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THE EARTH'S DEEPER CRUST: CASE HISTORIES FROM AFRICA

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ABSTRACT

A recently published review of African granulite facies rocks and charnockitic intrusives (Clifford, 1974) is supplemented by a consideration of certain detailed studies: geochronological data for Namaqualand, Uganda and Nigeria are considered in relation to available data from other African occurrences; studies of paragenetical mineralogy of rocks of specialized chemistry from Namaqualand and Rhodesia are highlighted; and the polyphase deformation in Namaqualand, Uganda and elsewhere is stressed. Finally, the economic aspects of granulites and intrusive charnockites are discussed.

The available information on the petrology and age of granulite facies rocks and associated intrusives of the charnockite suite has recently been reviewed (Clifford, 1974), and the distribution of these rocks has been discussed in terms of the structural domains in which they occur (fig. 1). This present paper emphasizes certain detailed studies of selected occurrences; notably mineral-paragenesis, geochronological and structural studies.

Amongst the wide range of African granulite-charnockite occurrences, Namaqualand (fig. 1) offers a good example of the application of a wide range of Earth Science techniques. In essence, the major part of the region is underlain by a sequence of predominantly gneisses and granulites of granitic composition, with quartzite and schist and a number of more local rock-types including hornblende and/or hypersthene gneiss and granulite; recognizable metasedimentary and metavolcanic rocks are usually ascribed to the Kheis System (Martin, 1965, p. 59). In the western part of the massif, Joubert (1971) has identified seven deformational episodes (designated F_{1-7}) prior to the deposition of the Upper Precambrian; of these F_1, F_2 and F_3 are the most important regional episodes of folding. He recognized, moreover, that the principal phase of regional metamorphism (M_2) accompanied and outlasted the major phase of isoclinal and recumbent folding (F_2). That metamorphism progresses from greenschist facies at the Atlantic Coast on the west, via kyanite- and sillimanite-bearing amphibolite facies assemblages, to granulite facies to the east and southeast (*ibid.*). The grade of metamorphism also

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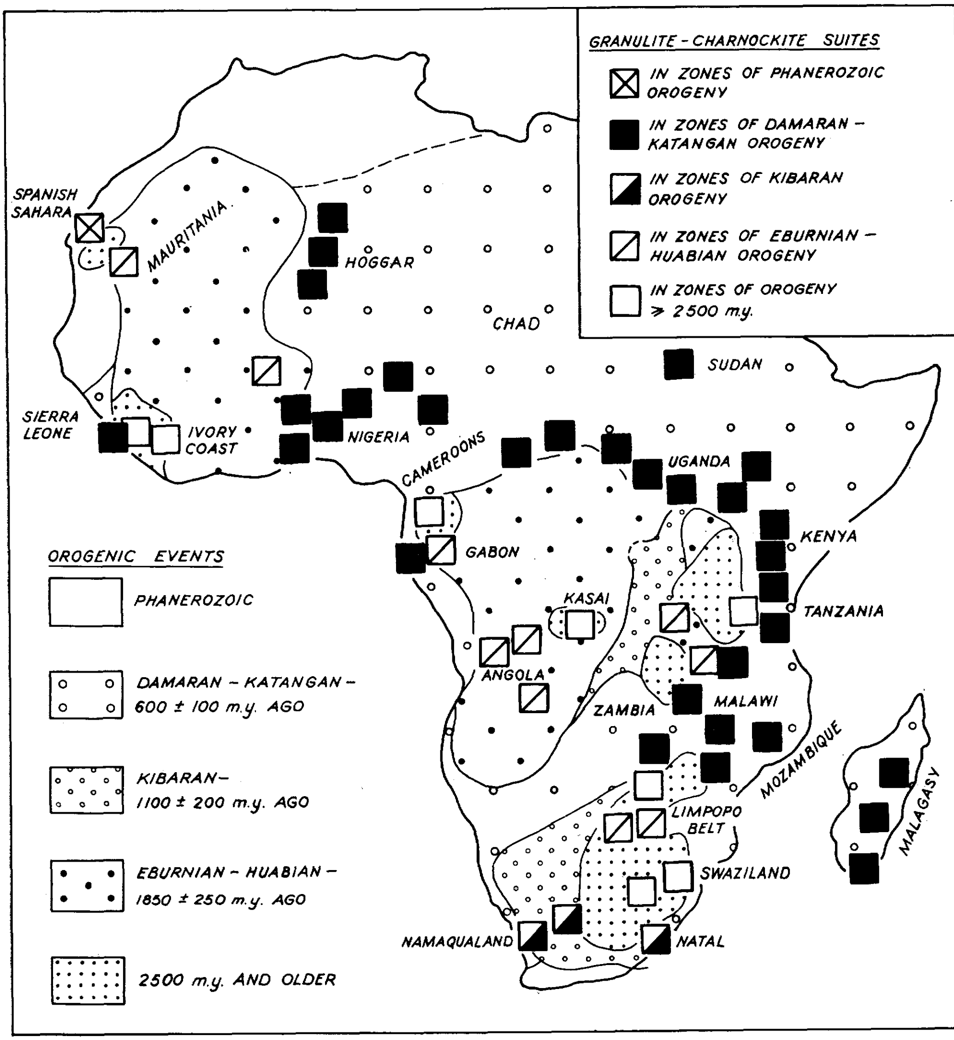

