CONTRASTING REGOLITH STRUCTURES: HYDROPLASTIC UNDULATIONS OR FLUIDISED PIERCEMENT GIVING MEGALOBES

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SUMMARY

Gilgai, seismites and periglacial patterned ground in the regolith, and in shallow water, can have much in common such as lobes, circles, polygons and stripes, even though their formative processes may vary. Expansion, contraction, loading, sorting, convection and shock may singly or together be involved. In this study from Accra, Ghana (Figure la), 700 m of regolith are exposed in a road section. There is reverse density grading of pisolitic ironstone (2.5 gcm^{-3}), quartz breccia (2.1 gcm^{-3}) and cracking clay (1.8 gcm^{-3}). Initially, at the margin of the gentle spur, ironstone loaded into quartz breccia gives sinusoidal undulations. Later, as the weathering of the bedrock Archaean gneiss proceeded, cracking clay in the centre pierced and engulfed lobes of breccia.

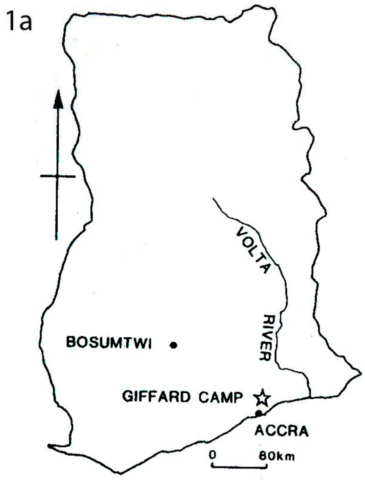

FIGURE 1a. LOCATION MAP OF ACCRA, GHANA. BOSUMTWI IS 160km FROM GIFFARD CAMP

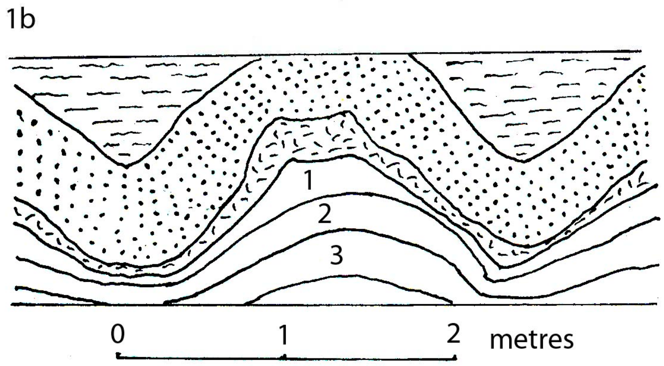

Figure 1a: Location map of Accra, Ghana.
b. Three layers of cracking clay beneath breccias.

PREVIOUS WORK

Bruckner (1955, 1956, 1957) recognised three rhythmic climatic variations going back to the mid-Pleistocene. They were: arid - breccia and stone layers; humid - layers of rotten rock; and, semi-arid - limonitic crust. A later study by McCallien *et al.* (1964) confirmed three stone layers and three increments of clay (labelled "1" "2" "3" in Figure lb). Megalobes of breccia in cracking clay also showed three stages of development: engulfment; basal central sagging; and, sideways injection of a pipe (Figure 3a). In places vertical mushroom structures have been tilted sideways like those in Western Poland, which are of the Saalian glacial age, some 340 ka (Brodzikowski & Van Loon 1980). There was a notable wet and warm period at this time (Brown *et al.* 1994, Maher & Thompson 1995, Dupont *et al.* 2001). The Giffard Camp sections at Accra could date from this time. The quartz breccia was derived from quartz veins in the Dahomeyan Gneiss concentrated on a former beach now at 36 m above sea level (Hilton 1966). A similar beach and quartz breccia deposit occurs at Kenai Lake in Alaska associated with the earthquake of 1964 (McCulloch 1969). The pisolitic ironstone may have originated as a glauconitic sand layer subsequently weathered. Later neotectonics caused the raised beach to be deformed to different levels (Anderson & Bruckner 1957). The shock of the Bosumtwi impact event at 1.07 Ma seems to pre-date the regolith structures (Jones *et al.* 1981), though four major earthquakes have shaken Accra in the last four hundred years.

