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THE MONZONORITE-ANORTHOSITE CONNECTION: THE PETROGENESIS OF TERRESTRIAL KREEP. J. Longhi, Lamont-Doherty Earth Observatory, Palisades, NY 10964 and J. Vander Auwera, LA Géologie, Pétrologie, Géochimie, Université de Liege, B-4000 Sart Tilman, Belgium.

There is a suite of rocks typically associated with Proterozoic massif anorthosites that bear some interesting similarities to lunar KREEP. In many cases (e.g., Laramie [1]) these rocks are plutonic and have traditionally been referred to as the jotunite-mangerite- \pm charnockite- \pm syenite suite. However, in the Rogaland district of southwestern Norway, where they are referred to as "monzonorites", these rocks are also present as fine-grained dikes and as the chill margin of a layered intrusion [2,3], and thus approximate magmatic liquid compositions are readily obtained by chemical analysis. Monzonorites are typically enriched in incompatible lithophile elements such as K (alkali feldspar is present), the rare earths (REE), and P. They have intermediate to low Mg', low-Ca pyroxene, and more evolved types have low Ti/Sm ratios. Much debate has developed over attempts to explain the link between monzonorites and massif anorthosites. One feature seems clear: monzonorites and associated anorthosites have different initial isotopic ratios [3,4], so a simple relation is not possible. However, there is apparently a continuum in major elements between the monzonorites and gabbros believed to represent magmas parental to the anorthosites. This continuum suggests a link via high pressure fractionation coupled with assimilation. Although more complicated, this scenario is similar that evoked for the early Moon: following the formation of ferroan anorthosites, continued fractional crystallization of the residual liquids at the base of the crust led to the formation of KREEP [5]. An attempt is made here to establish a link between monzonorites and high-Al gabbros which are nearly always found as ancillary intrusions associated with anorthosites, and which may record processes in lower crustal magma chambers.

Fig. 1 illustrates some of the evidence for a link by fractionation between monzonorites and gabbros. The upper panels show a continuous variation in TiO₂, P₂O₅, and MgO between gabbros and ferrodiorites of the Harp Lake Complex of Labrador [6] and the monzonoritic dikes of the Rogaland district of Norway [3]. Patterns for other elements (SiO₂, Al₂O₃, FeO, etc.) versus MgO are also continuous. Interpretation of the elemental variations are not straightforward, however. The peaked TiO₂-MgO pattern is as expected for fractional crystallization of a magma that eventually becomes saturated in ilmenite. Except for the subset of analyses with P₂O₅ above 2 wt %, the P₂O₅-MgO pattern is generally similar and indicates crystallization of a phosphate (apatite) between 2 and 3 wt % MgO. The samples with the highest P₂O₅ also have lower SiO₂ (43-45 wt%) and higher FeO (15-20 wt%) than those on the main trend. These samples are from dikes that show large regional variation in composition, and it seems possible that these dikes underwent an internal differentiation caused by differential flow of a crystalline matrix and interstitial liquid. The high-P-Fe, low-Si samples thus may be partial cumulates. If so, then the highest TiO₂ concentrations may be enhanced by accumulation as well. Experimental liquids obtained from gabbroic (HLCA) and monzonoritic (TJ) starting materials tend to mimic the high-MgO portion of the natural trend although it is clear that the specific compositions employed cannot be directly related. The steep trend of increasing TiO₂ with decreasing MgO for the natural samples in Fig. 1 indicates that fractionation must have involved extensive Fe-Mg equilibration.

Trace elements provide evidence of further complications. Several of the monzonoritic dikes lack negative Eu anomalies in their REE patterns and have only weak depletions of chondrite-normalized Sr relative to the light REE [3] — hardly what is expected from liquids residual to the formation of anorthosite. Phase equilibria complicates matters still more. Experiments on one of the most primitive monzonorites (sample TJ, the chill margin of the Bjerkeim-Sokndal intrusion [7]) show that plagioclase(pl) and orthopyroxene(opx) are together on the liquidus from 10 to 13 kbar. This pressure is consistent with experiments that showed aluminous opx megacrysts found in anorthosite plutons to have formed in this pressure range [8]. However, as Fig. 2 illustrates, the TJ composition is close to a thermal divide on the pl-opx(\pm pigeonite)-augite(aug) liquidus boundary in this pressure range, yet it would be extremely fortuitous for a residual liquid to remain on a thermal divide. One way to generate a liquid on a thermal divide would be in a second stage fusion of the lower crust: the first stage removes a granitic component leaving a pyroxene-plagioclase residuum, which would necessarily produce melts on the thermal divide at these pressures. This residuum would likely be depleted in incompatible elements and have positive Eu and Sr anomalies with respect to the other REE, so it would be necessary to invoke small degrees of melting to produce incompatible element enrichments and flatten out the Eu and Sr anomalies. Such a scenario would not, however, readily explain the continuous variation in major elements evident in Fig. 1 nor the continuous variation in mineral compositions between anorthositic and monzonoritic rocks [1].

