REMANENT MAGNETISM OF SOME MODERN BRICKS AND A BRICK KILN-IMPLICATIONS FOR ARCHAEOMAGNETIC WORK.

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RESUMEN

Investigaciones arqueomagnéticas en restos arqueológicos, tales como cerámica, ladrillos, hornos y arcilla cocinada, pueden proveer datos valiosos para la datación y correlación en arqueología. En este trabajo se reportan resultados de un estudio arqueomagnético de un horno moderno, para fabricación de ladrillos. Los materiales estudiados contienen registros fieles del campo magnético ambiental, al tiempo del calentamiento. Dentro de las fuentes potenciales de error, se tienen variaciones en el equilibrio térmico dentro del horno. Ello puede afectar los trabajos de determinación de intensidad, pero las determinaciones de la dirección no son aparentemente afectadas.

ABSTRACT

Kilns for making bricks and pottery constitute common remains of ancient activities, and as such they represent valuable objects for archaeological work. Techniques based on the study of remanent magnetism of bricks, pottery and baked soil can provide a means for datation and correlation of these remains. A study of a modern brick kiln is here presented. It is found that these materials are reliable recorders of the direction of ambient Earth's magnetic field at the time of heating-cooling. There are however some potential sources of error, since temperature measurements indicate strong gradients, with places at less than 40% the central temperature of the kiln. There, the remanence is a partial-thermoremanent magnetization, and its use for archaeointensity determinations could lead to errors. The directions of remanent magnetism from all places sampled reproduced within the statistical uncertainties of the technique the observed geomagnetic field direction.

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INTRODUCTION

During the past few years studies of palaeomagnetism have produced a revolution in Earth sciences. Palaeomagnetic studies have proved valuable in many applications of a variety of fields, some outside the current scope of the Earth sciences (Irving, 1964, Tarling, 1971; McElhinny, 1973). One of these applications, which had an early start and now constitutes an important part of palaeomagnetism, is the study of archaeomagnetism (Fogheraiter, 1899; Thellier and Thellier, 1959; Aitken, 1961).

In Mexico and Central America the possibilities of these studies are great, since there is a very large number of archaeological sites, and an equally large number of interesting problems and questions to solve. So far, only a few archaeomagnetic studies have been carried out in Mesoamerica (see Urrutia-Fucugauchi, 1975 for a summary), and they have emphazised the value of such studies. In this context a long-term archaeomagnetic program has been undertaken at the Palaeomagnetic laboratory of the Instituto de Geofísica (Urrutia-Fucugauchi, 1975, 1976). This work constitutes a progress report on these efforts.

The principal aims of this work, which is concerned with the study of bricks and a brick kiln, are twofold. Firstly, it was tried to implement a routine, giving special emphasis on the estimation of the reliability and precision of results; and secondly, to study the thermal conditions and remanence acquisition mechanisms occurring in modern bricks and corresponding brick kiln.

THERMOREMANENT MAGNETIZATION AND ARCHAEOMAGNETISM

Archaeomagnetism is generally defined as the study of 'fossil' magnetism in materials from archaeological sites (Aitken, 1961). A considerable proportion of archaeomagnetic work is done on bricks from pottery kilns and ancient fireplaces. Bricks have usually a thermoremanent magnetization (TRM) dating from their last heating-cooling. TRM is acquired by cooling from high temperatures through the Curie temperature(s) of the magnetic mineral(s) in the presence of a magnetic field. The TRM will be proportional to this field, and it will be 'frozen' by further cooling through the blocking temperature(s) of the magnetic mineral(s). Subsequent to this process TRM may decay either partly or totally, and other remanent magnetizations may be originated by a number of processes. For instance, if the material is subject to chemical changes forming or altering magnetic minerals, a chemical remanent magnetization (CRM) may be formed. Other possible secondary magnetizations are: isothermal remanent magnetization (IRM) which may be acquired by exposition to magnetic fields at low temperatures; anhysteretic remanent magnetization (ARM), which may be produced during laboratory tests by the action of an alternating field and a direct steady field.

