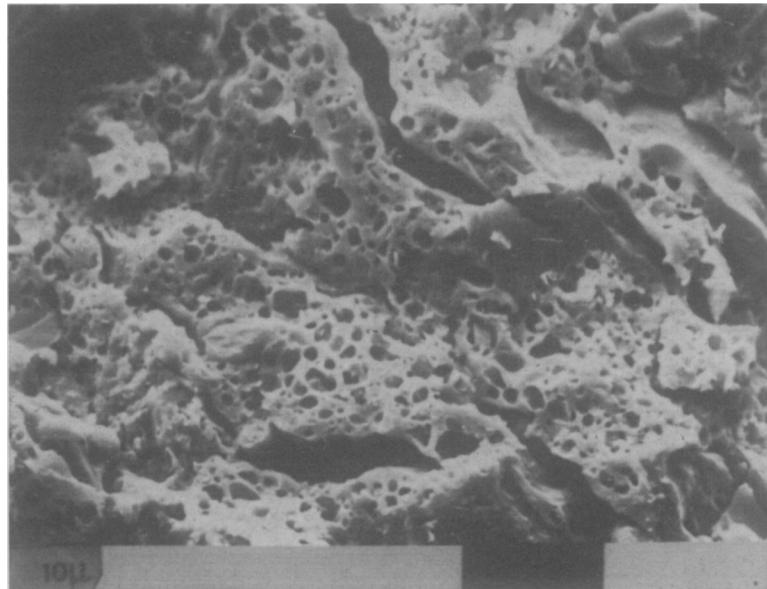


Figure 4. Continuous vitrification with fine bloating pores (CV(FB)): non-calcareous clay. Thessaly sherd (Tld): as received.

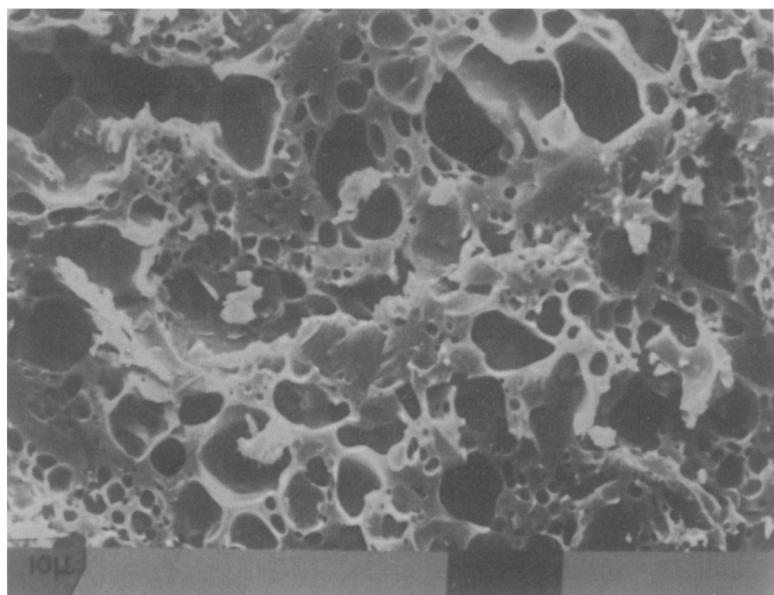


Figure 5. Continuous vitrification with medium bloating pores (CV(MB)): non-calcareous clay. Servia sherd (GR3d): as received.

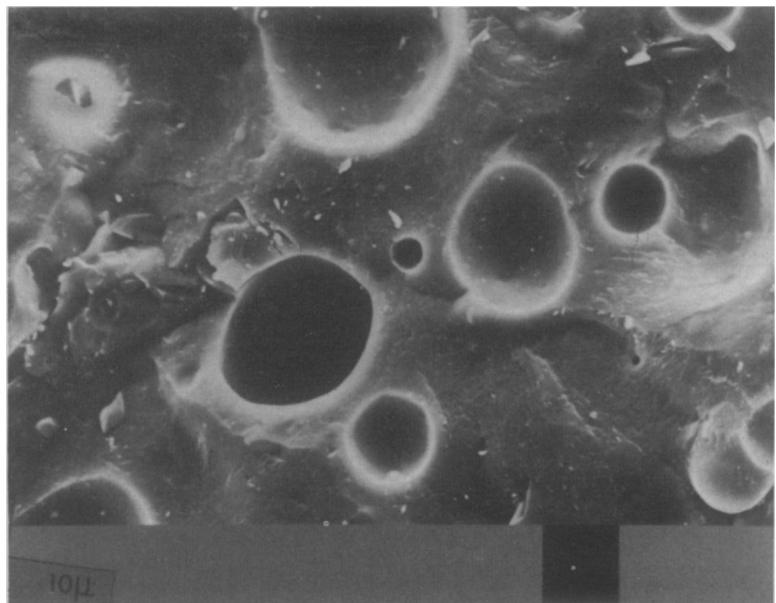


Figure 6. Continuous vitrification with coarse bloating pores (CV(CB)): non-calcareous clay. Romania sherd (R3a): refired at 1150 °C in oxidizing atmosphere.