FIG. 1. — *The distribution of granulite-charnockite suites shown in relation to the structural units of Africa.*

increases southwards and southwestwards from the Orange River; and from all of these data Joubert (*ibid.*, p. 123) suggests that the Namaqualand granite-gneiss massif is the site of a major regional thermal dome. Within this region particular interest attaches to the Nababeep district because of the presence of important bodies of cupriferous diorite, norite, anorthosite and hypersthenite that are grouped as the noritoid suite (Benedict *et al.*, 1964). Moreover, this area lies on the western edge of the culmination of M_2 metamorphism and has recently been the subject of detailed isotopic investigations (Clifford *et al.*, in press). These data are presently being supplemented by a comprehensive geochemical study of the metamorphic rocks and areally associated intrusive granites (by T. S. McCarthy) and of the ore-bodies (by D. Van Zyl). In addition, detailed electron microprobe analyses are being carried out by E. F. Stumpfl on the mineralogy of the metamorphic rocks and the ore-bodies.

The elevated grade of metamorphism in the Nababeep district is illustrated by the absence of primary muscovite and the presence of sapphirine-cordierite-bronzite, sillimanite-garnet-perthite, sillimanite-cordierite, and hypersthene-diopside-plagioclase assemblages in rocks of appropriate composition. Of these assemblages, the sapphirine-bearing paragenesis (Clifford *et al.*, in manuscript), is particularly worthy of note because of: (*a*) the instability of cordierite + spinel indicating pressure above 3.5 Kb and temperatures in excess of 765 °C (Seifert, 1974); and (*b*) the high alumina content (7.0 %) of the bronzite suggesting that temperatures close to 1 000 °C may have been attained (Anastasiou and Seifert, 1972). Additionally, almandine-rich garnets in associated quartzo-feldspathic rocks contain up to 20 %