STRATIGRAPHY

Clayey silt with the texture of the parent rock preserved gives way upwards to heavy cracking clay (Table 1). Together they form the sedentary weathering profile that may be several metres in thickness. Numerous quartz veins occur. Profiles are thin on the margins (0.5-l m) where there is subequal kaolinite and vermiculite (from biotite). In the centre cracking clay is thicker (1-3 m) being mostly montmorillonite. The quartz breccia is a lag concentration of muddy gravel with up to 20% clay plus silt. The massive quartz has abundant inclusions in two planes at right angles causing it to split into platy fragments. The plates trace out the flow movement. The pisolitic ironstone is also a muddy gravel but it does not show structure. It contains about two thirds iron oxy-hydroxides with common quartz in the centre of sub-spherical pisolites. Its origin is obscure. Either it was derived from a red loam ferruginized from upslope by iron-bearing colloids forming a 'bas-glacis' (Gunnell 2003) or it was a glauconitic marine sand of tsunami origin (Nahon *et al.* 1980). Small basin-fills and thin spreads of loam of two generations bore numerous termite mounds sometimes concentrating stone lines beneath their base. In places it is a double layer with the lower one deformed.

Table 1: Stratigraphy at Giffard Camp, Ghana.

Brown Loam (Termite Mounds)
Upper Stone Layer

____________Disconformity____________

Dark Clayey Loam
Lower Stone Layer

____________Unconformity____________

Pisolitic Ironstone
Quartz Breccia

____________Unconformity____________

	[Clay 1
Weathering	[Clay 2
Profile	[Clay 3
	[Saprolite Clayey Silt

Bedrock- Dahomeyan Biotite Gneiss (west),
Garnet Hornblende Gneiss (east)

THE STRUCTURES

Deformation began at the margins with loading of the heavier ironstone into the quartz breccia forming a gilgai-type pattern of sinusoidal undulations with a wavelength of three to six metres (Figure 3c). Some doughnut shaped masses of quartz breccia similar to those of cold climates (Krantz 1990) also occur (Figure 2b). A hydro-plastic mechanism is sufficient to explain movement of these features (Paton 1974). A second, later generation of structures in the centre of the spur was due to the heaving and churning of the buoyant cracking montmorillonitic clay which pierced and enfolded the breccia to form circular mega-lobes (Plaziat *et al.* 1990) (Figure 3a). These in turn shrink by clay splitting off the ends and blunting corners. Between the megalobes the kankur in the clay bunches up, in places piercing through to the surface in vertical clay pillars. Locally, the thrust planes with slickensides formed around spherical pressure centres. Two special vertisol structures were developed. Bi-convex lentils bounded by oblique planes of cleavage formed by lurching (Raistrick & Marshall 1939, Krishna & Perumal 1948) and recumbent-folded omelette structures on a thrust plane (Leeder 1987) (Figure 3d, e). Other features include overturning, smashed quartz 'balls', mushrooms and diapirism of clay. The main times of movement were when earthquakes greater than

