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The Beginnings of Pyrotechnology, Part II: Production and Use of Lime and Gypsum Plaster in the Pre-Pottery Neolithic Near East

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Characterization techniques of modern materials science have been used to extend a prior study (W. H. Gourdin and W. D. Kingery, "The Beginnings of Pyrotechnology: Neolithic and Egyptian Lime Plaster," Journal of Field Archaeology *2 [1975]: 133–50) of plaster materials and their processing in the Pre-Pottery Neolithic (ca. 7200–6000 B.C.). The "invention" of lime plaster can be traced back to at least the Epi-Paleolithic Geometric Kebaran (ca. 12,000 B.C.) and its use in architecture to the Natufian (10,300–8500 B.C.). The production of lime and gypsum plasters is described as a multi-step process requiring selection and collection of raw materials, heating of limestone at 800–900°C (gypsum at 150–200°C), slaking the quicklime in water to form the hydroxide, mixing with various additives, applying and shaping as a paste, and often coating with a slip coat and burnishing—a skilled craft activity having some structural similarities to pottery manufacture. Plaster production expanded in the Pre-Pottery Neolithic B (PPNB), and the geographic distribution of lime and gypsum plaster indicates interactions and technological interchanges throughout the Near East. Quite different interactive techno-complex areas are defined by lime plaster, gypsum plaster, and whiteware production, perhaps characteristic of the difficulties in applying ideas of "bounded" cultural regions. Rather inadequate comparative site data indicate coeval existence of egalitarian villages and of towns with a greater degree of social and economic complexity. The invention and innovation of plaster technology and its evolution into an industry is a classic case of the long time interval between initial invention and the subsequent technological innovation coming into general use. Once begun, the industry underwent autocatalytic development and there were further innovations such as mineral aggregate additions; surface slips; burnishing; use for beads, containers, and sculpture; fiber reinforcement; and composite material applications. PPNB sculpture techniques were developed to a level similar to those used today. Geographical distribution, patterns of production and usage, and product development are all supportive of the idea that incipient craft specialization and social complexity were well developed in the Pre-Pottery Neolithic. In addition, plaster innovations achieved conditions necessary for metal smelting, provided all the necessary technology, and set the stage for the subsequent adoption of pottery as a Neolithic industry. Describing the Neolithic revolution in terms of the "invention" of pottery, plaster, and agriculture is incorrect; it was rather a period of industry establishment based on much earlier inventions.*

Introduction

Plaster, which may be defined as a pasty composition that hardens on drying, subsumes mud plasters made of clays or marls, gypsum plaster manufactured by heating gypsum rock or alabaster, and lime plaster made by calcining limestone at a temperature of 800–900°C to form quicklime, which is slaked to form the hydrate that is used as a pasty mix. It has been said (Furlan and Bissegger 1975) that organically-bonded chalk cannot be distinguished from lime plaster, and that the plasters of aceramic

Çatal Hüyük in Anatolia are white clay; these statements are wrong, as we shall see.

A limestone hearth under a strong fire or a few limestone pebbles in a bright fire (Frierman 1971) will have a surface layer transformed into quicklime (CaO) which, when mixed with water, gives off heat, reacts with hide or hair, and can be smeared on a surface to set as a hard, rock-like product. Gypsum heated in a weak fire or an oven forms a powder that also sets to a hard, rock-like product. Thus, in lime-rich areas, the "discovery" of lime and gypsum plasters must have occurred many times. Intentional innovative uses of plaster probably did too; we have identified and shall describe its use as an adhesive to assemble a tool from flint microliths at Epi-Paleolithic Lagama North VIII (Bar-Yosef and Goring-Morris 1977). Many other such examples surely occurred.

What is more important than the "discovery" of plasters is their emergence as a sizeable production effort, that flowered in the Near East during the Pre-Pottery Neolithic B, well after the establishment of domesticated crops, animal husbandry, and sedentism but well before the widespread appearance of metal smelting and pottery vessels. Indeed, rectangular architecture and plaster floors have been taken as a hallmark of the PPNB in the Near East (Mellaart 1975; Aurenche 1981). But, as we shall see, plaster was used for much more than floors. Its various uses and the sophistication of manufacture and function can contribute to testing conjectures about the Pre-Pottery Neolithic as barbaric, primitive, or quite civilized; about society as egalitarian or more-or-less stratified; and about the nature of discovery, diffusion, innovation, and development of man's technology. The geographical distribution of plaster provides evidence of the extent of Neolithic technological interactions.

To make judgments about these questions it is essential to understand a bit about the nature of the material itself. Thus, we begin with a section on lime and gypsum plasters and possible changes occurring over time. Then we discuss methods for their identification and characterization and apply these methods to a range of samples from many Near Eastern sites as a basis for examining conjectures about life and technology in the Pre-Pottery Neolithic.

Plasters do not have the strength and hardness of flint, bone, or stone. Rather, they are porous materials easily crushed and often indistinguishable from surrounding soil and small lumps of gypsum rock or limestone. As a result, artifact identification is not very precise except for large objects or special contexts. One of these is the cache of objects found at Nahal Hemar Cave above the Dead Sea (Bar-Yosef 1985), and we are grateful for the opportunity to examine the plaster objects from that site.

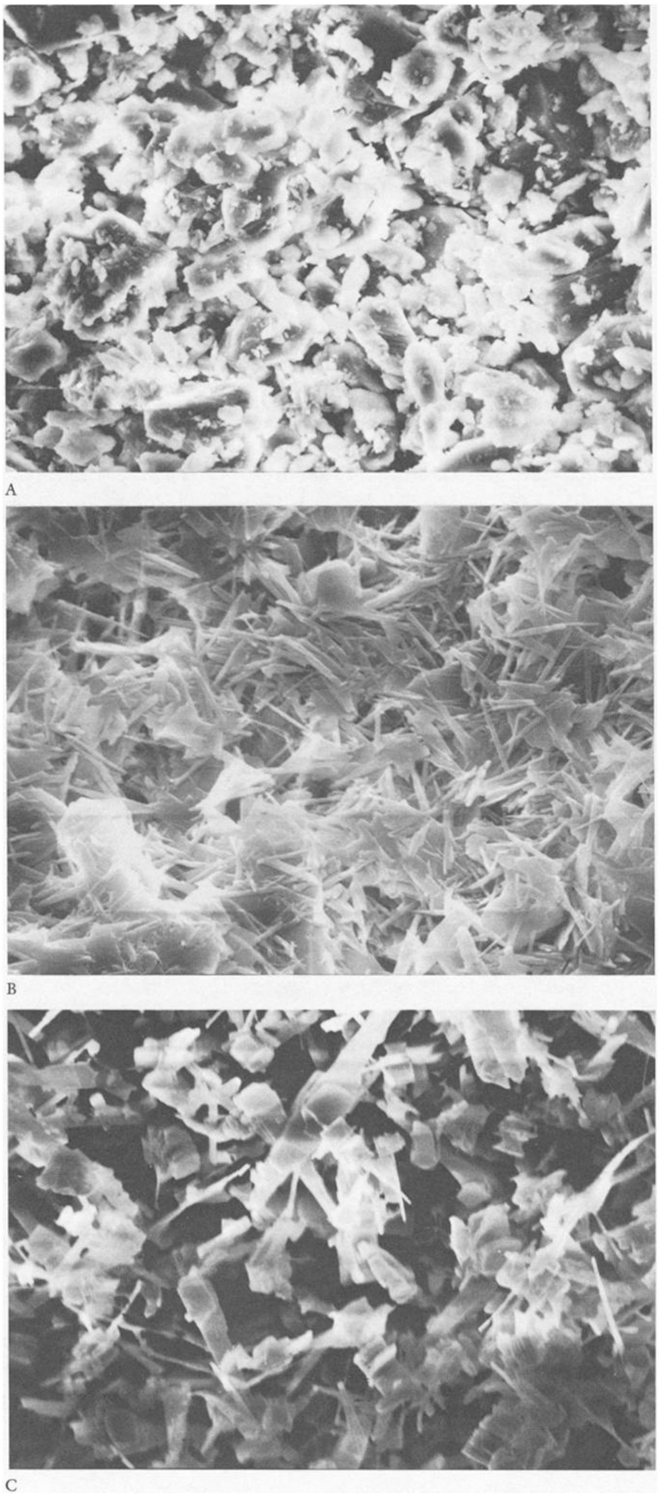


Figure 1. Gypsum microstructures. A) Ground gypsum rock (Colorado) consists of chunky grains with sharp edges and fractured surfaces (770×). B) Gypsum plaster consists in large part of fine lath-like crystals (1540×). C) After "pressure cooking" in an autoclave for two hours at 150 psi to simulate long exposure to occasionally moist conditions, there is grain coarsening and the crystals are more blocky (1540×).

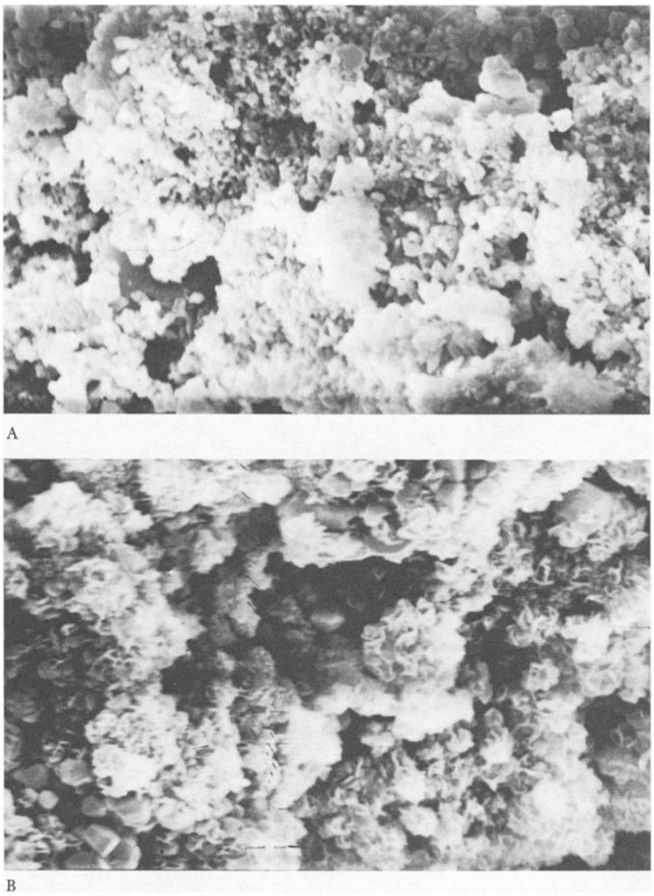


Figure 2. Lime microstructures. Limestones have a variable microstructure depending on geological conditions of deposition and consolidation. Many are chunky calcite grains such as Figure 1A, but softer materials are also common. A) Lime plaster is characterized by tiny spherical particles less than a micron in diameter that cannot be resolved with optical microscopy but are easily seen in the scanning electron microscope (2500×). B) After "pressure cooking" in an autoclave for two hours at 150 psi to simulate long exposure to occasionally moist conditions, there is grain coarsening and the development of surface features on some grains (2400×).

We have restricted this study to the aceramic Neolithic (roughly before 6000 B.C.) because plaster manufacture by that time had become a well-established technology for many applications. In passing, we note that the history of plaster development seems to be entirely different in China (Miao et al. 1981) and in Mesoamerica (Littman 1957; Kidder and Shepard 1944) than in the Near East.

Lime and Gypsum Plasters

We (Gourdin and Kingery 1975) have previously described in some detail the differences between lime plaster and gypsum plaster; our summary discussion here will be brief.