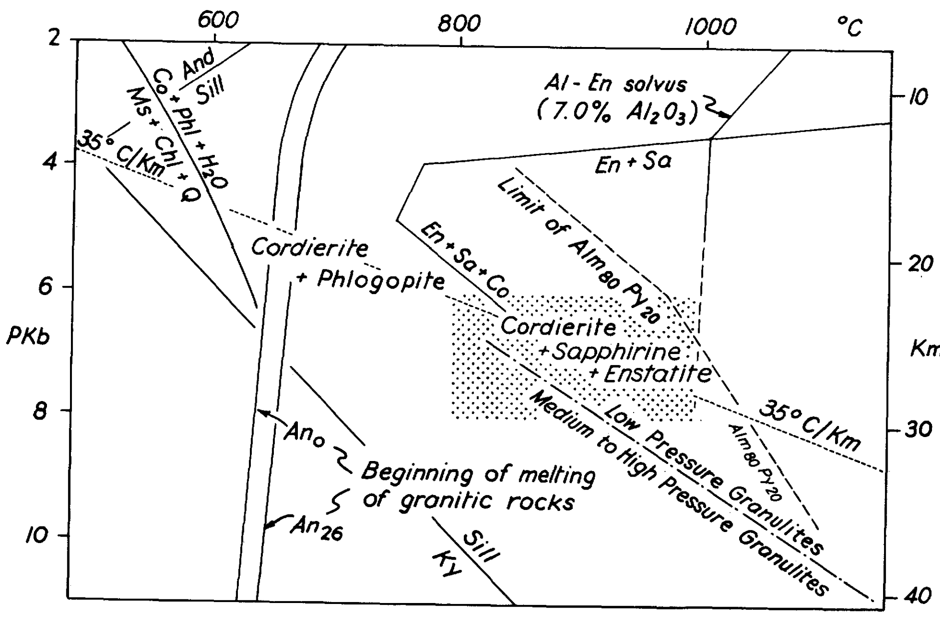

FIG. 2. — *Generalized PT field of metamorphism (stippled) in the Nababeep district, Namaqualand, South Africa, shown in relation to experimental data for: the stability of enstatite (En) plus sapphirine (Sa) plus or minus cordierite (Co), from Seifert (1974 and in manuscript); the PT fields of andalusite (And), kyanite (Ky) and sillimanite (Sill), given by Holdaway (1971); the breakdown of muscovite (Ms) plus chlorite (Chl) plus quartz (Q)* to *cordierite plus phlogopite (Phl) plus vapour, from Seifert (1970); the boundary between low-pressure granulites and medium-to-high pressure granulites, from the work of Green and Ringwood (1967); the upper stability of garnet $Alm_{80}Py_{20}$ (stable to the left), based on an interpolation of the data for almandine and pyrope given by Keesman* et al. *(1971) and Schreyer (1968) respectively; the beginning of melting of granitic rocks from Luth* et al. *(1964) and Winkler (1970) for An_0 and An_{26} respectively; and the Al-En solvus based on data given by Anastasiou and Seifert (1972).*

of the pyrope molecule; utilizing the curves for the stability of pyrope and almandine determined by Schreyer (1968) and Keesmann *et al.* (1971) respectively, the "crude" approximation to the minimum stability of $Alm_{80}Py_{20}$ (see fig. 2) gives some measure of the minimum pressure limit in the area. Finally, certain horizons are characterised by the assemblage hypersthene-diopside-plagioclase in rocks of basaltic composition; since these include olivine-normative types (T. S. McCarthy, personal communication) the coexistence of two pyroxenes plus plagioclase, suggests medium-to-high pressure conditions (Green and Ringwood, 1967; Lambert and Heier, 1968, p. 32). These data are summarized in figure 2 and indicate a pressure of 6-8 Kb and temperatures of up to 1 000 °C.

Rb-Sr isotopic data have been presented for a wide range of metamorphic and intrusive rocks of the Nababeep district, together with U-Pb isotopic data for the constituent zircon and apatite (Clifford *et al.*, in press). The metamorphic suite has yielded a Rb-Sr whole-rock isochron age 1 213 ± 22 m.yr. (1), with an initial $^{87}Sr/^{86}Sr$ ratio (R_0) of 0.7191 ± 0.0021 suggesting reworking of pre-existing crustal rocks; data from certain distinctive rock-types, including the hypersthene-diopside gneiss, indicate that Sr-isotopic homogenization was incomplete during this event.

TABLE 1. — *Summary correlation of dated events* (a) *in the Nababeep district, Namaqualand*

Age in m. yr.	Deformational and metamorphic events	Intrusive events
900 1 000		Emplacement of pegmatites
1 070 ± 20	F_{3b} tight folding	Emplacement of noritoid bodies
1 166 ± 26	F_{3a} east-west trending open folding	Emplacement of Rietberg granite
		Emplacement of Concordia granite
1 213 ± 22	F_2 recumbent folding M_2 granulite facies metamorphism	
	F_1 folding M_1 metamorphism	

(a) Based on data given by CLIFFORD *et al.* (in press), JOUBERT (1971 and 1972), and BENEDICT *et al.* (1964).

(1) All Rb-Sr ages in this paper refer to a ^{87}Rb decay constant of 1.39×10^{-11} yr^{-1}.