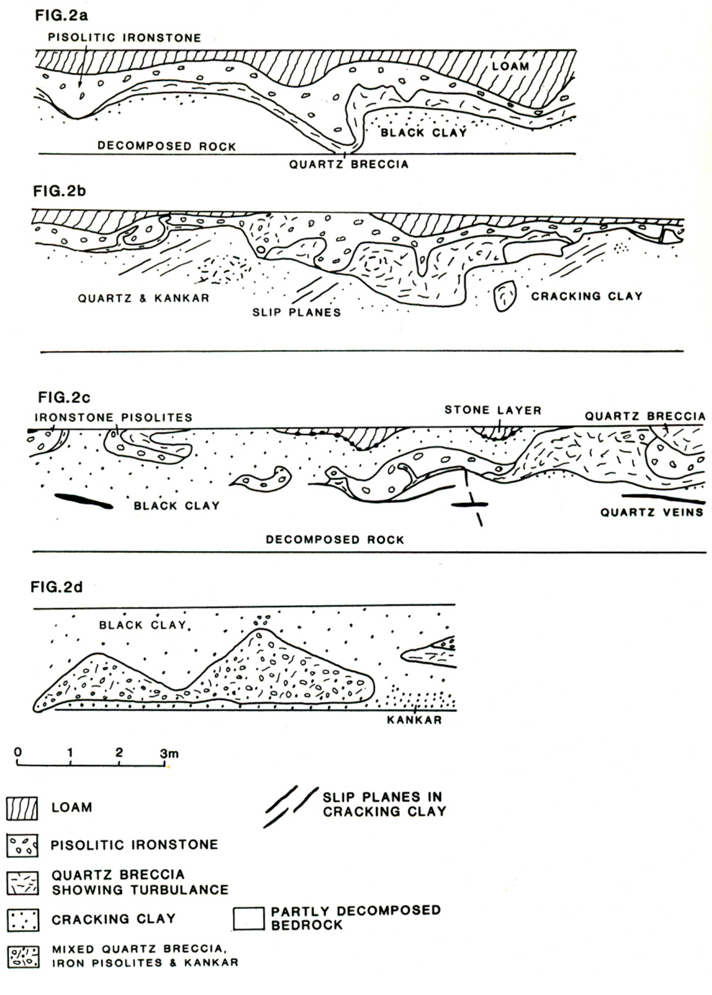

Figure 2a: Symmetric and asymmetric loading. **b**. Uprising cracking clay with central kankur ball and quartz breccia toroid. **c**. Advanced stage of breakup and local overturning. **d**. End stage in bags containing quartz, pisolites and kankur.

VIII coincided with a waterlogged clay in the middle of the wet season, as in June 1939. The forces available are 15 kg cm^{-2} for swelling clay and over 100 kg cm^{-2} due to cycles of stress in gravity waves (Lomnitz 1990). The latter strong enough to tear the quartz veins apart.

SIMPLE TO COMPLEX

Convolutions in Oligocene coastal sands in the Paris Basin are said to have been formed by a single triggering event. A storm surge or an earthquake can cause liquefaction (Cojah & Thiry 1992). Semi-continuous plastic flow, however, is typical of clay diapirism and extrusion through overlying clastic deposits (Schwan *et al.* 1980). Many structures, often in gravel with high internal friction, are frozen only part way through their evolution towards the level of neutral bouyancy. A clear example is in the glaciolimnic deposits in Western Poland (Brodzikowski & Van Loon 1980). Upward protrusions of gravel by loading were followed by sagging and tilting. Most complex is a combination of clay diapirism, thrusting, overturning of gravel, and stretching (Kahle 2002) and thinning like boudinage. Small surface basins are filled with loam and a stone layer which are deformed in sympathy with a wavy thrust plane (Figure 2c). One end point is a series of bags of breccia (Virkkala 1959) in a clay matrix (Figure 2d).

