SHORT COMMUNICATIONS

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Complex pyroxene assemblages of Proterozoic dolerites, S.E. Greenland

THE complex pyroxene assemblages which occur in Proterozoic tholeiitic dolerite dykes in S.W. Greenland have been described in a previous report (Hall *et al.*, 1986). Although the successive generations of these dykes are progressively Fe-rich, their pyroxenes do not show a simple sequential Fe-enrichment trend, such as that defined by successively differentiated units of layered intrusions and typified by the Skaergaard pyroxene evolution trend (Wager and Brown, 1968; Nwe, 1976). Although there is a slight shift in average pyroxene composition from one generation of dykes to another (Hall *et al.*, 1985), this is very largely outweighed by the extremely wide ranges of pyroxenes occurring in individual dyke samples. The principal chemical variation in these saturated pyroxenes is in their proportions of Ca, Mg, and Fe. The pyroxene assemblages cover a large portion of the saturated pyroxene quadrilateral. Si decreases slightly with increasing Fe content of the pyroxenes, while Al, Ti and Mn correspondingly increase, but the absolute concentrations of the latter three elements are all low and normal for pyroxenes of tholeiitic rocks (cf. LeBas, 1962; Nisbet and Pearce, 1977). The compositional variations occur both between different pyroxene grains and as extreme irregular zoning of individual grains, providing clear evidence of the complex sequential precipitation of different pyroxene phases (Hall *et al.*, 1986).

Two types of Proterozoic dykes are abundant in S.E. Greenland; one type is noritic and the other doleritic. We have so far examined the mineralogy of four representative samples of the dolerite dykes, as part of a major petrological study. There is at present some doubt about how these dykes correlate with the basic dykes of W. Greenland where three principal swarms have been recognised: (i) BN norites, (ii) MD dolerites, and (iii) Kangamiut dolerites and their metamorphosed equivalents (Zeck and Kalsbeek, 1981; Hall and Hughes, 1987). Eastwards, across the north Atlantic, a similar wide range of (meta-)norites, dolerites and gabbros in N.W. Scotland comprise the Scourie dyke swarm (Weaver and Tarney, 1981). Preliminary results of the petrological study of the S.E. Greenland dykes show that the compositions of the norites are distinctive and very similar to those of the BN and Scourie norite dykes (Weaver and Tarney, 1981; Hall and Hughes, 1987; authors' unpublished data), while the mineralogy and chemistry of the dolerite dykes closely resemble those features of the MD dolerites.

The mineral chemistry of the dolerites has been examined by energy-dispersive electron microprobe analysis at the Department of Earth Sciences, University of Cambridge. The four analysed dolerite samples each possess a highly complex pyroxene assemblage. The compositions of the pyroxenes in these four samples are compared in Fig. 1, in terms of their respective Ca:Mg:Fe proportions, to those of a newly analysed S.W. Greenland MD3 dolerite sample and those of a concurrently analysed Tertiary dolerite from S.E. Greenland. The most immediately obvious feature of these diagrams is the wide spread of compositions across the pyroxene quadrilateral of the Proterozoic dyke pyroxenes in contrast to the Skaergaard-type two-pyroxene assemblages which define a mid-Ca range pyroxene miscibility gap. This wide spread of compositions is also characteristic of the S.W. Greenland MD dykes (Hall *et al.*, 1985).

Two of the analysed samples are from the margin and core of the same dyke, and they possess rather different ranges of pyroxenes (Fig. 1*a*, *b*). The medium-grained core sample is an apparently normal, sub-ophitic textured dolerite. Its pyroxenes comprise variable augites, pigeonites, subcalcic augites and ferroaugites (Fig. 1*b*). The X_{Mg} [$= \mathrm{Mg}/(\mathrm{Mg}+\mathrm{Fe})$] values of these various pyroxenes range from around 0.72 to 0.35. There is a weakly defined miscibility gap between the most magnesian augites and pigeonites. Core-to-margin zoning in larger grains tends to be mainly from magnesian augite or pigeonite out towards