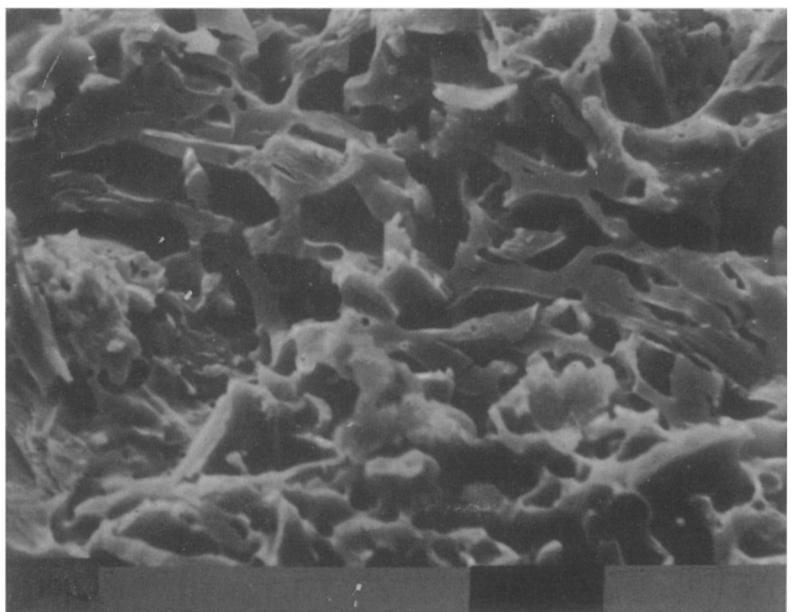


Figure 7. Extensive vitrification (V): calcareous clay. Servia sherd (GR1b): refired at 960 °C in oxidizing atmosphere.

Calcareous clays

In the case of pottery made from calcareous clays which normally contained more than 6% of calcium oxide, the development of vitrification was inhibited by the formation of crystalline phases with high melting temperatures; that is, calcium alumino-silicates (anorthite, gehlenite) and calcium/magnesium silicates (wollastonite, diopside). With increasing firing temperature the isolated areas of glass associated with the initial vitrification stage increased to some extent and tended to link up but the resulting vitrification structure then remained essentially unchanged over a firing temperature range of about 200 °C, from 850–1050 °C. The amount of glass associated with this stable extensive vitrification stage (V) varied inversely with the concentration of the crystalline phases formed, the overall areas of glass observed in the SEM becoming smaller and increasingly fragmented as the calcium oxide concentration increased from 6–38% (Figures 7–9). Thus for low calcium oxide concentrations (e.g. 5–10%), the network of glass tended to be coarser (Figure 7) than that observed for medium concentrations (15–25%) (Figure 8) and in pottery containing more than 30% of calcium oxide, a completely disturbed structure with essentially no smooth-surfaced areas of glass was observed (Figure 9). When fired above about 1050 °C, the amount of glass present

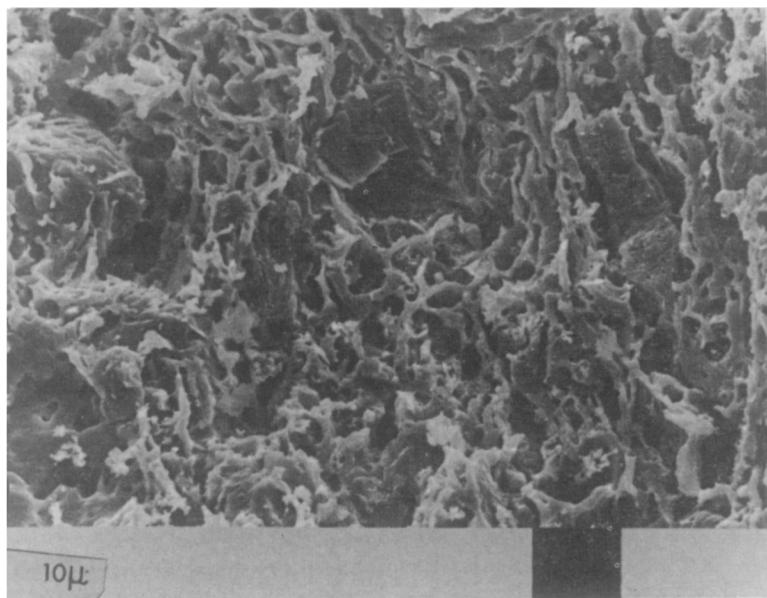


Figure 8. Extensive vitrification (V): calcareous clay. Servia sherd (GR2a): refired at 960 °C in oxidizing atmosphere.

increased rapidly and continuous vitrification with unconnected coarse bloating pores [CV(CB)], similar to that observed in pottery made from non-calcareous clays, was formed by about 1150 °C.

The effects of firing in a reducing atmosphere, as compared to an oxidizing atmosphere, were less pronounced for pottery made from calcareous clays. Although the temperature at which the initial vitrification structure (IV) was formed was lowered by about 50 °C in a reducing atmosphere, the temperatures at which the subsequent vitrification structures developed were essentially unchanged. Similarly, the size of the fine bloating pores, which developed in a reducing atmosphere in the areas of glass associated with