Gypsum plaster is made by heating alabaster or gypsum rock ($CaSO_4{\cdot}2H_2O$) at a temperature of 150–400°C to form the hemihydrate ($CaSo_4{\cdot}\frac{1}{2}H_2O$) which, when mixed with water, reacts to reform the dihydrate ($CaSO_4{\cdot}2H_2O$). Gypsum rock and gypsum plaster have exactly the same chemical composition and cannot be distinguished by chemical tests. Gypsum plaster, however, has a distinctive microstructure consisting of a forest of well-formed microscopic interlocking, needle-like crystals that cause the rehydrated reaction product material to cohere (FIG. 1A). This material is easy to form and use (it forms the core of modern wallboard and is widely used for sculptural purposes), but has limited application as a structural architectural material. The mix tends to set quickly and the resulting product is relatively soft and susceptible to chipping; it absorbs water, and can only be used for exterior purposes in dry climates.

Lime technology is a good deal more complicated. Lime plaster is made by heating limestone ($CaCO_3$) for an extended period at bright heat, 800–900°C, to form quicklime (CaO), which must be soaked in water to form slaked lime ($Ca(OH)_2$), a process in which considerable heat is generated. The slaked lime paste can be stored for some time before use, but after drying and standing in air, the product reacts with the atmosphere to form the carbonate, $CaCO_3$. The product is identical in chemical and crystalline composition to the original limestone, so it cannot be distinguished by chemical or x-ray diffraction tests. As with gypsum plaster, however, lime plaster has a distinctive microstructure consisting of microscopic spherical particles that is clearly different from the parent rock (FIG. 2A). Pure lime plaster has much residual porosity and no great strength; tempering or aggregate additions such as sand, gravel, and limestone are usually added to form a stucco or concrete.

Firing limestone to make quicklime in tonnage amounts requires heating for three or four days at temperatures of 800–900°C (bright heat) with constant fuel additions (Mellor 1923). The long firing is required because the decomposition reaction begins at the surface of each chunk of limestone, absorbing heat, and only slowly penetrates throughout. (Laboratory-size samples can be produced in an hour or less.) Measurements have shown that for each tone of quicklime produced in 19th-century kilns about 1.8 tons of limestone rock and two tons of wood (fir) fuel were required (Burnell 1856). For open-pit firing about twice that amount of fuel, or more, would have been needed. That is, production of significant quantities of lime plaster is a labor-intensive and energy-intensive activity requiring a rudimentary firing pit or kiln. After slaking the fired quicklime with water to form hydrated lime, the rather expensive and difficult-to-prepare paste is mixed with sand, ground limestone, or other aggregate filler (temper) material, both to increase the strength of the product and to extend the amount of mortar or stucco made from a given amount of slaked lime. Additions of stone may be made for aesthetic as well as structural reasons. In addition, burnishing the surface of the partially-dried "leather-hard" material with a rounded pebble or equivalent smooth hard object tends to smear out the surface with locally high compressive forces that give a denser, harder, smoother, stronger, more wear- and water-resistant surface. This can be particularly effective if carried out with platy ochre (red iron oxide) pigment particles mixed in with the paste.

Gypsum plaster has a solubility in water of about 0.2% weight at room temperature; the solubility of lime plaster depends on the water acidity, but is about 0.0015% weight. As a result, lime plaster is much more resistant to moisture; gypsum plaster, because of its solubility, is not well suited for exterior architectural use except in quite dry climates. Thus, even though lime plaster is more difficult and expensive to manufacture and to use, its properties make it the material of choice.

Because of their solubility, both gypsum and lime plasters can undergo metamorphic changes when exposed to moisture for long periods, more so as the ambient temperature is raised. In both cases the initial material consists of fine particles that, over time, are changed by processes well known to ceramic scientists as grain coarsening by "Ostwald ripening" and as densification and strengthening by "liquid-phase sintering" (Kingery, Bowen, and Uhlmann 1976). As a result, we should expect plasters exposed to wet conditions from time to time over several millennia to have a coarser grain size and perhaps become harder and stronger. Metamorphic changes can be accelerated by autoclave treatment (a more powerful pressure cooker) and we have tested this conjecture in the laboratory by preparing a gypsum plaster from Colorado gypsum heated at 150°C and a lime plaster made from natural New England limestone heated at 900°C. Accelerated metamorphosis was induced by heating in a steam autoclave at 150 psi, with the results illustrated in Figures 1 and 2. Electron microscopy of these samples revealed that grain coarsening does occur.

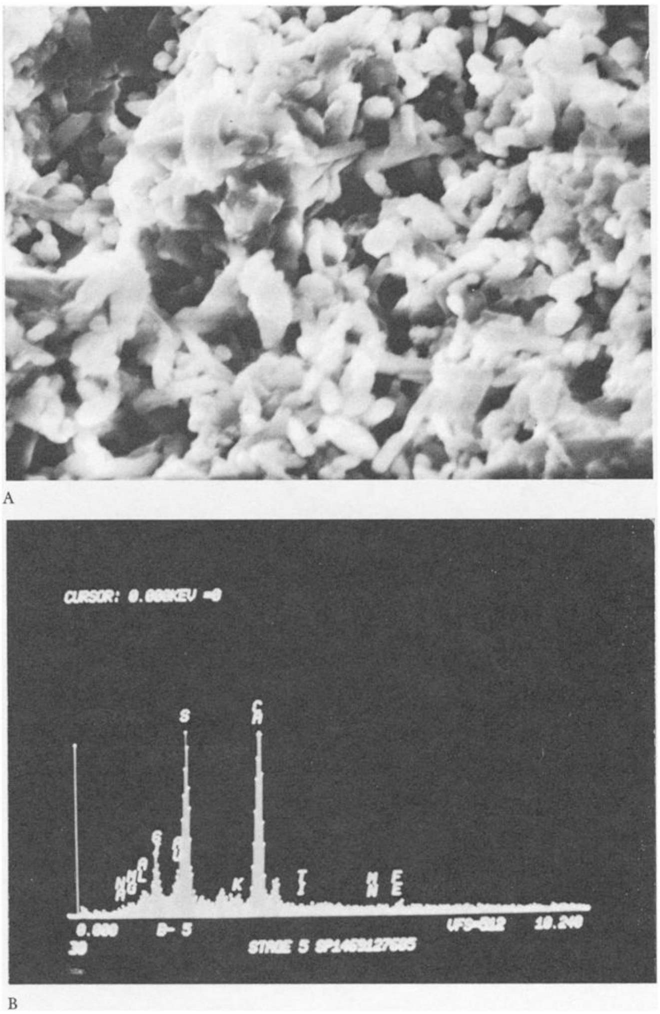


Figure 3. The A) microstructure and B) energy dispersive x-ray analysis of an Abu Hureyra vessel illustrate the elongated, lath-like grains and calcium sulphate composition of a storage jar made from gypsum plaster (2210×).

Methods of Identification and Characterization

Laboratory studies have been carried out primarily to confirm the use of either lime plaster or gypsum plaster as a bonding material. Because powdered limestone and gypsum rock have the same chemistry and x-ray diffraction patterns as lime plaster and gypsum plaster, respectively, the distinguishing characteristic must be ***microstructure***. Allowing for special cases of changes with time, the needle or lath-like morphology of gypsum plaster (FIGS. 1, 3) and the colloidal spherules of lime plaster (FIGS. 2, 4) are sufficiently different from rock samples to allow a determination to be made. Combined with energy dispersive x-ray analysis of the chemical compositions of samples, as illustrated in Figures 3 and 4, lime plasters and gypsum plasters can be unequivocably identified in the scanning electron microscope. Occasionally a weak, friable, poorly-consolidated limestone or a marly (i.e., high-lime) clay has some fraction of fine spherical particles, along with fragmented rock particles of calcite and fine clay-like material that cannot be unequivocably distinguished from material containing a fraction of added plaster.

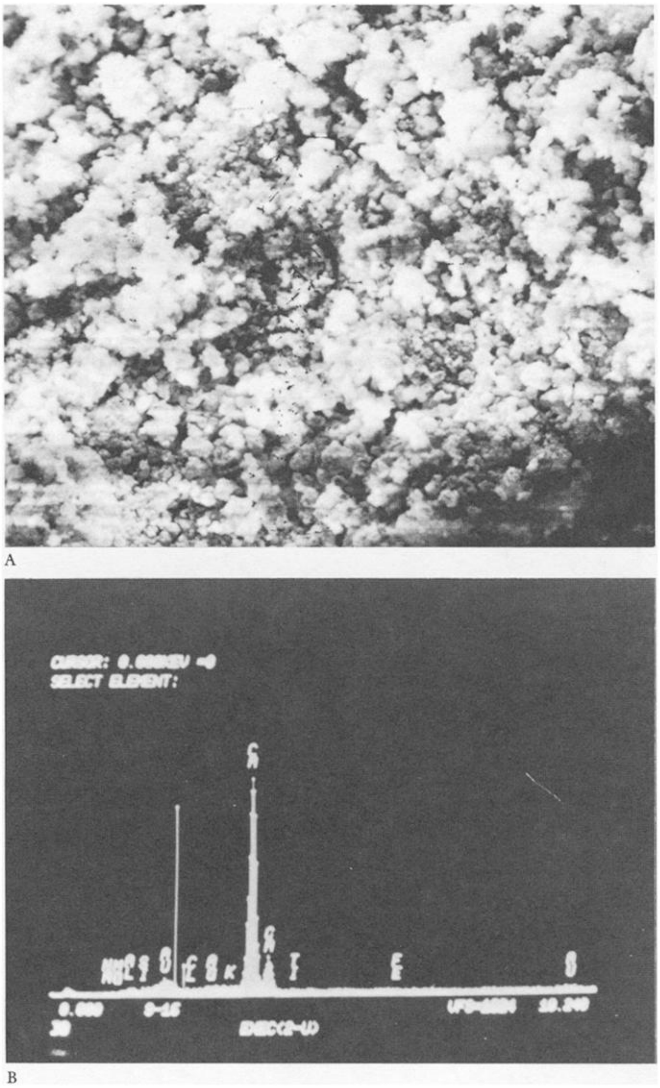


Figure 4. The A) microstructure and B) energy dispersive x-ray analysis illustrate that the plaster coating on the surface of a Byblos ceramic consists essentially of pure lime plaster (3690×).

The macrostructure of each sample was examined in order to characterize evidence of manufacture and nature of the materials. Plasters tend to have marks from burnishing, plastic modeling, or forming, and from scraping, as well as some surface indications of the wetness of the plaster such as dripping of a wet plaster, one bit of plaster being smoothed over another, occasionally with finger impressions present, or a fine network of rough surface and cracking where the material has been worked too dry. Examination with a 10× loupe and an optical binocular microscope may show the presence of residual vegetal temper, fine spherical pores, and small bits of black charcoal. A fractured surface, which preferentially exposes the characteristic bonding phase, was examined for each sample by scanning electron microscopy, including energy dispersive x-ray chemical analysis of the overall composition and individual constituents. Synthesized standards of calcium sulfate and calcium carbonate with clay and with quartz were prepared as standards to allow a semi-quantitative analysis of the constituents present. Many samples were impregnated with an epoxy resin under vacuum and prepared as thin sections for optical microscopic analysis. Some samples were examined by x-ray powder diffraction analysis and compared with synthesized standard mixtures of calcium carbonate and quartz; other samples were examined by the Debye-Scherrer x-ray diffraction method. These standard methods are similar to those previously used (Gourdin and Kingery 1975) and are described in detail in Gourdin's thesis (Gourdin 1974).

A Natufian Lime-burning Hearth

In Hayonim Cave, an early Natufian (10,300–9000 B.C.) site dated ca. 10,400–10,000 B.C. (Bar-Yosef 1983), there is a large opening to the outside (a chimney) at the rear of the cave. Five rounded structures or rooms were found. One structure (Locus 4), 2.5 m in diameter, containing a 20 cm-thick layer of white, porous material, was interpreted by the excavator as having been a lime-burning kiln. Scanning electron microscopy indicated that the material consisted of some residual limestone fragments surrounded by $CaCO_3$ spherulites 0.1–0.2 micrometers in diameter. Energy dispersive x-ray analysis indicated the composition was essentially pure $CaCo_3$. Here we have the first clear example of the production of quicklime for lime plaster.

