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To cite this version:

Marie Agnès Courty, Valentine Roux. Identification of wheel throwing on the basis of ceramic surface features and microfabrics. Journal of Archaeological Science, 1995, 22 (1), pp.17-50. 10.1016/S0305-4403(95)80161-8 . hal-01570037

HAL Id: hal-01570037
https://hal.science/hal-01570037

Submitted on 14 Feb 2019

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Journal of Archaeological Science (1995) **22**, 17–50

Identification of Wheel Throwing on the basis of Ceramic Surface Features and Microfabrics

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(*Received 28 June 1993, revised manuscript accepted 3 May 1994*)

Wheel throwing has long been identified in archaeology on the basis of specific surface features as well as internal diagnostic structures detected by radiographic techniques. On the basis of an experimental study, this paper proposes to re-examine the criteria of ceramic forming processes. Interpretation of the physical reaction of clay to hydric and mechanical stress helps to show the relationship between microfabrics and ceramic forming processes. Integrated analysis of surface features and microfabrics allows us to distinguish wheel throwing from wheel shaping of coil-built roughouts and gives us information that we can apply to a study of 3rd millennium archaeological materials from Mesopotamia, Iran and India. Our preliminary conclusions suggest that the 3rd millennium vessels, usually considered as wheel thrown, were initially formed by coiling and then shaped on a wheel.

Keywords: CERAMIC, WHEEL THROWING, MICROFABRICS, SURFACE FEATURE, PROTOHISTORY.

Introduction

Although there are differences of opinion concerning the date of the emergence of the wheel throwing technique, it is generally agreed that by the second half of the 3rd millennium this technique was commonly practised in Mesopotamia, the Indus Valley and Central Asia (see for example Blackman, Stein & Vandiver, 1993; Childe, 1954; Jarrige & Hassan, 1989; Johnston, 1977; Rieth, 1960; Sajko, 1982; Wright, 1989). Wheel throwing is associated with the process of urbanization, mass production and craft specialization. The skills required for this technique are difficult to learn and one can argue that their mastery cannot be acquired by each domestic group in a community, as is the case for handbuilding techniques (coiling, slab building, pinching, drawing, moulding) (Roux & Corbetta, 1989).

A series of surface features as well as microfabrics, listed as significant for the recognition of wheel throwing (Balfet, 1953; Shepard, 1956; Rye, 1981; Balfet, Fauvet-Berthelot & Monzon, 1983), have been applied by archaeologists. However, as several authors have pointed out (van der Leeuw, 1976; Rice 1987; Rye, 1981), these characteristics can be produced with forming techniques other than wheel throwing. It is therefore necessary to find surface features and microfabrics which are found exclusively in vessels made by wheel throwing.

For this purpose, we propose a multidisciplinary approach which involves both ethnoarchaeologists and soil specialists. On the basis of ethnographic as well as experimental data, surface features and microfabrics are studied so as to bring out attributes characteristic of particular ceramic forming techniques and methods. These attributes, applied to archaeological material, will enable us to distinguish the forming techniques and methods used in production. Preliminary results applied to 3rd millennium ceramics show that the approach leads to a reappraisal of our technological analysis of pottery and has direct repercussions on our archaeological constructs.

Commentary on Previous Investigations of Surface Features

Surface features usually taken into account for recognizing wheel throwing are the following:

1. The presence of striations and undulating ridges and grooves (rilling) running around the interior or exterior (or both) of the vessel walls, axial symmetry, regulatory of the wall thickness at a given height, regular thinning of the wall thickness from

0305-4403/95/010017+34 $08.00/0

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the base towards the top (Rye, 1981; Balfet, Fauvet-Berthelot & Monzon, 1983);
2. Concentric striations on the undersides of the vessel bases (Rye, 1981; Balfet, Fauvet-Berthelot & Monzon, 1983);
3. Ripples (oblique wrinkles) on the inner walls due to compression operations while narrowing the neck (collaring operation) or the base (Buson & Vidale, 1983);
4. Specific modes of fracture (spiral, helicoïdal) corresponding to stress imposed by wheel throwing (Balfet, Fauvet-Berthelot & Monzon, 1983; van der Leeuw, 1976: 245; Mery, 1991: 105);
5. Vertical fractures displaying a herringbone pattern due to the ascending movement of the clay; the pattern is visible with the naked eye (Balfet, 1953; Balfet, Fauvet-Berthelot & Monzon, 1983).

These different surface features have been observed on wheel-thrown ceramics. However, two points must be taken into account before these characteristics can be accepted as clear evidence of wheel throwing:

(a) Surface features can be polysemic, i.e. they can be the result of different forming processes. Thus, Rice (1987: 134) notes that rilling can be produced by wheel throwing as well as by the rotation of handbuilt volumes on tournettes;
(b) Surface features produced by final shaping operations can obliterate totally the ones produced during the first forming stages. Thus, as noted by van der Leeuw (1976: 123), ascending spiral striations can be due to a final treatment of a pot which has been handbuilt without any wheel at all.

Ethnographic examples and experiments demonstrate the validity of these two points. Several examples illustrate the problems with the first group of surface features. In a forming sequence practised from Burma to Japan, the body is first fashioned by coiling, then thinned by beating and then shaped on a wheel (Nakazato, 1979). The result is a pot whose surface features are identical to those observed on wheel-thrown pots. Another example comes from an experiment conducted in India in which the body was first fashioned by coiling, then thinned and shaped on a wheel (Figure 1). The result is a pot whose surface features obliterate the first step in the sequence, i.e. fashioning of the basic volume by coiling.

Concentric striations on the undersides of the vessel bases do not indicate wheel throwing, but the use of a rotational movement: they are caused by removing the vessel with a string while the wheel, or the turntable, is still moving; this operation is independent of the mode of forming.

Ripples on the inner vessel walls are due to compression when external pressures are applied to the pot revolving on the wheel (or turntable) during a final shaping operation for narrowing the neck or the base. Ripples do not occur during the first steps of the forming sequence, but only in the final stage of shaping a pot. Therefore, they cannot be significant of the mode of forming.

The mode of fracture of ceramics is an extremely complex problem, involving several factors so interconnected that it is not possible at the moment to identify a type of fracture which could be characteristic of a particular mode of forming. Van der Leeuw notes the following factors (1976: 245): "(A) the manner in which the vessel fell (or was hit), (B) the place of the impact, (C) tensions in the body . . . (D) weak spots or zones succumb easier than solid ones"; and the shapes, each of them having "its own tendencies when it breaks" (1976: 309).

The herringbone pattern visible in section is explained as the consequence of the ascending movement of the clay. However, this pattern has also been observed on non wheel-thrown pots, especially near the rims.

Other criteria, considered as indicative of modes of forming, are sometimes used by archaeologists less explicitly. One of these is "a series of aligned shallow fractures and ridges" (Rice, 1987: 137) perpendicular to the diameter of the pot. These fractures and ridges are supposed to correspond to marks left by the edge of a scraping tool while the pot is moving rapidly, i.e. while turning. In fact, such marks depend on two factors: dryness of the clay and position of the tool while scraping. They can be obtained without any rotative device, as has been shown in experimentation.

Another criterion is the shape of the rim: if the rim shape is complex, it is thought to indicate wheel throwing. However, the technique for fashioning the rim is not necessarily related to the technique for fashioning the body. The body can be handbuilt whereas the rim can be wheel shaped.

Previous Investigations of Internal Structures

Bordet & Courtois (1967) were among the first authors to suggest that the different pottery forming techniques are characterized by specific internal structures observed in thin section. They assumed that pinched and drawn pottery would not show a preferential orientation of particles, unlike coil-built pottery which is characterized by zones with a preferential orientation, surrounded by non-oriented zones. These authors described a specific microfabric for wheel-thrown vessels formed by an homogeneous "fluidal" structure.

Investigations reported by Rye (1977) confirmed that the different ceramic operations, such as coiling, drawing, beating or wheel throwing, can be distinguished by specific orientation of detrital grains incorporated in the clay and by the orientation of air voids. Rye (1977) interpreted the arrangement patterns of ceramics to reflect significant differences in mechanical pressures applied to the clay for the various fabrication procedures. This author advised the use of

Figure 1. Experiment conducted in India with the potter Har Kishan. The basic volume has been made by coiling. Put on the wheel, coils are joined by gestures parallel to coils while the wheel rotates very slowly. The shaping is done on the wheel. The result is a pot whose surface features are similar to the ones produced by wheel throwing.

radiographic techniques for identifying orientation of asymmetrically shaped grains and voids which are not clearly recognized by a visual inspection. Radiographic techniques have since been used by several authors to obtain an image of large fragments of ceramic vessels in order to reveal the technique and sequence of manufacture (Vandiver, 1987; Carr, 1990; Carr & Riddick, 1990; Vandiver *et al.*, 1991). Joins between elements, particle and void distribution, orientation and shape, fracture patterns and paste texture have been shown to be clearly visible on radiographic images and to be specific to some pottery forming operations (Table 1; Vandiver, 1987; Carr, 1990). According to Carr (1990), the spatial resolution of radiographic techniques would make it possible to observe particles only down to silt size (62·5 μm), although Vandiver *et al.* (1991) have stated that a spatial resolution of 2–5 μm can be obtained by using high resolution film radiography. These authors have, however, insisted on the reduction of the theoretical high spatial resolution of X-ray sources because their limit of penetration is proportional to the average density of the fabric. Moreover, the difficulty in distinguishing light mineral inclusions from voids is known to make the interpretation of radiographic images ambiguous (McGovern, 1989).

Rye (1977) did not encourage study of clay microstructures, which he considered to be destroyed by firing in most cases. The use of thin sections was also not recommended because only a small part of the vessel can be imaged. Carr (1990) suggested that the last steps of making a pot may modify the clay arrangement produced by initial forming stages.

Rye (1981) has outlined the complexity of the factors that influence the plasticity of clay, such as water content, electric charge of clay platelets, texture and mineralogy of clay. However, he argued that clay texture and mineral content do not affect internal structures significantly. Distribution patterns of asymmetrical grains considered to be significant of some ceramic forming techniques have therefore been identified by studying vessels prepared from a variety of raw materials (Carr, 1990).

The process of making pottery has been described mechanically as plastic deformation controlled by compressive, tensile and shear forces (Rye, 1977). Ceramic structural patterns have, however, not been thoroughly explained in terms of these specific mechanical stresses. Rye (1981) suggested that a detailed study of the interrelationships between the clay and the coarse inclusions, expressed in terms of mathematical parameters, should provide a more objective basis to the study of ceramic technology.

Methodology

Pottery making is first described and analysed in order to identify and interpret structural changes and surface modifications for each step of the manufacturing sequence. Specific experimental data are then presented so as to investigate thoroughly two parameters: the physical constraints (mechanical and hydric) and the mineralogy of clay.

Ceramic manufacturing process

(1) *Extraction and preparation of the clay.* Raw materials can be collected from a variety of deposit sites such as flood plain and karst, where clay-rich sediments and soils are widely available. Selection of the clay may depend on its quality, although ethnographic studies suggest that cultural factors may also influence selection of raw materials (Rye, 1977; Rice, 1987). Complexity of deposits in alluvial basins and karstic systems often induces marked lateral variability in mineralogical and textural properties of clay-rich sediments. Kneading will make clay more homogeneous and will tend to erase the complex nature of raw materials. Texture of raw materials, especially the amount of coarse particles, is often further modified by clay preparation operations: drying, crushing, grinding, sieving, winnowing or decanting (Arnold, Neff & Bishop, 1991). Addition of organic or mineral temper, incorporation of specific chemical constituents, and mixing with organic matter followed by ageing is often performed to increase clay workability and reduce shrinkage during drying (Rice, 1987). Wedging and kneading are carried out to eliminate large air bubbles and provide a uniform distribution of fine air bubbles, coarse particles and moisture (Rice, 1987).

(2) *The forming methods and techniques.* Several authors (Rye & Evans, 1976; Rice, 1987) note that vessels are frequently manufactured in separate stages by some combinations of different construction techniques. In archaeology, such combinations have been identified on big jars (Dales & Kenoyer, 1986), but rarely on other types of vessel.

In fact, *the method* of making a pot is a complex sequence of activity which involves phases, stages and operations, each of which can be achieved through different techniques. Three main forming phases should be considered: fashioning of the body (lower part, upper part), of the orifice (neck and rim) and of the base. The fashioning of the body can be divided into two stages: the forming of the roughout and of the preform:

Roughout: hollow volume which does not present the final geometrical characteristics of the pot. A roughout is usually obtained by thinning operations.
Preform: a pot with its final geometrical characteristics but whose surface has not been subjected (or will not be) to finishing techniques. A preform is obtained by shaping a roughout. As far as we know, only one forming sequence does not distinguish between roughout and preform, the one involved in moulding according to which the preform is obtained at once.

Each of the different phases and stages here mentioned can comprise different operations (e.g. the throwing of a roughout comprises several thinning operations).

Techniques involved in forming phases, stages and operations relate to physical modalities according to which clay is fashioned. These modalities can be described on the basis of the following three parameters:

Table 1. Microfabrics proposed for identifying forming techniques. Integrated from: (1) Rye, 1977; (2) Rye, 1981; (3) Vandiver, 1987; (4) Carr, 1990

Forming technique	Cross-section of body wall	Normal view of body wall	Normal view of base and other criteria
Coiling	no preferred orientation, random (2) (4)	parallel sub-horizontal preferred orientation (1) (4), inclusions oriented perfectly along the centres of coils (2), elongation and alignment of pores but less consistently than in a thrown vessel (3)	spiral or circular orientation (1) (4), separation often visible along coils (3)
Drawing	unlikely to be observable (2), weakly parallel to tandem (4)	weakly vertical to vertical (2) (4)	random to weakly radiating (4)
Moulding	parallel to weakly (4), random if pressure was light (2), less porosity on the side applied on the mould (3)	random (3) (4)	random (4), often fracture visible between parts moulded separately (1)
Pinching	generally weakly parallel (2) (4)	random (4), similar to beating but without sign of compaction (2)	random (4)
Slab building	parallel (2) (4), laminar fractures occur if strong pressure was used in forming slabs (2)	random (2) (4)	random (4), often fracture visible along junction between slabs (2)
Beating	voids flattened and perfectly parallel to the walls (2), characteristic laminar fracture (1) (2), strong compression of the fabric	random, star shaped cracks around large mineral inclusions (1)	not discussed
Turntable (slow wheel)	lowered porosity at joins, alignment of pores (3)	inclusions and porosity aligned and inclined in a steeper direction than the external finger traces if high force is applied on the clay wall (3)	not discussed
Throwing	parallel (1) (2) (4)	slanted (4), horizontal to weakly diagonal alignment of inclusions and pores (2) (3). The rapidity of the lifting action may be reflected by the angle which inclusions take to horizontal (1)	spiral orientation (2) (4)

- the source of energy
- the type of pressure
- the clay mass onto which the pressures are exerted.

There are two main sources of energy involved in the forming of ceramics:

- the pressure of the fingers/hands.
- the pressure of the fingers/hands combined with rotational kinetic energy.

Often, the kinetic energy is improperly assigned to the centrifugal force. Centrifugal force is, by definition, normal to the axis of rotation and therefore cannot produce an ascending movement of particles. The kinetic energy depends on the moment of inertia and on the angular velocity of the wheel/turntable. Both turntable and wheel have a kinetic energy when they are in motion. These two devices present, however, basic differences related to the amount of rotational kinetic energy necessary for throwing pots. The wheel device, whatever the type (stickwheel or kickwheel), presents a moment of inertia sufficient for the rotational motion to resist friction of the finger/hand pressure necessary for centring, hollowing and thinning a mass of clay. This empirical observation can be clarified by reference to basic physical principles that have established a direct relationship between the importance of the moment of inertia and the slowing down of the device for a given pressure. On the other hand, turntables do not provide kinetic energy sufficient for the rotational motion to resist friction of the pressures necessary for centring, hollowing and thinning a mass of clay.

Pressures on clay are always exerted by hands/fingers on both sides of the clay wall. They consist of two main types:

- Discontinuous pressures. The pressures are applied successively to the clay. They are not combined with kinetic energy, but can be exerted with a slow rotative movement. The beating technique is a specific example of discontinuous pressures exerted, with a tool, on a roughout made with or without the help of rotational kinetic energy.
- Continuous pressures. The pressures are continuously applied during the rotational movement (minimum one wheel revolution). They are always combined with rotational kinetic energy and generally relate to wheel throwing. Applied on roughouts made without rotational kinetic energy, they are used in shaping preforms on the wheel. Continuous pressures are also used in fashioning operations which do not use a rotative device, the rotational movement being operated, for example, by the potter walking around the pot (orbiting technique).

A roughout can be homogeneous when formed out of a mass of clay or heterogeneous when formed out of assembled elements:

- Mass of clay. The mass is flattened or hollowed according to the objective: preparing a flat element for making a base or for moulding purposes, forming a hollow volume, etc. Continuous pressures exerted on a mass of clay and combined with rotational kinetic energy are used in throwing a roughout on the wheel. Discontinuous pressures exerted on a mass of clay without rotational kinetic energy are used in techniques such as modelling (pinching, drawing).
- Assembled elements. Distinct elements (coils, slabs) are assembled for making a roughout. Continuous pressures exerted with rotational kinetic energy on each distinct element are met with thinning of coils (e.g. fashioning big jars). Discontinuous pressures exerted without rotational kinetic energy on assembled elements are met with coiling, slab building, etc.