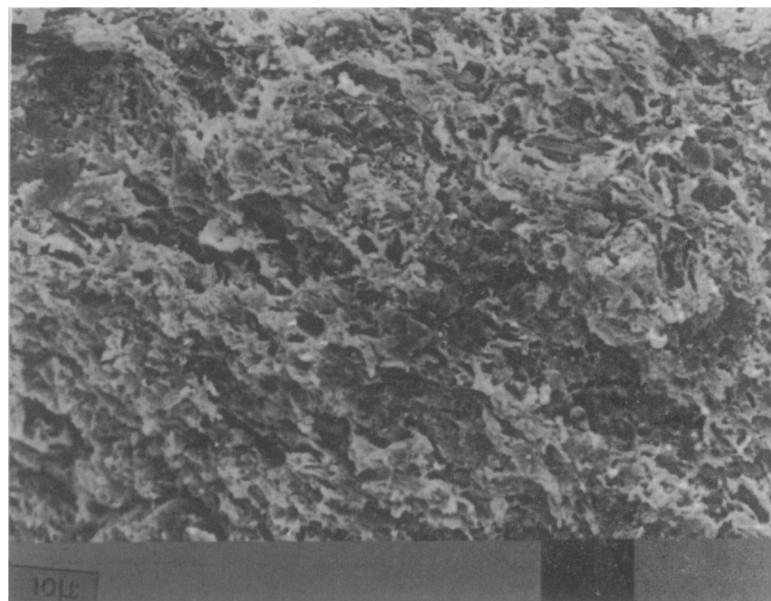


Figure 9. Extensive vitrification (V): calcareous clay. Jericho sherd (JR2c): re-fired at 900 °C in oxidizing atmosphere.

the extensive vitrification structure (V), remained essentially unchanged from 850 °C to 1050 °C when the amount of glass present again began to increase. The fact that a reducing atmosphere does not produce a more rapid development of melt is again consistent with the equilibrium phase relationships since, in a calcareous clay, the stable crystalline phases will be calcium iron silicates rather than fayalite and these have high melting temperatures comparable to those of the calcium silicates/alumino-silicates associated with an oxidizing atmosphere.

The concentration of calcium oxide necessary to form the framework of calcium silicates/alumino-silicates, and thus establish an extensive vitrification structure (V) which is stable over a 200 °C range from 850–1050 °C, depends critically on the particle size and distribution of the calcite in the original clay. When the calcium oxide was shown by X-ray scanning in SEM to be fine-grained and evenly distributed (Figure 11), as little as 5% was sufficient to establish the stable vitrification structure. However, when the calcium oxide was less uniformly distributed through the pottery and some at least was present as inclusions (Figure 12), then the vitrification structure depended on the proportion of the total which was sufficiently fine-grained to react with the clay minerals to form crystalline phases. Typically, for an average calcium oxide concentration of greater than about 15%, a sufficient concentration of crystalline phases were formed for the vitrification structure to be stable in the 850–1050 °C. However, the areas of glass observed in the SEM tended to be less fragmented than would have been expected on the basis of the average calcium oxide concentrations and the vitrification structures observed varied between different areas within the same pottery sherds. In particular, continuous areas of glass containing fine bloating pores (Figure 10) which were similar to those observed in pottery made from non-calcareous clays and fired in a reducing atmosphere frequently developed. However, in contrast to the situation for pottery made from non-calcareous clays, no significant increase in the size of the bloating pores occurred in the 850–1050 °C firing temperature range. When the concentration of the

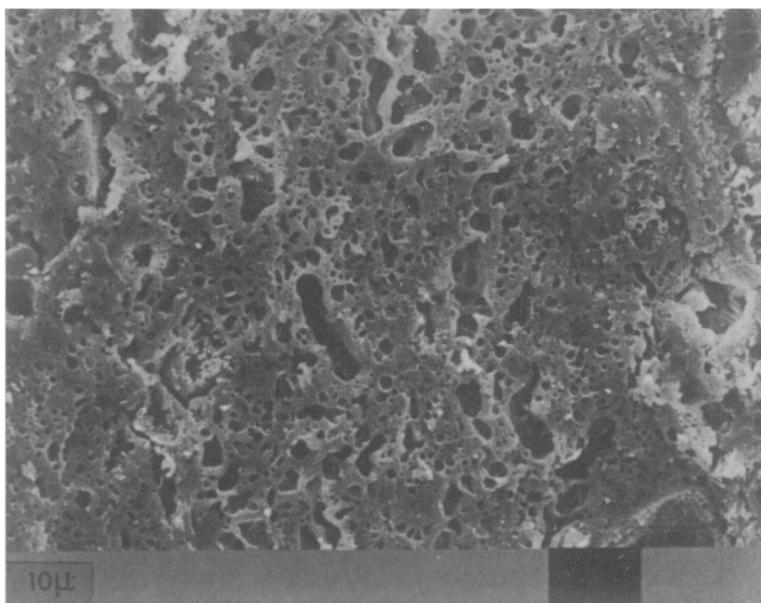


Figure 10. Continuous vitrification with fine bloating pores (CV(FB)): calcareous clay. Egypt sherd (EG3f): as received.

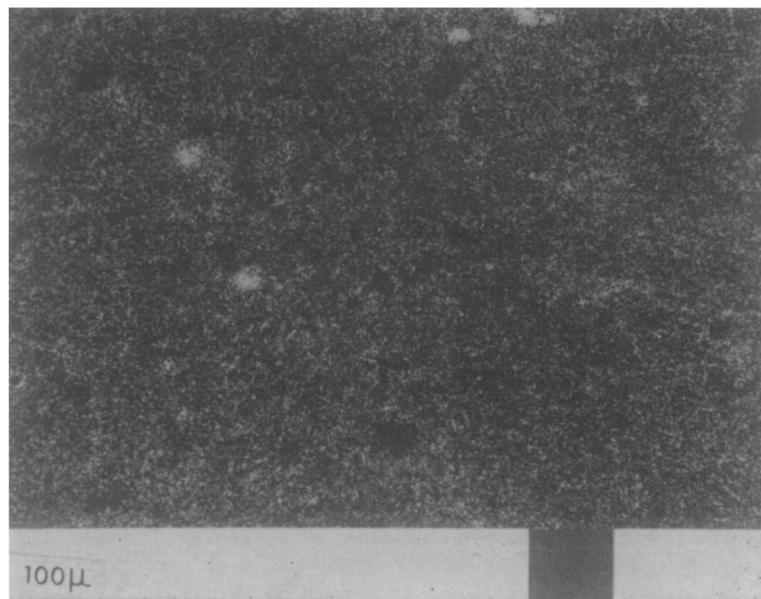


Figure 11. Calcium distribution (X-ray scanning) in Iraq sherd (IR3b: Halaf type: 17% calcium oxide).