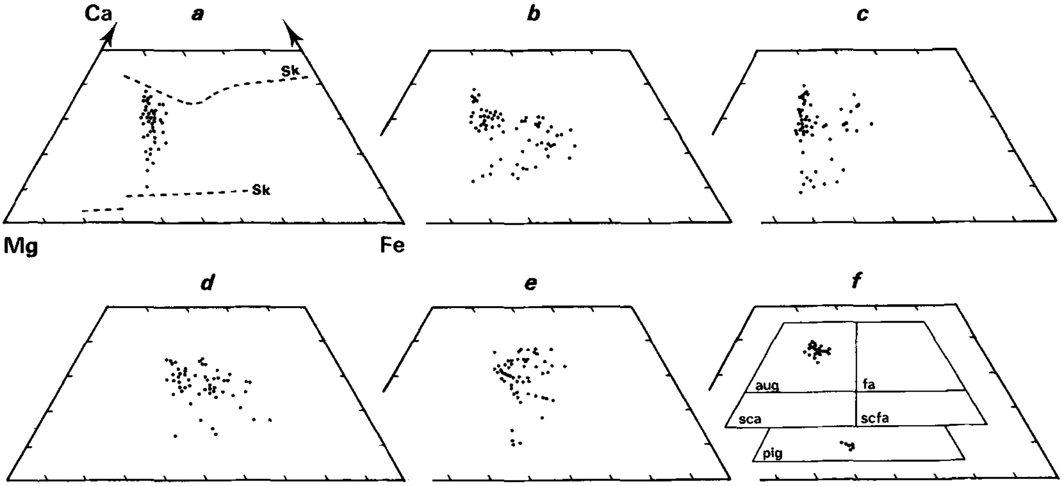

FIG. 1. Compositions of various pyroxene assemblages in: (*a*) and (*b*) margin and core samples respectively of a Proterozoic dolerite dyke from S.E. Greenland (samples GGU 314378 and 314379) compared to the Skaergaard pyroxene evolution trend (Sk, dashed line); (*c*) and (*d*) core samples of two S.E. Greenland Proterozoic dolerite dykes (GGU 314410 and 314417 respectively); (*e*) a third generation (MD3) Proterozoic dyke from S.W. Greenland (GGU 179092); and (*f*) a Tertiary olivine dolerite from S.E. Greenland (GGU 314383). The compositional fields shown in (*f*) are those of augite (aug), ferroaugite (fa), subcalcic augite (sca), subcalcic ferroaugite (scfa) and pigeonite (pig).

ferroaugite or subcalcic ferroaugite rims, but the zoning is not regular within any given grain and also varies from one grain to another (cf. Hall *et al.*, 1986). The pyroxenes of the fine-grained margin sample also comprise augites, subcalcic augites and pigeonites, but in this case define a linear array with respect to their Ca : Mg : Fe proportions (Fig. 1*a*), the more calcic pyroxenes having slightly higher X_{Mg} values than the Ca-poor ones ($X^{\mathrm{AUG}}_{\mathrm{Mg}} = 0.75$ compared to $X^{\mathrm{PIG}}_{\mathrm{Mg}} = 0.65$). This linear array corresponds to the tie-line between established co-existing pigeonite–augite pairs (Davidson and Lindsley, 1985). The pyroxenes in this marginal dyke sample thus appear to have been simply quenched, with two-pyroxene tie-line compositions. Zoning tends to be from Ca-poor cores to the most Fe-rich augitic margins.

The other two samples have pyroxene assemblages with no regular pattern of chemical evolution, neither simple Fe-enrichment nor Ca-enrichment, but appear to have pyroxene populations compositionally, and presumably genetically, half-way between those of the dyke core and margin samples described above (Fig. 1*c*, *d*). They consist of augites, ferroaugites, subcalcic augites and pigeonites with ranges of X_{Mg} values from 0.71 to 0.33. These pyroxene assemblages are clearly similar to that found in the S.W. Greenland MD3 dolerite which was analysed concurrently (Fig. 1*e*).

A low oxygen fugacity (f_{O_2}) and local ionic availability along the clinopyroxene–plagioclase cotectic have been argued to be key factors controlling the precipitation of variable Ca-poor clinopyroxene assemblages (Hall *et al.*, 1986). Basic magmas with a relatively high f_{O_2}, such as many calc-alkaline magmas, crystallise early magnetite together with relatively magnesian, chemically uniform pyroxenes. A wide variety of pyroxenes can be precipitated from rapidly cooled high-f_{O_2} magmas where local Fe-depletion in the liquid is brought about by the early nucleation of magnetite phenocrysts. However, such pyroxene assemblages are different from those described here in that they are quenched and co-precipitated, rather than sequentially crystallised.