Architectural Plasters

Samples of architectural plasters, summarized in Table 1, were obtained from a number of sources and examined to verify that the bonding material was or was not lime or gypsum plaster. This seemed desirable since field identifications, such as "concrete" or "white layer," even when explicitly stated are often vague and are sometimes based on no more evidence than a native worker's opinion (which is, however, often quite reliable). Occasionally, a report describes the same material as "lime plaster" on one page and "plaster of Paris" (i.e., gypsum plaster) on another. Most samples received were 1 cc or so in volume. Samples extracted from museum objects were smaller, typically 100 mg or so, about 1 cu mm or less. The samples, relevant observations, and identifications of binding material are described in Table 1. Most were rather poorly consolidated with one smooth surface. One exception was a floor from Çatal Hüyük (Mellaart 1967), which con-

Table 1. Architectural plaster and lime-burning hearth.

*Site**	*Sample description†*	*Optical microscopy*	*Scanning electron microscopy*	*Energy dispersive X-ray analyses, etc.*	*Nature of bond material*
Hayonim Cave	No. 86-2. A crumbly, porous, whitish layer about 20 cm thick found in one of three hearths (Bar-Yosef and Goren 1973).	Porous aggregate of crystalline calcite particles bonded with soft microcrystalline calcite.	Polycrystalline calcite grains with bonding of 0.1 μm spherical particles indicating lime plaster.	EDAX indicates nearly pure calcium carbonate.	Incompletely calcined lime plaster.
Eynan ('Ain Mallaha)	No. 86-1. A hard rock-like brown material shaped as a bench-like structure (Perrot 1966, 1975).	Hard consolidated aggregate of crystalline calcite particles in a microcrystalline calcite bond.	Polycrystalline calcite grains bonded with 0.5–1 μm spherical calcite particles.	EDAX indicates 90 wt% or more $CaCO_3$ plus a small amount of aluminosilicate.	Incompletely calcined lime plaster metamorphosed by long exposure.
Yiftahel	No. 86-6. Rock-hard grey floor material about 4 cm thick with one smooth surface (Garfinkel 1985).	Dense metamorphosed polycrystalline calcite aggregate with some areas of porous microcrystalline material.	Mostly dense agglomerate of 1 μm spherical grains bonded together. Some areas of 0.1–0.5 μm spherical calcite particles.	EDAX indicates 90 wt% or more $CaCO_3$ plus a small amount of aluminosilicate.	Lime plaster metamorphosed by long exposure.
Çatal Hüyük	No. 86-17. Grey floor material ca. 2.5 cm thick. Bottom 1 cm monolithic; upper portion consists of many layers, each about 0.5 mm thick. Level unknown. (Mellaart 1967).	Friable layers of grey microcrystalline calcite.	Porous aggregate of 0.5–1 μm spherical particles intermixed with 10μ grains of calcite and quartz.	EDAX indicates about 75% $CaCO_3$ plus lesser amounts of quartz and aluminosilicate.	Lime plaster.
Hacilar	No. 86-18. Grey floor material with smooth, hard, red surface. In bulk of material are pieces of various mineral tempers including a piece of crushed floor surface. Level unknown. (Mellaart 1970).	White matrix of microcrystalline calcite bonding an array of mm-size rounded and irregular mineral and hematite fragments.	Binder material is 0.2–1 μm spherical particles of calcite.	EDAX indicates binder is nearly pure calcium carbonate.	Lime plaster.
Tell Ramad	No. 86-23. Nine cm-thick floor with one smoothed dense surface (Contenson and van Liere 1964; Contenson 1971).	Inhomogeneous material with many particles of charcoal, ash, and minerals as well as vegetal material and spherical bubbles.	Matrix phase is mostly 0.5–1 μm spherical calcite particles bonding mineral particles.	EDAX indicates about ⅔ $CaCO_3$ and ⅓ silicate, mostly SiO_2.	Lime plaster.
Byblos	No. 86-25. Grey moderately friable floor material containing occasional 5 mm pebbles (M. Dunand 1973).	Mineral fragments, mostly calcite, bonded with grainy microcrystalline calcite.	Mostly 2–5 μm calcite grains.	EDAX indicates nearly pure $CaCO_3$.	Mostly compacted limestone powder with minor lime plaster.
'Ain Ghazal	No. 85-7. Grey wall plaster, painted red (Rollefson 1983).	Many mineral fragments in matrix of microcrystalline calcite bonding phase.	Bonding matrix is 0.5–1.5 μm spherical calcite particles.	EDAX indicates about half $CaCO_3$ with substantial SiO_2 and minor aluminosilicate.	Lime plaster.
'Ain Ghazal	No. 85-6. Grey floor plaster, painted red containing occasional large (ca. 1 cm) pebbles (Rollefson 1983).	Many pebbles and mineral fragments in a soft microcrystalline calcite bond.	Bonding matrix is 0.2-1 μm spherical calcite particles.	EDAX indicates about half $CaCO_3$, half SiO_2.	Lime plaster.

Table 1. (cont.)

*Site**	*Sample description†*	*Optical microscopy*	*Scanning electron microscopy*	*Energy dispersive X-ray analyses, etc.*	*Nature of bond material*
Jericho	No. 85-1. Floor plaster; whitish grey friable material with one smoothed surface. ROM Acc. 1955—65-40B (Kenyon 1957).	Porous structure of mineral fragments bonded with microcrystalline calcite.	Mostly mineral fragments of limestone and some silicate with main phase of 0.5–1 μm spherical calcite particles.	EDAX indicates about ¾ $CaCO_3$, ¼ SiO_2 and silicates. 1972 test at ROM reported 79% of sample reacted with HCl, releasing CO_2 gas (i.e., presumably $CaCO_3$).	Lime plaster.
Jericho	No. 85-10. Floor sample with smoothed thin skim coat that is whiter than coarser grey interior. Sample taken from interior. Ashmolean 1936.439 (Garstang 1936).	Crumbly material with many silicate, quartz, and calcite mineral fragments.	Mostly mineral fragments with minor amount of 0.2–1.0 μm spherical particles of calcite.	About ¾ $CaCO_3$, ¼ SiO_2, minor silicate minerals.	Lime plaster.
Ali Kosh	No. a/69/190–210. Outer whitish gray, porous layer wiped onto inner grayish red layer of a wall. (Hole and Flannery 1962).	Porous aggregate of fine particles.	Fine particles of 0.5–5 microns consisting of gypsum intermixed with clay in agglomerates on the order of 10–40 microns.	Gypsum mixed with a minor amount of clay.	Gypsum plaster.
Ali Kosh	No. a/81/190–200. Whitish surface layer on probable architectural fragment. (Hole and Flannery 1962).	Porous aggregate of polycrystalline particles.	Fine particles 0.5–5 microns consisting of gypsum intermixed with clay.	Gypsum mixed with a minor amount of calcareous clay.	Gypsum plaster.
Ali Kosh	No. a/68/220–230. Coarse, grayish white surface layer on probable architectural fragment. (Hole and Flannery 1962).	Porous aggregate of coarse and fine particles.	Mixture of gypsum particles up to 100 microns bonded with fine particles of a mixture of clay and gypsum plaster, and another calcium-bearing mineral.	Gypsum, calcareous clay, and quartz mixture.	Gypsum plaster and clay.

*Other sites at which architectural plasters have been reported with a clear indication of the nature of the bond material are: Abu Gosh (Balfet 1978); Beisamoun (Balfet 1978); Beidha (Kirkbride 1967, 1968); Bouqras (Akkermans et al., 1983); Far'ah (de Vaux 1961); Kül Tépé (Merpert, Munchaev, and Bader 1976); Laboueh (Balfet et al. 1969a, 1969b); Nahal Oren (Noy, Legge and Higgs 1973); Shaqaret M'siad (Kirkbride 1966a, 1966b); Tell Assouad (Cauvin 1972); Tell Sotto (Merpert, Munchaev, and Bader 1976, 1977); Umm Dabaghiyah (Kirkbride 1975); Yarim Tépé (Merpert, Munchaev, and Bader 1976); Tépé Guran (Meldgaard, Mortensen, and Thrane 1963).

†Samples No. 86-1 and No. 86-2 received from collection of Institute of Archaeology, Hebrew University, Jerusalem, courtesy of O. Bar-Yosef. Sample No. 86-6 received from collection of Israel Department of Antiquities and Museums, courtesy of Mr. A. Eitan, Director of Department of Antiquities and Museums. Samples No. 86-17 and 86-18 received from collection of the Ankara Museum, Ankara, Turkey, courtesy of Museum Director, Inci Bayburtluoglu, and Turkish Director of Museums and Antiquity, Nurettin Yardimci. Samples 86-23 and 86-25 received from collection of Musée de l'Homme, Paris, courtesy of H. Balfet. Samples No. 85-7 and 85-6 received from collection of The Institute for Archaeology, London, courtesy of Kathryn Tubb. Sample No. 85-1 received from collection of the Royal Ontario Museum, Toronto, courtesy of T. Cuyler Young. Sample No. 85-10 received from collections of the Ashmolean Museum, Oxford, courtesy of R. Moorey. Samples No. a/69/190-210, No. a/81-190-20, and No. a/68-220-230 courtesy of F. Hole.

sisted of a base layer about 2 cm thick on which were replastered some 50 thin layers of about 0.5 mm thickness. A sample of Hacilar floor plaster (Mellaart 1970) included a piece of a hard, dense previous surface with a burnished red surface as part of the aggregate in the new floor. The material from Eynan ('Ain Mallaha) (Perrot 1966, 1975) was from a bench-like structure that was clearly formed from a pasty material; it was tan in color and of a very hard rock-like material, apparently metamorphosed by long exposure. A similar hard material occurred at Yiftahel (Garfinkel 1985). The sample from Tell Ramad is presumed architectural, but it had a thickness of about 9 cm and may possibly have served some other function. There are no plaster floors at Ali Kosh (Hole and Flannery 1962), but three layers from walls or architectural fragments were analyzed and found to be gypsum plasters with grit inclusions and minor amounts of clay. All samples contained mineral aggregate material of a larger particle size than that of the cementing matrix; this material was of secondary interest for the present research and not studied in any detail. Surfaces examined by scanning electron microscopy were fracture surfaces that exposed primarily the bonding matrix rather than the aggregate.

Jericho and Ganj Dareh Mud Brick

Samples of three bun-shaped bricks and three cigar-shaped bricks collected by Kathleen Kenyon (collections of the Ashmolean Museum, Oxford, and the Royal Ontario Museum, Toronto) were examined. It was the pristine shape of these bricks and what seemed to be a high lime content when examined with a binocular microscope that drew our attention. Part of the strength is related to the heavy polyvinyl acetate coating used for conservation. For the record, the microstructure of a PVA-coated surface is illustrated in Figure 5. In this case, energy dispersive x-ray analysis and x-ray diffraction analysis indicated a very high lime content, but the electron-microstructure of several samples are consistent with a very limy marl that is a mixture of clay and fine, irregular, fractured lime particles rather than a lime plaster additive. This was also true of samples of mud brick and mud plaster supplied by P. E. L. Smith from Level D at Ganj Dareh (Smith 1970, 1974).

Non-Architectural Plasters

The several categories of non-architectural plasters, which are summarized in Table 2, include the following: as an adhesive; containers and vessels; sphere; sculpture; beads; and miscellaneous uses.

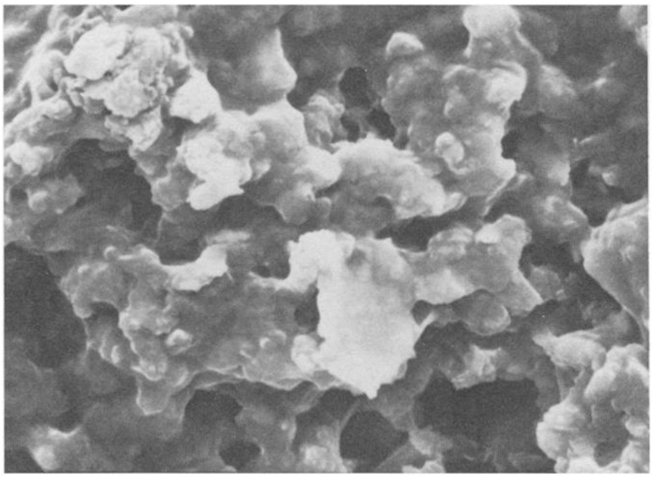


Figure 5. The surface of a Jericho mud brick is obscured by heavy application of polyvinyl acetate added for conservation purposes (2000×).