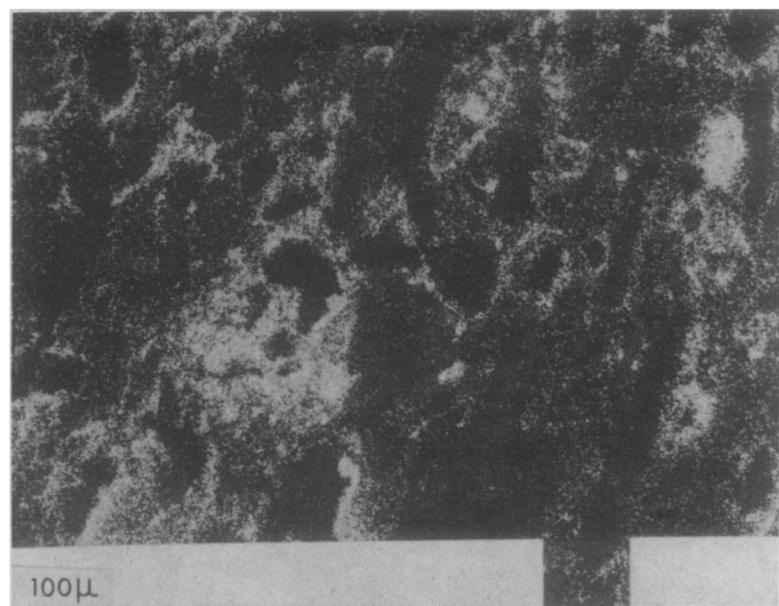


Figure 12. Calcium distribution (X-ray scanning) in Egypt sherd (EG7i).

non-uniformly distributed calcium oxide was less than about 10%, the concentration of the crystalline phases formed was normally such that some increase in the amount of glass occurred during firing in the 850–1050 °C range and the vitrification structures observed were very similar to those formed in pottery made from non-calcareous clays.

Classification of the Pottery

The results presented above indicate that, on the basis of the composition and the vitrification structure developed during firing, it is possible to assign the clays used in making the pottery to one of two basic groups, that is, non-calcareous (NC : CaO content <6%) and calcareous (C : CaO content >6%). The calcareous clays can be further subdivided into those containing sufficient fine-grained and evenly distributed calcite to achieve an extensive vitrification structure (V) which is stable over the 850–1050 °C firing temperature range and those in which the proportion of fine-grained calcite in the total calcite present is insufficient to achieve stability and the amount of glass increases over this firing temperature range; the latter clays are marked with an asterisk

Table 1. Vitrification stages and firing temperature ranges

Vitrification stage	Firing temperature ranges (°C)			
	NC (O)	NC (R)	C (O)	C (R)
NV No vitrification	<800	<750	<800	<750
IV Initial vitrification	800–850	750–800	800–850	750–800
V Extensive vitrification	850–950	(FB) ^a	800–900	850–1050
CV Continuous vitrification		(FB)	850–950	850–1050
		(MB)	900–1000	

^aFB(fb), high (low) concentration of fine bloating pores (0·2–4 μm diameter). MB(mb), high (low) concentration of medium bloating pores (2–10 μm diameter).