Cross-cutting granites and related rocks give a Rb-Sr isochron age of 1 166 ± 26 m.yr., and these events were post-dated by the intrusion of largely dioritic bodies of the cupriferous noritoid suite; zircon recrystallization 1 070 m.yr. ago is interpreted as the age of emplacement of these bodies. Isotopic events at 1 000 and 900 m.yr. ago, recorded by zircon and apatite, are believed to reflect the imprint of regional pegmatite emplacement. Table 1 summarizes this sequence of dated events and serves to emphasize: (1) the delicate interplay of metamorphic, deformational and structural events in Namaqualand; and (2) the structural correlation of this

TABLE 2. — *Ages of African granulite-charnockite suites* ([a]) *in relation to the structural units in which they occur* (see fig. 1)

Structural domain (and age of last major orogenesis)	Territory	Age of granulite-charnockite suite in m. yr.	Dating method
⩾ 2 500 m. yr.	Congo	2 860 ± 120	Rb-Sr (isochron)
		3 020 ± 125	Rb-Sr (isochron)
		2 865	U-Pb (mineral)
	Ivory Coast	2 860 ± 140	Rb-Sr (isochron)
		2 915 ± 115	Rb-Sr (isochron)
	Sierra Leone	⩾ 3 020 ± 50	Rb-Sr (isochron)
	Cameroons	> 2 490	Pb/α (mineral)
	Gabon	> 2 500	Pb/α (mineral)
	Tanzania	2 280 – 2 750	Rb-Sr (isochron)
Eburnian-Huabian (1 850 ± 250 m. yr.)	Mauritania	3 090 ± 135	Rb-Sr (isochron)
	Southern Africa (Limpopo Belt)	> 2 690 ± 60	Rb-Sr (isochron)
Kibaran (1 100 ± 200 m. yr.)	South Africa (Namaqualand)	1 213 ± 22	Rb-Sr (isochron)
Damaran-Katangan or Pan-African (600 ± 100 m. yr.)	Algeria (Hoggar)	3 030	Rb-Sr (isochron)
	Uganda	2 655 ± 117	Rb-Sr (isochron)
		2 900	U-Pb (mineral)
	Rhodesia	> 2 850 ± 50	Rb-Sr (mineral)
	Sierra Leone	> 2 600	Rb-Sr (rock)
		> 1 340 ± 130	K-Ar (mineral)
	Nigeria	> 2 340 ± 70	Rb-Sr (isochron)
		> 635	Rb-Sr (isochron)
	Dahomey (Kouandé Gneiss)	⩾ 1 750 ± 230	Rb-Sr (rock)
	Malawi	1 122 ± 29	Rb-Sr (isochron)
	Tanzania (Pare Mts)	936 ± 63	Rb-Sr (isochron)
	Kenya	> 855 ± 30	K-Ar (mineral)
	Tanzania (Loibor Serrit)	731 ± 8	Rb-Sr (isochron)

([a]) The sources of reference are given in CLIFFORD (1974).

region with the Kibaran zone of 1 100 ± 200 m.yr. orogeny in eastern Zaire (Congo), Rwanda, Burundi and southwestern Uganda (Holmes, 1951; Cahen *et al.*, 1972).

Although there have been few similar detailed multi-disciplinary studies of other granulite-charnockite occurrences in Africa, a number of excellent studies in specialized branches of Earth Science have been published. In particular, important advances have been made in the field of geochronology. These data are summarized in Table 2, and indicate at least two important events of granulite facies metamorphism at c. 2 900-3 000 and 1 200 m.yr. ago; and it is of interest to note that comparable events at c. 2 900 and 1 000 m.yr. ago have been recognized in Madagascar (Vachette *et al.*, 1969). Of these events, evidence for the 1 200 m.yr. granulite facies metamorphism is most extensively preserved in the Namaqualand segment of the Kibaran orogenic zone discussed above. In contrast, examples of c. 3 000 m.yr. granulite facies metamorphism occur widely in Africa and include notable occurrences, with associated charnockitic intrusives, in Kasai (Congo), Sierra Leone, Ivory Coast, Gabon, Cameroons and Tanzania. In addition, a large number of similar suites that occur as remnants in more modern orogenic zones are logically correlated with the 3 000 m.yr. metamorphic event: (1) in Eburnian-Huabian zones in the Limpopo Belt of southern Africa, and in Mauritania and Gabon; (2) in Damaran-Katangan zones in the Hoggar, Uganda, Rhodesia, and perhaps Nigeria; and (3) in Hercynian zones in the Spanish Sahara (fig. 1). As a corollary, it should perhaps be stressed that there is as yet no clear evidence of prograde granulite facies metamorphism of Eburnian-Huabian (1 850 ± 250 m.yr.) or Damaran-Katangan (600 ± 100 m.yr.) age (see fig. 1 and Table 2); in all cases that have been studied thusfar, the granulite facies suites are apparently remnants of older metamorphic events. The granulite-charnockite suite of the Spanish Sahara provides a good example of this relationship for it has been correlated with similar high-grade metamorphic rocks in Mauritania (Arribas, 1960) that are c. 3 000 m.yr. old (Table 2) and occurs as a tectonic slice in the post-Devonian nappes of the Mauritanides of northwestern Africa (figs. 1 and 3; Sougy, 1969). In