In the case of an assemblage of uniaxial single domain grains with initial magnetic moment M_0, the magnetic moment will follow an experimental relation

$$M_t = M_0 \, e^{-t/\tau} \tag{1}$$

where M_t is the moment at time t, and represents the relaxation time of the grains, which can be expressed as

$$\tau = \frac{1}{C} \, e^{\frac{\nu K}{kT}} \tag{2}$$

where C is a frequency factor ($10^{10} s^{-1}$), K is an anisotropy factor, k is the Boltzman constant, T is the absolute temperature, and ν is the grain volume.

If the relaxation time is small, let say in the order ot 100-1000 sec, the magnetization will decay soon after it has been acquired. On the other hand, if is large, the magnetization will be stable for long periods. We may also note that becomes small if the temperature increases, giving a critical blocking temperature, or if the grain volume decreases, giving a critical locking volume.

Alternatively, application of a given magnetic field at low temperatures will generate a magnetization, called viscous remanent magnetization (VRM). The rate at which VRM is acquired may increase if the temperature increases. VRM constitutes a common source of secondary overprinting. VRM differs from IRM in its coercivity characteristics.

Another possible effect which is capable of deviating remanent magnetizations from the original magnetic field is due to anisotropy. In general, TRM may be deflected away from the direction of the magnetic field towards the direction of maximum susceptibility or easy magnetization.

EXPERIMENTAL DETAILS

The brick kiln studied is of a relatively rudimentary type, very popular in most parts of Mexico. The kiln was formed by layers of adobe bricks (sun-dried blocks of clay), constituting a rectangular structure of some 3 meters high (Fig. 1). Two types of bricks were used for the kiln. The difference is only in the dimensions: ('Ladrillo') 6 x 10 x 22 cm. and ('Ladrillón') 7 x 14 x 28 cm. The introduction of fuel (usually wood or discarded industrial material) is made through a system of tunnels in the structure, which also serve as ventilation system. The disposition varies greatly with the size of the kiln, and the preferred design of the place.

The thermal conditions within the brick kiln were estimated by using two platinum-platinum/rodium thermocouples located in the kiln ground, near the center and one of the edges of the kiln (Fig. 1). The thermocouples were protected by silica plates. Miscellaneous woods were used to fire the kiln.

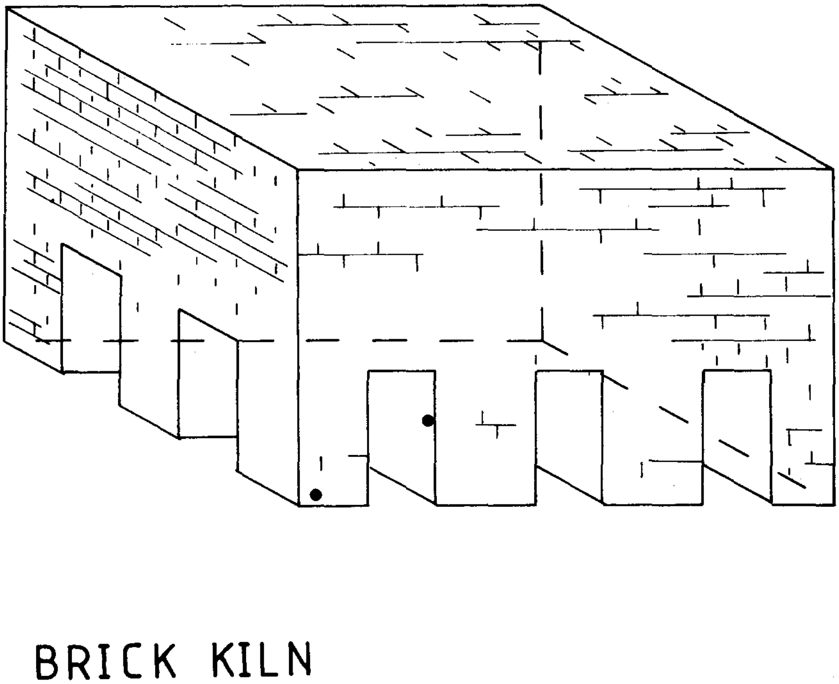

Fig. 1. Simplified schematic representation of a brick kiln showing the position of the two thermocouples (not at scale). Archaeomagnetic samples were collected from four zones: external zone comprising the central portion of some ~1 x 1 x 1 m; intermediate zone comprising the rest of the brick kiln; and the baked soil zone comprising the baked floor of the kiln.