Table 2. Pottery from central and south-east Europe and Anatolia

Sherd no.	Provenance	Pottery type	Fabric	% CaO	Clay type	Vitrification stage	Firing temperature (°C) (atmosphere)
Neolithic							
C1a	Bylany, Czechoslovakia		M	4.1	NC	NV	< 750 (R)
C1b	Bylany, Czechoslovakia		C	2.9	NC	NV	< 750 (R)
Y1a	Divostin, Yugoslavia	Starcevo	C	5.5	NC	NV	< 750 (R)
Y1b	Dobrovodica, Yugoslavia	Starcevo	C	1.6	NC	NV	< 750 (R)
H1a	Berettyo Ujfalu, Hungary	Herpaly	C	2.1	NC	NV	< 750 (R)
H1b	Berettyo Ujfalu, Hungary	Herpaly	C	2.7	NC	IV+	750-850 (R)
T1e	Tsani, Thessaly	Sesklo monochrome	M	2.6	NC	NV	< 800 (O)
T1b	Tsani, Thessaly	Sesklo "Solid style"	F	1.8	NC	NV+	≤ 800 (O)
T1c	Tsani, Thessaly	Sesklo "Solid style"	M	1.6	NC	V	850-950 (O)
T1a	Tsani, Thessaly	Sesklo monochrome	F	1.4	NC	V	850-950 (O)
T1d	Tsani, Thessaly	Sesklo	M	1.9	NC	CV (FB)	850-950 (R*)
T1f	Tsangli, Thessaly	Sesklo	M	30	C	NV+	≤ 800 (O)
Chalcolithic							
B2a	Gradeshnitsa, Bulgaria	Graphite painted	M	2.3	NC	NV	< 750 (R)
B2b	Gradeshnitsa, Bulgaria		C	3.0	NC	V+(FB)	800-900 (R)
B2c	Karanova, Bulgaria	Gumelnitsa	C	3.7	NC	NV	< 750 (R)
M2a	Dikilitosh, Macedonia	Graphite painted	M	4.1	NC	NV+	≤ 750 (R)
M2b	Dikilitosh, Macedonia	Graphite painted	M	3.0	NC	NV	< 750 (R)
M2c	Dikilitosh, Macedonia		M	4.4	NC	V+(FB)	800-900 (R*)
Y2a	Gomolava, Yugoslavia	Vinca	F	2.9	NC	NV	< 750 (R)
Y2b	Vinca, Yugoslavia	Vinca	C	11	C	IV	800-850 (O)
T2b	Dimini, Thessaly		M	14	C	NV	< 800 (O)
T2a	Dimini, Thessaly		F	15	C	IV	800-850 (O)
RS2d	Koshilovtsi, S.W. Russia	Cucuteni-Tripolje	C	18	C*	NV	< 800 (O)
RS2c	Koshilovtsi, S.W. Russia	Cucuteni-Tripolje	C	34	C	NV	< 800 (O)
RS2a	Koshilovtsi, S.W. Russia	Cucuteni-Tripolje	F	6.9	C	V	850-1050 (O)
AN1a	Hacilar, Anatolia		M	20	C	NV	< 800 (O)
AN1b	Hacilar, Anatolia		M	18	C	NV	< 800 (O)
Bronze Age							
B3a	Karanova, Bulgaria		M	3.3	NC	V+(fb)	800-900 (R)
Y3a	Gomolava, Yugoslavia	Kostolac	M	2.5	NC	IV	750-800 (R)
H3a	Toszeg, Hungary	Nagyrev	C	2.6	NC	NV	< 750 (R)
H3c	Berettyo Ujfalu, Hungary	Gyulavarsand	M	1.8	NC	NV	< 750 (R)
H3d	Berettyo Ujfalu, Hungary	Gyulavarsand	C	1.5	NC	IV	750-800 (R)
R3a	Ostrovul Corbulu, Romania	Cotsofeni	M	5.2	NC	NV+	≤ 750 (R)
T3a	Dimini, Thessaly	Thessalian EBA	C	3.7	NC	IV	800-850 (O)
T3b	Lianokladhi, Thessaly	Thessalian MBA	M	1.5	NC	IV	750-800 (R)
AN2c	Dombai Marsh, Anatolia	EBA II-III	C	10	C*	NV	< 750 (R)
AN2b	Dombai Marsh, Anatolia	EBA II-III	M	33	C	NV	< 750 (R)
AN2d	Dombai Marsh, Anatolia	EBA II-III	F	37	C	NV	< 800 (O)
AN2a	Dombai Marsh, Anatolia	EBA II-III	F	35	C	IV	800-850 (O)

(i.e. C*) in the subsequent tables of results (Tables 2-5). Because, in reality, the clays used to make the pottery varied widely both in terms of their original mineralogical composition and their subsequent treatment (i.e. refining and addition of temper), this division of the clays into two basic groups clearly involves considerable simplification. However, it does enable one to highlight the primary differences and similarities in the overall range of clays used.

Having thus established the types of clay used to make the pottery, the firing temperatures employed in its manufacture can then be estimated from the vitrification structures observed in the pottery in its as-received state and after refiring at known temperatures.

Table 3. Pottery from Servia (Macedonia)

Sherd no.	Fabric	% CaO	Clay type	Vitrification stage	Firing temperature (°C) (atmosphere)
Early Neolithic					
GR1d	C	4.3	NC	NV	< 750 (R)
GR1c	F	6.7	C*	NV	< 750 (R)
GR1a	F	6.7	C*	CV(FB)	850–950 (R)
GR1b	F	10	C	NV	< 800 (O)
GR1k	M	14	C	V	850–1050 (O)
Middle Neolithic					
GR2c	M	2.1	NC	IV	800–850 (O)
GR2b	F	1.4	NC	V+(FB)	800–900 (R)
GR2f	C	1.5	NC	V+(FB)	800–900 (R*)
GR2a	F	21	C	IV	800–850 (O)
GR2d	M	15	C	V	850–1050 (O)
Late Neolithic					
GR3a	F	1.4	NC	V	800–900 (R)
GR3d	M	2.9	NC	CV(MB)	900–1000 (R*)
GR3c	F	7.4	C*	NV+	≤ 750 (R)
GR3b	F	9.0	C*	IV	750–800 (R*)
GR3e	M	10	C	NV	< 750 (R)
Early Bronze Age I					
GR4b	C	2.2	NC	NV	< 750 (R)
GR4c	M	2.2	NC	NV	< 750 (R)
GR4e	C	2.3	NC	NV	< 750 (R)
GR4a	C	14	C	NV	< 750 (R)
Early Bronze Age II					
GR5b	M	1.2	NC	NV	< 750 (R)
GR5a	C	2.4	NC	NV+	≤ 750 (R)
GR5i	C	2.0	NC	IV	750–800 (R)
GR5h	M	2.3	NC	CV(MB)	900–1000 (R)
GR5j	F	11	C	V	850–1050 (O)
GR5k	F	15	C	V	850–1050 (O)

The stages in the development of vitrification during firing which can be defined are given in Table 1 together with the approximate associated firing temperature ranges. These firing temperature ranges assume a heating rate of 200 °C hour⁻¹ and a soaking time of 60 min at the peak temperature. If significantly faster heating rates (800 °C hour⁻¹) and shorter soaking times (1 min) were employed in the manufacture of pottery then firing temperatures higher by about 50 °C would have been required in order to reach the vitrification stages observed in the pottery in its as-received state.