A final option is assimilation-fractionation. In this scenario the compositions of the monzonoritic parent magmas (derived by high pressure crystallization of gabbroic liquids) are altered by assimilation of

MONZONORITE-ANORTHOSITE CONNECTION: Longhi J. and Vander Auwera, J.

granitic crust at lower pressures (i.e. ≤ 7 kbar) where the pyroxene-plagioclase thermal divide is no longer present. Thus the present location of the TJ composition near the thermal divide is accidental and the incompatible element patterns are hybrids. Further work is needed to verify this hypothesis.

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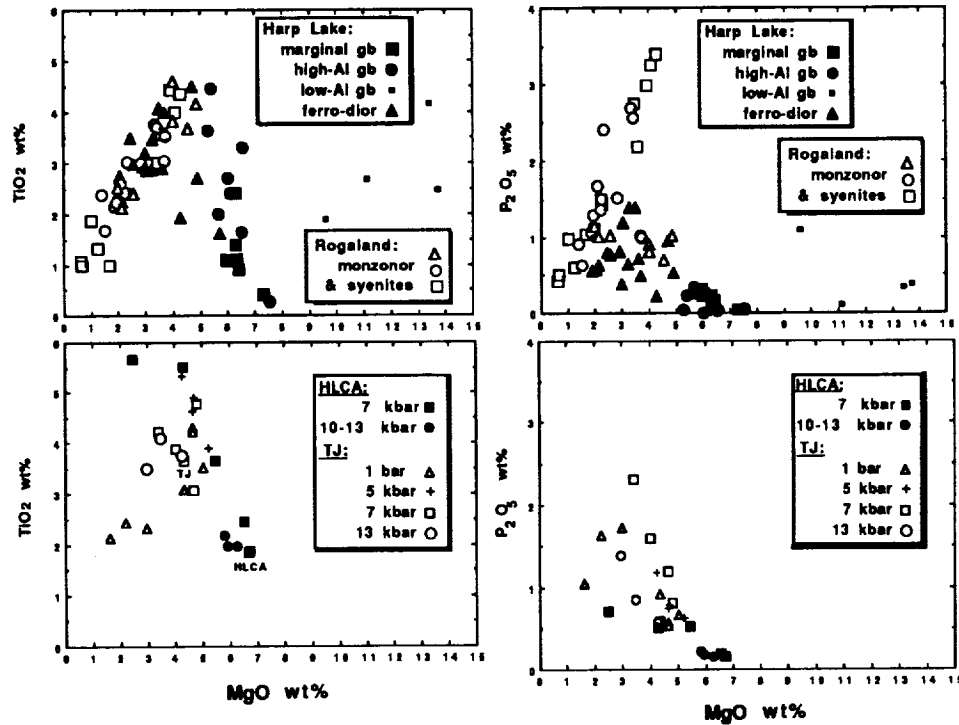


Fig. 1

Fig. 1 Major element variation in gabbros and monzonoritic rocks associated with the Harp Lake (Labrador) [6] and Rogaland (Norway) [3] anorthosites compared with liquid compositions ([8] and this study) obtained from experiments in graphite capsules on natural compositions. Fig. 2 Liquidus equilibria on the plagioclase + ilmenite saturation surface at lower crustal pressures. Liquids shown as filled squares; dashed tie lines connect coexisting pyroxene compositions (small open circles).

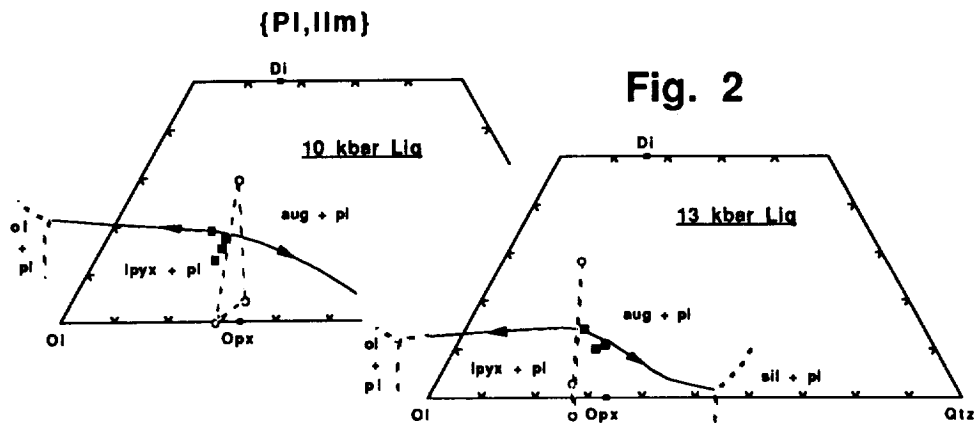


Fig. 2