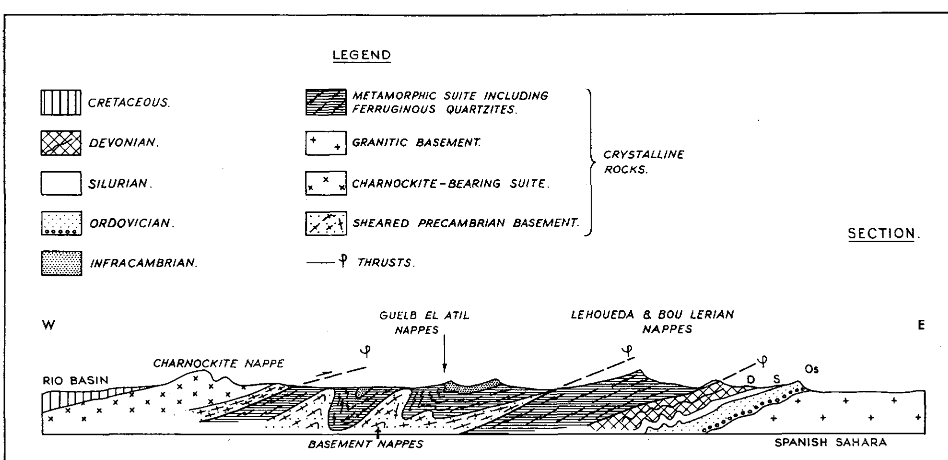

FIG. 3. — *Schematic cross-section across the Mauritanide Zone in the Spanish Sahara (after Sougy and Bronner,* in *Sougy, 1969); length of section approximately 150 km.*

the zones of Precambrian orogenesis, the most detailed documentation of granulite remnants is in the Damaran-Katangan orogenic zone (fig. 1). In Nigeria, granulite facies metamorphism was followed by amphibolite facies metamorphism and the development of granite-gneiss c. 2 350 m.yr. ago: subsequently the younger event of Damaran-Katangan tectonism and low-grade metamorphism was superimposed (Grant, 1970). Within the eastern African correlative of this zone in Malawi (see fig. 1) the granulite remnants have yielded a Rb-Sr isochron age of $1\,122 \pm 29$ m.yr. whereas the superimposed regional amphibolite facies metamorphism has given an isochron age of 718 ± 25 m.yr. (Clifford *et al.*, in preparation); and it is tempting to suggest that the similar c. 700 m.yr. age obtained by Spooner *et al.* (1970) for certain Tanzanian granulites (see Table 2) reflects the imprint of the latter metamorphism. Amongst all of the examples, however, the most detailed work is Macdonald's restudy of Grove's (1935) classic area in the West Nile region of Uganda (fig. 1). In that investigation, Macdonald (1964) demonstrated that the granulites (termed the Watian) were affected by a subsequent (Aruan) tectonism accompanied by amphibolite facies metamorphism, a later (Mirian) tectonism accompanied by epidote amphibolite facies metamorphism, and finally by a period of mylonitization (Chuan tectonism) (fig. 4). In recent geochronological studies, Leggo (1974) suggests the following age-correlation for these events:

Chuan	?650 m.yr.
Mirian	1 000 m.yr.
Aruan	2 550 m.yr.
Watian	2 900 m.yr.