In some instances, the vitrification structure observed in the pottery was intermediate between two of the defined stages and this is indicated by adding a plus sign (i.e. NV+, IV+, V+) to the vitrification stage specified in the tables of results (Tables 2–5) and increasing the associated firing temperature range accordingly. In the case of pottery made from calcareous clays (C*) containing insufficient fine-grained calcite to produce a stable extensive vitrification structure, the vitrification stages and firing temperature ranges associated with non-calcareous clays are given in Tables 2–5. Similarly, when the distribution of calcite was such that stable but continuous vitrification, comparable in appearance to that produced in pottery made from non-calcareous clays when fired in a reducing atmosphere, was observed in at least some areas of the pottery, the vitrification stages associated with both calcareous and non-calcareous clays are given (i.e.

Table 4. Pottery from Egypt

Sherd no.	Provenance	Fabric	% CaO	Clay type	Vitrification stage	Firing temperature (°C) (atmosphere)
Neolithic						
EG1b	Merimde	M	4.8	NC	CV(FB)	850–950 (R*)
EG1a	Merimde	C	8.5	C*	NV	< 750 (R)
Badarian						
EG2a	Hammamiya	F	7.9	C*	NV	< 750 (R)
EG2b	Hammamiya	C	8.3	C*	CV(FB)	850–950 (R)
Predynastic						
EG3a	Hammamiya	C	7.1	C*	NV	< 800 (O)
EG3d	Hammamiya	M	23	C	V–CV(MB)	850–1050 (R*)
EG3b	Naqada	F	4.5	NC	NV	< 800 (O)
EG3c	Naqada	M	23	C	V–CV(FB)	850–1050 (R*)
EG3e	Hierakonpolis	M	23	C	V–V+(FB)	850–1050 (R*)
EG3f	Hierakonpolis	M	24	C	V–CV(FB)	850–1050 (R*)
EG3g	Armant	F	4.8	NC	NV	< 750 (R)
EG3h	Armant	F	5.2	NC	NV	< 800 (O)
Protodynastic						
EG4a	Abadiya	C	5.0	NC	NV+	< 750 (R)
EG4c	Abadiya	F	9.0	C*	V	800–900 (R)
EG4d	Mahasna	M	35	C	IV	800–850 (O)
EG4b	Naqada	F	20	C	V	850–1050 (O)
EG4e	Naqada	F	30	C	V	850–1050 (O)
4th Dynasty						
EG5b	Giza	M	3.7	NC	NV	< 800 (O)
EG5a	Giza	M	26	C	V–V+(fb)	850–1050 (R*)
EG5c	Giza	M	21	C	V	650–1050 (O)
13th/17th Dynasty						
EG7c	Tell el-Dab'a ^a	F	3.7	NC	NV	< 800 (O)
EG7d	Tell el-Dab'a ^a	M	4.3	NC	NV	< 800 (O)
EG7f	Tell el-Dab'a ^a	M	3.3	NC	NV	< 800 (O)
EG7g	Tell el-Dab'a ^a	C	3.0	NC	NV	< 750 (F)
EG7h	Tell el-Dab'a ^a	C	2.3	NC	NV	< 800 (O)
EG7e	Tell el-Dab'a ^a	M	5.0	NC	CV(FB)	850–950 (R)
EG7j	Tell el-Dab'a ^a	C	9.2	C*	V+(fb)	800–900 (R)
EG7i	Tell el-Dab'a ^a	C	21	C	V–V+	850–1050 (O)
EG7k	Tell el-Dab'a ^a	C	18	C	V–CV(mb)	850–1050 (R)
EG7a	Tell el-Dab'a ^a	M	8.2	C*	NV	< 750 (R)
EG7b	Tell el-Dab'a ^a	M	18	C	NV	< 800 (O)
EG7m	Tell el-Dab'a ^a	C	18	C	IV	750–800 (R)
EG7l	Tell el-Dab'a ^a	M	34	C	IV	800–850 (O)
EG7n	Tell el-Dab'a ^a	M	3.7	NC	NV	< 750 (R)
EG7o	Tell el-Dab'a ^a	C	3.5	NC	NV	< 750 (R)
EG7q	Tell el-Dab'a ^a	M	20	C	IV	750–800 (R)
EG7p	Tell el-Dab'a ^a	M	19	C	V	850–1050 (O)
EG9a	Kerma	M	3.6	NC	NV+	< 750 (R)
EG9b	Kerma	M	3.6	NC	CV(FB)	850–950 (R)

^aThe sequence from Tell el-Dab'a includes pottery manufactured in Egypt from Nile clay (EG7c–7h) and marly clays (EG7i–7k) as well as imported Syro-Palestinian pottery (EG7a–7b) and Palestinian amphorae (EG7l–7m) (M. Bietak, pers. comm.).