Figure 6. Photograph of the blade back of a microlith from Geometric Kebaran site Lagama North VIII, showing plaster used as an adhesive material. The thickness of the blade back is 2 mm (8×).

As An Adhesive

Several of the microliths from the Geometric Kebaran site Lagama North VIII (Bar-Yosef and Goring-Morris 1977) display signs of an adhesive used for hafting. Remnants of this extend along the back of the blade, as shown in Figure 6, and there are traces along the side of the blade as well. Radiocarbon dates for the Epi-Paleolithic site are ca. 12,000 years B.C. (Bar-Yosef 1983). The adhesive material contains some limestone particles, but is mostly lime plaster spherulites about 1 micrometer in di-

Figure 7. Microstructure of a Tel Ramad *Vaisalle Blanche* (whiteware vessel) illustrating the lime plaster structure (2700×).

ameter that result from grain coarsening over time, as has been illustrated in Figure 2. The chemical composition is nearly pure calcium carbonate, and there is no doubt that the material is lime plaster.

Containers and Vessels

Six different types of vessels have been studied: a complete storage vessel from Abu Hureyra (Ashmolean Museum, Oxford; Moore 1975); fragments of *Vaiselle Blanche* (whiteware) from Tell Ramad (Musée de l'Homme, Paris; Contenson 1971); the plaster lining of a pottery vessel from Byblos (Musée de l'Homme, Paris; Dunand 1973); a fragment from a cord-plaster composite container from Nahal Hemar Cave (Institute for Archaeology, Hebrew University, Jerusalem; Bar-Yosef 1985); and a basket-impressed vessel from Ali Kosh (Hole and Flannery 1962).

The plaster jar from Abu Hureyra had a thickness of 4–5 cm and a height of 55–60 cm. Macroscopic examination indicated the body was made of plaster and that it contained particles of charcoal 0.5–2 mm in dimension, and particles of a white mineral material of 0.1–1 mm size in a matrix of plaster. The bottom section was built up in slabs, and then rows of slabs were added in four discernible layers to increase the height of the vessel. In order to get a smooth surface, a skim coat of plaster appears to have been applied over the surface. Electron microscopic observation and energy dispersive x-ray analysis show that the plaster material is a porous gypsum. There are elongated grains characteristic of gypsum plaster (FIG. 3) along with coarser particles of gypsum rock fragments added as an aggregate material to the plaster.

Three samples of whiteware, or Vaiselle Blanche, vessel sherds from Tell Ramad were examined. In each of them there were many mineral fragments, vestiges of vegetal material, and residual bubbles; one contained charcoal particles. Two of these samples were fairly soft; the other was much harder. In every sample the fracture surface indicated nearly pure calcium carbonate with microstructures typical of lime plaster (FIG. 7). The harder sample showed signs of metamorphic particle agglomeration, similar to that found in the architectural plasters from 'Ain Mallaha and Yiftahel. In none of the samples examined was there appreciable ash content, and all of these whiteware vessels were bonded with a lime plaster. It has been suggested that a pozzolanic reaction between lime and ash to form a hydrated calcium silicate was used in fabricating Vaiselle Blanche (Balfet et al. 1969a, 1969b). We see nothing in the samples we have examined that corresponds to such a reaction and nothing in the data reported by Balfet et al. (1969a, 1969b) to demonstrate the presence of the calcium silicate gel required by that hypothesis.

Two fragments of plaster bowls with basket impressions on the exterior were examined from the Ali Kosh preceramic phase at Chagha Sefid (Hole 1977) and found to be gypsum plaster. Both bowl fragments were white, relatively soft, and contained rounded pores, but no flakes of charcoal. In addition, three samples of yellowish-gray coatings on low-fired reddish clay were found to contain mixtures of heated gypsum and calcareous clay, which may be intentional plasters (a69/680–690, a94/180–200, and a71/190–220).

A sherd of Byblos pottery displayed an interior coating of plaster ca. 3 mm thick. Upon examination the coating turned out to be pure calcium carbonate with the microstructure illustrated in Figure 4, a lime plaster.

At Nahal Hemar (Bar-Yosef 1985), containers were discovered that were made of a composite construction consisting of cord or rope coiled to form a cylinder that was fixed in shape by coatings of asphalt or a white plaster on both the inside and outside surfaces. A tiny fragment of plaster from one of these containers was examined. Fibers of the cordage are visible along with the plaster material that consists of nearly pure calcium carbonate in the form of a mixture of calcite fragments and spherical particles of the lime plaster.

Plaster Ball

A spherical object about 30 mm in diameter from Abu Hureyra (Moore 1975; Ashmolean Museum acc. no. 1938.371) was found to consist of gypsum with a microstructure that was partly elongated grains characteristic of gypsum plaster such as illustrated in Figure 3, together

Table 2. Non-architectural plasters.

Site	*Sample description**	*Optical microscopy*	*Scanning electron microscopy*	*Energy dispersive X-ray analyses, etc.*	*Nature of bond material*
Lagama North VIII	No. 86-12. 44 mm-long quartz microlith with traces of white adhesive material along back and sides. From Hlld 35–43 Rectangle (Bar-Yosef and Goring-Morris 1977).	Uniform porous microcrystalline material.	Fine mineral fragments of calcite mixed with 0.5 μm spherical particles of bonding material.	Nearly pure $CaCO_3$.	Lime plaster.
Abu Hureyra	No. 85-11. 60 cm-high storage jar with 4–5 cm wall thickness. Built up in sections and layers. Contains 0.5–1 mm charcoal and mineral particles. Ashmolean Acc. 1978-543. (Moore 1975).	Particles of limestone, charcoal, sandstone, and gypsum bonded in porous microcrystalline matrix.	Bonding phase is micron-size lath-like crystals with length-to-diameter ratio of 5, typical of gypsum plaster. Some crystals have lower length-diameter ratio indicative of metamorphosis.	Bond phase is nearly pure $CaSO_4$	Gypsum plaster.
Nahal Hemar	No. 86-14. Plaster facing on interior and exterior of cordage-plaster-composite cylindrical container (Bar-Yosef 1985).	Vegetal fibers, fragments of mineral calcite and microcrystalline calcite matrix.	Vegetal fibers interspersed with crystalline calcite fragments with bonding matrix of 0.5–1.5 μm spherical particles of calcite.	Nearly pure $CaCO_3$.	Lime plaster.
Byblos	No. 86-24. Smooth white plaster facing 1 mm thick on one side of brown pottery vessel sherd with 5 mm wall thickness. (Dunand 1973)	Uniform microcrystalline calcite.	0.2–1.0 μm spherical particles of calcite.	Nearly pure $CaCO_3$.	Lime plaster.
Tell Ramad	No. 86-20. Fragment of a *Vaisalle Blanche* sherd ca. 1 cm thick with smoothed surface and rim on one side (Contenson 1971).	Quartz, limestone, charcoal, mineral particles, vestiges of vegetal temper and small bubbles in a matrix of microcrystalline calcite.	Mineral particles with major bond phase of 0.3–1.0 μm spherical particles.	Nearly pure $CaCO_3$ at fracture surface.	Lime plaster.
Tell Ramad	No. 86-21. Hard, dense fragment of a *Vaisalle Blanche* bowl ca. 1 cm thick with smoothed surfaces (Contenson 1971).	Smaller amount of mineral than 8–20, vestiges of vegetal temper and small bubbles, but no charcoal in matrix of microcrystalline calcite.	Mineral particles with major bond phase of 0.3–1.0 μm spherical particles showing signs of metamorphic particle agglomeration.	Nearly pure $CaCO_3$ at fracture surface.	Lime plaster.
Tell Ramad	No. 86-22. Hard fragment of a *Vaisalle Blanche* bowl with smoothed surfaces (Contenson 1971).	Larger amount of limestone mineral particles, smaller amounts of vegetal temper and bubbles in matrix of microcrystalline calcite.	Lots of mineral particle fractures with bond areas of 0.3–1.0 μm spherical particles.	Nearly pure $CaCO_3$ at fracture surface.	Lime plaster.

Table 2. (cont.)

Site	*Sample description**	*Optical microscopy*	*Scanning electron microscopy*	*Energy dispersive X-ray analyses, etc.*	*Nature of bond material*
Abu Hureyra	No. 85-12 Coarse grey plaster ball about 30–35 mm diameter with surface built up in layers. Ashmolean Acc. #1978. 571 AH73-678 (Moore 1975).	Occasional particles of charcoal and quartz. Many 0.5 mm lumps of limestone distributed in microcrystalline matrix.	Some areas lath crystals 2 × 10 μm, some areas porous nonprismatic crystals 10 × 20 μm probably resulting from in situ alteration.	Nearly pure $CaSO_4$.	Gypsum plaster.
Jericho	No. 85-2A. Fine plaster of chipped spot on facial area of Kenyon Jericho skull No. D-15. Acc. No. 1955.165.1, Royal Ontario Museum (Kenyon 1957).	Fine mixture of quartz particles in matrix of microcrystalline calcite containing fine bubbles.	Fracture surface mainly 0.2–0.8 μm diameter $CaCO_3$ spherulites.	About 80% $CaCO_3$ with minor SiO_2.	Lime plaster.
Jericho	No. 85-2B. Hard coarse area of beard with black coloration. Sample taken from under chin of Kenyon Jericho skull No. D-15. Acc. No. 1955.165.1, Royal Ontario Museum (Kenyon 1957).	Mixture of quartz particles in matrix of calcite.	Mineral particles bonded with 0.5–1 μm diameter spherical $CaCO_3$ particles.	About 70% $CaCO_3$ with lesser SiO_2.	Lime plaster.
Jericho	No. 85-13A. Surface white plaster layer of sculpture fragment built up in layers about 10 mm thick indicated by step joins. Ashmolean Acc. #1958.755 JD402.1 (Kenyon 1957).	Uniform microcrystalline calcite with small bubbles and minor quartz particles.	Mostly 0.5–1 μm spherical particles of $CaCO_3$.	About 90% $CaCO_3$ with remainder SiO_2.	Lime plaster.
Jericho	No. 85-13B. Sample of same sculpture fragment 10 mm below surface. Tan color, coarse structure.	High mineral concentration in microcrystalline matrix.	Fracture surface mostly irregular fine mineral (clay and limestone with smaller amount of 0.3–1.0 μm $CaCO_3$ particles).	Fracture surface about ⅔ $CaCO_3$ and ⅓ aluminosilicate.	Lime-clay mixture.
Jericho	No. 85-13C. Sample of same sculpture fragment taken 45 mm below surface. Tan color, coarse structure.	High mineral concentration in microcrystalline matrix.	Fracture surface almost entirely fine mineral mixture of clay and limestone.	About ⅔ $CaCO_3$, ⅓ aluminosilicate.	Limy clay.
Jericho	No. 85-14A. Sample of sculpture fragment painted red taken from 3 mm thick worked white smoothed surface layer. Ashmolean Acc. #1964.698d.	Contains some fine quartz particles and occasional fine charcoal in microcrystalline matrix.	Mineral particles in matrix of 0.3–1.0 μm spherical particles of $CaCO_3$.	More than 80% $CaCO_3$ with remainder SiO_2.	Lime plaster.

Table 2. (cont.)