PROCESSES

Under special circumstances an earthquake of Richter magnitude 7 can liquefy gravel, though with increasing mud matrix cohesion can prevent movement. Above a content of 15% clay the soil may be matrix-supported. If saturated, an activation energy of 7 $kcalmole^{-1}$ is enough to overcome inertia causing a quick condition (thixotropy). Viscosity of the mud slurry may be reduced from 10^5 poise to 2 x 10^3 to 3 x 10^4 poise (Ruxton 1985), which is enough to allow movement of muddy gravel. If the geometry and pore pressure are right, fluidisation can commence. Particles can be aligned in the direction of movement forming flow patterns (McLaughlin & Brett 2004). With sufficient density differences loading alone in saturated layers may cause hydroplastic deformation often with 'push aside' structures as in gilgai fields. Piercement phenomena may require some form of shock as with earth tremors or even thunderstorms (Haantjens 1965) particularly on slippery clay. Some other processes can produce pit and mound microrelief: tree throw (Embleton-Hamann 2004); and large worms (Haantjens 1965). Following on from Table 2, can orthogonal fissures caused by activated crossing faults produce a polygonal pattern such that later rounding of corners would produce flattened spherical shapes—megalobes? Then can plastic shear flow of the granular material lead to fluidization after liquefaction? Shapes of breccia masses are such that there is minimal surface area so giving few sharp corners and many spheres (Demoulin 1996), toroids, bulbous forms, bowls and cones. Pore water pressures are different in clay and breccia, the boundary being similar to a semi-permeable membrane (Heidecker 1968). The breccia groundmass, when saturated, would be a swollen gel. When the activation energy of the potassium bentonite is exceeded (7 kcal $mole^{-1}$) the pisolitic fine conglomerate would burst out

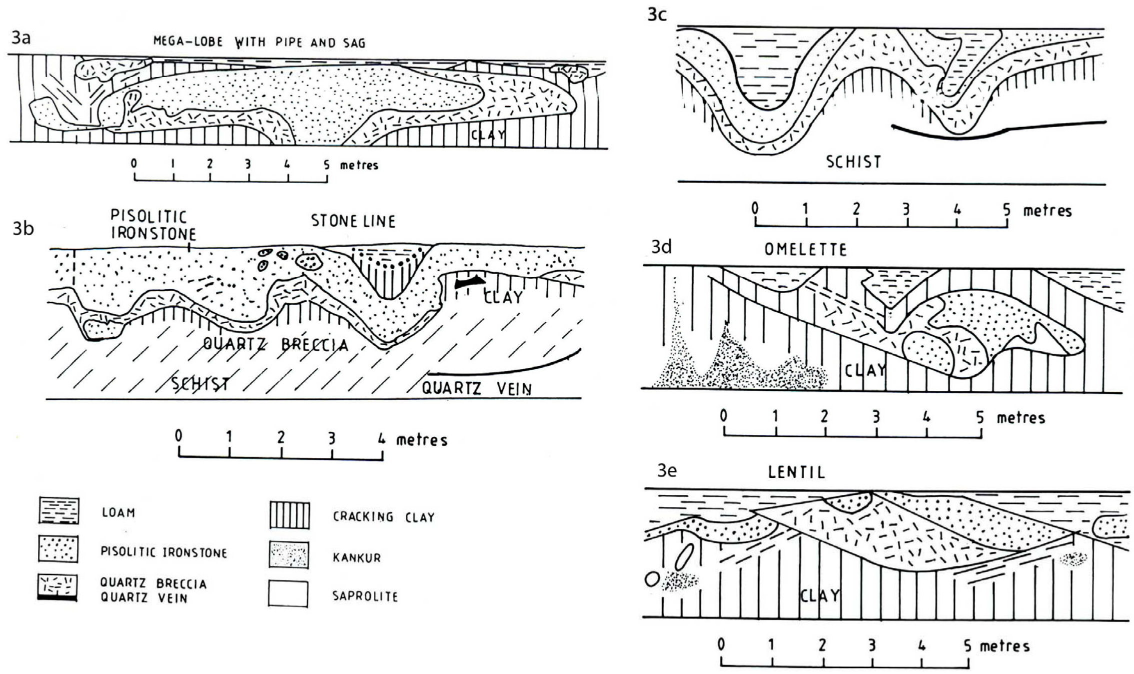

Figure 3a: Cracking clay engulfing a megalobe. **b**. Pisolitic ironstone planed off by erosion and a deformed stone layer in loam. **c**. Hydroplastic undulations. **d**. Recumbent-overfold 'omelette'. **e**. A lurching lentil structure.

into the cracking clay (Figure 3a). The slurried mixture injected would have a viscosity of less than 10^5 poise (Visher & Cunningham 1981). Syneresis causes micro-cracks in the quartzite allowing whisps of clay to enter producing local pressure, fracture and breakage.