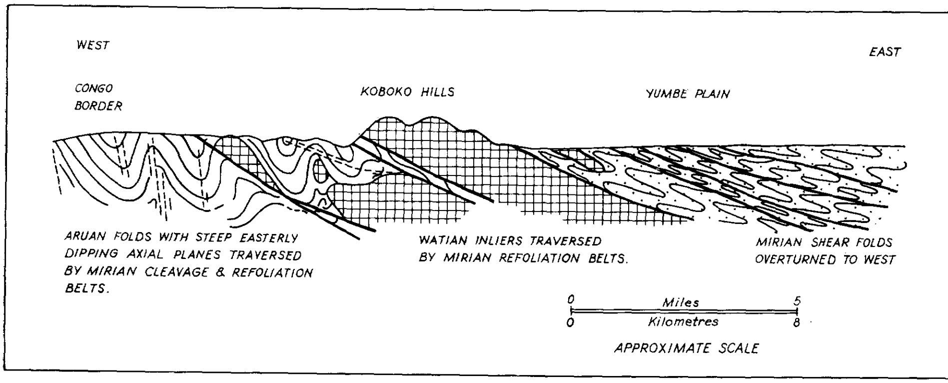

FIG. 4. — *Diagrammatic structural cross-section of the Mt. Wati area, West Nile, Uganda (after Macdonald, 1964).*

Because of the imprint of these subsequent events, with the exceptions in Namaqualand, Sierra Leone, Tanzania and the Limpopo Belt of southern Africa (fig. 1), the paths of prograde metamorphism that culminated in granulite facies conditions have largely been obliterated in most African examples. Determination of the PT conditions of metamorphism must therefore rely entirely on the study of coexisting