Site	*Sample description**	*Optical microscopy*	*Scanning electron microscopy*	*Energy dispersive X-ray analyses, etc.*	*Nature of bond material*
Jericho	No. 85-14B. Sample of coarse internal structure of same sculpture fragment as above. Coarse structure, brown color. Ashmolean Acc. #1964.698a.	Friable structure with high mineral concentration including limestone, quartz, and charcoal in microcrystalline matrix.	Fine mineral particles with no indication of spherical particles.	Fracture surface about ⅔ $CaCO_3$, ⅓ aluminosilicate.	Limy clay.
Nahal Hemar	Nos. 86-8, 86-10. Two different sculpture fragments with smooth surface and uniform cream-colored structure. (Bar-Yosef 1985).	Fine mineral fragments of calcite plus vegetal fibers in a fine microcrystalline matrix.	Vegetal (hardwood) fibers about 10 μm in diameter in matrix that is about half mineral fragments and half 0.5 μm spherical particles of $CaCO_3$.†	Nearly pure $CaCO_3$.	Lime plaster.
Nahal Hemar	No. 86-11. Sample from side of sculpture "eye" fragment. This fragment is white with a smooth worked surface (Bar-Yosef 1985).	Fine mineral fragments of calcite plus vegetal fibers in a fine microcrystalline matrix.	Vegetal fibers in matrix that is about half mineral fragments and half 0.5–1.0 μm spherical particles of $CaCO_3$.	Nearly pure $CaCO_3$.	Lime plaster.
Jericho	No. 86-16. Sample from surface at back of neck of Garstang sculpture illustrated in Fig. 10. (Garstang 1936).	High concentration of mineral fragments in white microcrystalline matrix of calcite.	Fracture surface is fine mineral fragments with 0.5–1.0 μm spherical particles of $CaCO_3$.	About 90% $CaCO_3$; remainder mostly SiO_2.	Lime plaster.
Jericho	No. 86-15. Sample from 5 mm below surface at back of neck of Garstang sculpture illustrated in Fig. 10. (Garstang 1936).	High concentration of mineral fragments in grey microcrystalline matrix of calcite.	Porous structure with high concentration of fine mineral fragments with bonding phase of clay and 0.5 μm spherical particles of $CaCO_3$.	About ⅔ $CaCO_3$, remainder a mixture of SiO_2 and aluminosilicate.	Lime plaster/clay.
Nahal Hemar	Nos. 86-9, 86-13, 86-7. Samples of two beads formed by modeling plaster around a central cord (Bar-Yosef 1985).	Crystals of calcite 2–3 mm across in a microcrystalline calcite bond.‡	Crystals of calcite in a porous bond phase of 0.5–2.0 μm spherical particles of calcite.	Nearly pure $CaCO_3$.	Lime plaster.
Chagha Sefid	No. SA/B4/569. Fragment of a bowl with exterior basket impressions and built in slabs from Ali Kosh phase (Hole 1977).	Surface white layer and interior coarser mixture. A soft, white plaster with some rounded pores and very little temper.	Blocky to elongated particles, 1–10 microns range in the interior with rare occurrence of particles measuring 40–50 microns, and 1–5 microns in the surface region, and having some fusing at the edges. Ostwald ripening probable.	Pure gypsum.	Gypsum plaster.

Table 2. (cont.)

Site	*Sample description**	*Optical microscopy*	*Scanning electron microscopy*	*Energy dispersive X-ray analyses, etc.*	*Nature of bond material*
Chagha Sefid	No. SA/A2/557. Fragment of a thin-walled bowl with exterior basket impressions, excavated in Ali Kosh phase (Hole 1977).	White, relatively soft, with rounded pores.	Blocky to elongated particles, 1–10 microns with some fusing at the edges.	Pure gypsum.	Gypsum plaster.

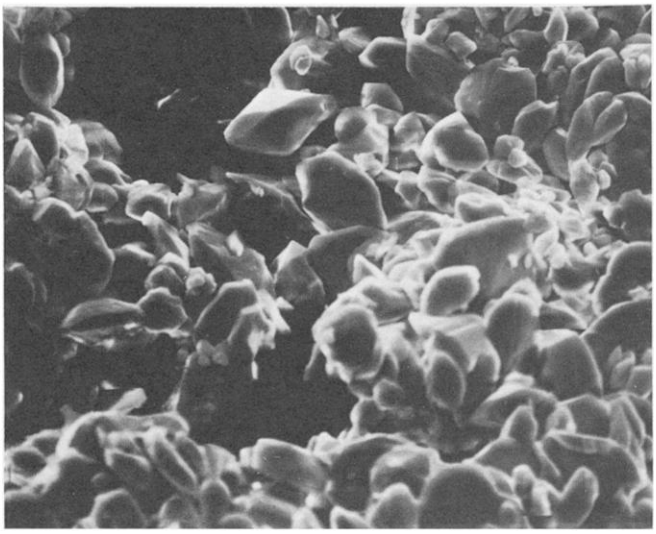
*Samples No. 86-8 86-9, 86-10, 86-7, 86-11, 86-13, 86-12, and 86-14 from collection of the Institute of Archaeology, Hebrew University, Jerusalem, courtesy O. Bar-Yosef. Samples No. 85-11, 85-12, 85-13, and 85-14 from collection of the Ashmolean Museum, Oxford, courtesy of R. Moorey. Samples No. 86-24, 86-20, 86-21, and 86-22 from collection of the Musée de l'Homme, Paris, courtesy H. Balfet. Samples No. 86-15 and 86-16 from collection of the Israel Museum, Jerusalem, courtesy of Tamar Noy. Sample No. 85-2 from collection of the Royal Ontario Museum, Toronto, courtesy of T. Cuyler Young. Samples No. SA/B4/569 and No. SA/A2/557 courtesy of F. Hole.

†Examination by Martha Goodway, Conservation Analytical Laboratory, Smithsonian Institution, established that fibers are wood. She reported that a sculpture fragment from Nahal Hemar, Israel, contained fiber bundles not more than 5 mm in length, with particles of plaster adhering to them. Several fragments were mounted in Aroclor (© Monsanto) 5442, whose index of refraction is ca. 1,66, for microscopic examination. The fiber bundles were broken in blunt fracture. Their color was a rich yellow-brown. With the insertion of the selenite (Red I) plate, the fibers displayed positive elongation. This is the optical behavior of left-handed cellulose characteristic of most vegetable fibers (M. Goodway 1987; B. Luniak 1953). Comparison was made with preparations of both right-hand (flax, Cargille 2E) and left-hand (manila, Cargille 11D) fibers. Several pitted vessels were observed in the mounted fibers in which the rows of pits were set so that the pits were alternate (rather than opposing). Such vessels are characteristic structures of nonconiferous wood (McCrone and Delly 1973), i.e., hardwood.

‡Surface decoration of sample 86-9 consisted of emerald-green crystals of dioptase, copper metasilicate monohydrate, $CuSiO_3 \cdot H_2O$, identified by EDAX analysis and x-ray diffraction pattern.

with some faceted grains thought to have formed by metamorphic grain coarsening over time (FIG. 8).

Figure 8. Microstructure of a gypsum plaster ball from Abu Hureyra with faceted grains developed over time by a grain-coarsening process (850×). Other areas contained more typical elongated laths as shown in Figure 3.



Sculpture

PLASTERED SKULLS

Plastered skulls are known in the PPNB from Jericho (Garstang 1936; Kenyon 1957), from Beisamoun (Le Chevallier 1978), and from Tell Ramad (Contenson 1971). The PPNB plastered skull from Jericho in the Royal Ontario Museum (D115 of Kenyon 1983; R.O.M. acc. no. 1955.165.1) was made in a manner similar to modern processes for sculpture. Facial features were modeled in plaster over an armature, an adult male skull in which the right side had been crushed inward and the mandible was missing. Two pieces of shell were inset into the plaster to form an eye. The top and back of the cranium were left bare of plaster. The sculpture was shaped with a coarse mixture of grayish-white plaster and aggregate, then a fine skim coat which was colored pink with an addition of iron oxide was wiped over the surface.

There is less aggregate in the skim coat, so that the composition has been altered to give a smooth appearance and the color of skin. The surface has been smoothed by working with fingers to form the fine plaster into a compacted surface. Shell eyes, only one of which remains, were placed in the eye sockets on top of the reddish skim coat, and the sockets were carefully modeled. A strip of plaster was placed over the left eye and another strip was added for the brow ridge. A coarse mixture of plaster and aggregate was laid on in a thick, sticky consistency for the beard. The remains of the beard resemble the appearance of a pasty whipped cream overbeaten to form peaks. There are finger impressions under the chin where the head was held as the beard was applied. Then a black paint was brushed onto the upper lip in vertical strokes and hair was suggested by circumferential strokes across the top of the skull. Residual flecks of paint indicate that the beard was also painted black.

Thus, the composition and working methods were adjusted to produce particular results, as can be seen with microscopic examination. The skull has suffered from damage to the right side before sculpting and also during burial. The paint has chipped, the pink skin color and black beard color have faded, and dirt has settled into the porous material. The plaster modeling of one eye is mostly missing, including some of the shell inlay. Cracking of the plaster and skull, dirt from burial, and polyvinyl acetate used in conservation make it difficult to appreciate the original appearance and visual effect of the piece. The sutures of the skull are cracked and loose, making the shape out-of-round and adding to the fragility. The nose and mouth are somewhat raised from their natural anatomical position because the lower jaw was not incorporated. If the head is rotated backward or viewed from an angle slightly below the head, the unnaturally foreshortened proportions disappear.

Tiny, microscopic fragments were taken from beneath the chin from the hard plaster used in the beard and from the pink surface slip coating in a chipped spot near the nose, and a sample was also taken from the interior of the nose as a representative of the softer plaster beneath the surface layer. A fleck of black paint was dislodged from the mustache. The sites of sampling cannot be discerned except by microscopic determination.

Analysis by scanning electron microscopy and energy dispersive x-ray techniques indicates that the base material consists of a paste made from a fine lime plaster containing an aggregate filler of fine white sand (FIG. 9). X-ray diffraction and energy dispersive x-ray analysis show that the mixture used contained about 20% quartz sand and a minor amount of clay. For the beard area, a higher concentration of sand was used to give a coarser texture, but lime plaster was still the bonding material. Energy dispersive x-ray analysis identified the black pigment as a manganese-dioxide black in which some iron was present as a lesser constituent. Iron oxide rather than a ferruginous clay addition was used to color the skin pink.

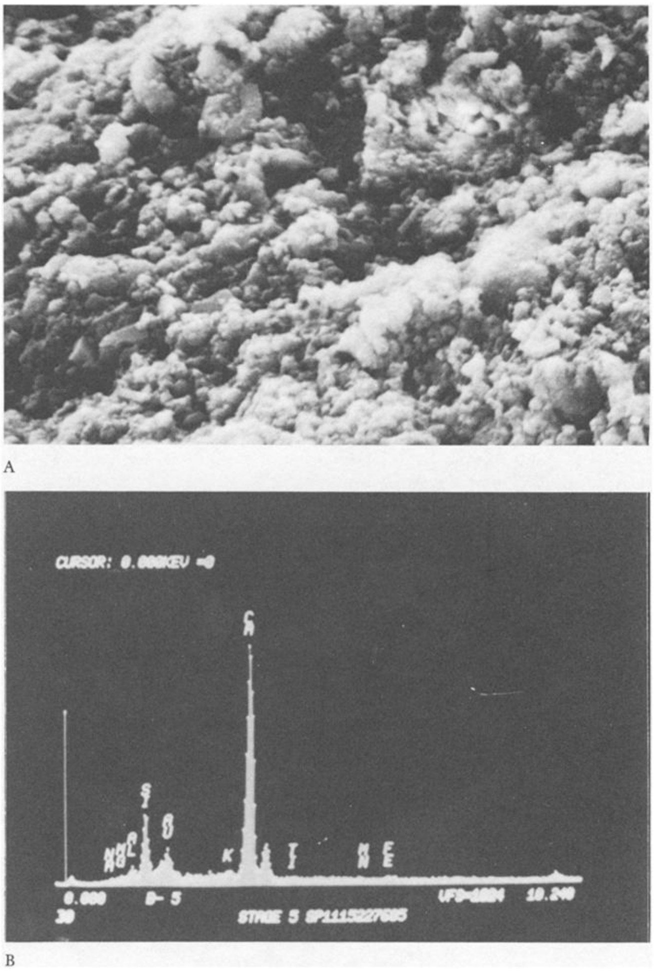


Figure 9. The A) microstructure (2700×) and B) energy dispersive x-ray analysis of the Jericho skull material indicates unequivocably that it is a lime plaster containing a fine white sand as a tempering aggregate.