On the basis of the parameter "rotational kinetic energy" we can distinguish two broad families of techniques. The two other parameters, "type of pressures" and "clay mass", enable us to define subfamilies. In Figure 2, each fashioning stage includes only one operation. As a matter of fact, each stage can comprise several operations which can be achieved according to different techniques. For example, shaping a preform can be done first by beating (paddling), i.e. without rotative kinetic energy, and second by wheel shaping, i.e. with rotative kinetic energy (e.g. Tataki ceramics, Nakasato, 1979). Wheel throwing corresponds specifically to the fashioning of a roughout by continuous pressures combined with rotational kinetic energy on a mass of clay. Such a use of the rotational kinetic energy reflects a totally original concept in ceramic forming techniques. In this regard, wheel throwing has to be clearly distinguished from wheel shaping combined with handbuilding techniques. Wheel shaping uses kinetic energy only in order to thin and/or shape a volume obtained originally without kinetic energy (e.g. ethnographic examples in Spain, Crete, Croatia, Burma, Japan, The Philippines, etc.). Wheel throwing and wheel shaping are distinct from other modes of fashioning not only on the basis of the use of kinetic energy in fashioning clay, but also on the basis of the specific motor skills required. These skills are the same for wheel throwing and wheel shaping. They contrast, by their complexity, with the skills involved in modelling techniques, i.e. those without rotative kinetic energy (Roux & Corbetta, 1989).

(3) *The finishing techniques.* The finishing techniques can take place immediately after the forming sequence or after a drying stage, depending on the nature of the operations. Specific finishing techniques such as those associated with glazed wares are not here considered. One can distinguish two main operations of finishing:

- operations which transform superficially the outline of the wall (e.g. scraping, turning). (Finishing

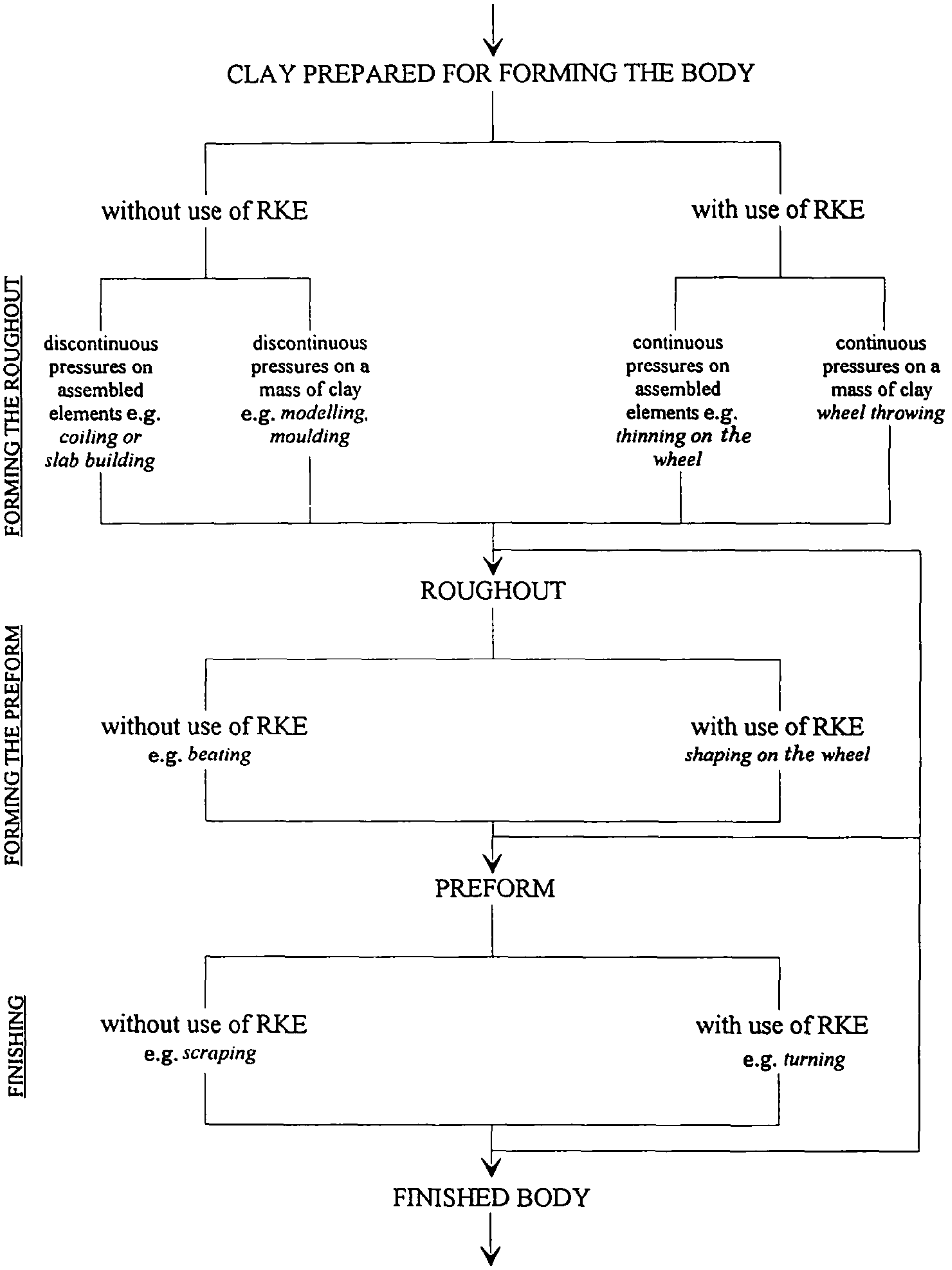

Figure 2. Classification tree of ceramic forming techniques. RKE is the abbreviation for rotative kinetic energy.

operations are distinguished from shaping operations according to the degree of transformation of the wall);

- operations which transform the surface "state" of the wall (e.g. smoothing, polishing, burnishing, slip, painting).

These operations can be made with or without the help of rotational movement or kinetic energy.

(4) *Drying.* Two operations of drying are distinguished:

- drying clay pots as a necessary operation before firing,
- drying clay pots to obtain a leather hard consistency which will enable shaping or finishing operations such as beating, scraping, etc.

According to the technical operation, drying is done at different stages of the forming sequence (e.g. either before or after shaping the preform).

(5) *Firing.* Firing techniques and type of kilns are various, but not closely related to forming techniques.

Table 2. List of the tests conducted in India in order to bring out stigma characteristic of families of techniques. RKE is the abbreviation for rotational kinetic energy

Tests	Roughout thinning	Preform shaping	Finishing (smoothing)
1	without RKE on clay mass (moulding)		without RKE
2	without RKE on clay mass (moulding)		with RKE
3	without RKE on assembled elements	without RKE	without RKE
4	without RKE on assembled elements	without RKE	with RKE
5	without RKE on assembled elements	with RKE	with RKE
6	with RKE on clay mass	with RKE	with RKE
7	with RKE on clay mass	without RKE (beating)	—

Experimental procedure

Two experimental procedures were adopted, each corresponding to a distinct objective.

Procedure A. A wide variety of forming techniques were considered for a well-defined mineralogical type of clay. The objective was to bring out empirical laws on the mechanical and hydric behaviour of a specific clay material, taking into account different forming techniques. In order to investigate the physical constraints imposed by the various families of techniques, a controlled series of tests was designed so that a single parameter varied at a time (Table 2). The accumulation and diversification of tests will enable us to determine the traits which differentiate among the techniques. The tests were conducted in Uttam Nagar (suburb of New Delhi, India), with one potter and his wife. The potter, Har Kishan, specializes in wheel throwing, whereas his wife specializes in coil building. The tests focused on the different methods and techniques for fashioning the body (bases were made at the same time as roughouts, necks and lips at the same time as preforms). The clay was prepared by Har Kishan from clays of different origin. Materials were soaked, stirred and then decanted and sieved to eliminate the largest impurities.

Procedure B. Ceramics made from a variety of mineralogical types of clay were studied (Table 3). The study of clay variability, although not systematic, highlights the general value of the empirical laws brought out in procedure A. In order to investigate the clay mineralogy parameter, pots were collected from various countries: France (Paris), India (New Delhi, Orissa), Africa (Mali), The Philippines (Leyte, Cebu, Ilo Ilo islands). For each pot, the forming methods and techniques are known (Table 3).

Methods of Analyses

Surface features

A close examination of the morphology and the co-occurrence of surface features was conducted in order to discover attributes characteristic of a given forming technique. The response of clay to the specific constraints of the forming method may help to explain these characteristics. The analysis of surface features presented in this study is based on sherds from procedure A, excluding sherds from tests 1 and 2 (moulded ceramics). They were excluded since they do not present the surface features usually taken into account to recognize wheel throwing.

Microfabrics

Basic principles for microfabric analysis. Analysis of ceramic microfabrics focuses on the plastic deformations of clay materials that are interpreted with the help of the empirical and theoretical knowledge of soil mechanics. Like ceramics, soil materials usually consist of a complex arrangement of various structural units that comprise aggregates, micro-aggregates, crystallites, domains and quasi-crystals (Tessier & Quirk, 1979; Tessier, 1984). Hydric and mechanical stresses induce considerable changes which can be investigated at all levels of structural organization (Tessier, 1990). Because the small size of clay particles is beyond resolution of the naked eye (Tovey, 1986), study of clay microfabrics and arrangement of basic particles is traditionally performed by using microscopic and submicroscopic techniques. Individual fine particles cannot be directly observed in thin sections for two main reasons: (1) the resolution power of the light microscope, and (2) the relative thickness of the section. Interference colours of the fine mass studied between crossed polarizers, however, can provide information on orientation and distribution patterns of anisotropic clay minerals, what is called in soil micromorphology the birefringence fabric of the fine material. When the fine mass is composed dominantly of clay, a random arrangement of equidimensional or slightly prolate speckles of oriented clay, smaller than the observable fabric unit, has a speckled birefringence fabric (Bullock *et al.*, 1985: 91). Elongated birefringent zones or streaks that are built up by the juxtaposition of smaller, more or less parallel arranged domains of oriented clay particles have a striated birefringence fabric (Bullock *et al.*, 1985: 91). A preferred parallel orientation of the whole clay mass has a strial

Table 3. Experimental study, main characteristics of the clay materials and ceramic forming operations

Location	Clay texture	Clay mineralogy	Coarse fraction	Ceramic forming operations	
				Roughout	Preform
Mali A (Africa)	fine (0–5 μm) Fe oxides	kaolinite (smectite)	200–400 μm 10–40% chaff temper	without RKE lower part: moulding upper part: coiling	without RKE, beating
Mali B (Africa)	fine (0–5 μm) Fe oxides	smectite (kaolinite)	200–400 μm 10–40% chaff temper	without RKE lower part: moulding upper part: coiling	without RKE, beating
Danao-Cebu (Philippines)	medium (0–10 μm)	smectite kaolinite Fe oxides (carbonates)	400 μm 40%	without RKE lump modelling	without RKE, beating
Leyte (Tanaun) (Philippines)	coarse (0–20 μm)	kaolinite smectite (illite) Fe oxides	200–400 μm 20%	without RKE lump modelling	with RKE, shaping on turntable
Ilo Ilo (Philippines)	medium (0–10 μm)	kaolinite smectite Fe oxides	200 μm 30%	without RKE lump modelling	with RKE, shaping on turntable
Orissa Baripada (India)	very coarse (0–30 μm)	illite (kaolinite) Fe oxides	30–150 μm 20%	with RKE wheel throwing	without RKE, wheel throwing
Orissa Puri (India)	medium (0–10 μm)	smectite (kaolinite) Fe oxides	50–200 μm 15%	with RKE wheel throwing	with RKE, wheel throwing
Orissa Bhubaneshwar (India)	medium (0–10 μm)	smectite illite Fe oxides	50–150 μm 15%	with RKE wheel throwing	with RKE, wheel throwing
Paris Material A	fine (0–5 μm)	smectite illite	80–150 μm 30%	(a) with RKE, wheel throwing (b) without RKE, coiling	(a) with RKE, wheel throwing (b) with RKE, shaping on turntable
Paris Material B	fine (0–5 μm)	illite (smectite) calcitic silt	30–150 μm rare	(a) with RKE, wheel throwing (b) without RKE, lump modelling	(a) with RKE, wheel throwing (b) with RKE, shaping on turntable
Delhi	coarse (0–20 μm)	illite, smectite, interstratified illite/vermiculite, kaolinite mixed with a pure smectite	80–150 μm 10%	various tests (cf. Table 2)	

birefringence fabric. Observation of clay-rich aggregates under the scanning electron microscope (SEM) provides better resolution, which allows for the identification of the geometrical arrangement of clay domains and coarse particles from zones that are not larger than a few square micrometres in size. Visual identifications are often completed by physical measurement of pore size distribution (Bruand & Tessier, 1987) and by low angle X-ray scattering to examine the assemblage of crystals and of elementary silicate sheets within basic particles (Tessier, 1990). Similarly to soil materials, most of the deformations produced by successive ceramic forming operations take place when clay is in a plastic state. A plastic state is defined by the property of a body to deform progressively when under stress without returning to its original form when the pressure is released. The interparticular porosity of clay materials is saturated because of the presence of a continuous water film around platy-shaped clay particles, while larger pores are not saturated with water. The reduced adherence between particles allows them to slide on each other while cohesion is maintained by electrostatic forces (Azzaoui, 1988). Compression stress results in clay particles aligned normal to the major compressive stress, while shear stress results in clay particles aligned along the direction of shear (Kirby & Blunden, 1991). Rearrangement of a particular clay at a given stress state will, however, depend on material texture, solution electrolytic composition, stress ratio or material energetic history (Kirby & Blunden, 1991). Moreover, structural changes of clay materials at a given stress are directly related to their mineralogical characteristics (Azzaoui, 1988). The specific behaviour of the different pure clay mineralogical species is well known from experimental investigations (Tessier, 1990). However, it is difficult to extrapolate from these investigations to understanding clay deformations during ceramic forming operations due to the complex composition of deposits. Two main groups are generally distinguished: illite and kaolinite, formed of separate particles, are highly sensitive to stresses; smectite, characterized by a lattice structure, is of moderate to low sensitivity (Tessier, 1984). The zero electric charge of pure kaolinite clay platelets greatly weakens electrostatic cohesion favourable to a parallel rearrangement of clay particles under hydric or mechanical stress. Cohesion forces are also weakened for illite, generally packed in the form of micro-clay domains (Tessier & Quirk, 1979). The micro-clay illitic domains will consequently display a parallel arrangement under hydric or mechanical stress. Smectite clay is formed of quasi-crystals that can be seen as a system of stacked layers which will slide against each other less easily because of the considerable extension of contact surfaces (Tessier, 1984; Delage, 1987).

Clay materials used for ceramic production often have a high content of fine silt-size particles that may consist of mica flakes, especially when source materials are derived from flood plain deposits, or of calcite particles. Abundance of rigid fine silt-size mica grains induces the same mechanical behaviour as coarse kaolinite with formation of a preferential parallel arrangement under hydric or mechanical stress (Tessier, pers. comm.). Abundance of sand-grade particles, by increasing the rigidity of the clay, may greatly constrain its mechanical deformations (Delage, 1987). The mechanical behaviour of carbonate-rich materials is more complex, depending upon the interactive forces between carbonate grains and clay particles (Delage, 1987).

Observation tools. Visual identification of ceramic features from freshly cut sections of ceramics with the naked eye and through the binocular microscope has been combined with the study under the petrographic microscope of thin sections made from different parts of the vessels and study of ceramic sections at the submicroscopic level with the SEM. Microscopic observations have been complemented by the study of selected samples through tests taking physical measurements of the very fine porous system. At this stage of the investigations, observation of cross-sections perpendicular to the wall surface in the plane which is parallel to the vessel height have been preferred, as they allow the specific effect of normal, shear and stretching stresses on clay arrangement to be simultaneously observed. However, cross-sections tangential to the clay walls can also be used to interpret deformation of the clay materials under physical constraints (Gibson & Woods, 1990; Pierret, 1994). The study has been greatly facilitated by the excellent preservation observed in most cases of the microstructural patterns of ceramics, not only in plain polarized light (PPL) but also in crossed polarized light (XPL) in which a birefringence fabric similar to the ones of soils can be described, according to Bullock *et al.* (1985). As previously suggested (Rye, 1977), firing effects may, however, partially or totally obliterate the original clay fabrics, especially for carbonate-rich clay materials, because of the masking effect induced by carbonate alteration during firing (Tite & Maniatis, 1975; Maniatis & Tite, 1981). In this case, orientation patterns of pores and coarse particles, when present, may help to identify the type of deformation.

Preliminary conclusions on the complementary use of radiographic analysis for studying microstructure of the same experimental materials (Pierret, 1994) are not reported here. Our choice was first to focus on high resolution techniques in order to understand mechanical deformation of clay during forming operations.

Results and Interpretation

Surface features

We will mention here two surface features which appear to be characteristic attributes, i.e. able to differentiate wheel throwing from wheel shaping of coil-built roughouts.