Table 2: some properties and processes.

	Margin	Centre
Bedrock	Acid gneiss	Basic gneiss
Structure	Undulating	Piercement, lobe
Wavelength	3-6 m	11-15 m
Clay	50% kaolinite	Montmorillonite
Viscosity slurry	10^5 Poise	2×10^3 Poise
State	Plastic flow	Liquefaction
Fluidisation	> 2 cm/sec	> 0.3 cm/sec
	Gravel	Saprolite
Friction angle	32°	21°
Pressure	Syneresis	Leaky osmosis
Activation energy	Bingham slurries	3-7.5 kcalmol^{-1}

DISCUSSION

With three unconformities one would expect the age of the older structures to be of the order of 10^5 years. Obermeier (1996) claimed deposits less than 80 ka old would be too loose to develop the structures and not more than 240 ka old because cohesion and diagenesis would make them too indurated to be disturbed. The swelling clay is still active but most of the pisolite-breccia masses are fossil. In addition, surface mapping revealed that slightly raised outcrops lay on the circumference of two large circles 47 m in diameter. Such palimpest patterning would be ancient. The third previous humid and warmest period at 340 ka is suggested (White 2004). The large circles may be secondary 'protrusions' of Parker & McDowell (1955). Denudation rates on the ferruginized surfaces in West Africa are extremely low (Gunnell 2003) usually less than 2 m/My. In contrast, the rate of formation of an iron crust can vary between l mm/300 y in Guinea (Nahon & Lappartient 1977) and l mm/y at Conakry (Percival 1965). For chemical weathering on acid gneiss in West Africa, Nahon (1986) estimates 1 m of saprolite would take 50 ky to form as on the margin of the spur at Giffard Camp. Basic gneiss in the centre of the spur would weather twice as fast. Mechanical erosion would dominate in the semi-arid time (Langbein & Schumn 1958). Presently Accra is typical dry savannah (Hilton 1966) with seasonal climate of 732 mm average annual rainfall and 26°C mean annual temperature. Biotite is abundant. It weathers to vermiculite which breaks down to iron oxide and amesite.

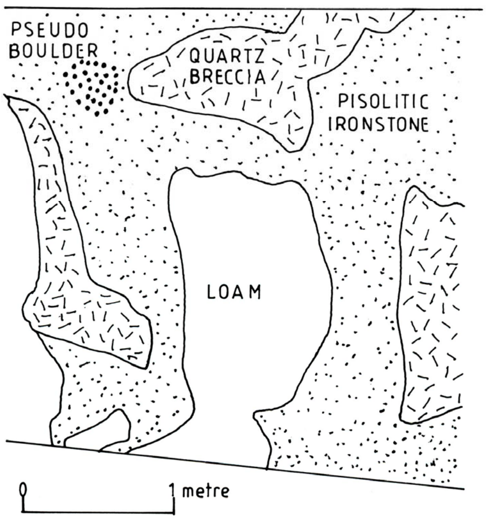

Figure 4: Map of surface polygon.

EARTHQUAKES

Accra, Ghana, lies at the intersection of two faults on the coast of West Africa: one E-W; and one NE-SW. Two major earthquakes occurred on the mainland in Accra in 1862 (MM 9) and in 1906 (MM 7, closest to the site studied). An offshore earthquake, some 30 km south of Accra, in 1939 was MM 9. Aftershocks lasted for nine months. Also early on in 1636 there was another large earthquake (Ruxton 1996).

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