JERICHO SCULPTURAL FRAGMENTS

Jericho sculptural fragments of a shoulder and leg in the Ashmolean Museum (Kenyon 1983; acc. no. 1958.775) are up to 45 mm thick, corresponding to nearly solid structures that were built up in layers about 10 mm thick, between which incipient fractures can be seen at the joins. On this sample there is no residual paint present, but some similar sculptural fragments are painted with red ochre or black manganese pigment where a thin, white skim-coat underlay serves as a ground for the painting.

The fragments are heavily conserved with polyvinyl acetate so that the surface now represents that illustrated in Figure 5 rather than its original state. Near the surface there is a thin, smooth, white coating; occasional bits of charcoal can be seen in the smooth-worked surface. At a depth of 10 mm below the surface, the color is grayish-brown, the texture is coarse, and there are numerous mineral fragments visible. Even further from the surface, at a depth of 45 mm, the color is also grayish-brown but even more mineral fragments exist, corresponding to a quite different material than the surface coating. Two other Jericho sculpture fragments examined (Ashmolean Museum acc. no. 1958.774 and 1964.698) showed essentially similar structures; one of these (acc. no. 1958.773) had rough striations in the interior, which were impressions of reeds used in a bundle as the sculpture armature.

Scanning electron microscopy and energy dispersive x-ray analysis indicated that the surface layer of these samples had calcium carbonate as the principal ingredient, with a microstructure like that shown for the Jericho skull in Figure 9, indicating an intimate mixture of lime plaster and quartz sand. In contrast, the sample 10 mm from the surface had a lower concentration of lime plaster and was a mixture of lime plaster, mineral silicate, and clay. The material 45 mm below the surface had the microstructure of a limy clay with mineral fragments much like that of the Jericho mud brick. These samples were subjected to x-ray diffraction analysis, which indicated, in agreement with microscopic observations, that the surface layer consisted of calcite with about 15–20% quartz sand. The sample from 10 mm below the surface was about 50% quartz with clay in a lime bond, while the sample from 45 mm below the surface included feldspar in addition to sand, clay, and lime.

These sculptures were made over a bundled-reed armature on which was first built up a core of limy clay with a composition very much like the "mud" brick of this period. Additional layers were added, which consisted of a mixture of the limy clay with a lime plaster added to increase the hardness. Finally, the surface was modeled with a thin, smooth, white coating that consisted of nearly pure lime plaster.

JERICHO SCULPTURED HEAD

A wonderful, complete Jericho sculptured head (FIG. 10) was recovered by the Garstang excavation (Garstang 1936) and sampled in the Conservation Laboratory at the Israel Museum in collaboration with Dr. Tamar Noy. A tiny surface fragment from the back of the neck was found to consist of a pure white plaster containing some limestone fragments (FIG. 11A). A sample taken from about 5 mm below the surface consisted of a plaster mixed with limestone fragments, quartz particles, and clay (FIG. 11B). Thus, this sculpture used limestone rather than sand as a filler material and the interior was a more heterogeneous composition which, if it had been brought to the surface only by surface working, would have included the fine clay constituent as well as the lime plaster, indicating that a skim coat was separately applied as it was for the other Jericho sculptures.

'AIN GHAZAL STATUES

Several 'Ain Ghazal statues (Rollefson 1983, 1984) have been sent to the Archaeology Institute in London for conservation. Dr. Kathryn Tubb (Tubb 1985 and personal communication in 1986) has found scanning electron microscopy and x-ray diffraction evidence of lime plaster at the surface and interior, in combination with a mineral aggregate. She concluded that the entire statue, which was built up on a reed bundle armature, was made from a single material and that working the surface brought a thin layer of fine plaster to the surface, as is known to happen with the preparation of frescoes.

NAHAL HEMAR CAVE SCULPTURES

Finally, fragments of sculpture have been recovered from the PPNB Nahal Hemar Cave above the Dead Sea (Bar-Yosef 1985). One of these fragments has an eye modeled on the surface with asphalt, soft red ochre, and brilliant green particles of emerald-like dioptase (hydrous copper silicate, $CuSiO_3{\cdot}H_2O$; see below). A sample from about 5 mm below the surface of this fragment was found to consist completely of calcium carbonate, being a mixture of fine, crushed limestone used as an aggregate in a lime plaster matrix. A special feature of this sculpture and two other fragments examined is the use of vegetal fibers (FIG. 12) as a reinforcing additive to form a fiber-plaster matrix composite. Martha Goodway of the Conservation Analytical Laboratory, Smithsonian Institution, has determined that these fibers are wood fibers (TABLE 2). In one of the sculpture samples, the calcite filler material is in the form of small calcite crystals added to enhance the reflectance in a way similar to the beads described below.

Beads

In the material recovered from the Nahal Hemar Cave are some delightful beads (Bar-Yosef 1985). Some of these are wooden with a surface coating of plaster; others are modeled of plaster over a rod that has been withdrawn to leave a hole; and still others have been directly modeled over a piece of string or cord. We have examined the

Figure 10. A sculpture from the Pre-Pottery Neolithic B excavated by Garstang at Jericho (Garstang 1936). (Courtesy of the Palestine Exploration Fund.)

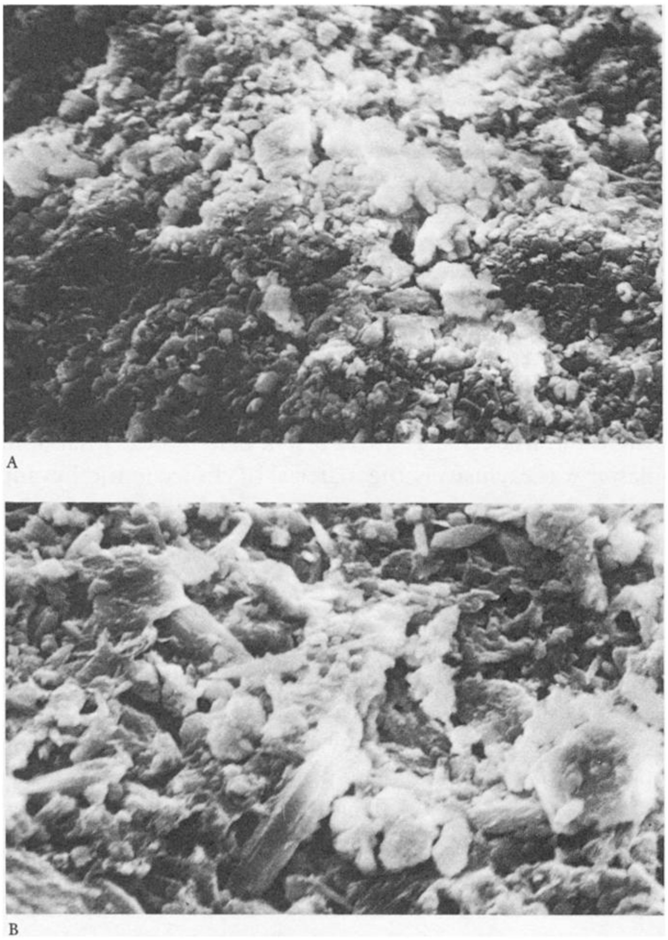


Figure 11. A) The surface layer of the Garstang Jericho sculpture consists of limestone particles bonded with a white lime plaster. B) About 5 mm below the surface the mixture is more heterogeneous, consisting of limestone fragments, quartz particles in clay, bonded with lime plaster.

Figure 12. Scanning electron micrograph of fibers used to strengthen the Nahal Hemar sculpture by forming a fiber-plaster matrix composite. Particles of lime plaster are seen adherent to the fibers (350×).

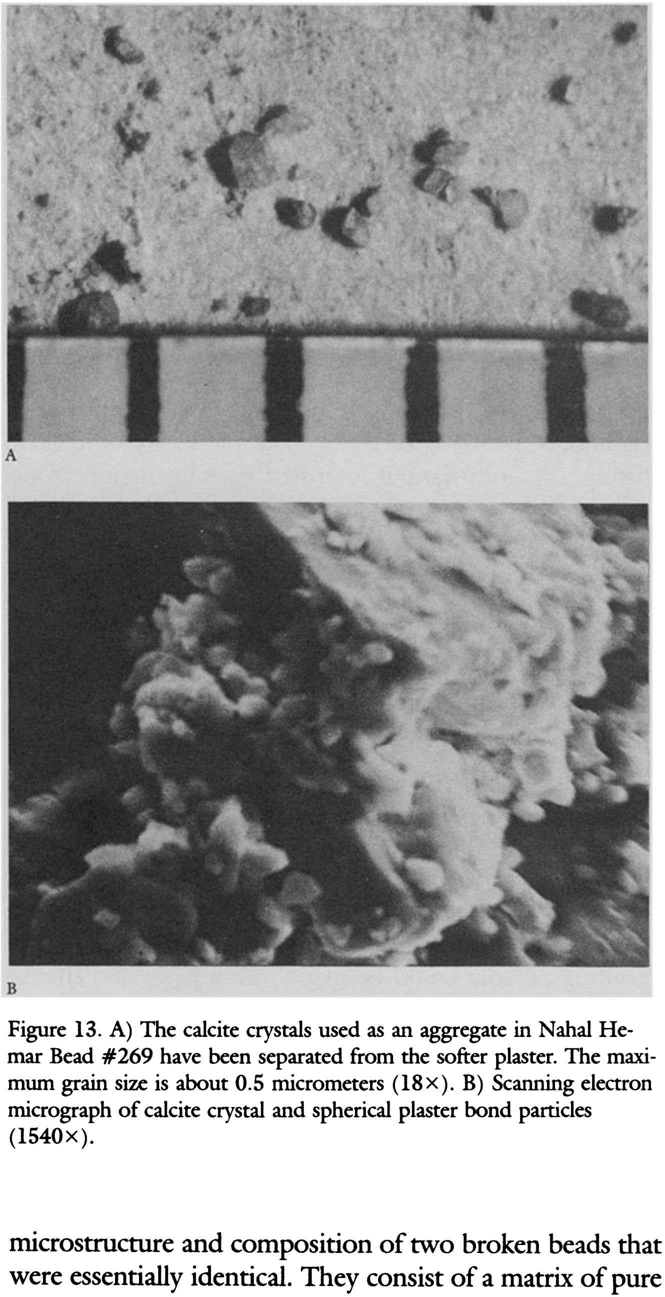


Figure 13. A) The calcite crystals used as an aggregate in Nahal Hemar Bead #269 have been separated from the softer plaster. The maximum grain size is about 0.5 micrometers (18×). B) Scanning electron micrograph of calcite crystal and spherical plaster bond particles (1540×).

microstructure and composition of two broken beads that were essentially identical. They consist of a matrix of pure lime plaster binding particles of translucent calcite (identified petrographically and by x-ray diffraction), which give a pleasing sparkle to the uncoated surfaces. The calcite grains are about 0.1–0.5 mm in size, as illustrated in Figure 13.

The surfaces of these beads were mostly coated with red ochre, emerald-green crystals, or with an asphalt layer coated with green crystals. The emerald-green crystals were identified petrographically and by x-ray diffraction as dioptase (a hydrated copper silicate, $CuSiO_3 \cdot H_2O$, which is a clear emerald green, but too soft for use in modern jewelry).

El Kowm Plasters

C. Maréchal (Maréchal 1982) has reported that gypsum plaster was used for floors, architectural discs and cones, Vaiselles Blanches, coatings on pottery vessels, a gaming board, and a figurine at El Kowm.

Discussion

Aside from the view that "we can regard as the hallmark of the period [PPNB] the fine lime-plastered floors, often laid on a gravel bed" (Mellaart 1975: 57), not much has been made of the role of plaster in the material culture of the Pre-Pottery Neolithic. This may be partly due to the friability of plaster objects; bits and pieces are difficult to distinguish from natural lumps of gypsum or limestone. Nevertheless, along with hunting, herding, and agriculture; making stone beads and vessels; working obsidian, flint, chert, wood and bone; and weaving and making mats and baskets, plaster production and use was a significant component of aceramic Neolithic life. Its place in, and influences on, that society and its evidences for or against conjectures about that society are worth pursuing.