After the firing, bricks which were chosen for the archaeomagnetic measurements were oriented *in situ* with a magnetic compass and carefully removed. Some few samples of baked soil of the floor were also oriented and collected. In the laboratory, one of two cylindrical specimens were drilled from each brick sample. The direction and intensity of remanent magnetism (NRM) was measured on a Digico complete results spinner magnetometer (Molyneux, 1971). Soil samples, which were of an irregular shape were measured on an archaeomagnetic attachment to the Digico meter. The stability of remanence directions was tested by alternating field (AF) and thermal demagnetization. AF demagnetization was carried out using a digitally controlled AF apparatus (de Sa and Widdowson, 1974). Thermal demagnetization was carried out by a progresive method using an electric furnace located in an automatically controlled magnetic field-free space (Stephenson, 1967). A viscosity test was performed in order to estimate VRM effects. Samples were left exposed to the Earth's magnetic field for periods of 15 days, first in a direct position and then in a reverse one. The intensities of remanent magnetization, RM_d and RM_r, were measured at the end of the periods. A viscosity coefficient was defined as (Smith and Prévot, 1976).

$$\nu = \frac{\overrightarrow{VRM}_{15\ days}}{\underbrace{(\overrightarrow{PRM} + \overrightarrow{VRM})_{in\ situ}}_{\text{Stable NRM}}} \times 100 \tag{3}$$

where

$$\overrightarrow{VRM}_{15\ days} = \frac{1}{2}(RM_d + RM_r)$$

$$\overrightarrow{PRM} = \text{primary remanent magnetization}$$

Then, samples were kept to a temperature of some 200°C for about 2 hours under the influence of a vertical laboratory field (intensity of 0.05 mT). From equation (2), and assuming that K , the anisotropy constant, does not vary with temperature, we have that

$$T_1 \ln C\tau_1 = T_2 \ln C\tau_2 \tag{4}$$

That is, by changing the temperature or the time we can have equivalent effects upon the remanences. For instance, by heating a sample to 200°C for only 2 hours, we could study the effects of maintining a temperature of 20°C for about 50 000 years. The results are simply expressed as

$$V - PTRM(\%) = \frac{NRM_{200} - NRM}{NRM} \times 100 \tag{5}$$

where V-PTRM represents a viscous-partial thermoremanent magnetization (Pullaiah *et al.*, 1975).

Finally, a long-term experiment was carried out in order to study an eventual NRM decay. Samples were left inside a field-free space for a period of about 6 months, during which some 4-5 measurements of remanent magnetism were carried out.

RESULTS AND DISCUSSION

The most interesting result of the temperature measurements was the confirmation of a strong thermal gradient, with temperature around 900°C near the center of the kiln to temperatures of less than 300°C at the edges (Fig. 2). The maximum temperature observed was of about 1000°C, and was attained at the center of the kiln during the peak of fuel wood supply. The temperature fluctuations approximately followed the fuel wood input variations.