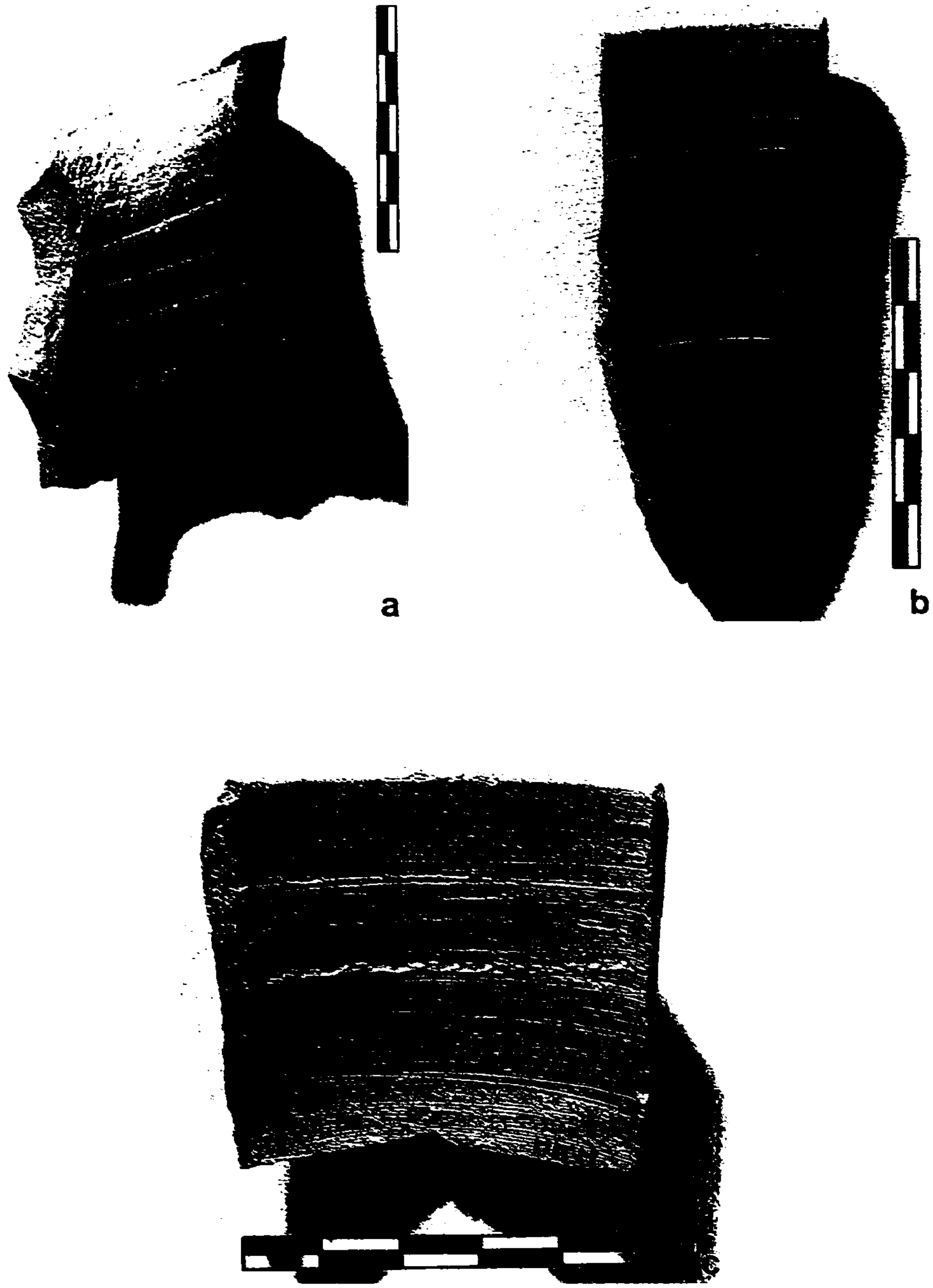

Figure 3. Experimental material. Grooves obtained while wheel shaping roughouts made either by throwing or coiling: (a) nail prints (b, c) impurity prints. Scale bar is in cm.

Grooves (Figures 3 & 4). Grooves usually designate the dips between ridges that one can observe on wheel-thrown pots. The grooves which are of particular interest are elongated fine parallel hollows running around the interior of a vessel: they are combined with parallel striations. The morphologies of grooves, their location and relation to other surface features allow us to differentiate (Table 4) grooves obtained while shaping a pot on the wheel (whatever the technique for building the roughout, Figure 3) and grooves that are characteristic of joins of coils (Figure 4). In the first case, grooves are obtained by dragging along an impurity or by finger nails while shaping on the wheel. Grooves corresponding to impurities (Figures 3(b) & (c)) present angular edges whose outlines are more or less sharp and regular depending on the shape of the impurity, flat surface in between, rectilinear trajectory and no preferential location on walls. Grooves corresponding to nail prints (Figure 3(a)) present rounded edges, with a raised surface in between, rectilinear trajectory and no preferential location on walls. In the second case, joining of the coils has not been made

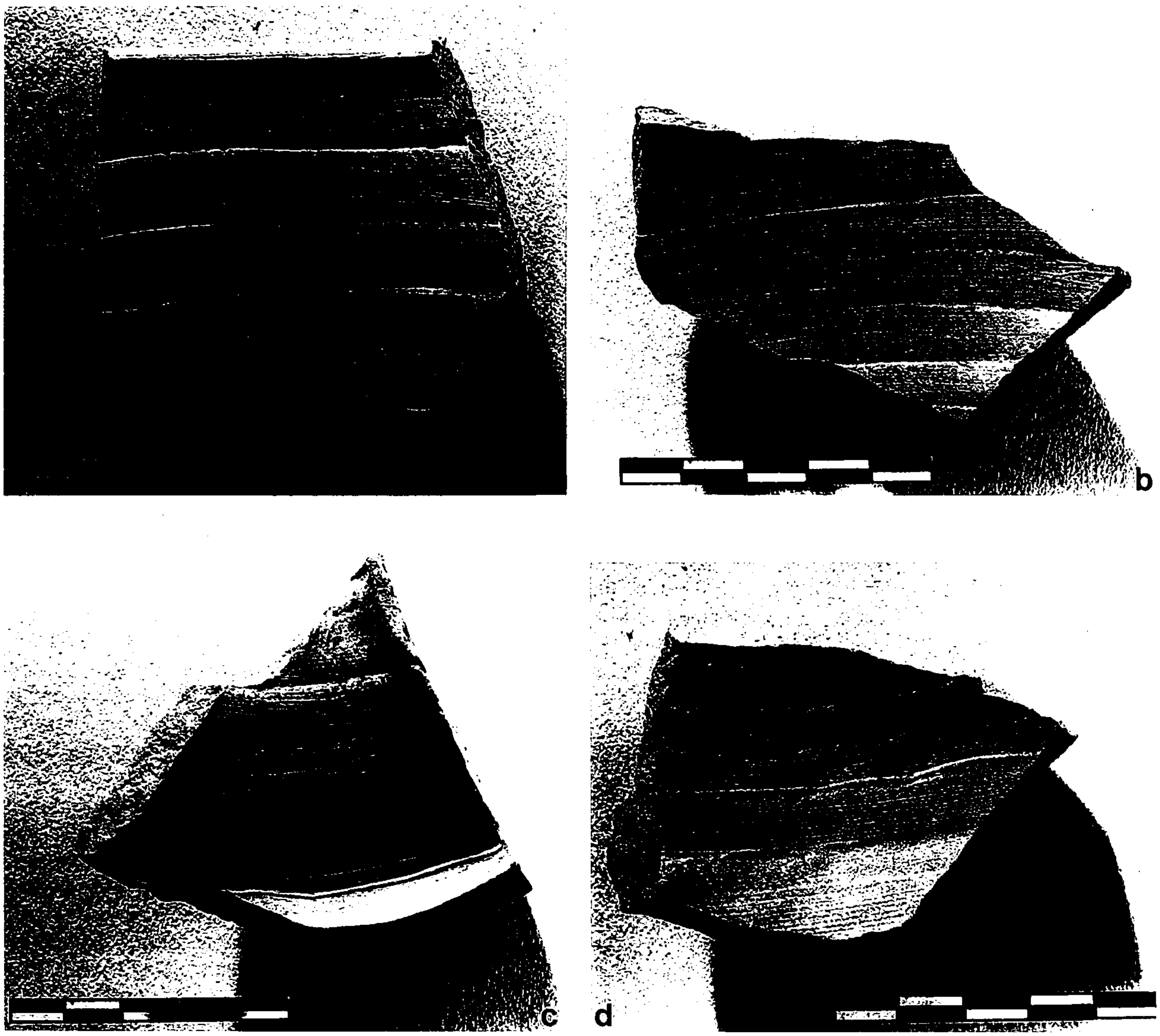

Figure 4. Experimental material. Grooves corresponding (a, b) to joins of coils left visible and (c, d) to compressed joins of coils. Scale bar is in cm.

by vertical or oblique gestures, but by continuous pressures parallel to the coils. When joins of coils have been left more or less visible depending on the thoroughness of shaping (Figure 4(a) & (b)), grooves present rounded edges, possible fissures, raised surface in between, no rectilinear trajectory, no preferential location on walls. When joins of coils have become visible under compressional operations (Figure 4(c) & (d)), grooves present rounded or angular edges whose outlines are more or less irregular, raised surface in between, no rectilinear trajectory, preferential location (zones of compression), crossing ripples of compression. These compressional operations narrow the neck or the base by outer pressures combined with rotative kinetic energy. The surface features of coil-built rough-outs shaped on the wheel (Table 4) could not be reproduced experimentally by wheel throwing alone.

Rilling (Figure 5). Rilling is defined as "the spiral ridges or striations around the interior or exterior surface of a vessel thrown on wheel formed by finger pressures in 'lifting' the clay; also called throwing marks" (Rice, 1987: 481). Rilling is usually associated with wheel throwing. However, rilling can present a different morphology in relationship with various forming techniques:

(A) Rilling on wheel-thrown ceramics (Figure 5(a)). Uneven rilling is considered here. It presents ridges which can be prominent "bands", noticeable on the interior and exterior of the walls. Their edges are irregular, with "clay barbs", which correspond to the clay falling out after rising. The spaces between alternate ridges are not homogeneous and are often filled with clay droplets.

Table 4. Attributes of grooves which distinguish between those obtained while wheel shaping, whatever the forming technique of the roughout, and the ones that are characteristic of joins of coils

Shaping operations	Mode of formation	Edges	Surface in between grooves	Trajectory	Location on walls	Ripples of compression	Fissures on grooves
Wheel thrown or coiled roughouts shaped on wheel	Dragging impurity (Figure 3(b) & (c))	—angular —outlines more or less sharp and regular depending on the shape of the impurity	not raised	rectilinear	not preferential	—	—
	nail prints (Figure 3(a))	rounded	raised	rectilinear	not preferential	—	—
Coiled roughouts shaped on wheel	joins of coils left visible (Figure 4(a) & (b))	rounded	raised	not rectilinear	not preferential	—	possible
	compressed joins (Figure 4(c) & (d))	—rounded or angular —outlines more or less irregular	raised	not rectilinear	preferential (zones of compression)	common	—

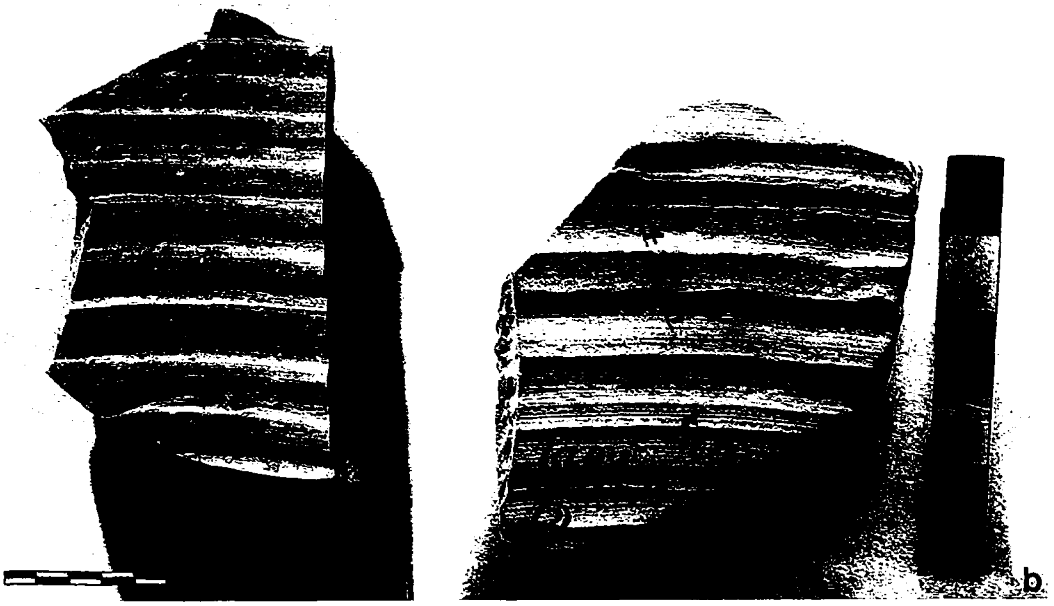

Figure 5. Rilling: (a) rilling corresponding to a rapidly wheel-thrown pot, (b) rilling corresponding to a coil not properly levelled (pre-Harappan vessel from Kalibangan). Scale bar is in cm.

This type of rilling is typical of rapid lifting of the clay through more or less symmetrical pressures while throwing. As a matter of fact, no rilling appears when the pressures applied onto the clay wall are perfectly symmetrical and of regular strength while slowly lifting the clay. The faster the rising of the clay, the more uneven is the rilling. Even rilling is not characteristic of wheel throwing in the sense that it can be obtained while wheel shaping, whatever the forming technique of the roughout.

(B) Rilling on ceramics whose roughouts have been formed by coiling (archaeological example in Figure 5(b)). Ridges are prominent bands without any clay barbs or irregular dips, often visible on only one side of the wall. Here, the rilling is not caused by a fast rising of the clay, but by the presence of coils of different thickness which have not been levelled. According to our ethnographic observations, such surface features are never encountered with wheel throwing. Moreover, they could not be reproduced by throwing.

Other attributes, currently under study, which should provide information about forming technique include:

- *Cracks* (Figure 6(a)). They are never found on coil-built roughouts shaped on the wheel, but they are extremely common on wheel-thrown pots. These cracks could be the result of the high quantity of water necessarily added with wheel throwing. Their random distribution, their dentritic morphology and the fact that they appear on ceramics thrown rapidly suggest that they may develop because of the heterogeneous hydration of the clay mass.
- *Compression undulations* (Figure 6(b)). These are distinct from ripples and seem to be more common with the coiling technique combined with wheel shaping operations. It could be due to a phenomenon of differential hydration within the clay mass. This hypothesis is supported by the fact that compression undulations have been observed on wheel-thrown pots made of clay that shrank rapidly in hot weather.

In conclusion, it is essential to distinguish between base, orifice and body. Only the body of a vessel is relevant for determining the mode of forming. The significant surface features are usually the results of the potter's "awkwardness". Consequently, numerous body sherds have to be examined in order to come across significant surface features.

Microfabrics

Procedure A. Observation under the binocular microscope of perpendicular sections from all the ceramics made from the same clay (illite clay mixed with a minor proportion of smectite) using a variety of techniques reveals three main types of meso-scale microstructure that differ by their density, degree of homogeneity and morphology of large voids (Table 5). These three types are better defined at a higher level of organization through the microscopic observation of thin sections and under the SEM by the orientation of coarse size inclusions, the fine porosity pattern and characteristics

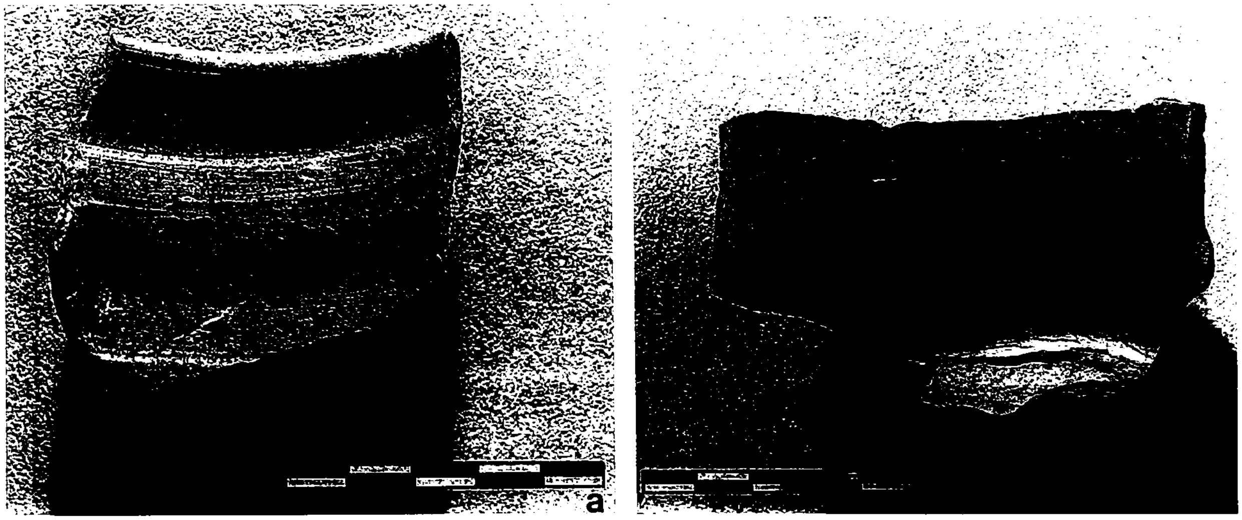

Figure 6. (a) Cracks distributed at random on a wheel-thrown pot (from Uttam Nagar, India). (b) Compression undulations on a pot whose roughout has been made by coiling. These undulations seem to be more common on coil-built roughouts shaped on the wheel than on wheel-thrown pots. Scale bar is in cm.

of the fine mass fabrics which help to distinguish a few subtypes (Table 5).