Before the advent of plaster, materials such as wood, bone, flint, and stone had long been shaped by cutting, flaking, and abrasive polishing; heat treatment was used to affect the properties of these materials in such shaping methods; and fire was used for cooking. With plaster there was introduced a revolutionary pyrochemical industry in which rocks were *chemically altered* by fire such that the resulting powder could be made into a paste and shaped in the same way as natural clay. After shaping, the new form hardened into an artificial rock that could be of large expanse such as flooring, or of complex shapes such as sculpture, or with beautiful surface treatment as beads and jewelry. This was a whole new concept of material manipulation. The production of appreciable amounts of lime plaster was a multi-step process requiring selection of limestone free from impurities that cause "dead-burning"; heating for several hours to several days (depending on the amounts being fired) at a "bright" temperature of 800–900°C (a temperature equal to or greater than required for firing pottery, and maintained for much longer time periods); slaking with water and allowing to age; adding a suitable aggregate or "temper"; and then applying and shaping as a paste. Working of the surface by burnishing at the proper time to obtain local high pressures was required to obtain the best hardness and water resistance. Mixing of the plaster with tempering additives was necessary to improve strength and hardness and to optimize the ratio of benefits to the cost of manufacture measured as the energy, time, and materials required. The preparation and use of plaster was a widely-practiced, energy-intensive, labor-intensive, skilled activity.

Geographical Distribution, Techno-complex Areas, and Technology Diffusion

Plaster floors and objects are widely distributed in the Near East. If we distinguish between lime plaster and gypsum plaster distribution, as we must on the basis of their different technologies, we see quite clear "techno-complex" areas (Clarke 1968) as illustrated in Figure 14. At no site have both lime plaster and gypsum plaster artifacts been identified, but definitive data are sparse and we should probably be a bit careful (Maréchal 1982; Le Mière and Maréchal 1985). Present data indicate that lime plaster was exclusively the material of choice in the Levant and Anatolia; gypsum was the material of choice in the drainage area of the Tigris and Euphrates and further to the east.

These separate areas of lime plaster and gypsum plaster concentration are partly explained by the relative abundance of raw materials, and we might imagine that less abundant fuel in the lowlands was a factor. Lime and gypsum, however, are both widely distributed throughout the region. In sites with gypsum plaster there are limestone bowls; in sites with lime plaster there are alabaster bowls. In each site there is only one type of plaster making—either gypsum or lime—evidencing a continuing skilled, conservative tradition.[1] In contrast to the distributions of the *type* of plaster used, plaster vessel and container production (using lime plaster at some sites and gypsum plaster at other sites) is concentrated in a much smaller area of Syria and the Levant (Byblos, Tell Ramad, Tell Sukas, Ras Shamra, Abu Hureyra, El Kowm, Bouqras, Beidha, Nahal Hemar, 'Ain Ghazal) while not encountered in either Anatolia or Iraq. If these geographic techno-complex regions of technological interaction and commonality of plaster types and objects yielded different ceramic types they would probably be identified as different "cultural" areas.

We have demonstrated that plaster production in the Pre-Pottery Neolithic was, in the 7th millennium, a skilled craft that was both energy- and labor-intensive. What is more, the craft existed over areas that otherwise evince techno-complexes that are distinctive in technological repertories. How, we may ask, did this circumstance come to be? The *process* of technology diffusion is not part of the archaeological record, but there is a good deal of historical

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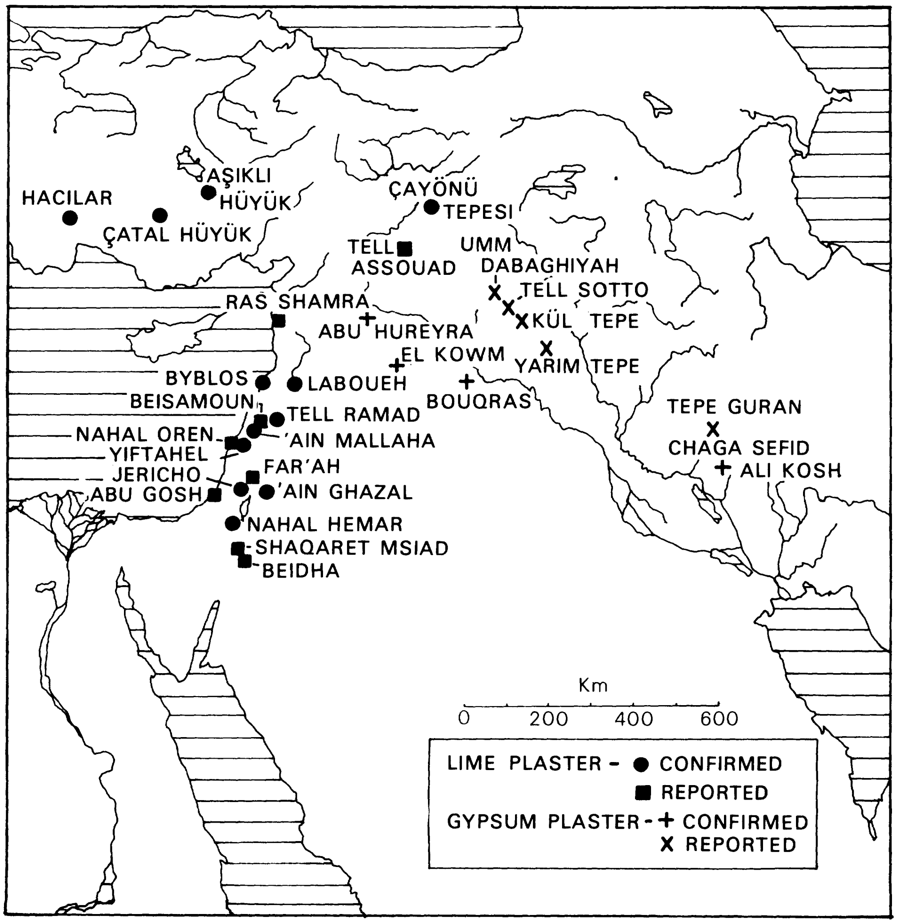
[1] The use of lime plaster as a cultural component and indicator is perhaps supported by the fact that its distribution roughly matches that of later dark, burnished ceramic ware of Anatolia, western Syria, and the northern Levant (Amuk A), which is largely absent in Iraq.

data that has recently attracted the interest of scholars and is highly pertinent for interpreting the archaeological record. Technology transfer is essentially a learning process. Case studies of technology transfer show that it is knowledgeable, capable people (Rogers 1971; Smith 1977; Ruttan and Hayami 1973; Jeremy 1981) who bring new technology into an active and receptive culture (Dorn 1979; Hacker 1977; Hughes 1962). These studies "confirm a humanistic appraisal of technology because they emphasize that technology is confined within men, not in the materials they use or the objects which their skills create" (Stapleton 1975: 317), a result also found in a detailed analysis of the American firearms industry (Smith 1977). Well-known examples in ceramic history are the late 16th-century movement of Korean potters to Japan as a result of the so-called Teabowl Wars of 1592–1598 (Cort 1986) and the diffusion of porcelain technology throughout Europe from Meissen in the 18th century (Kingery 1987). If this is so in literate societies, how much more so it must have been in prehistory.

The basis for this seems to be embedded in Polanyi's (1958) analysis of the importance of "tacit" knowledge in carrying out skilled activities; that is, "the premises of a skill cannot be discovered focally prior to its performance, nor even understood if explicitly stated by others" (Polanyi 1966: 87). Polanyi used the simple skill of riding a bicycle as an example. It is hard to imagine learning such a skill by studying the physical laws of centrifugal and centripetal forces or through written direction. A reviewer of an earlier draft of this report asked, "But what about these third millenia [sic] recipes for beer production, glass-making, and metal manufacture?" While they may be useful data for temple or palace records, administrative quality control and general interest, such *descriptions* of technical operations, like those of Pliny and Vitruvius in Roman times, Theophilus in medieval times, and Biringuccio and Agricola during the Renaissance are all incomplete and sometimes even misleading; they have never served to *direct* the activities of craftsmen, who themselves have been mostly illiterate.

Figure 14. Geographical distribution of lime plaster and gypsum plaster in the Pre-Pottery Neolithic.



We conclude that in the Pre-Pottery Neolithic there was social interchange and communication over wide regions fostered not only by migrant traders and prospectors, but also by the movement or relocation of apprentices or skilled craftsmen by exogamy or other social processes. That is, while extensive trading and mineral procurement networks, of which obsidian is the most studied, are known to have been in place during the Pre-Pottery Neolithic, trade mechanisms and the social interactions affecting skilled-craft production are quite different. Ethnographic sources suggest social processes such as exogamy that can lead to interaction and communication, but we agree with Childe (1946) and Trigger (1984) that historical data must be combined with archaeological data to interpret the actual processes that occur over long periods of time in ways not accessible to ethnographic study. As a result, we think that historical studies of technological process are entirely relevant in interpreting the archaeological record (and, for that matter, so are sociological studies of social and technological change; i.e., Hamblin, Jacobsen, and Miller 1973).

Intra-site and Site-to-Site Variations and Their Social Implications

Gourdin and Kingery (1975) calculated that the amount of limestone required to produce the plaster for the terrazzo floor of one room at Çayönü Tepesi (Braidwood et al. 1971) was about 4000 lb, and for the rooms of a house at Jericho more than 1000 lb. They commented that the quantities of material employed and temperature requirements indicate that lime production was an organized community effort. The trench at Jericho did not produce evidence of a complete house, but recently Garfinkel (1985) has excavated a complete structure at Yiftahel that has a plaster floor 17 m long × 7.5 m wide × 3–6 cm thick, with a total floor weight of about seven tons; another structure has an area about 8 m × 8 m, is 1–3 cm thick, and has a weight estimated at 1.6 tons (Garfinkel 1987a). Garfinkel contrasts these with 'Ain Ghazal (Rollefson and Suleiman 1983; Rollefson 1984, 1985), where floor thicknesses are recorded as having no plaster at all (12 floors), 2–3 cm (11 floors), 4–10 cm (32 floors), and 12–14 cm (seven floors). He quotes Kenyon's observation that some Jericho floors are unplastered, some are "good" or "excellent" plaster floors, and some are "unusually thick" plaster floors, noting that quantitative data are not supplied (Garfinkel 1987b) and concurs that an organized community effort is indicated. He proposes a social approach toward interpreting the plaster structures, questioning the possibility of a ranked society, labor employment, or labor specialization, and concludes that the nature and properties of plaster floors should receive more attention as indicators of social and economic phenomena and be more quantitatively described in future excavations. We agree.

While there do not seem to be available in accessible form quantitative data for the architectural use of plaster, there are some quite clear indicators. In the PPNB at Beidha many houses with plaster floors are 30 sq m or so, but there is one with a 63 sq-m burnished-plaster floor; some floors were unplastered (Kirkbride 1966a, b). At Munhata there is an area of plaster floors that extends over 200 sq m (Perrot 1964), and at Tell Ramad both houses and alleys have plaster floors (Contenson 1971). At Çatal Hüyük lime plaster floors were "occasionally used," but always occur in association with the numerous "shrine" areas (Mellaart 1967). At aceramic Hacilar the small rooms had mud plaster floors, while the larger ones had red, burnished-lime plaster floors (Mellaart 1970). At Aşikli Hüyük the small rooms had mud plaster floors and the larger ones red, burnished-lime plaster floors (Todd 1966). In contrast, at small village sites such at Jarmo, a village of not more than 20–30 houses, walls were of *pisé* construction with mud floors and no plaster (Braidwood, Howe, and Reed 1961). A pattern emerges in which there are intra-site and site-to-site variations in the use of plaster, ranging from small villages with mud floors covered with reed mats (as today) to larger towns with extensive use of plaster floors. More important rooms are covered with plaster floors, while less important areas were not; in some towns, almost all floors were of lime plaster. Plaster floor thickness and surface finish vary within any site. Where entire houses have been excavated, we find PPNB plaster floors as large as 63 sq m at Beidha, 90 sq m at Çayönü, and 110 and 64 sq m at Yiftahel, requiring processing of several tons of raw material for each floor.