Table 5. Pottery from Jericho

Sherd no.	Fabric	% CaO	Clay type	Vitrification stage	Firing temperature (°C) (atmosphere)
Pottery Neolithic A					
JR1d	C	17	C	NV	< 800 (O)
JR1c	C	24	C	NV+	≤ 800 (O)
JR1a	C	8.1	C*	NV+	≤ 800 (O)
JR1b	C	9.5	C*	NV+	≤ 800 (O)
Pottery Neolithic B					
JR2a	C	35	C	NV	< 800 (O)
JR2b	C	38	C	NV	< 800 (O)
JR2c	C	35	C	NV	< 800 (O)
JR2d	C	38	C	IV	800–850 (O)
Early Bronze Age					
JR3e	M	18	C	NV	< 800 (O)
JR3b	M	18	C	NV+	≤ 800 (O)
JR3a	M	25	C	IV	800–850 (O)
JR3c	C	19	C	IV	800–850 (O)
JR3d	M	23	C	V	850–1050 (O)
Early–Middle Bronze Age					
JR4b	C	27	C	NV	< 800 (O)
JR4a	M	31	C	V	850–1050 (O)
JR4c	M	27	C	V	850–1050 (O)
Middle Bronze Age					
JR5a	C	24	C	NV	< 800 (O)
JR5b	F	21	C	IV+	750–850 (R)
JR5c	C	27	C	V	850–1050 (O)
JR5d	M	33	C	V	850–1050 (O)

V – V+ (FB), V – CV(FB), etc.). In the tables of results (Tables 2–5), the firing temperature ranges given assume firing in either an oxidizing or a reducing atmosphere (O to R respectively) and should be modified according to the data given in Table 1 if these assumptions are incorrect. The decision regarding the firing atmosphere was based on the colour of the pottery (i.e. oxidizing for red, buff or brown sherds and reducing for grey or black sherds) except when bloating was observed, either in the as-received state or after refiring in an oxidizing atmosphere ("incipient" bloating), in sherds whose colour suggested firing in an oxidizing atmosphere. In these instances, the final oxidizing atmosphere must have been preceeded at some stage during the original firing by a reducing atmosphere and therefore firing temperature ranges assuming a reducing atmosphere are given, the atmosphere being marked with an asterisk (i.e. R*) in the tables of results.

In principle, for the pottery made from non-calcareous clays, more precise firing temperatures than the 50 °C to 100 °C ranges quoted could be determined by refiring each sherd to progressively higher temperatures until a definite increase in the extent of vitrification over that in the as-received state was observed. However, because of uncertainties regarding the firing atmosphere and firing time employed in antiquity, the precision with which the firing temperature could be determined even with extended refiring measurements, would still be somewhat limited. Also, this approach would not be applicable to pottery made from calcareous clays because of the inherent stability of the associated extensive vitrification structure over the 850–1050 °C range. Furthermore, a high precision in the estimation of the firing temperature has only limited

archaeological significance since experimental firings have indicated that the temperatures reached in different parts of pottery kilns can vary by as much as 100 °C (Mayes, 1961, 1962).

Results

The results for the pottery sherds from central and southeast Europe, Anatolia, Servia (Macedonia), Egypt and Jericho are presented in Tables 2–5. The pottery is divided into coarse (C), medium (M) and fine (F) fabrics on the basis of the density and size of the non-plastic inclusions observed under the optical microscope. The data on the clay types, vitrification stages, firing temperatures and firing atmospheres are based principally on the SEM examinations as discussed in the section "Classification of the pottery" and summarized in Table 1.

The results for the pottery from central and southeast Europe (excluding Thessaly and southwest Russia) (Table 2) indicate that, with one exception (Y2b), non-calcareous clays were used and that the pottery was fired in a reducing atmosphere normally at temperatures below 800 °C such that no, or only initial, vitrification was produced. However, a few sherds had been fired to higher temperatures, sufficient to develop extensive or continuous vitrification in association with fine bloating pores. In contrast, both non-calcareous and calcareous clays were used to make the pottery from Thessaly and calcareous clays were used to make that from southwest Russia. The Thessalian pottery examined which was mainly medium and fine textured was normally fired in an oxidizing atmosphere and the majority of that made from non-calcareous clays was fired at temperatures in excess of 800 °C such that vitrification (i.e. IV, V or CV(FB)) was produced.

The pottery from Servia (Table 3) was again made from both non-calcareous and calcareous clays, the latter including clays (C*) containing insufficient fine-grained calcite to produce a stable vitrification structure in the 850–1050 °C range. The pottery made from non-calcareous clays and "unstable" calcareous clays (NC and C* respectively), was, with one exception (GR2c), fired in a reducing atmosphere and the firing temperatures were normally less than 800 °C such that no, or only initial, vitrification was produced. However, some sherds had again been fired to higher temperatures sufficient to develop extensive or continuous vitrification with bloating pores. In contrast, the pottery made from stable calcareous clays (C) which was predominantly medium and fine-textured and included two sherds of imported pottery (GR5j and GR5k) was mainly fired in an oxidizing atmosphere at temperatures in excess of 800 °C such that initial or extensive vitrification was produced.