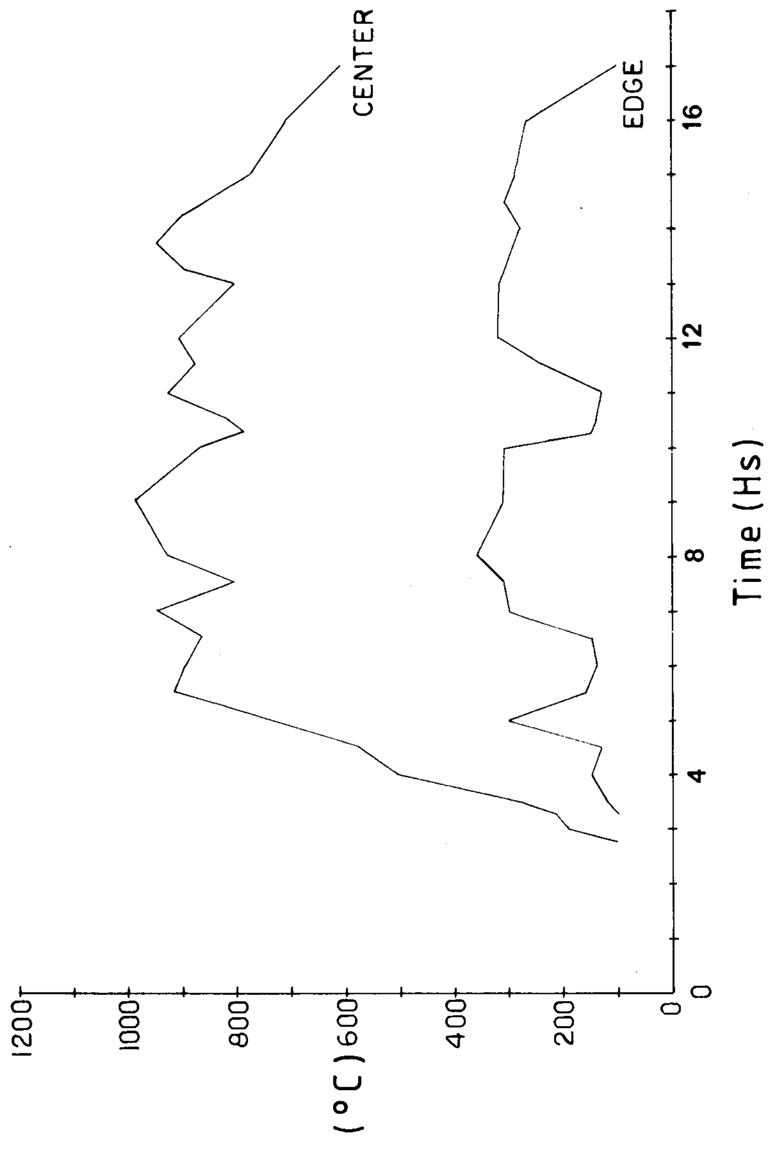

Fig. 2. Approximate temperature variation within the brick kiln. Absolute temperature measured could be in error since calibration and uncertainties were difficult to estimate.