It is significant that the Fe–Ti oxide phase in the S.E. Greenland dolerites precipitated late in the crystallisation sequence, and was originally ulvöspinel, now re-equilibrated to ilmenite–titanomagnetite exsolution pairs. This suggests a subsolidus oxidation reaction:

$$\begin{array}{ccccccc} 6[\mathrm{FeTiO_4}] & + & \mathrm{O_2} & = & 6[\mathrm{FeTiO_3}] & + & 2[\mathrm{Fe_3O_4}] \\ [\mathrm{Usp}] & + & \mathrm{O} & = & [\mathrm{Ilm}] & + & [\mathrm{Mt}] \end{array}$$

The theoretical magnetite so formed is incorporated in a more Fe-rich titanomagnetite in the ulvöspinel–magnetite solid-solution series. The titanomagnetite exsolution lamellae have an Fe : Ti ratio of around 4:1, roughly equivalent to $\mathrm{Usp_{60}Mt_{40}}$. The ilmenite and titanomagnetite occur together in approximately equal proportions, indicating an original Fe–Ti oxide of the composition $Usp_{85}Mt_{15}$. Graphical pyroxene thermometers (e.g. Saxena *et al.*, 1986) suggest a very wide range of crystallisation temperatures (around 1350 to 1000 °C) for the S.E. Greenland dykes, for which the late-stage precipitation of near end member ulvöspinel indicates f_{O_2} conditions of $-\log f_{O_2} = 13$ (cf. Lindsley, 1976).

In contrast to the Proterozoic dolerites, the pyroxenes in the Tertiary olivine-dolerite dykes of S.E. Greenland are relatively chemically uniform pigeonite–augite pairs (Fig. 1*f*), which suggest a crystallisation temperature of between 1100 and 900 °C. These dykes contain early precipitated titanomagnetite, and their chilled margins carry microphenocrysts of ilmenite and magnetite. The combination of this pyroxene assemblage and the composition and early precipitation of the Fe–Ti oxide phases in these Tertiary rocks clearly indicate that they crystallised under slightly higher f_{O_2} conditions than did the neighbouring Proterozoic dykes.

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References

Davidson, P. M. and Lindsley, D. H. (1985) *Contrib. Mineral. Petrol.* **91**, 390–404.
Hall, R. P. and Hughes, D. J. (1987) Ibid. **97**, 169–82.
——— and Friend, C. R. L. (1985) *J. Petrol.* **26**, 253–82.
———— (1986) *Mineral. Mag.* **50**, 491–502.
LeBas, M. J. (1982) *Am. J. Sci.* **260**, 267–88.
Lindsley, D. H. (1976) In *Oxide Minerals* (D. Rumble, ed.) Min. Soc. Amer. Short Course Notes Vol. 3, pp. L61–88.
Nisbet, E. G. and Pearce, J. A. (1977) *Contrib. Mineral. Petrol.* **63**, 149–60.
Nwe, Y. Y. (1976) Ibid. **55**, 105–26.
Saxena, S. K., Sykes, J., and Eriksson, G. (1986) *J. Petrol.* **27**, 843–52.
Weaver, B. L. and Tarney, J. (1981) *Contrib. Mineral. Petrol.* **78**, 175–88.
Wager, L. R. and Brown, G. M. (1968) *Layered Igneous Rocks*. Oliver and Boyd, London, 588 pp.
Zeck, H. P. and Kalsbeek, F. (1981) *Chem. Erde*, **40**, 1–22.

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*Department of Geology,
Portsmouth Polytechnic,
Portsmouth, PO1 3QL*

R. P. HALL
D. J. HUGHES
L. JOYNER

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First occurrence of dalyite in extrusive rock

THE potassium-zirconosilicate dalyite, $K_2ZrSi_6O_{15}$, has so far been described from four localities: in peralkaline granites from Ascension Island (Van Tassel, 1952; Roedder and Coombs, 1967; Harris *et al.*, 1982) and from Antarctica (Harris and Rickard, 1987); in peralkaline quartz syenites from the Azores (Cann, 1967), and from Western Norway (Robins *et al.*, 1983). This is the first account of dalyite from an extrusive rock. It was found in the Sierra de Cabras, two km W of Cancarix in the Province of Albacete, SE Spain. Here, by processes of selective erosion, the remnants of a lava-filled crater rise above their surroundings of alpine deformed Mesozoic and Tertiary sediments (Fuster *et al.*, 1967). The volcanic body extends 1100 m NS and 800 m EW. Layers of breccias, lithic tuffs and glassy flows mark the conically inclined contacts with the country-rock. The mass of the body—several tens of millions of m^3—is composed of holocrystalline