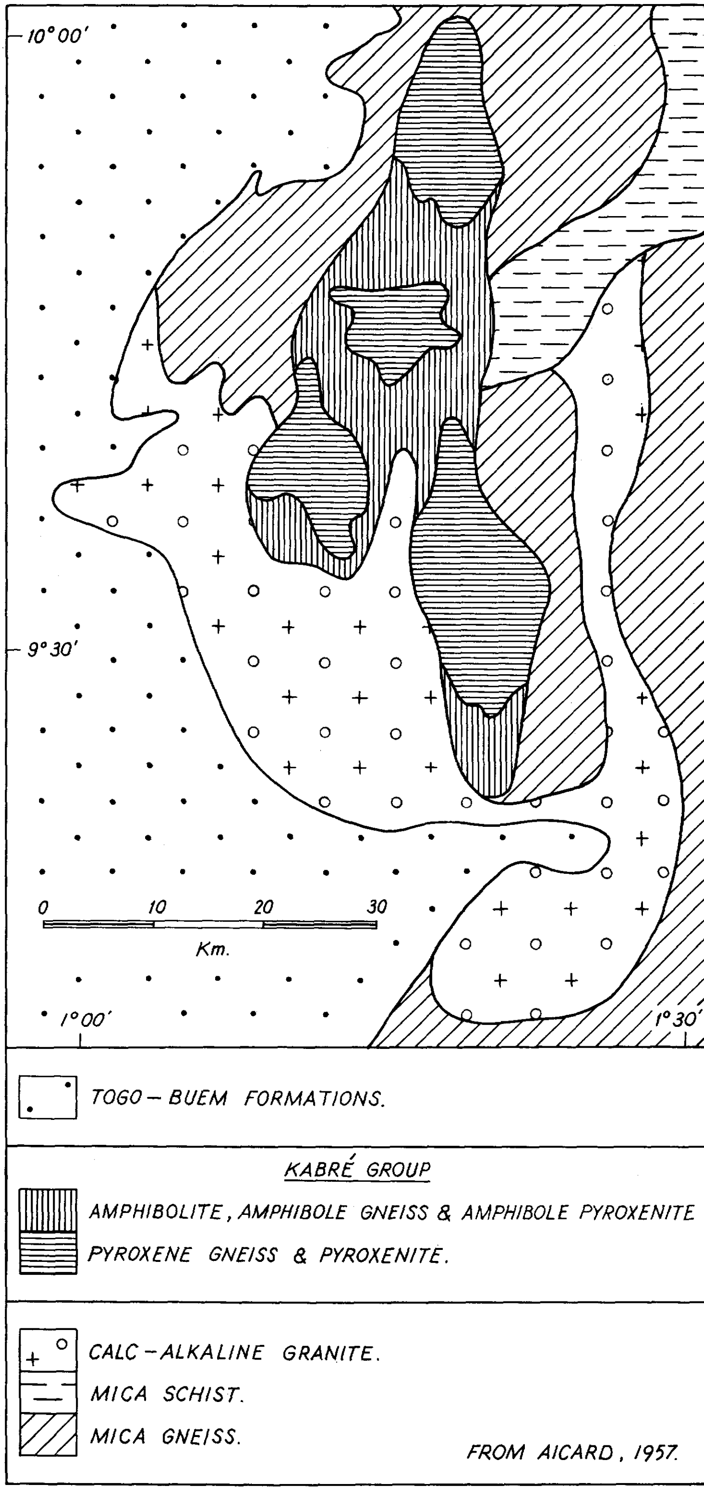

FIG. 5. — *The Kabré Massif of Togo, West Africa (after Aicard, 1957).*

minerals *within* the granulite facies suites. Regrettably, few mineralogical data have yet been published for African occurrences. Notable exceptions are the detailed paragenetical studies of: enderbitic gneiss from the West Nile region of Uganda (Groves, 1935; Howie and Subramaniam, 1957; Howie, 1965); sapphirine rock from the Labwor Hills of Uganda (Nixon *et al.,* 1973); and enstatite-cordierite-sillimanite rock from the Limpopo Belt in Rhodesia (Chinner and Sweatman, 1968). In the last of these examples, Chinner and Sweatman (1968) noted an earlier enstatite-kyanite-quartz assemblage reflecting pressures in excess of 10 Kb, and a later cordierite-sillimanite paragenesis formed at 8-10 Kb. In addition, it is noteworthy that the enstatite contains over 5.5 % Al_2O_3 which, in terms of the Al-enstatite solvus determined by Anastasiou and Seifert (1972), indicates that a temperature close to 950 °C was attained. These data are of especial interest because this high-grade metamorphism is older than 2 700 m.yr. (Van Breemen, 1970), and the data therefore provide a measure of both crustal thickness (>35 km) and average geothermal gradient (<30 °C/km) at that time. Hopefully, investigations of this type will enable us to recognise possible temporal and spatial changes in geothermal gradients and minimum crustal thickness through time. Correlation of these variations with knowledge of the chemical compositions of dated granulite occurrences may then provide an opportunity to chart the chemical and physical evolution of the "third dimension" of the earth's crust.

Finally, it is prudent to consider African granulite-charnockite areas in the context of economic geology. As elsewhere in the world, the African granulite facies suites are heterogeneous. Amongst the constituent rock-types, it is generally agreed that quartzite, highly aluminous schist and gneiss, ironstone, graphite gneiss and marble are of metasedimentary origin. In contrast, the premetamorphic origin of the typomorphic hypersthene gneiss and granulite has been the subject of wide debate. On the basis of major chemistry, however, it has been noted that the majority of African suites have chemical patterns that are consistent with a former igneous source material (Clifford, 1974). If this identification survives current tests, the African granulites provide a large number of "targets" in the search for *metamorphosed* volcanogenic ores. Equally, many of the provinces are characterized by "charnockitic" plutons: extensive bodies of basic and acid-to-ultrabasic composition occur in the Lulua Massif (Kasai) and the Man Massif (Ivory Coast) respectively (Delhal, 1963; Bolgarsky, 1950); important anorthosites are characteristic of many granulite terrains including those of the Limpopo Belt, southern Malawi and Tanzania (Bahnemann, 1972; Bloomfield, 1968; Sampson and Wright, 1964); a wide range of granitic rock types bearing hypersthene and/or fayalite have been described in detail from Natal and Nigeria (McIver, 1966; Oyawoye, 1964); and a large number of small retrogressively metamorphosed bodies of basic-to-ultrabasic composition have been identified notably in Togo (fig. 5), Dahomey and Kenya (Aicard, 1957; Pougnet, 1957; Schoeman, 1951). In view of the economic importance of the hypersthenic intrusives in Namaqualand (see p. 290), these charnockitic intrusives now deserve reinvestigation.

In the foregoing pages, an attempt has been made to "highlight" certain important aspects of African occurrences of granulite facies rocks and charnockitic intrusives. Many more data are required before we are in a position to radically influence petrologic thought. Nevertheless, Africa represents almost 20 % of the earth's land surface and, if the present rate of acceleration of these studies is maintained, it is confidently anticipated that the results will make a dramatic contribution to our understanding of the evolution of the continental crust.

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