(A) Microfabrics of wheel-thrown ceramics. Wheel-thrown ceramics (type I1a, Table 5) generally present a random orientation and distribution of the coarse grain fraction, and the occurrence of elongated vesicular pores (Figure 7(a)) which become predominantly parallel to the clay walls near the rim. Clay domains and fine silt-size inclusions generally do not present a subparallel alignment to the clay walls but appear to be finely imbricated and randomly distributed (Figure 7(b) & (c)). At medium magnification, this results in a speckled birefringence fabric. Detailed observation at higher magnification reveals the existence of two sets of small birefringent streaks of oriented clay, not perpendicular to each other, but regularly distributed, that are observed when the stage of the light microscope is rotated under crossed polarizers. Under SEM this fabric appears to be formed by the intersection of a few micrometre size stacks of clay domains that are densely compacted and have a face to face contact (Figure 7(d)). Coarse grains are finely embedded within the stacks of clay domains (Figure 7(d)). The compacted and oriented clay domains delineate stacks of more open clay domains of random orientation (face to face, face to edge and edge to edge). Discontinuous zones with a broadly subparallel orientation to the ceramic walls of assymmetrical coarse grains, such as micas, and well-elongated large vesicular pores are often observed and appear to be finely imbricated in random orientated zones (Figure 7(e)). The subparallel orientation of clay domains and silt-size inclusions is more clearly visible near the rim and is often associated with fine fissuration subparallel to the clay walls. Zones with subparallel orientation display a parallel striated birefringent fabric of the fine mass that results in an edge to edge alignment of clay domains and fine silt-size micas (Figure 7(f)). Under SEM these zones appear to be predominantly formed of densely compacted stacks of parallel clay domains (Figure 8(a)).

At medium magnification, pottery thrown rapidly on the wheel (type I2) displays an irregular discontinuous network of fine fissures, a random orientation of coarse grains (Figure 8(b)) and a common occurrence of large size aggregates which give a heterogeneous aspect to the fine mass. At higher magnification (Figure 8(c)) and under the SEM (Figure 8(d)), the fine mass consists of irregularly sized stacks of clay domains, with no preferential orientation and with a high internal porosity, that are mixed with randomly oriented fine silt-size particles. The random orientation of clay domains and silt-size inclusions is reflected by a predominant random birefringent fabric.

Beating of the wheel-thrown roughout results in an increased density of the fine mass and vesicular pores aligned almost parallel to the clay walls. Fine subparallel alignment of the fine mass is only observed in the surficial zone of the clay walls, whereas the internal structure shows the same orientation pattern of clay domains and coarse grains as in non-beaten wheel-thrown roughouts.

(B) Microfabrics of coil-built ceramics. In thin sections, coil-built ceramics (type II1, Table 5) differ from wheel thrown ones by the clearly discernable elongated shape of vesicular pores (Figure 9(a)) and occurrence of structural discontinuities at a centimetric interval (Figure 9(b)). The latter are generally characterized by an abrupt contact of diagonal direction between zones

Table 5. Summary of the main diagnostic attributes characteristic of ceramic forming operations

Forming operations	Microfabric type	Microstructure	Asymetrical sands and coarse silt	Porosity	Fine mass fabric
Wheel-thrown normal Smectite-illite clays	IIa	very dense, homogeneous	random orientation	rare parallel, elongated large vesicles, randomly oriented, fine pores	regular network of oriented medium size clay domains; coarse cross-striated b-fabric, common subparallel striated clay domains related to shear stress
Wheel-thrown normal Coarse sand-rich clays	IIb	very dense, homogeneous	random orientation	occasional elongated vesicules	dense regular network of oriented large size clay domains; coarse cross-striated b-fabric, rare subparallel striated clay domains related to shear stress
Wheel-thrown normal Illite clays with micaceous fine silt	IIc	very dense, homogeneous	random orientation	rare random oriented fine pores	regular network of oriented very small size clay domains; very fine cross-striated b-fabric, very common subparallel striated clay domains related to shear stress
Wheel-thrown rapid Smectite-illite clays	I2	less dense, slightly heterogeneous	random orientation	subparallel large fissures, randomly oriented fine fissures	random network of clay domains mosaic speckled b-fabric
Coiled shaped on wheel Smectite-illite clays	II1	very dense, heterogeneous, regularly spaced structural discontinuities	random to subparallel orientation	oblique long fissures or elongated long vesicles along coil joins	two fabrics juxtaposed: (a) random or twisted with a mosaic speckled b-fabric and mammilated voids (b) subparallel alignment of clay domains with a subparallel striated b-fabric and subparallel fine fissures related to tensile stress
Coiled shaped on wheel Illitic clays with micaceous fine silt or kaolinite rich clays	II2	dense, heterogeneous, regularly spaced structural discontinuities	random to subparallel orientation	regular network of subparallel large to fine fissures	subparallel alignment of clay domains with a subparallel striated b-fabric related to tensile stress
Modelled	III	irregular density, irregular heterogeneity	subparallel orientation	subparallel elongated vesicles, regular network of subparallel large to fine fissures	common subparallel alignment of large size clay domains related to tensile stress

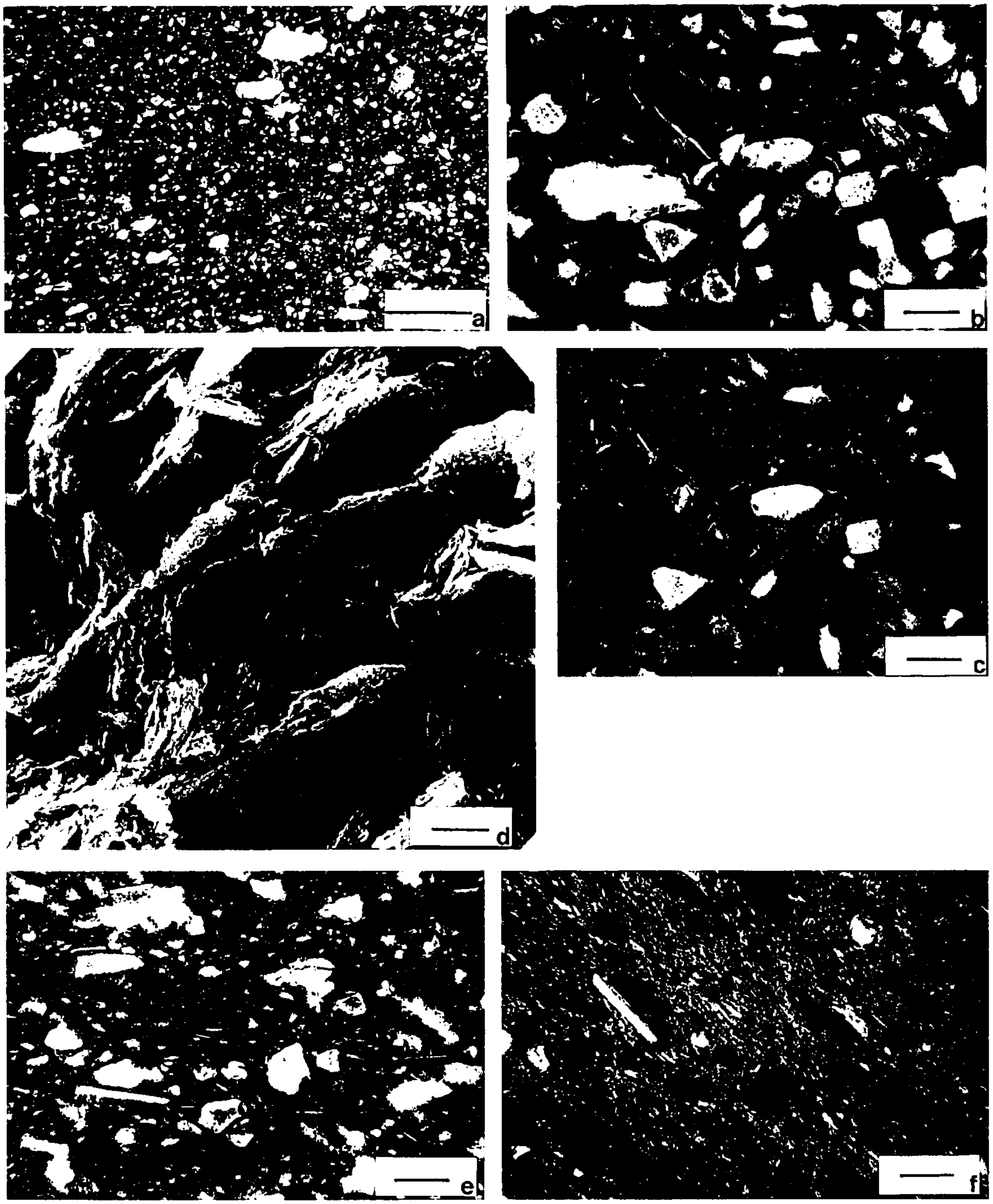

Figure 7. Experimental protocol A, wheel-thrown ceramics. (a) Low magnification showing the dense fabric, the random orientation of coarse grains and the slight elongation of the few vesicular pores. (b) Higher magnification, plane polarized light: random orientation of the coarse grains and of the very fine fissures at the boundary between coarse grains and the clay mass. (c) Same view as (b), cross polarized light showing some of the birefringent streaks (the whole birefringent pattern is detected from a full rotation of the stage). (d) Close view under SEM showing the geometrical intersection of two stacks of oriented and densely packed clay domains that delineate stacks of more open clay domains of random orientation. (e) Subparallel orientation of the vesicular pores and of the asymmetrically shaped grains observed in small zones, seen in plane polarized light. (f) Same view in cross polarized light after a 45° stage rotation to show the parallel striated birefringent fabric of the fine mass. Scale bar: (a) 1 mm; (b, c, e, f) 100 μm; (c) 2 μm.

formed by a dense packing of large size aggregates of random internal orientation (Figure 9(d)) and zones with a subparallel fine fissuration (Figure 9(c)). Long fissures and elongated vesicular pores, with a diagonal direction to the clay walls, are sometimes observed at the contact between the two structural zones (Figure 9(b)). These structural discontinuities correspond to the joins between adjacent coils. At higher

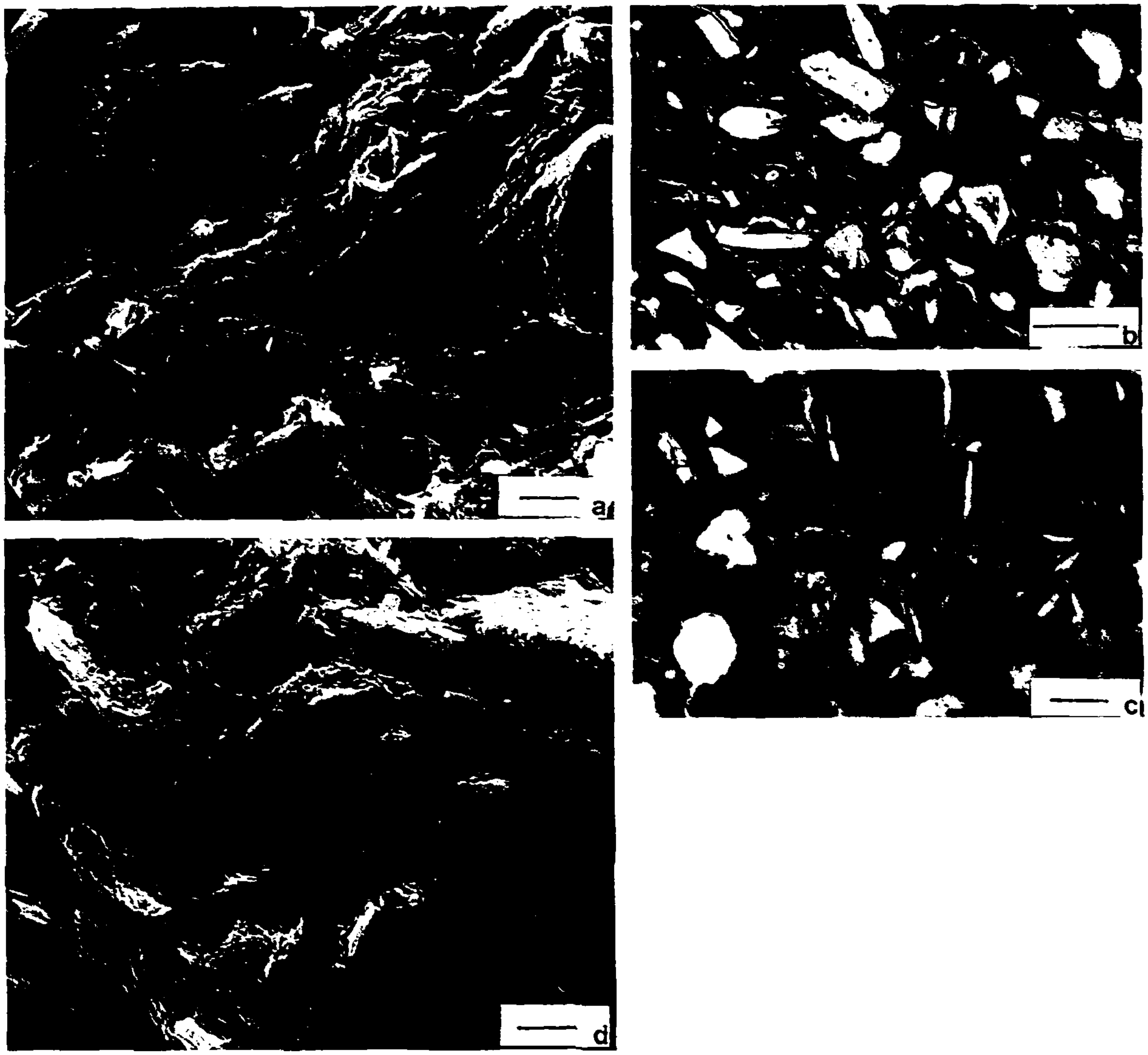

Figure 8. Wheel-thrown ceramics (continuation). (a) Close view under the SEM showing the dense subparallel alignment of clay domains from the small zones seen in Figure 7(e). (b) Fine fissuration network of a wheel-thrown ceramic formed rapidly on the wheel, plane polarized light. (c) Higher magnification of (b) in plane polarized light showing random orientation of clay domains, very fine fissures and the coarse grains. (d) Close view under SEM showing absence of preferential orientation and fine imbrication of irregularly sized stacks of clay domains and silt-size inclusions. Scale bar: (a) 3 µm; (b, c) 1 mm; (d) 5 µm.

magnification, the dense zones (Figure 10(a)) are composed of small size, randomly oriented clay domains and have a speckled birefringence fabric (Figure 10(b)). Under SEM, dense packing, the random distribution of clay domains and the absence of specific orientation-patterns of clay domains around coarse sand grains (Figure 10(e)) stand out even more distinctly. On the contrary, zones with a subparallel fine fissuration display a well-delineated subparallel alignment of clay domains, silt-size inclusions (Figure 10(c)) and birefringent streaks (Figure 10(d)).

Wheel shaping a coil-built roughout on a wheel obliterates structural discontinuities between coils but does not significantly modify the internal arrangement of clay domains and coarse grains.