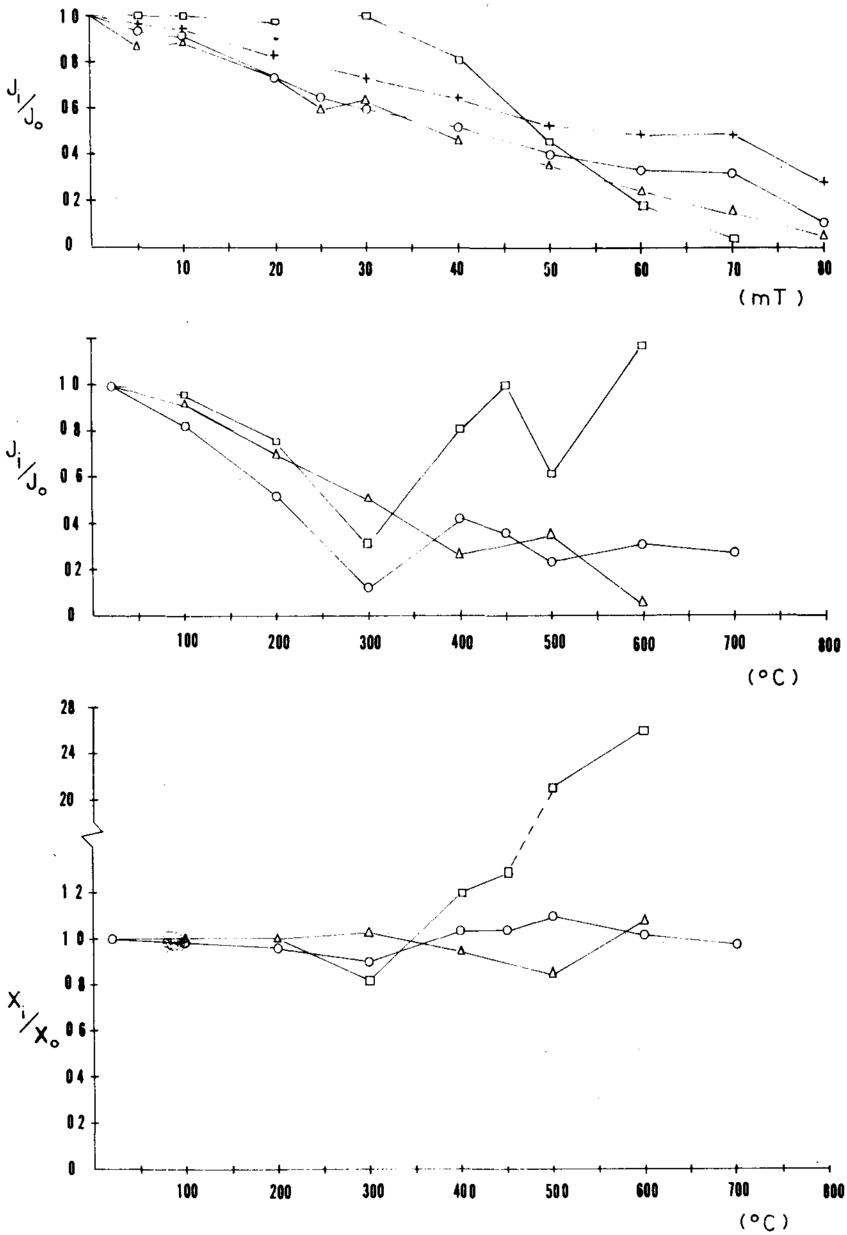

Fig. 3. Changes in intensity of remanent magnetism in response to (a) AF demagnetization and (b) thermal demagnetization. Samples marked by • correspond to the internal zone; samples marked by + and ▲ correspond to the intermediate zone; and samples marked by ■ correspond to the external zone. The changes in bulk susceptibility with the thermal treatment are included in Figure (c).

The initial directions were well grouped around the present geomagnetic field direction. This direction was estimated at the experiment site, with a topographic orientation, and magnetic compass and inclinometer. The parameters are declination 5° and inclination 60°. The intensity measured with a proton magnetometer was about 49 750 nT (gammas).

The pilot samples were very stable to both AF and thermal demagnetizations. In general, the intensity decreased with the treatments (Fig. 3a, b). Comparison of the results for the three zones, seems to indicate that samples from the external zone were more susceptible to oxidation during laboratory heating. It is likely that conditions within the furnace varied depending upon position (e.g. see temperature variations in Fig. 2), and that predominantly oxidizing and reducing atmospheres were present. It was observed that most bricks presented a reddish colour after heating, whereas some others presented a dark red-black colour. This however is not a good indicator since variations in composition of e.g. aluminum and iron oxides could produce similar colour changes. During laboratory heating, the pilot sample from the external zone suffered chemical changes with large increases in intensity and susceptibility (Fig. 3b, c), possibly as a result of laboratory oxidation.

The viscosity tests indicated that viscous effects are of negligible importance The viscosity coefficients were lower than 4% in the external zone, and even lower in the other zones (Table 1). Results of the long-term zero-field storage also indicate that viscous effects and remanence decay are very small. The variations observed did not follow a consistent path, and are possibly due to instrumental fluctuations and measurement errors, with a small real magnetic behaviour (Table 1).

Table 1.

Results of viscous test and long-term zero-field storage

Site	No. of Specimens	ν (%)	V-PTRM (%)	Zero-field intensity variation (% of initial intensity)
1. Exterior	3	3.6	7.5	± 15
2. Intermediate	5	3.5	6.7	± 6
3. Interior	3	0.7	3.1	± 7
4. Baked soil	2	1.4		

All remaining specimens were AF demagnetized at a 30 mT field. The treatment reduced slightly the initial dispersion. For the statistical analysis, unit weight was given to specimen directions to compute sample means; then sample means were given unit weight to compute site means (Irving, 1964). Fisher statistics was used for the analysis (Fisher, 1953). Results are summarized in Table 2. The precisions are very high (k large, and α_{95} and θ_{63} small), which indicates stable remanences.