The pottery from Egypt (Table 4) was also made from both non-calcareous and calcareous clays. When made from non-calcareous clays (NC), the pottery was fired in either oxidizing or reducing atmospheres and the firing temperatures were normally below 800 °C such that no vitrification was produced. When fired to higher temperatures, a reducing atmosphere was employed and continuous vitrification with fine bloating pores was developed. The pottery made from calcareous clays (C*) containing insufficient fine grained calcite (7–10% of calcium oxide) to produce a stable vitrification structure was, with one exception (EG3a), fired in a reducing atmosphere and a range of firing temperatures from less than 750 °C up to about 950 °C was employed without any obvious preference. The pottery made from "stable" calcareous clays (C) was fired in either oxidizing (O) or reducing (R or R*) atmospheres and the firing temperatures were normally in excess of 800 °C such that initial or extensive vitrification was produced. This group of pottery included several sherds in which, because of the non-uniform distribution of fine grained calcite, areas of continuous vitrification with bloating

pores were observed (Figure 10) as well as or instead of the more fragmented vitrification normally associated with the extensive vitrification stage in calcareous clays (Figures 7 and 8). Although the presence of bloating pores indicates that, at some stage during the original firing the atmosphere must have been reducing, the colour of these sherds establishes that the final phase of the firing was normally oxidizing (i.e. R* atmosphere in table).

The pottery from Anatolia (Table 2) and Jericho (Table 5) was made exclusively from calcareous clays and the majority was fired in an oxidizing atmosphere. In the case of the Anatolian pottery and the neolithic pottery from Jericho, the firing temperatures were normally less than 800 °C such that no vitrification was produced. In contrast, a high proportion of the bronze age pottery from Jericho was fired at temperatures in excess of 800 °C such that initial or extensive vitrification was produced. In addition this later Jericho included medium and fine-textured fabrics whereas the neolithic pottery examined was exclusively coarse-textured. Further, the pottery from both Anatolia and Jericho included some sherds which contained more than 30% of calcium oxide and which exhibited a completely disturbed structure without obvious visible areas of glass (Figure 9) when fired in the 850–1050 °C range.

Conclusions

The results presented above indicate that the ceramic technologies, as defined in terms of the type of clay and the firing parameters (i.e. temperature, atmosphere, time) employed, varied quite considerably. However, in spite of this inherent complexity, a number of underlying trends can be inferred from these data.

First, with the exception of the Thessalian pottery, the majority of the pottery made from non-calcareous or "unstable" calcareous clays (NC and C* respectively) was fired in a reducing atmosphere at temperatures below 800 °C such that no, or only initial vitrification was produced. The few sherds which had been fired at higher temperatures, exhibited bloating pores in association with extensive or continuous vitrification and since bloating is, on the basis of laboratory experiments, indicative of a fast heating rate, it seems probable that these higher firing temperatures resulted from the chance positioning of the pottery during firing rather than from any deliberate firing procedure. In contrast, the majority of the pottery made from "stable" calcareous clays (C) was fired in an oxidizing atmosphere and although the full range of firing temperatures was employed, temperatures in excess of 800 °C, such that initial or extensive vitrification was produced, predominated in the case of the pottery from Servia (Macedonia), Egypt and Jericho (bronze age). These pottery groups were therefore comparable, in terms of the type of clay and firing procedures used, to pottery from Iraq spanning the period c. 6000 BC to c. AD 650 (Tite & Maniatis, 1975) and to medium and fine-textured bronze age pottery from Thera, Phylakopi (Melos) and the Peloponnese (Maniatis & Tite, 1978). In these circumstances, it is clear that the use of the higher temperatures necessary to produce extensive vitrification represents a deliberate firing procedure.

In considering the reasons for the use of these different types of clay and different firing procedures, a primary factor is clearly the availability of the appropriate clay. However, when both non-calcareous and calcareous clays were used in a particular region, there is some evidence for deliberate selection from among the available clays. For example, at Servia (Macedonia), calcareous clays were normally used only to make medium and fine-textured pottery and this is comparable to the situation previously noted for Thera and Phylakopi (Melos) (Maniatis & Tite, 1978), where all the medium and fine-textured pottery was made from calcareous clays and non-calcareous clays were only used to make coarse pottery. Similarly, it seems probable that in Egypt,

calcareous clays containing more than 15% of calcium oxide were specifically selected or prepared for the manufacture of the pottery which was fired to temperatures in excess of 800 °C since the pottery made from non-calcareous clays was normally fired at temperatures below 800 °C. One major advantage of using calcareous clays is that the extensive vitrification structure remains essentially unchanged over a temperature range of about 200 °C (from 850–1050 °C), whereas with non-calcareous clays the extent of vitrification increases progressively with increasing firing temperature. Therefore, if the stronger and more durable pottery associated with an extensive vitrification structure is being produced, the control of firing temperature needed to achieve a consistent quality is much less critical in the case of calcareous as opposed to non-calcareous clays. In view of the fact that pottery made from calcareous clays was fired at temperatures above 800 °C more frequently than was pottery made from non-calcareous clays, it seems probable that the ancient potters were aware of the different firing characteristics for these two types of clay.

A further fact to emerge from these results is that, in any particular region, the types of clay and the firing procedures employed remained essentially unchanged during the period from the Neolithic to the Bronze Age. A possible exception was the tendency to employ higher firing temperatures (> 800 °C) for the bronze age pottery from Jericho as compared to those (< 800 °C) employed for the neolithic pottery. However, no comparable changes in firing procedure occurred in any of the other regions studied during the period when the early stages in the development of a copper-based metallurgy were taking place (Renfrew, 1969). In particular, the chalcolithic graphite-painted pottery from Bulgaria (B2a) and Macedonia (M2a, M2b) was fired at low temperatures similar to those used for the earlier neolithic pottery and the estimated firing temperature of less than about 750 °C for the graphite-painted sherds was in agreement with that published by Kingery & Frierman (1974) for a comparable sherd from Karanova in Bulgaria.

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