(C) Microfabrics of moulded ceramics (press moulded). At medium magnification, moulded ceramics (type III, Table 5) differ from coil-built and wheel-thrown ceramics by the common occurrence of large size aggregates and more abundant fine fissures and vesicular pores that display a preferential subparallel alignment to the clay walls (Figure 11(a)). At higher magnification, the fine mass shows a regular subparallel orientation of clay domains, silt-size inclusions and mica coarse grains (Figure 11(b)), with a subparallel striated birefringence fabric. SEM observations reveal that the subparallel alignment results from an irregular edge to edge contact of small size clay domains whereas no preferential orientation of clay domains is observed around coarse grains (Figure

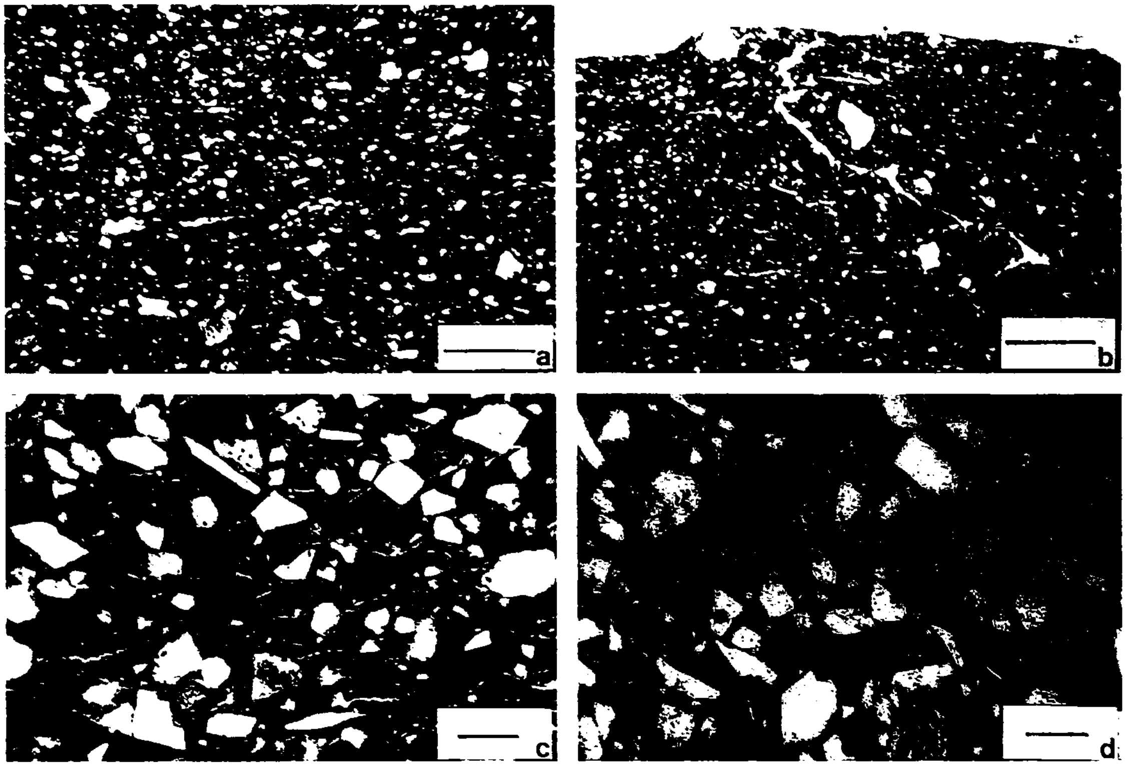

Figure 9. Procedure A, coil-built ceramics. (a) Dense homogeneous internal fabric at low magnification. (b) Structural discontinuity at a join between two coils marked by a fissural network. (c) Regular network of subparallel fine fissues in the zones reorganized by tensile stress. (d) Microfabric of the inner part of the coil with a very dense internal structure and random orientation of clay domains and coarse inclusions. Scale bar: 1 mm.

11(c)). Long subparallel fissures develop throughout the fine mass independently from the poorly oriented clay domains (Figure 11(c)).

Discussion. Comparison of these observations suggests that the three roughout forming techniques studied differ by microfabrics that are specific of mechanical and hydric stress exerted on the clay mass. Microscopic and submicroscopic observations, however, indicate that in all cases studied, deformation has produced structural changes at the level of micrometre-size clay domains. Physical measurement of the porosity shows that wheel-thrown, coil-built and moulded ceramics present a similar size distribution of the very fine porosity domains (Figure 12). This suggests that the amount of energy has never been sufficient to induce reorganization at the level of quasi crystals or clay platelets. Size distribution of the very fine porosity domains is thus suggested to be a characteristic of the raw material not of the forming technique. The greatest structural reorganization is always observed for wheel-thrown ceramics where the regular network of oriented coarse-size clay domains indicates influence of shear stress on the whole plastic clay mass during formation of the roughout. Homogeneity of the deformation observed suggests that the water content was high enough to reduce cohesion forces between clay domains which could move very easily to form an extremely dense edifice. The rare occurrence of microfissures suggests that homogeneous incorporation of water into the clay mass minimizes the effects of tensile stress. The striated birefringent fabrics seem to result from shear failures that would form locally along zones where hydric pressures were high. The very high water content would have considerably reduced cohesion forces between clay domains and fine silt inclusions that would easily realign along a direction approximately parallel to the pressure exerted. The well-developed face to face contact between clay domains and the fine embedment of silt grains indicate that this local reorganization corresponds to a plastic flow deformation.

The stronger development of microfissures found in the rapidly wheel-thrown ceramics suggests a more heterogeneous incorporation of water into the clay mass. Microfissures are interpreted as having developed during drying along discontinuous shear failures that would have formed during wheel throwing because of an increased hydric pressure. In this specific case, heterogeneity of the whole clay mass and random orientation of clay domains indicate a lower degree of reorganization that is tentatively assigned to the rapid throwing of the clay walls.

Pressures of the fingers/hands seem to be responsible for a deformation of the rare vesicular pores which

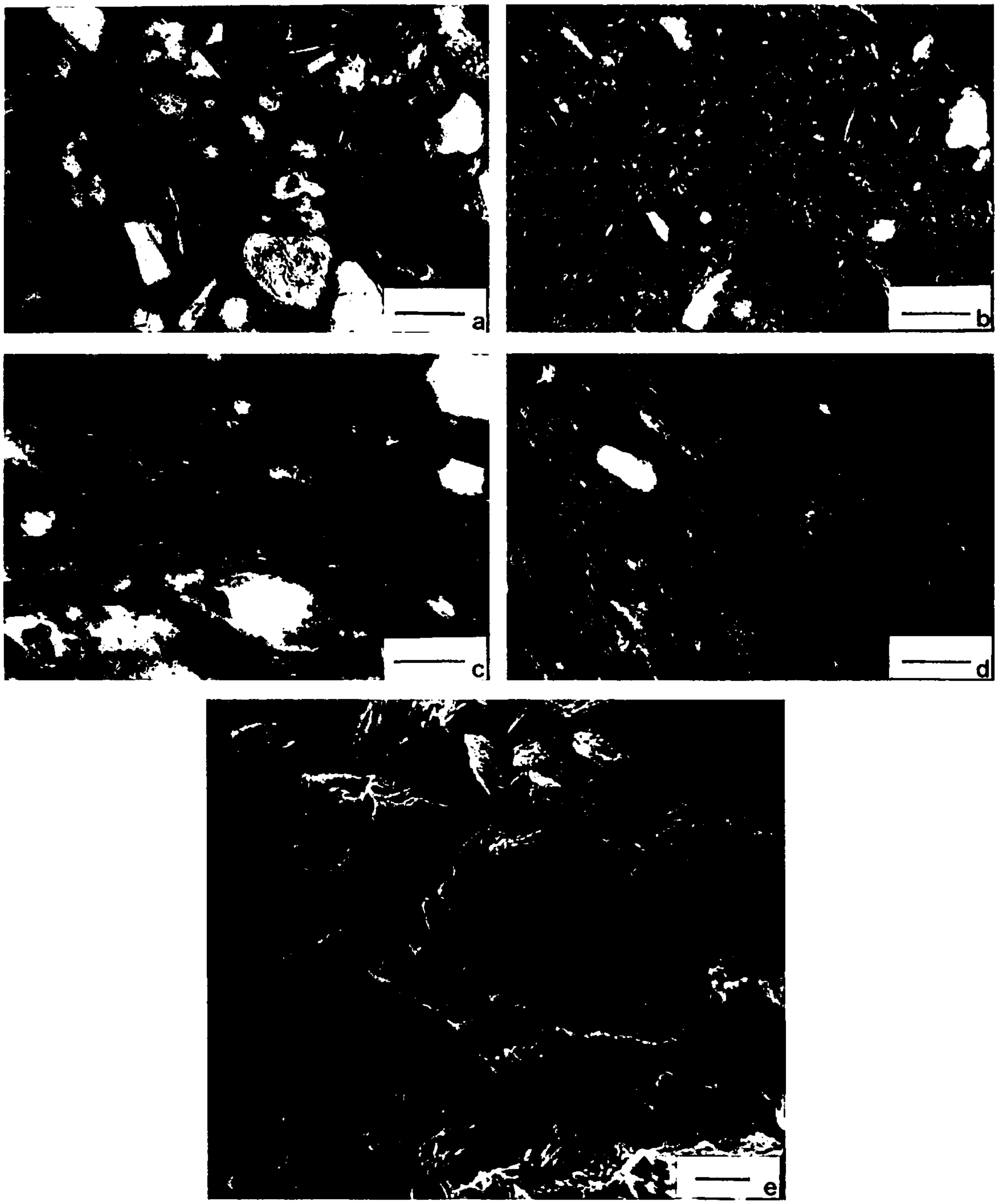

Figure 10. Procedure A, coil-built ceramics. (a, b) Random orientation of clay domains and coarse inclusions seen at high magnifications: (a) plane polarized light; (b) in cross polarizers, speckled birefringence fabric. (c, d) Subparallel orientation of clay domains and coarse inclusions seen at high magnification: (c) plane polarized light; (d) in cross polarizers, striated to strial birefringence fabric. (e) Zone of type (a) seen under the SEM: dense packing of coarse inclusions and clay domains made of randomly organized clay particles and fine silt-size inclusions. Scale bar: (a, b, c, d) 50 µm; (e) 7 µm.

present an elongated shape and have their long axis broadly parallel to the clay walls. The better development of a subparallel orientation of clay domains near the rim suggests that the clay domain arrangement originally formed by shear stress could be locally modified by tensile stress created by hand/finger pressures during shaping operations at a stage when water was discontinued.

Microfabrics of coil-built ceramics indicate local shearing that seems to be preferentially located at the joins between coils. Absence of shear-induced structural changes within dense zones of coils suggests that the random orientation of clay domains and coarse grains is retained from the preparation of coils. For moulded ceramics, rare occurrences of reoriented clay domains and preservation of structural heterogeneities,

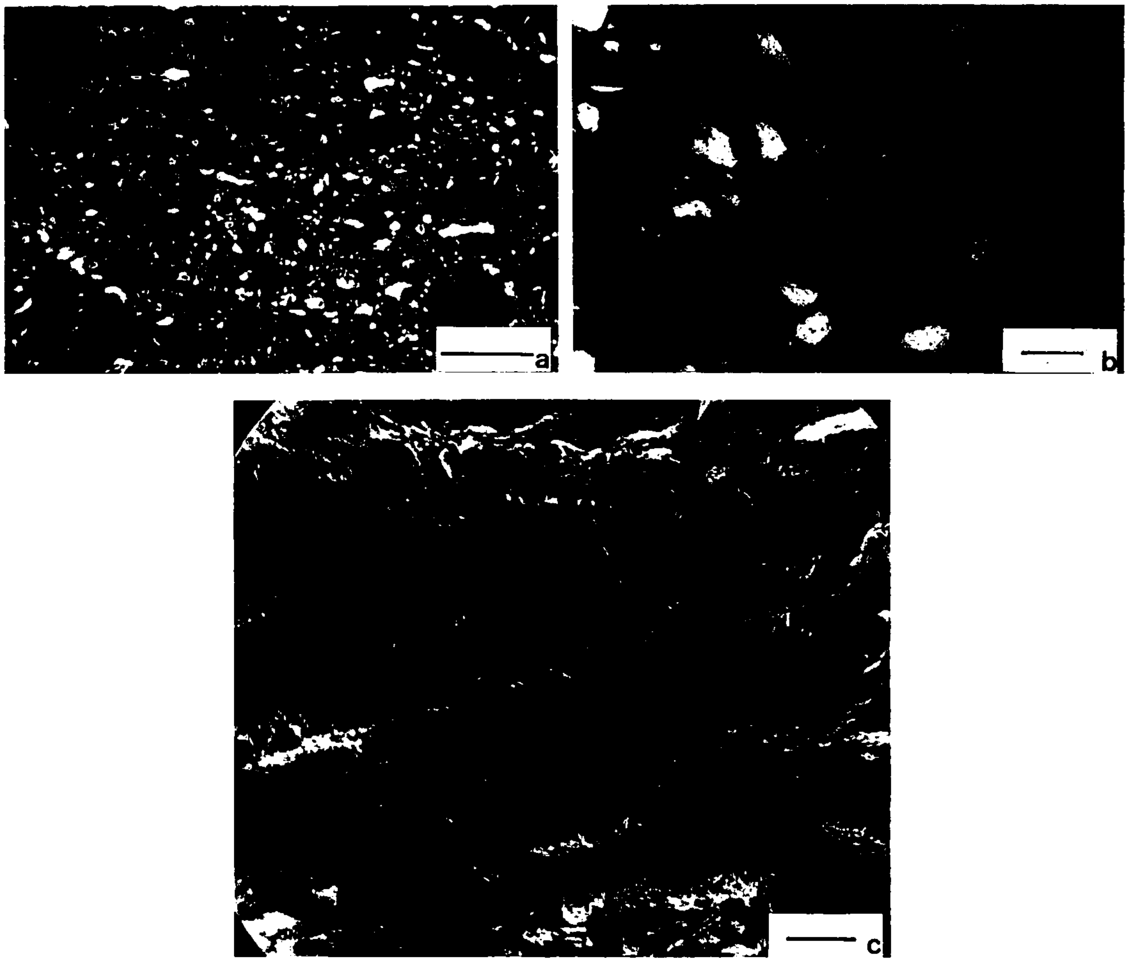

Figure 11. Procedure A, moulded ceramics. (a) Dense homogeneous internal fabric at low magnification with a weakly expressed subparallel orientation of the few elongated veiscular pores. (b) Subparallel orientation of clay domains, silt-size particles and asymmetrical coarse grains seen at high magnification. (c) Same geometrical arrangement, seen under SEM, that clearly differs from the subparallel alignment of wheel-thrown ceramics shown in Figure 8(a). Scale bar: (a) 1 mm; (b) 100 µm; (c) 5 µm.

apparently inherited from the raw material, indicate that shear stress was not sufficient to change pre-existing organization of clay domains. The lesser degrees of structural reorganization observed for both coil-built and moulded ceramics indicates that cohesion forces were high enough during roughout formation to inhibit rapid mobility of clay domains among each other. This is in clear contrast to wheel-thrown ceramics that most probably results from lower water content when the roughout is formed by coiling or moulding. Furthermore, stronger development of subparallel alignment of clay domains together with common occurrence of interconnected networks of subparallel microfissures and general elongation of vesicular pores for coil-built and moulded ceramics, suggest a higher degree of tensile stress that most probably results from maintenance of high cohesion forces between particles. In conclusion, the degree of structural disorganization is lower for coiled and moulded ceramics compared to wheel-thrown pots because significantly less water is employed in making their roughouts. The edifice of clay domains thus formed is consequently less dense and less homogeneous. Structural heterogeneities, such as the one resulting from assemblage of the coils, are thus rather well preserved, although they are often detected only at a high level of observation because of the great density of clay.

SEM observations show that location of zones with a subparallel orientation in wheel-thrown ceramics corresponds to a specific reorganization of clay domains and silt-size inclusions. Coiled and moulded roughouts have a more general subparallel orientation. This subparallel alignment does not result from plastic flow deformation as shown by the absence of a well-developed face to face contact between clay domains. Geometrical relationships between clay domains and silt-size inclusions suggest that the subparallel realignment resulted from mechanical compression induced by tensile forces. This is probably related to maintenance of stronger cohesion forces between clay domains and silt-size inclusions because pressures are

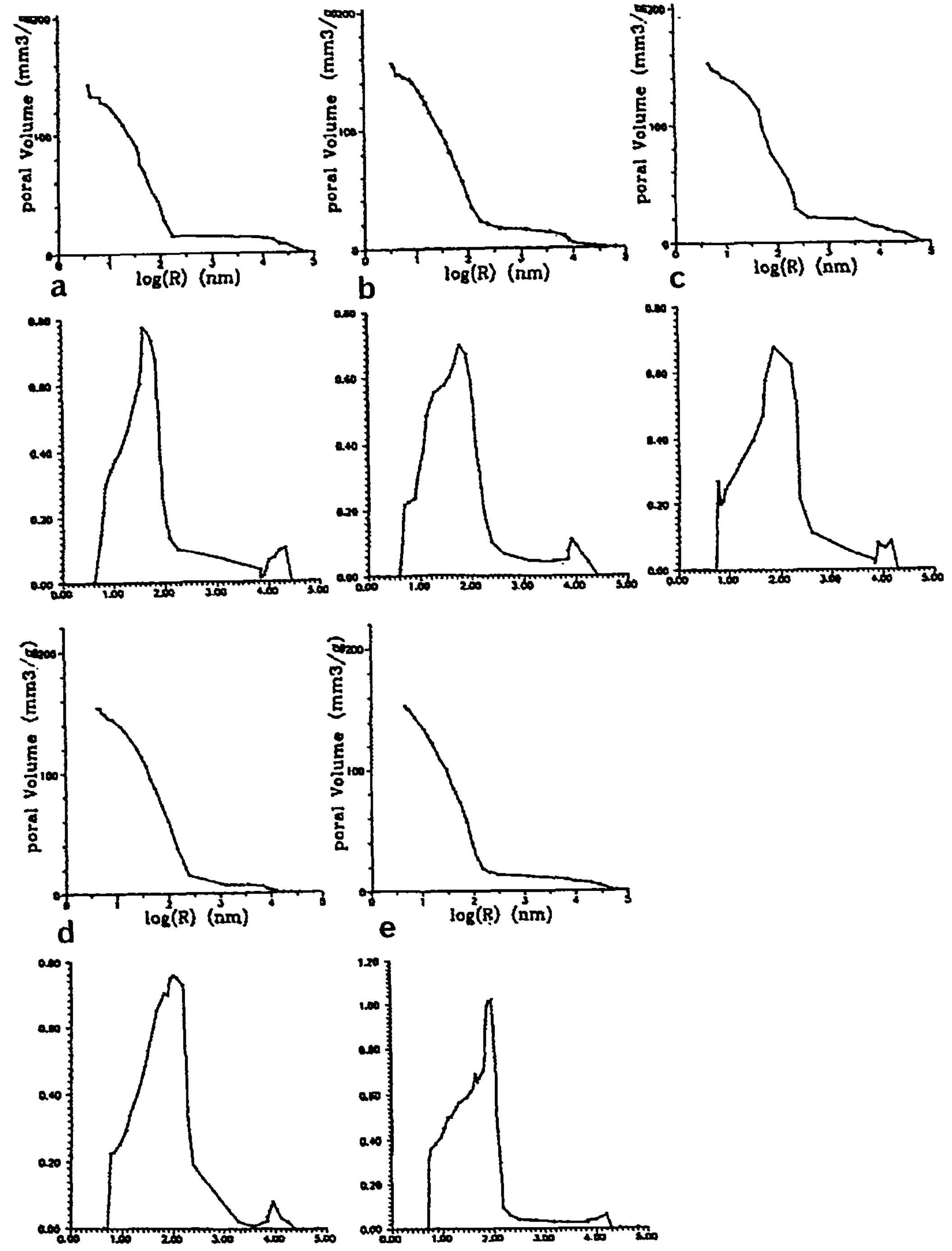

Figure 12. Pore volume and pore size distribution of experimental ceramics (protocol A) obtained from physical measurement. (a) moulded, (b) wheel thrown, (c) wheel thrown and beaten, (d) coil built, (e) coil built and shaped on a wheel. The similarity observed in the curves suggests that the different forming and finishing operations do not affect the geometrical arrangement at the level of quasi crystals or clay platelets.