As has been pointed out, the production of several tons of calcined limestone is not a trivial accomplishment. Since at least twice as much wood as limestone is required for the firing, ten or more tons of fuel would have been required for production of one house floor. To obtain the bright temperature (800–900°C) required, an efficient fuel such as wood and a crude furnace are necessary. To maintain a bright temperature for the 2–4 days required to produce necessary tonnage amounts, a long period of constant attention is needed. After slaking the lime, mixing with aggregate, and installation, the final step of burnishing and polishing such a large area requires substantial additional effort. Garfinkel (1987b) has emphasized that the only study available of floor thicknesses (at 'Ain Ghazal) found a wide variety. This circumstance suggests differential access to this resource within the community. Some of this variation, however, may result from added layers of plaster on older buildings; also, all the structures are not coeval. He suggested that there may have been a ranked society with some sort of exploitation of inferior status individuals or perhaps a system of labor employment with payment for services. Perhaps the existence of a class of specialized craftsmen may be indicated, but he thinks it unlikely that such a complex economy existed. In contrast, Redman suggests, "Village farming sites such as Jarmo, Beidha, Munhata, Ali Kosh, and Hassuna were probably all egalitarian tribal communities. There is no strong evidence for craft specialization, or for significant status or economic differentiation within these villages or between settlements" (Redman 1978: 205).

We have confirmed that lime plaster was in use at Epi-Paleolithic Lagama North, that there was a primitive lime-burning hearth at Epi-Paleolithic Hayonim Cave, and that there was architectural use of lime plaster at Natufian 'Ain Mallaha. By the PPNB, the knowledge of plaster production technology was widespread, and there were many plaster-floored towns such as Jericho, Beidha, Byblos, Hacilar, Çayönü, and Çatal Hüyük—whereas other contemporaneous sites such as Jarmo, Ganj Dareh, Ali Kosh, Can Hasan III, and Mersin XXXIII show little architectural use of plaster. Within plaster-using sites, the material was employed preferentially for certain structures. Different levels of sophistication (Schirmer 1983) and application thicknesses (Garfinkel 1987b) indicate that this was an unequally-distributed, labor-intensive, energy-intensive product.

Excavation data with regard to architectural plaster use is inadequate and is only one indication, not the best, of social organization. The towns with extensive plaster, however, are also ones with larger concentrations of rare and exotic trade items, areas devoted to specialized manufacturing activity as at Beidha, extensive development of cultic and shrine areas, carefully crafted sculptures, and a level of technical sophistication that reinforces the notion of skilled production and the non-egalitarian distribution of architectural plasters. The coeval existence of isolated egalitarian tribal villages and towns (with neighboring villages) having sophisticated craft development and fairly complex social and economic organization and differentiation during the PPNB is indicated.

Invention, Innovation, and Technology

The discovery of Epi-Paleolithic microliths bonded into a haft with lime plaster at Lagama North VIII dating to 12,000 B.C., lime plaster produced in modest amounts of Hayonim Cave ca. 10,400–10,000 B.C., and lime plaster used architecturally at the Natufian base camp at Eynan ('Ain Mallaha) ca. 9000 B.C. support the hypothesis that the invention of a new technology occurs long before its widespread adoption. Invention is essentially an individual achievement (e.g., Usher 1954) that will recur from time to time but only rarely becomes part of the archaeological record. Innovation brings an invention into technological practice and has usually been treated by economic theorists (Schumpeter 1934; Schmookler 1966; Fellner 1971) as involving both perceived utility and entrepreneurial action. Once adopted, a proven, safe, and reliable technology invariably becomes conservative and subsequent modifying innovations are gradual and incremental (Sahal 1981). This is perfectly rational and particularly true of complex technologies that are not well understood by their practitioners. In the case of lime plaster architecture and objects, widespread use, conservative technology, and modifying innovations developed by or during the 7th millennium. Doubtless a factor in these developments was the appearance of permanent architecture, which brought with it the desirability of a building material resistant to environmental weathering.

The development of a plaster-manufacturing technology was fairly rapid, and it was quickly adopted over a wide region. In this respect it is also characteristic of successful new technology in general and fits the model of a "self-catalyzed" chemical process; that is, initial adoption of a new style or a technique accelerates the rate of subsequent adoptions that occur at an increasingly rapid rate; positive feedback processes lead to a multiplier effect (Renfrew 1984). The labor- and energy-intensive use of tonnage quantities of plaster as an architectural material having a perceived utility, sufficient for the multiplier or autocatalytic effect to take hold and leading to a successful innovation and establishment of its manufacture, is difficult to imagine outside of towns with available surplus labor and social organization to direct its employment. Recent studies (Moore 1982) have pushed back the earlier stages of the "agricultural revolution" to the Epi-Paleolithic. By the 6th millennium agriculture and stock-breeding had become the principal, and often only, sources of subsistence. The skilled craft of plaster manufacture and the sophisticated applications of plaster discussed above, along with its architectural use in large quantities, are explicable only with the conjecture that the emergence of towns was accompanied by a modified social structure. Without such a hypothesis, the development of the craft and its applications remain virtually unexplainable.

Once plaster manufacturing technology emerged it was subject to a constant series of innovative modifications and improvements, each of which was small in itself but of substantial cumulative importance. One of these was the idea of adding a mineral tempering material to produce a concrete (e.g., a cemented aggregate) of greater strength at lesser cost. This led to the use of aggregate materials having aesthetic, as well as practical, utility. One sees this in the terrazzo floor at Çayönü and, in a different context, in the use of crystalline calcite grains in the jewelry beads from Nahal Hemar.

A further innovation was the use of fiber reinforcement, seen in the Nahal Hemar sculpture—equivalent in every respect to modern-day fiber-reinforced plastics and the forerunner or follower of fiber-reinforced *pisé* and mud brick manufacture. This concept of composite construction was also evidenced in the plaster-coated, coiled-cord containers found at Nahal Hemar and the later lime-plaster ceramic composite vessels from Byblos. One of the most striking aspects of this idea of composite construction was the applied coating of emerald-like dioptase crystals on the surface of plaster beads.

The use of tempering aggregates and fibrous reinforcements markedly improves the mechanical properties of plaster. Use of the same techniques with clays is different in that clays require additives to avoid shrinkage cracks during drying as well as to improve dry strength. No one seems to have commented on the fact that the large "mud bricks" from Jericho and Ganj Dareh do not display shrinkage cracks as might have been expected. It is probable that the very high lime content of the "mud" brick and its relatively low clay content are the reasons these defects are lacking, defects absent also in the interior of Jericho sculpture. Although the relationship of mud-brick compositions to the use of straw-fiber reinforcement has not been studied, it may be related to the later development of fired pottery technology; when large wares are made, the drying process is a barrier more critical than the problems of firing.

Finally, we come to the sculptural technology, which required several innovations. One was the use of a tied bundle of reeds as an armature for the overlying sculpture and a way of providing rigidity to the initial plaster or marly clay paste, an innovative concept that is connected with other innovations centered around the idea of composite material utilization. Then, we find that the underlying material was chiefly a high-lime clay having good dry strength and low drying shrinkage. The same mineral mixture was used for mud brick. Entire sculptures of this material would have a dull surface, be subject to moisture erosion, and have low hardness and poor polish. As a result, in the near-surface layer slaked lime was added to the mixture to increase the dry strength and speed the drying process, much as it was used at Proto-Elamite Anshan (Iran), ca. 3200–2800 B.C. (Blackman 1982) and as it is used today for stucco construction. The influence of lime as a soil stabilizer is well known and such a use is extensively practiced in modern engineering (Boynton 1980). As the final step, white plaster containing an aggregate of fine sand or limestone fragments was prepared and applied as a more-or-less thin coating on the surface. The smooth, hard, white surface thus produced was suitable for sculpture or more often was used as a ground for subsequent painting. The general construction method of the sculpture is isomorphous with the gravel-base plaster-surface architecture. The process of optimizing the construction method and materials for sculpture was essentially identical to modern practice. It provides strong support for the view of a complex technology practiced within a society having some level of emergent craft specialization.

Many authors have commented that the first ceramic vessels from this area are characterized by such a high level of quality that the technology must have been imported. All the inventive and innovative requirements for ceramic manufacture, however, were already present within the preceding, widespread plaster technology. Firing procedures for lime plaster were more stringent than for pottery—requiring longer heating at about the same temperature. The use of mineral tempering additives and fibrous vegetal additives was practiced. The use of slip coatings and of ochre red and manganese black paints were accomplished techniques. The use of burnishing leather-hard material to form a hard, smooth, more impermeable surface was well known. The widespread appearance of pottery vessels should be considered, like that of plaster manufacture, an "auto-catalytic" or "multiplier effect" phenomenon for which the rate-limiting factor was social choice, not technical capability. In assessing the emergence of ceramics we remember that the earliest ceramic vessels (the oft-repeated invention) are found in "pre-pottery" levels at many different and widely separated sites (Saxon 1976) and that early pottery had neither strength nor impermeability superior to the materials it displaced. We believe the most likely reasons for the widespread adoption of ceramics were social changes engendered by the transformation to agriculture and stock-breeding as the only source of subsistence (Moore 1982). This would have led to a decreased cultural role for all modes of gathering. There was a growth of settlement size to a point where previously-used competing materials—suitable wood, basketry materials, soft and easily-carved stone—were less available in the immediate vicinity. As a result, pottery production was faster and more fuel-efficient than in the past. There also would have been associated changes in food storage and preparation. Thus, manufacture of pottery vessels became a more cost-effective alternative for these societies.

Occasional metals were smelted in the 7th millennium (Wertime 1973, 1975). During smelting rocks are *chemically altered* by fire as in plaster manufacture—and as in the later 7th-millennium pottery production of red and black, iron-containing pottery decoration. As with pottery, the concepts and tools necessary for metal manufacture were in hand in a continuing pyrochemical tradition long before widespread use (Renfrew 1984).

Summary

Using modern materials-science techniques necessary to characterize plaster materials and their processing, we have evaluated the nature and uses of lime and gypsum plasters in the Pre-Pottery Neolithic (ca. 7200–6000 B.C.). We find that the initial "invention" and use of these materials can be traced back at least to the Epi-Paleolithic Geometric Kebaran (ca. 12,000 B.C.) and the architectural use to the Natufian (10,300–8500 B.C.). Plaster-manufacturing technology rapidly spread through the changing societies of the 7th millennium Pre-Pottery Neolithic B.

The production of lime plaster is a multi-step process requiring extensive heating of limestone at 800–900°C, slaking, mixing with various additives, shaping and smoothing a paste in a skilled way, adding a slip layer, and often polishing or burnishing. It is a labor- and energy-intensive skilled craft activity. The geographical distribution of lime and gypsum plaster indicates technological, and perhaps even technologist, interchange over wide regions. There are distinct techno-complex areas, however, in which lime or gypsum plaster was preferred and another distinct area where whiteware and other gypsum or lime-plaster vessels were produced. The different distributions of plaster use and vessel production illustrate the difficulty of applying ideas of "bounded" cultural regions. Intra-site and inter-site data are less than adequate, but they indicate in concert a coeval existence of egalitarian villages and more socially-complex towns in which there was at least incipient craft specialization during the PPNB.

Neolithic plaster technology is a classic case of the separation of invention of a technique from the innovation of wide social acceptance and technological production. Once begun, the plaster industry underwent rapid development and further innovations such as mineral aggregate additions, use with surface slips, burnishing, application as beads, use for containers and sculpture, fiber reinforcement, and composite material developments. PPNB sculpture techniques developed to a point equivalent to those used today, and must be seen within the framework of craft specialization. Plaster innovations supplied the requirements for metal smelting and provided all the technology necessary for, and set the stage for, the subsequent adoption of pottery as a major industry in the ceramic Neolithic.

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