Table 2.

Summary of archaeomagnetic data: bricks-brick kiln

Site details	No. of Specimens	Dec (°)	Inc (°)	k	α_{95}	θ_{63}
1. Exterior	6	5.7	58.2	237	4.4	5.3
2. Intermediate	13	5.2	56.5	240	2.5	5.1
3. Interior	5	6.1	60.1	239	4.2	4.4
4. Baked soil*	4	3.5	59.8	130	8.1	7.1

* Results correspond to initial data (no demagnetization tests were applied).

The mean directions correspond closely with the expected directions of declination 5° and inclination 60° (Fig. 4). The k values are very similar for brick samples of the three zones (Table 2). In an attempt to observe any possible dependance on the number of samples used, a simple experiment was designed. All sample directions of site 2 (Intermediate zone) were written down in cards. Then these cards were drawn at random, and were used for computing the corresponding Fisher statistics. A typical result in terms of the k parameters is shown in Figure 5. In general, fluctuations occurred when the number of samples was less than 7-8. The fluctuations however were between the expected 95% confidence limits (Cox, 1969). Nevertheless, these results suggests that an optimum number of samples per site is of about 7-8.

The results support that bricks and baked soil from kilns are reliable indicators of the direction of the geomagnetic field at the time of the last heating-cooling. Care should be taken in selecting the samples; this because the thermal conditions and heating-cooling environment can vary drastically within a given kiln, thus affecting the magnetic properties and remanence record. I should mention however that most samples of pottery and bricks currently analysed for archaeomagnetism come from smaller kilns, and in many cases with a single opening. The remanent magnetization direction is close to the ambient field in the cases studied, and no major problems have been detected. Problems, however, may occur in archaeointensity studies (Thellier and Thellier, 1959). The TRM of samples from the exterior zone and possibly of parts of the intermediate zone is a partial TRM. Methods of intensity determination which involve laboratory TRMs (Thellier and Thellier, 1959; Shaw, 1974; Urrutia-Fucugauchi, 1980a, b) will then give an error in intensity values. Also, the effects on the TRMs of varying partial oxygen pressure and iron oxide composition should be taken into account (Kono and Tanaka, 1977; Urrutia-Fucugauchi, 1979). A logic next step in this project is the study of a reconstructed ancient pottery kiln.