exerted onto clay of lower water content for coil-built and moulded ceramics compared to wheel-thrown ceramics. In thin sections, distinction between the two types of striated birefringent fabrics is impossible because of the difficulty of observing geometrical arrangements of individual clay domains. However, geometrical relationships between zones with a subparallel alignment and zones with a random orientation are not the same in wheel-thrown ceramics as in moulded or coil-built ceramics. Constant wetting during roughout formation by wheel throwing is, in fact, a discontinuous operation that causes hydric conditions to oscillate between a low cohesion, close to saturation, just after addition of water and a high cohesion just before addition of water. Fine imbrication between subparallel and random microfabrics probably reflects these constant hydric changes. A homogeneous subparallel alignment of clay domains for wheel-thrown ceramics is therefore impossible, as it would require maintenance of a very low cohesion during the roughout formation that would most probably induce the structural collapse of the vessel. A secure identification of the clay domain arrangement relevant to wheel-thrown roughouts thus requires observation of various structural zones and cannot focus on local zones that may have been highly affected by shear failures.

The rare occurrence of elongated coarse grains in the ceramics studied explains why we have given little attention to orientation of coarse grains as a factor in differentiating forming techniques. The elongated mica grains have, in general, a random orientation in the wheel-thrown roughout whereas they often have a subparallel orientation in the coil-built ceramics and always have a subparallel orientation in the moulded ceramics.

The marked structural differences for the forming techniques studied suggest that the considerable shrinkage during drying and firing should partly preserve the structural relationships between clay domains that have been achieved during formation of the roughout as long as the original morphology of the clay domains has not been transformed by firing. For this reason, the moderate temperature at which the experimental ceramics were fired (*c.* 700–800°C) makes this material highly suitable for a comprehensive understanding of structural changes induced by forming operations.

Procedure B: results and discussion. Observation of experimental ceramics made from clay of various mineralogical composition reinforces the discrimination between the two sets of microfabrics relevant to the two roughout forming techniques: with rotative kinetic energy (wheel throwing) and without rotative kinetic energy (coiling, moulding, lump modelling). Important variations of internal structures that seem to be largely dependent upon the mineralogical composition of clay and its preparation are, however, identified within each of the two groups.

(A) Roughouts made with rotative kinetic energy. Wheel-thrown ceramics made from clay with either large size illitic particles with a high content in iron oxides (Baripada), or of various mineralogical types of clay with abundant coarse grains (Paris A, Puri and Bhubaneshwar) share similar characteristics to the wheel-thrown ceramics from procedure A but differ by certain attributes (type IIb). They also display a very dense edifice characterized by a regular pattern of finely imbricated clay domains and coarse inclusions with occasional elongated vesicular pores (Figures 13(a) & (b)). The cross-striated birefrigence fabric is better defined in cross polarizers and the two sets of small size birefringent streaks form a regular network around the randomly distributed coarse sand grains. The main difference from the microfabrics described in procedure A is the rare occurrence of zones of shear failures characterized by a subparallel alignment of clay domains and long mica particles and striated birefringence fabrics. This difference can be explained by the greater abundance of coarse sand grains which greatly constrain reorganization of clay domains and fine silt-size inclusions. The clay mineralogy is also supposed to influence the ability of clay domains to slide on each other.

In the case of iron rich illitic materials, iron oxides appear to increase adherence between clay domains (Chauvel, 1977), thus preventing elementary illitic particles from sliding on each other. In the case of smectite-rich raw material, the reduced potential of clay domains to slide upon each other can be explained by the specific structural organization of smectite quasi-crystals known in soil mechanics (Tessier, 1990).

The situation is slightly different in the case of wheel-thrown ceramics made from fine illitic clay with rare coarse sand grains (Paris B, type IIc in Table 5). A very dense fabric nearly devoid of fine pores is observed at a low magnification (Figure 14(a)). At a higher magnification, the microfabric is characterized by preferential subparallel alignment of fine silt-size micas and illitic clay domains and a well-defined striated birefringent fabric (Figure 14(c) & (d)). This subparallel alignment does not seem, however, to result from an overall face to face contact of individual illitic particles. The internal structure predominantly consists of small size clay domains formed of weakly organized illitic particles that are surrounded by stacks of aligned (face to face contact) illitic particles and fine silt-size mica grains. The small size of shearing planes explains the resulting subparallel striated birefringent fabric, although the type of structural organization does not significantly differ from the one described in procedure A. The more common occurrence of zones with a subparallel striated birefringent fabric, as compared to procedure A, can be explained by the strong tendency of illitic clay domains to display a parallel arrangement under shear stress during wheel throwing and, also, to the reduced amount of coarse grains. Careful preparation of clay by decantation may also have favoured the dispersion of illitic clay and the preferential face to face contact of clay domains and fine silt-size inclusions during settling. Dispersion induced by decantation during clay preparation in protocol A would have been more limited because of the presence of smectite together with illitic clay.

Roughouts made without rotative kinetic energy. Coil-built ceramics made from Paris material B (illitic, rare coarse grains) are similarly characterized by the occurrence of two types of microfabrics (type III, Table 5). One microfabric is defined by a well expressed subparallel alignment of illitic clay domains and fine silt-size

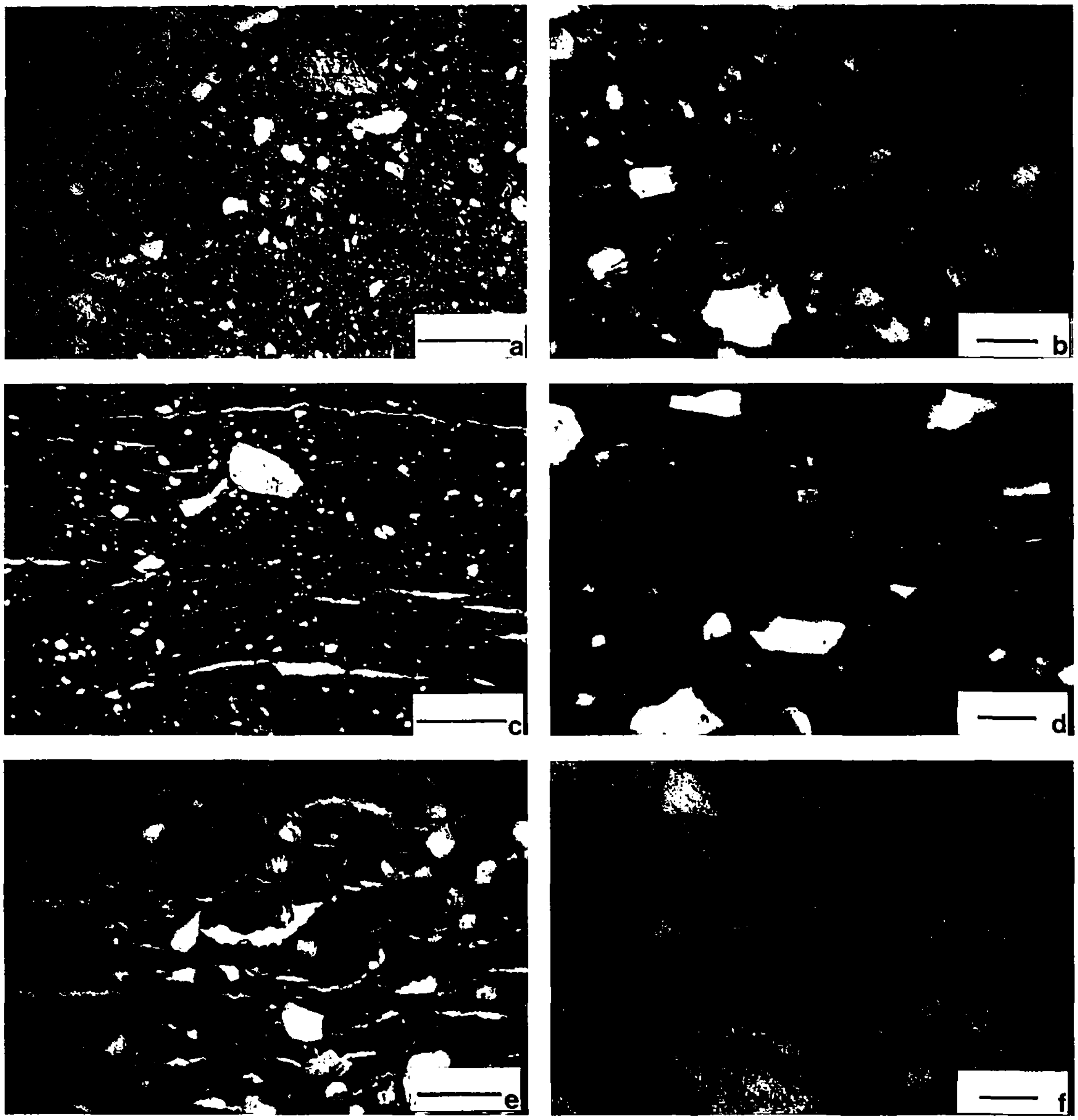

Figure 13. Procedure B, ethnographic ceramics. (a) Orissa, Baripada, wheel-thrown ceramic; dense homogeneous microfabric, at low magnification in plane polarized light; (b) random orientation of clay domains. Silt-size inclusions and coarse sands observed at higher magnification in plane polarized light. (c) Mali, material A, coil-built part: well-expressed network of fine subparallel fissures at low magnification in plane polarized light; (d) dense microfabric with a subparallel alignment of clay domains at higher magnification in plane polarized light. (e) Danao, Cebu, Philippines, lump-modelled ceramic: well-expressed network of subparallel fissures at low magnification in plane polarized light; (f) view at higher magnification in plane polarized light showing weak reorganization of clay domains in between abundant coarse sand grains. Scale bar: (a, c, e) 1 mm; (b, d, f) 100 µm.

micas (Figure 14(e)). The second microfabric consists of a compact imbrication of large size clay aggregates that displays a twisted ("zig zag") arrangement of illitic particles and silt-size micas (Figure 14(b) & (f)). Oblique vesicular pores and microfissures are rarely observed at the contact between the two types of internal structures. As with the interpretation of structural discontinuities observed in coil-built ceramics of procedure A, juxtaposition of two different microfabrics seems to be produced by assemblage of the coils. The very small size of coils (0·5 cm) and the fine adjustment between coils explain why the successive coils are not always recognizable. The twisted microfabric seems to correspond to the internal part of the coils that has been less affected by tensile and shear stress as compared to the inter-join zones that have a subparallel microfabric. The "zig zag" deformation is interpreted as resulting from rupture deformation of a material that was originally formed of clay domains with a face to face contact. As with the interpretation of wheel-thrown ceramics made from the same clay, this face to face arrangement would be inherited from decantation during preparation of the clay. This suggests that the water content within coils would not

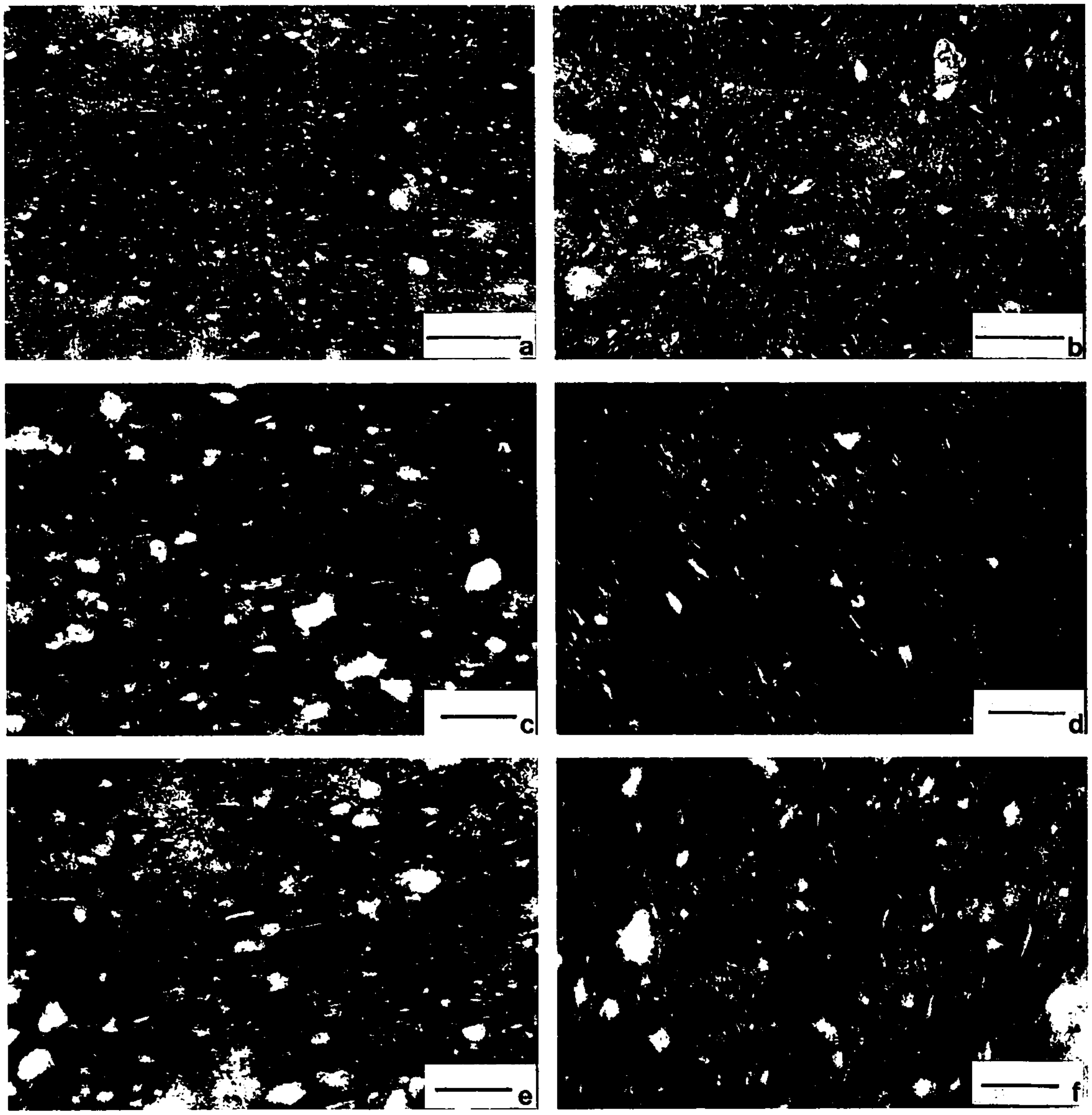

Figure 14. Procedure B, experimental ceramics, Paris material B. Wheel-thrown ceramic: (a) dense homogeneous microfabric, at low magnification in plane polarized light; (c) subparallel alignment of fine size clay domains and fine silt-size micas at higher magnification in plane polarized light; (d) striated birefringence fabric in cross polarizers. Lump-modelled ceramic: (b) dense microfabric made of compacted aggregates, at low magnification in plane polarized light; (e) subparallel alignment of fine size clay domains and fine silt-size micas at higher magnification in plane polarized light; (f) twisted "zig zag" microfabric. Scale bar: (a, b) 500 μm; (c, d, e, f) 50 μm.

have been high enough to allow clay domains to easily slide on each other. As with the interpretation presented for moulded ceramics of procedure A, the clearer development of the subparallel orientation indicates a stronger effect of tensile stress than shear stress as compared to wheel-thrown ceramics. Absence of a twisted "zig zag" microfabric in the coil-built ceramics described in procedure A is interpreted as resulting from the occurrence of smectite together with illitic clay that would reduce dispersion of individual clay particles during decantation of the raw material. This original microfabric is suggested to be specific of predominantly illitic clay prepared by decantation. At the present stage of our investigation, we cannot, however, conclude whether the twisted microfabric is produced only by coiling or if it also characterizes modelled ceramics made from illitic clay prepared by decantation.

The other coil-built ceramics made from various types of clay rich in coarse sand grains (Mali, Paris material A) display a regular network of partly interconnected fine tissues of subparallel orientation (Figure 13(c)) and a predominant subparallel internal structure (type II2, Table 5). At high magnification, the subparallel orientation of coil-built ceramics made from a predominantly kaolinitic clay appears to be formed by the regular alignment of clay domains, silt-size inclusions and strongly compressed chaff temper (Mali A,

Figure 13(d)). For the coil-built ceramics made from a predominantly smectitic clay (Mali B), the subparallel orientation of clay domains is less visible, although the preferential alignment is clearly marked by the orientation of silt-size inclusions and strongly compressed chaff temper. The preferential alignment of the coarse elongated grains is also, in general, better defined. As with the coil-built ceramics described in procedure A, contact between coils is generally identified by occurrence of structural discontinuities that are marked by juxtaposition of dense and poorly organized zones with zones of subparallel alignment.

The lump-modelled and moulded ceramics made from various clays (ceramics from the Philippines, bases of the ceramics from Mali A or B) are similar to the moulded ceramics described in procedure A, characterized by a regular network of partly interconnected fine fissures that have a preferential subparallel orientation (Figure 13(e); type III in Table 5). The fine clay mass generally displays an irregular orientation of clay domains and coarse inclusions, except for asymmetrical grains that have a broadly defined subparallel orientation to the clay walls (Figure 13(f)). Abundance of large aggregates of weakly transformed soil materials suggests that modelling induces less structural changes than coiling. This hypothesis is reinforced by structural differences between the moulded base and the coil-built body of the ceramics from Mali A or B. The moulded fabrics are generally of lower density as compared to the coil-built part and internal organization of the fine mass often displays a highly random orientation of clay domains and silt-size inclusions. This suggests that tensile forces exerted when stretching the coils are more capable of producing structural changes as compared to the tensile forces exerted during beating. Great development of fine tissues can be explained by the high amount of large size chaff temper that will retain moisture during the forming operations but will suffer important shrinkage during drying. This may also result from a heterogeneous wetting of clay that would induce differential shrinkage.

Preliminary conclusions. Observations from the two experimental procedures establish a clear correlation between ceramic forming techniques and relevant microfabrics (Table 5). However, the diversity of microfabrics observed in the different situations studied should not be oversimplified. This diversity is due not only to the successive forming operations and to the mineralogy of clay but also to the preparation procedures which can affect the initial structure of fabrics. In all the situations studied, criteria that have been traditionally used to distinguish between ceramic forming techniques, such as orientation of elongated vesicular pores, fissures and asymmetrical coarse grains, are found to be highly ambiguous. These mesoscale features appear to be influenced predominantly by tensile stress caused by finger/hand pressures that may be exerted within a similar range by different ceramic forming techniques. Moreover, orientation of large voids and asymmetrical coarse grains of roughouts has been shown to be significantly modified when a different technique was used for subsequent operations (shaping and finishing stages), as a consequence of the effect of tensile forces exerted by finger/hand pressures. An additional problem is that asymmetrical coarse grains and large voids may not always be present in sufficient amounts, as illustrated by the experimental ceramics from Paris, material B. These conclusions are fully consistent with soil physics, that has demonstrated the necessity of studying the geometrical arrangement of clay domains and coarse inclusions for reconstructing the energetic history of clay materials (Tovey, 1986; Delage, 1987). Microscopic observations performed at different levels of magnification for recognizing clay domain patterns (light microscope) and individual clay domains (SEM) permit the identification of two types of subparallel alignment: one is related to shear stress and appears to be specific to microfabrics of wheel-thrown ceramics; the other one is related to tensile stress. The subparallel alignment observed in coil-built, moulded and lump-modelled ceramics is always of the tensile type. The two types of subparallel alignment are clearly distinct, especially under SEM, for large size clay domains such as those found in smectite-rich clay. The distinction is more difficult for illitic or kaolinitic clays which consist of small size rigid particles, especially when individual clay particles have been originally dispersed during preparation of clay by decantation. The resultant similarity between microfabrics that have a different energetic history explains why a parallel orientation of asymmetrical coarse grains has been previously described for various forming techniques, i.e. forming with or without rotative kinetic energy (see Table 1; e.g. Carr, 1990). The limited resolution power of the techniques used in previous studies has not permitted us to observe the arrangement of clay domains. As previously stated (Vandiver, 1987), the radiographic technique is certainly well appropriated to a rapid visualization of structural discontinuities between assembled elements and should be used in combination with the microscopic study of microfabrics. Efficiency of the radiographic technique requires, however, that structural discontinuities such as the ones between joins of coils are marked by significant variations of clay density or of geometry, size and abundance of voids (Pierret, 1994).

Application onto the Archaeological Material

Archaeological material selected

The archaeological material selected belongs to 3rd millennium sites located in Syria, Iran and India:

- Tell Leilan, Khabur, North Syria. Occupation periods: PII (end of 3rd millennium) and PI (beginning of 2nd millennium) (Weiss, 1990).

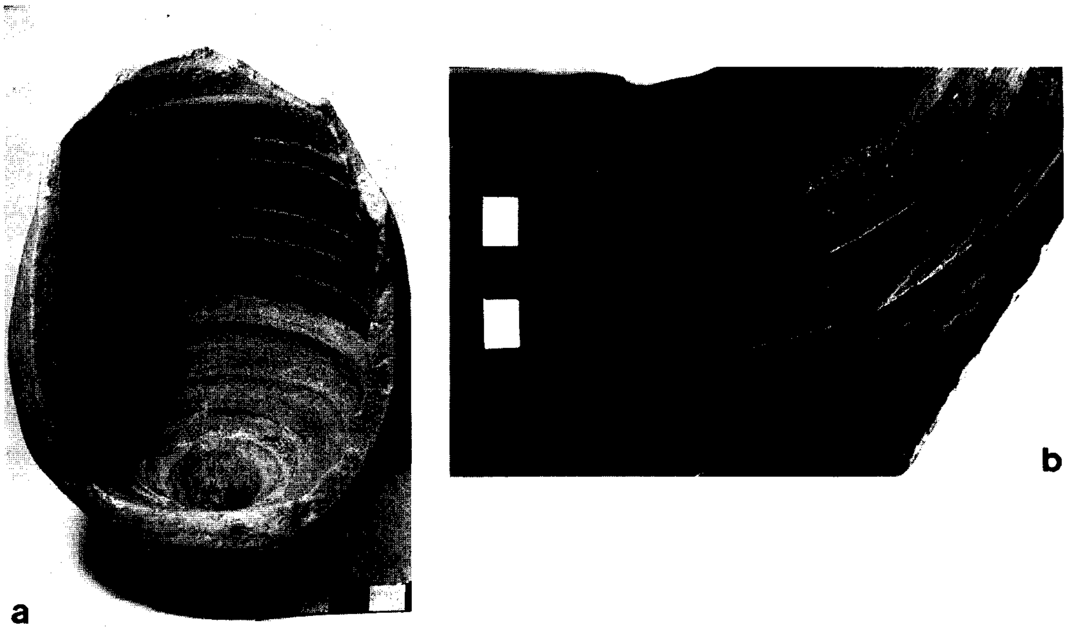

Figure 15. Kalibangan vessels displaying grooves characteristic of joins of coil. (a) Harappan period, (b) pre-Harappan period. Scale bar is in cm.

- Shari-i-Sokhta, Hilmand, Eastern Iran, Occupation periods: from PI to PIV (end of the 4th millennium up to the end of the 3rd millennium, with a gap of occupation between PIII and PIV) (Tosi, 1979).
- Kalibangan, Rajasthan, North West India. Occupation periods: pre-Harappan (first half of the 3rd millennium), Harappan (second half of the 3rd millennium) (Thapar, 1975).

For Tell Leilan, only a few sherds of the fine ceramics, usually considered as wheel thrown, have been examined. For Kalibangan and Shar-i-Sokhta, the available archaeological material of each period (thousands of sherds) has been described and classified according to main categories of surface features. The surface features here presented correspond to an opportunistic sampling: they are the ones which are supposed to be characteristic for wheel throwing and whose attributes are characteristic enough to give us clues about forming processes. Selective sampling of ceramics for microfabric analysis has been done within each of the main categories of surface features. Fifty ceramic thin sections have been examined for each site. Within the framework of this article, only main results are given for all the periods.

Surface features analysis

The Tell Leilan sherds considered here display surface features which are highly ambiguous, i.e. characteristic of wheel shaping, but not significant of the technique for making the roughout. To the contrary, the numerous sherds of Kalibangan and Shar-i-Sokhta which could be examined display characteristic attributes. For the earliest periods of Kalibangan and Shar-i-Sokhta, the ceramic assemblages present three main groups of surface features:

1. The first group shows an absence of any rotative movement. Bands of striations are in all directions, even on rims, and the walls present irregular, unstretched surfaces.
2. The second group shows the use of rotative movement. Bands of parallel striations, some undulating, run around the walls. The walls, for some of the vessels, present stretched surfaces.
3. The third group shows the use of kinetic energy. Parallel striations and rilling run around the walls, there are ripples of compression and the surfaces of walls are stretched.

During the second half of the 3rd millennium, the third group of surface features became predominant. In the past, wheel throwing was inferred on the basis of this third group. Now, the question is the following: to which forming methods and techniques does the third group of surface features correspond? Is it characteristic of wheel throwing or of wheel shaping of coil-built roughouts? In the framework of this article, we propose to comment on some surface features, illustrated by photographs, which are common and characteristic enough to propose hypotheses on the forming techniques practised by Kalibangan and Shar-i-Sokhta potters.

Grooves, Kalibangan.

- Figure 15(a). Small restricted vessel. Harappan period. Grooves run at regular wide intervals

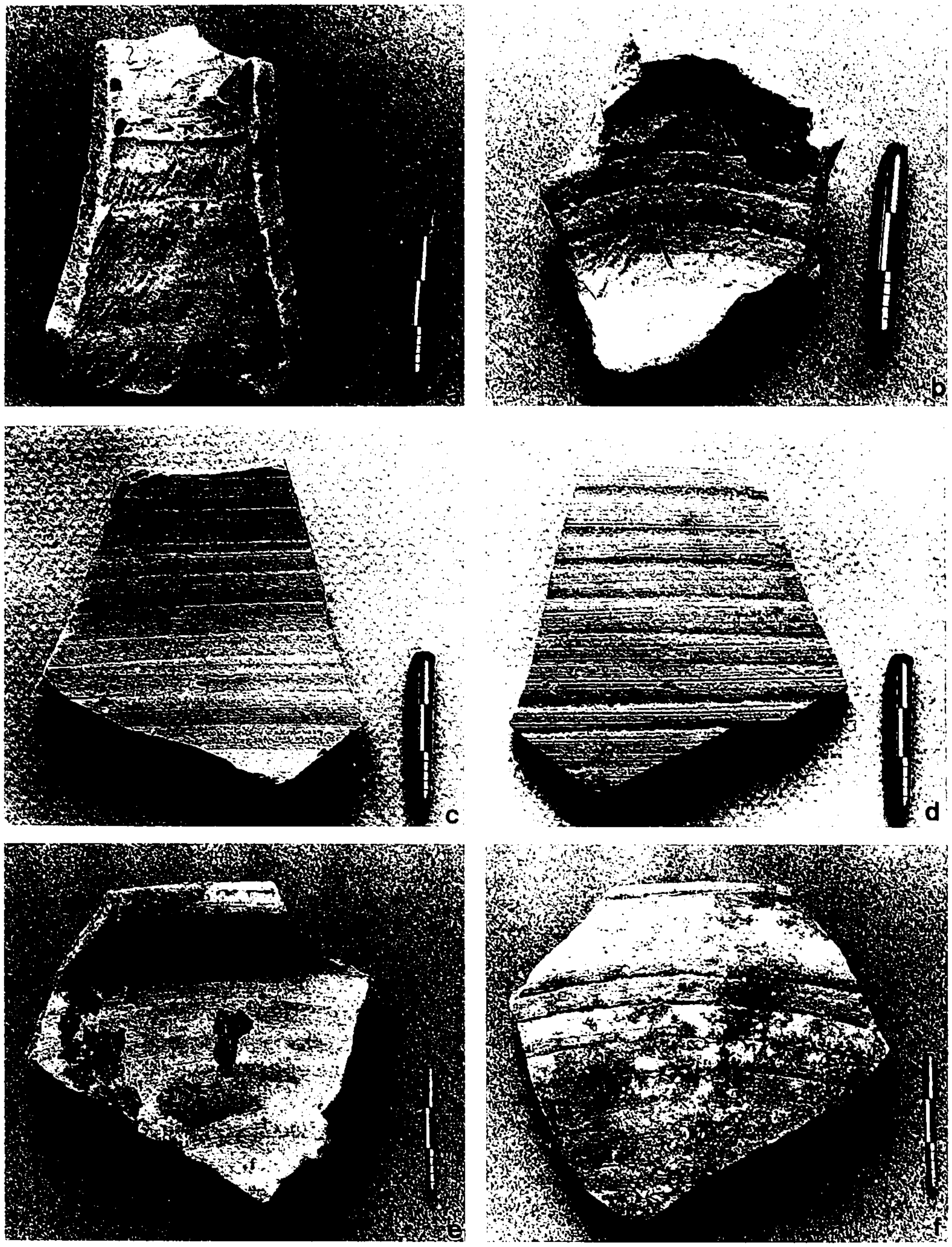

Figure 16. Shar-i-Sokhta vessels displaying grooves characteristic of joins of coils (a, b) period II, (c, d, e, f) period IV. Scale bar is in cm.

around the interior of the wall. They are combined with parallel striations. They present the following characteristics: rounded or angular edges whose outlines are more or less irregular, raised surface between the grooves, no rectilinear trajectory, no preferential location on the walls (not located on compression zones). Such grooves are not comparable to dips encountered with rilling or with grooves obtained while throwing. By reference to our experimental study, they would correspond to joins of coils left visible.

- Figure 15(b). Large restricted vessel. Pre-Harappan period. The grooves also run at regular wide intervals. Some of them are located by a compression zone; they present rounded or angular edges, slightly raised surface in between the grooves, no rectilinear trajectory. Such grooves cannot be obtained while throwing. They present the same morphology as joins of coils which have been, on one hand left visible, and on the other hand compressed (for the ones located near the maximum diameter).

Grooves, Shar-i-Sokhta.

- Figure 16(a). Small restricted vessel. Period II. The grooves are located on a zone of compression marked out by ripples. They are characterized by a trajectory which is not rectilinear as well as by irregular edges. Their morphology strongly recalls the grooves obtained while compressing joins of coils (Figure 4).
- Figure 16(b). Small restricted vessel. Period II. The grooves, running at regular wide intervals and located on a zone of compression, present the characteristics of compressed joins of coils as well as of joins of coils left visible.
- Figure 16(c) & (d). PIV. The outer and inner side of the walls present corresponding grooves running at regular wide intervals. Their morphology cannot be associated with any throwing operation: neither raising the clay too fast, nor trailing nails or impurities. They are similar to joins of coils.
- Figure 16(e) & (f). Restricted vessel. PIV. The inside of the vessel does not present parallel striations with a stretched surface, i.e. surface features significant of wheel shaping. The outside of the vessel presents parallel grooves running at regular wide intervals as well as parallel striations. These grooves present all the characteristics from joins of coils. The roughout appears, then, to have been coil built, whereas the preform appears to have been carelessly shaped on a wheel.

Rilling, Kalibangan.

- Figure 5(b). Pre-Harappan. The observable "band" cannot be the result of raising clay by throwing: there is no fallout of the clay despite the prominent ridge it corresponds to. Such a band appears to be a coil not properly levelled.

The surface features here analysed enable us to propose the following hypothesis: during the 3rd millennium, Kalibangan and Shar-i-Sokhta potters were forming roughouts by coiling and shaping preforms on a wheel. Roughouts were not thrown on the wheel. To reinforce this hypothesis, the study of the surface features now has to be completed by an analysis of the microfabrics.