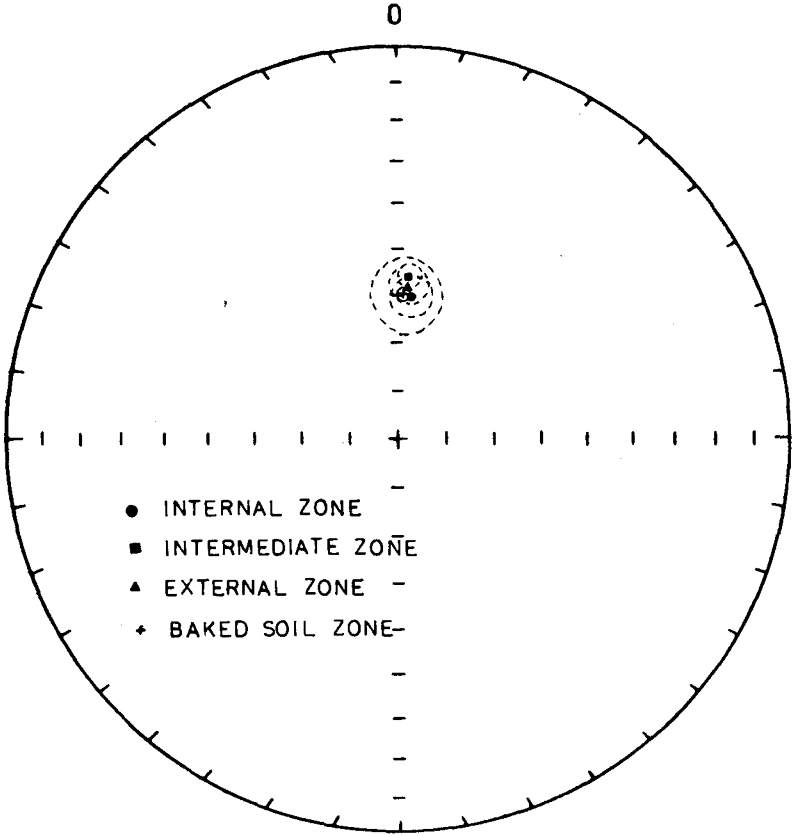

Fig. 4. Mean directions determined for all zones within the brick kiln (see Fig. 1). The observed geomagnetic direction is indicated by +.

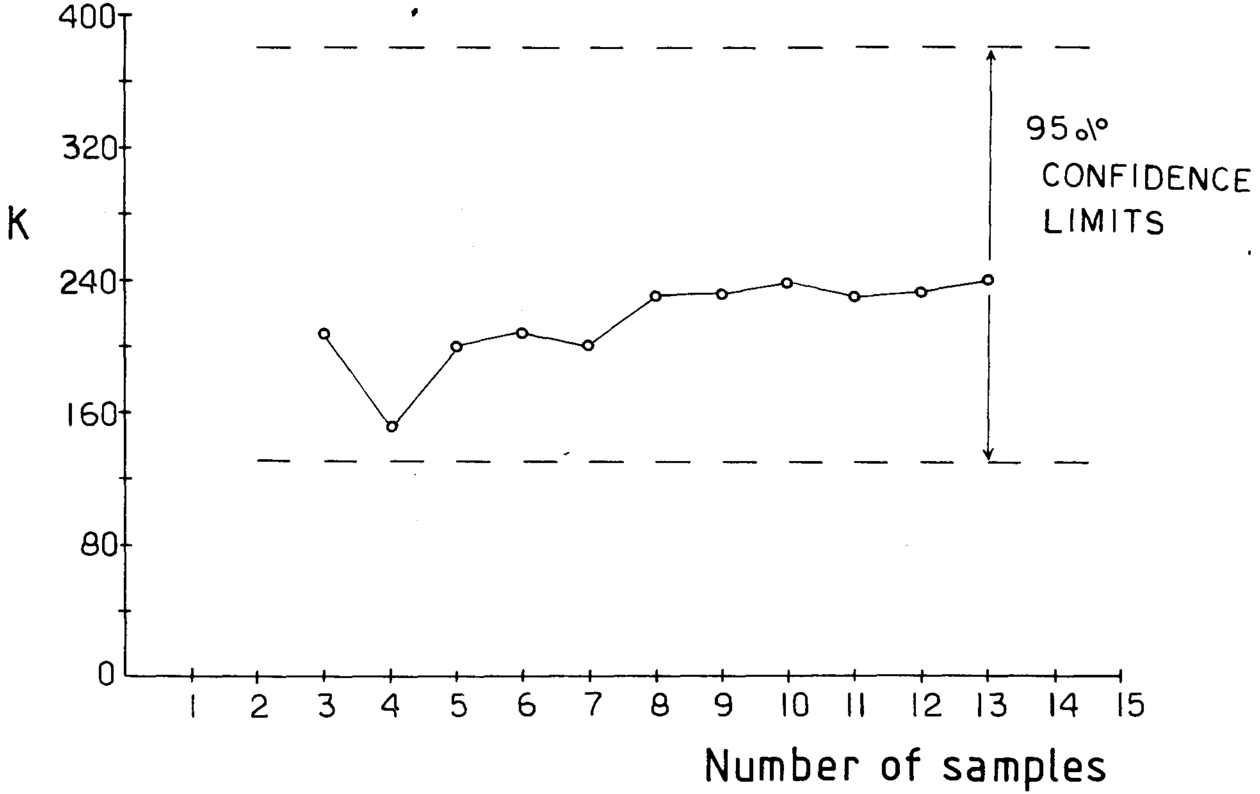

Fig. 5. Variation of the parameter k with number of samples. Sample directions were chosen at random and used for the analysis. The 95% confidence limits for N = 13 are also indicated.

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