Microfabrics analysis

All the archaeological ceramics studied present very dense and broadly homogeneous microfabrics that resemble situations encountered in experimental ceramics from Delhi and Paris B clays. They are generally made of fine textured clay with a minor proportion of fine sand grains that have mostly a subangular to angular shape. The rare occurrence of asymmetrical grains does not allow a preferred orientation to be identified. Based on the birefringence fabric of the ceramics studied, three types of clay are recognized:

- Illitic clay that may consist either of very fine size (a few micrometres) illitic clay domains or of larger size illitic clay domains with abundant silt-size micaceous inclusions; all the ceramics from Kalibangan are made from illitic clay that is, moreover, the predominant type of clay present in the surrounding of the site (Courty, 1990); a few ceramic fragments from Shar-i-Sokhta are also made from illitic clay, except for period III; no ceramics made from illitic clay have been observed in the samples selected from Tell Leilan, which is situated in a region where pure illitic clays are not present (unpublished data). For this category of clay, the geometrical arrangement of clay domains is clearly identified in plane polarized light and birefringent fabrics can be studied in cross polarizers.
- Illitic clay mixed with fine silt-size calcitic particles together with a minor amount of smectite or of kaolinite or of non-identifiable clay. Some of the ceramics from Shar-i-Sokhta are made from this type of clay material, except for period III, and a few ceramics from Tell Leilan (period I and II) are also made from this type of clay material. The geometrical arrangement of clay domains can be broadly identified in plane polarized light whereas the birefringent fabrics are strongly masked due to physico-chemical transformation of the carbonate-rich clay induced by firing (Tite & Maniatis, 1975; Maniatis & Tite, 1981).
- Highly calcitic clay of variable mineralogy. This type of clay material is very common for the ceramics studied from Shar-i-Sokhta including all the ceramics selected from the period III assemblage. It is also very common for the period I and II ceramics selected from Tell Leilan for which clay mineralogy dominantly consists of palygorskite together with a minor amount of illite. All the ceramics made from this highly calcitic clay material present a melted aspect that does not allow recognition of the geometrical arrangement of clay domains in plane polarized light; the birefringent fabrics are totally masked due to important physico-chemical transformations of the highly calcitic clay induced by firing. In this case, the geometrical distribution of voids, together with variations in the density of the fine mass, are the only features to describe the internal structure of the clay.

All the ceramics observed present a set of characteristics that can be assigned to coil-built microfabric (type II, Table 5) defined on the basis of the experimental study. Occurrence of a continuous, subparallel, fine fissural network (type II2, Table 5) appears to be exceptional (Figure 17(a)) and in most cases the void

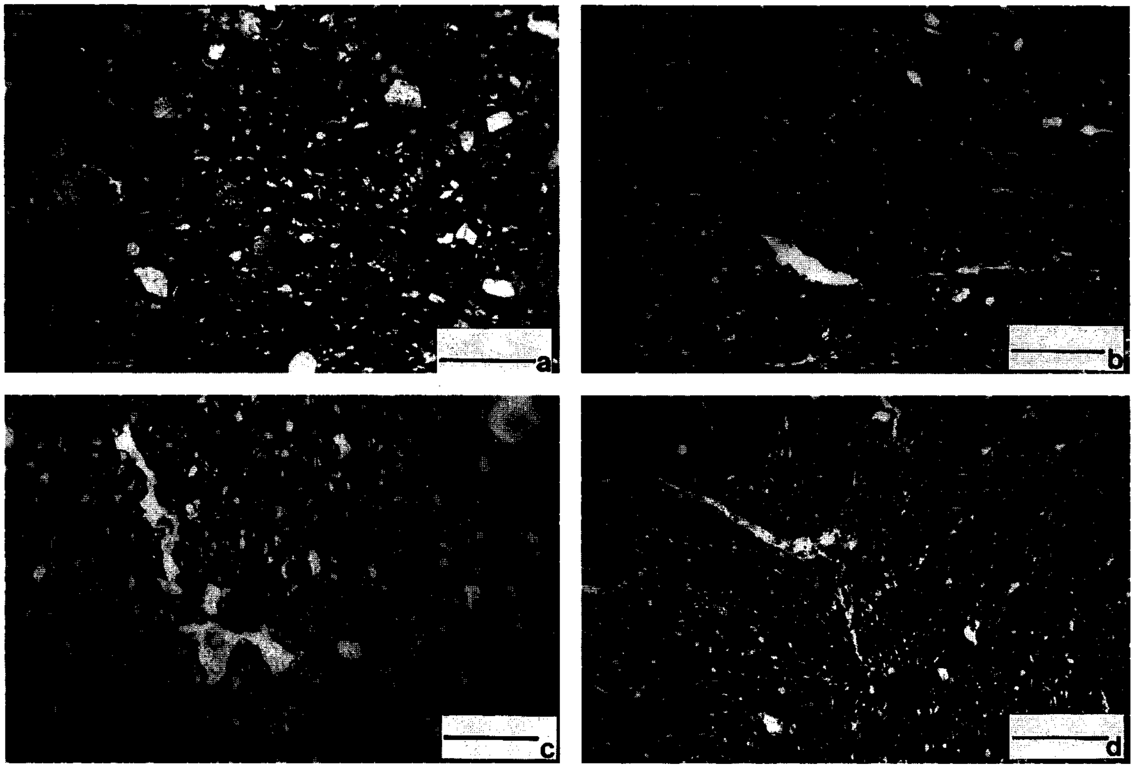

Figure 17. Thin sections of archaeological ceramics viewed at low magnification (plane polarized light): very dense and broadly homogeneous microfabrics with void patterns specific to the coiling technique. (a) Shar-i-Sokhta, PII: continuous, subparallel fissural network. (b) Tell Leilan, PII: strongly compressed, diagonal vesicular pores along a structural discontinuity between two coils. (c) Kalibangan, Harrapan: mammilated vesicular pores along a structural discontinuity between two coils. (d) Shar-i-Sokhta, PI: fine cracks along a structural discontinuity between two coils. Scale bar: 1 mm.

network is limited to a few elongated fine fissures, fine cracks and vesicular pores, defined for type II1 (Figure 17(b), (c) & (d)). Structural discontinuities that occur at regularly spaced centimetric intervals are easily recognized when they are delineated by elongated vesicular pores of diagonal orientation (Figure 17(b)) or by a network of fissures (Figure 17(c) & (d)). They are often difficult to detect at low magnification because of the high density of clay. At high magnification, the structural discontinuities are marked by a sharp contact between dense zones with a mammilated structure (compaction of millimetric size aggregates) and zones with a broadly defined subparallel alignment of clay domains and silt-size inclusions. Based on their morphology, their regular spacing and their strong similarity to structural discontinuities found on experimental pieces from procedure A (cf. Figure 9(a) & (b)), the structural discontinuities are assumed to be joins between small size coils.

At higher magnification, two subtypes of microfabrics similar to the coil-built type II1 (Table 5) are clearly recognized in most of the ceramics made from illitic clay (i.e. Kalibangan), and also for some of the ceramics made from calcitic-rich illitic clay, although the internal structure is less visible in the latter case (i.e. Shar-i-Sokhta period III and Tell Leilan):

- Subtype A: a subparallel alignment of clay domains and silt-size inclusions (Figure 18(a), (b), (c) & (d)).
- Subtype B: a dense packing of poorly defined millimetric size aggregates with an internal twisted ("zig zag") microfabric (Figure 18(e) & (f)). Interpretation based on the study of the experimental materials suggests that the common development of a twisted microfabric is the consequence of preparation of illite-rich clay by decantation.

Each subtype can be observed throughout a ceramic fragment (4–6 cm long) or both subtypes can be finely imbricated. Subtype A microfabric is often associated with a regular network of subparallel aligned elongated vesicular pores (Figure 18(a) & (c)), whereas subtype B internal structure is often associated with diagonal elongated vesicular pores (Figure 18(e)). In addition to the occurrence of elongated pores, the abrupt juxtaposition of microfabric subtype B is interpreted to result from structural discontinuities between successive coils. When visible, the birefringent fabric of the subtype A microfabrics consists of subparallel streaks and the subtype B internal structure consists of randomly distributed small patches of oriented clay domains. A regular network of cross-striated

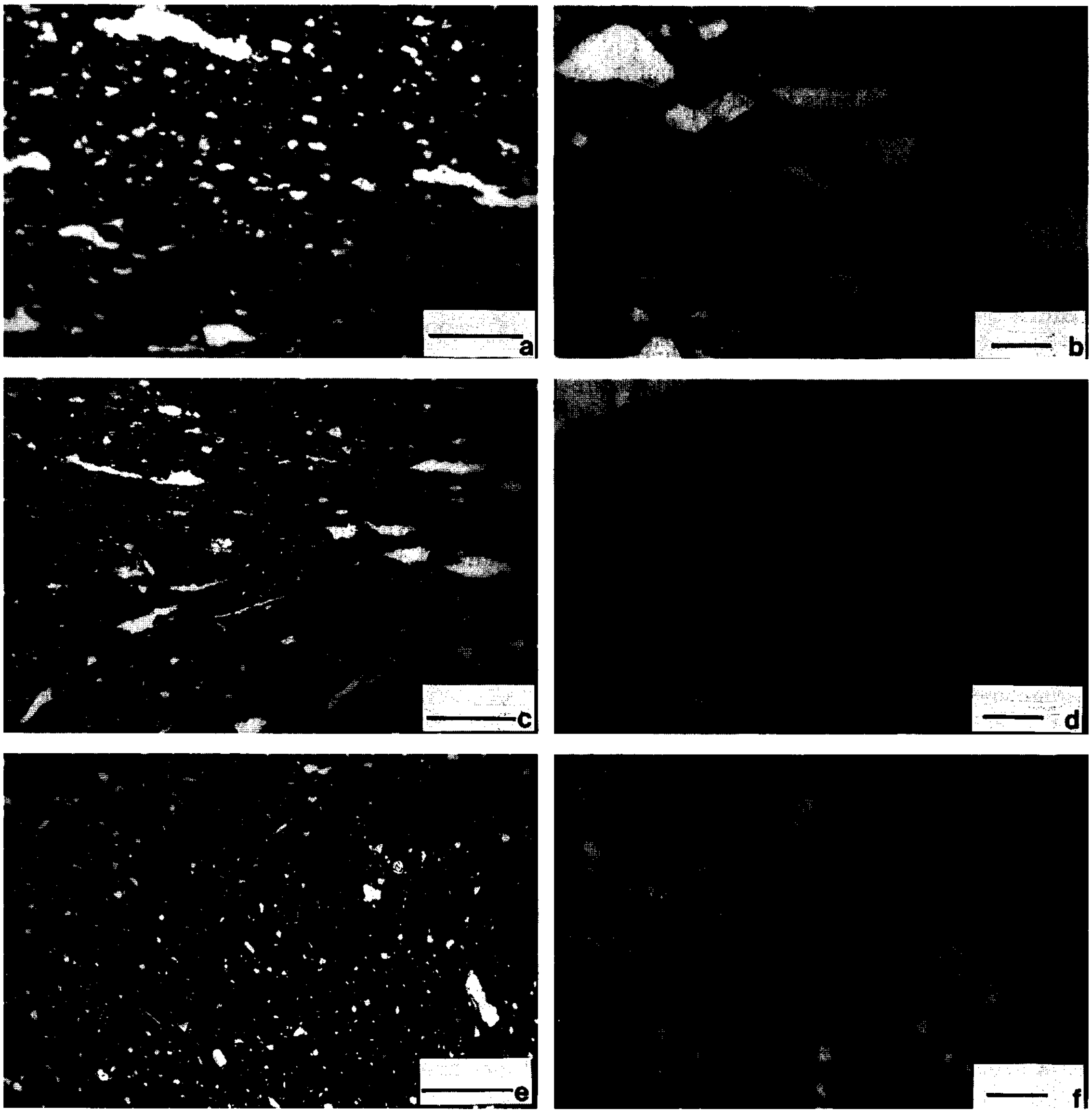

Figure 18. Thin sections of archaeological ceramics (plane polarized light): (a) Kalibangan, Harappan: ceramic made of fine illitic clay showing, at low magnification, a dense homogeneous microfabric with a random orientation of coarse grains and a few subparallel elongated vesicular pores. (b) Close view showing the subparallel alignment of clay domains and silt-size inclusions with evidence of distortion and compaction of the stacks of micaceous fine particles. (c) Leilan, PII: ceramic made of calcitic illitic clay showing, at low magnification, a dense homogeneous microfabric with strongly compacted, elongated vesicular pores, with a subparallel to diagonal orientation. (d) Close view showing subparallel alignment of clay domains and silt-size inclusions. (e) Kalibangan, Harappan: ceramic made of coarse illitic clay showing, at low magnification, a dense broadly homogeneous microfabric with a poorly defined contact between zones of different internal structure. (f) Close view from the left zone formed of strongly compacted aggregates with an internal twisted ("zig zag") microfabric. Scale bar: (a, c, e) 1 mm; (b, d, f) 100 μm.

birefringence fabric has never been observed. The geometrical relationship between the subparallel aligned and the random or twisted microfabrics is clearly similar to the one observed in the experimental coil-built ceramics made from illitic clay material prepared by decantation (Paris, material B). Following the results of the experimental study, the overall occurrence of a subparallel microfabric is also a diagnostic criteria of ceramics made by coiling that have suffered important structural changes induced by tensile stress during assemblage of coils.

When applied to the archaeological material usually considered as wheel-thrown, the combined analysis of surface features and microfabrics can provide convergent results. Unlike previous conclusions (Blackman, Stein & Vandiver, 1993; Thapar, 1975; Wright, 1989), the ceramics of the 3rd millennium here studied appear to have been formed first by coiling (for the roughout) and second by shaping on the wheel (for the preform). In Shar-i-Sokhta, the rotative kinetic energy was used for shaping coil-built roughouts as early as PI (end of the 4th millennium). Its general practice was attested in

PIII (for the Rud-i-Biyaban ceramics). In Kalibangan, kinetic energy was used for shaping coil-built roughouts during the pre-Harappan period (mainly on vessels from the so-called fabrics B and C). Its general practice was attested during the Harappan period. In Tell-Leilan, categories of fine vessels from PII and PI show the use of kinetic energy for shaping coil-built roughouts.

Conclusions

In this paper, it has been argued that the technological analysis of archaeological ceramics should be reassessed in view of recognizing the complex forming processes described in ethnographic literature. Experimental studies have been conducted which enable us to identify surface features and microfabrics characteristic of various pottery forming techniques, both of which provide complementary evidence of the complex sequences involved in ceramic forming processes. The results of the study help to distinguish wheel throwing from wheel shaping of coil-built roughouts. Applied to archaeological material, technological analysis shows that 3rd millennium ceramics were initially formed by coiling, then shaped on a wheel. This observation directly affects our interpretative constructs. We will consider three of them:

First, the history of ceramic techniques. The emergence of wheel throwing has been considered up to now as the result of the invention of the fast wheel. Our study shows that this proposition does not hold as such. Wheel throwing appears more like an evolution of concept, developed through a stage of wheel shaping. Wheel shaping corresponds, above all, to an evolution of technique, in the sense that, for the first time, rotative kinetic energy is used in clay fashioning. Rotative kinetic energy is less than is needed for throwing, but is far superior to energy needed for surface finishing only. It requires, in particular, turntables rotating around an axis.

Second, the functioning of ancient rotative devices. Several authors (Amiran & Shenav, 1984; Edwards & Jacobs, 1986) studied the ancient rotative devices found in the Near East and raised the question of how they could be used for wheel throwing. Now, the archaeological data show that only wheel shaping occurred during the 3rd millennium. Thinning and/or shaping a pot on a wheel needs less rotational kinetic energy than throwing a pot on a wheel. Therefore, the 3rd millennium rotative devices have to be considered as not thought of or used in the same way as the later conceived fast wheel, whose kinetic energy greatly increases efficiency.

Third, techno-economical inferences. Archaeologists have advanced the notion of mass production appearing in the 3rd millennium in connection with the invention of wheel throwing. This notion must be re-examined when we consider that, size being equal, the forming process associating coiling and wheel shaping takes much more time than throwing a pot on a wheel. As for craft specialization, the fact is that thinning or shaping on a wheel require the same specific skills as wheel throwing. These skills, complex and difficult to acquire, strongly suggest the existence of pottery specialization during the 3rd millennium.

Other constructs could be considered on the basis of a detailed study of the emergence of wheel shaping, its mastery and thoroughness in relationship, for example, to the morphology of pots, their function and their rate of manufacture.

Acknowledgements

This research project was funded by grants from the French Ministry of Foreign Affairs (Centre des Sciences Humaines, New Delhi) and from the Centre National de la Recherche Scientifique, France (G.D.R. 743). Dr M. C. Joshi, Director General of the Archaeological Survey of India, Professor Maurizio Tosi, IsMEO, Rome, and Professor Harvey Weiss, Yale University, are gratefully acknowledged for providing access to the ceramic collections from Kalibangan, Shar-i-Sokhta and Tell Leilan. Assistance was generously provided by Madhu Bhala at the Kalibangan section of the A.S.I. and by Stephano Pracchia at IsMEO. The technological study of Kalibangan and Shar-i-Sokhta materials was conducted in collaboration with Bertille Lyonnet (CNRS), in charge of the morphological typology.

We would like to express our gratitude to Har Kishan and his wife as well as to Fance Franck for their patient assistance with the preparation of the experimental ceramics. We sincerely thank Alain Gallay of the Department of Anthropology, Genève, for providing the ethnographic collection from Mali, as well as Annie Fourmanoir for providing some ceramic pieces.

We are highly grateful to Daniel Tessier of the laboratoire des Sols, CNRA, Versailles for skilful assistance with the study of clay physical behaviour. The staff at the laboratoire des Sols, CNRA, Versailles made the SEM available to us and kindly provided access to the porosimetry equipment. M.-A. Courty wants to express her appreciation for the stimulating discussions with Louis-Maire-Bresson, Nicolas Fedoroff, Chris Moran and Alain Pierret at the laboratoire de Science des Sols et Hydrologie, INA P-G.

Michael Chazan and Fance Frank are gratefully acknowledged for critical review of the paper and for improving the English.

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