

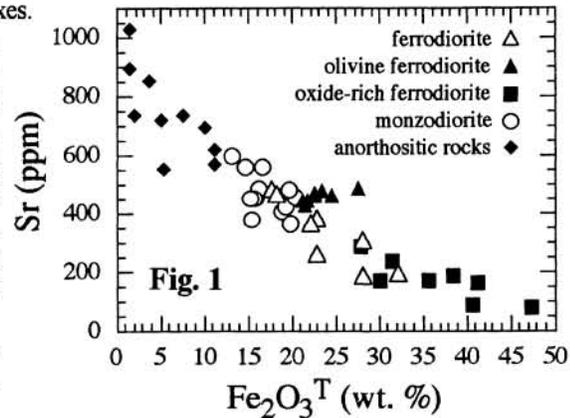
SILICATE LIQUID IMMISCIBILITY IN ANORTHOSITE SUITES: VIEWING THE MOON FROM WYOMING AND LABRADOR Gregory A. Snyder, Jeremy Mitchell, Lawrence A. Taylor, and E. Craig Simmons*, Planetary Geosciences Institute, Dept. of Geological Sciences, University of Tennessee, Knoxville, TN 37996-1410; *Dept. of Geochemistry, Colorado School of Mines, Golden, CO 80401.

There is mounting evidence that silicate liquid immiscibility (SLI) plays an important role in the evolution of late-stage liquids in terrestrial anorthosite massifs. Evidence for its importance is found in the ubiquitous occurrence of ferrodiorites (jotunites) and monzodiorites which are suggested to be the mafic and silicic end-members of SLI in terrestrial massif anorthosites. Importantly, these two rock types must be proven to be contemporaneous for the SLI model to be valid. In some instances, similar rocks are found comingled as pillows (i.e., liquids) in the plutonic environment, thus suggesting both synchronicity as well as consanguinity. Similar processes could have been operable during lunar anorthosite evolution in the early crust of the Moon.

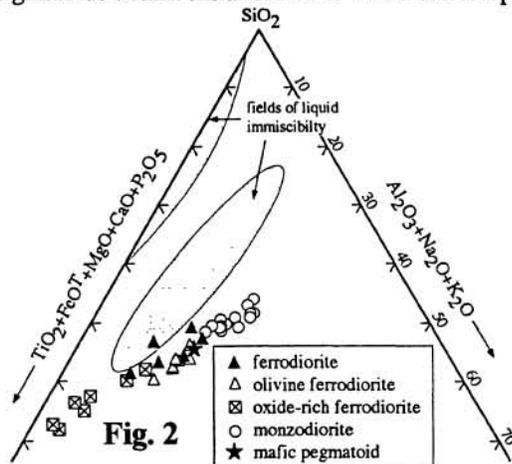
INTRODUCTION -- Silicate liquid immiscibility (SLI) has been observed in experimental studies of various initial compositions [1]. Furthermore, trace- and major-element two-liquid partition coefficients have been established between the mafic and silicic end-members of SLI [2]. Two natural examples where bulk compositions are appropriate for liquid immiscibility to occur are Proterozoic anorthosite complexes and Fe-enriched basalts. There is clear petrographic evidence that SLI does occur naturally in Fe-enriched basalts, but direct evidence is sparse for its importance in the origin of anorthosite complexes.

TERRESTRIAL ANORTHOSITE MASSIFS -- On Earth, massif anorthosites are restricted mostly to the mid-Proterozoic. They are comprised chiefly of plagioclase and hypersthene with compositions ranging from An₄₀ to An₈₀ and En₃₀ to En₈₀, respectively [3]. Associated rocks include granites, leuconorites, troctolites, gabbros, and monzodiorites. Fe-enriched dioritic rocks are a ubiquitous, albeit volumetrically small, component of Proterozoic anorthosite complexes. They commonly occur as dikes and pods within anorthosite and as cumulates in intrusions.

In the **Laramie Anorthosite Complex, southeastern Wyoming**, these dioritic rocks form two distinct groups. The first group, referred to as ferrodiorite, ranges from oxide-rich varieties (up to 40 vol.% Fe-Ti oxide) to more felsic ferrodiorite (olivine-free) and olivine ferrodiorite. Experiments show that these oxide-rich rocks are close to liquid compositions [4]. P and Ti enhance the solubilities of apatite and Fe-Ti oxide in a silicate melt and lead to a very dense melt, capable of readily segregating from the host [4]. The second group, called monzodiorites, is much more potassic and felsic than the ferrodiorites. On major and trace-element variation diagrams, both groups of diorites typically form one smooth trend, ranging from silicic monzodiorite to silica-poor oxide-rich ferrodiorite, implying a single differentiation sequence (Fig. 1). This interpretation is complicated by the fact that ferrodiorite samples have compositions that are similar to mafic pegmatoids within the anorthosite which are composed of melts residual to the anorthosites. This implies that the



melt remaining after extensive plagioclase fractionation is ferrodioritic in composition. *How, then, could there be a single evolutionary trend resulting both in Fe-enrichment to oxide-rich ferrodiorite and silica-enrichment to monzodiorite?* When plotted on the SLI diagram of Roedder [5], these groups of rocks form a smooth trend with oxide-rich ferrodiorite at the mafic end, ferrodiorite and olivine ferrodiorite in the middle, and monzodiorite at the "granitic" end (Fig. 2). Although this evidence of an immiscible relationship between the ferrodiorites and monzodiorites is not conclusive, it is strongly suggestive from experimental data on these rocks [6]. It is likely that the anorthosite residual magmas will evolve to one side or the other of a gently sloping immiscibility field as a function of oxygen



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fugacity, silica activity, crystallization history, and crustal contamination.

Ferrodiorites are also common in the **southern Nain Anorthosite Complex, Labrador** as layered rocks along Fox Inlet and as pillows in a hydrous granitic matrix on Tunungayualuk Island [7,8]. Wiebe [7,8] suggested that these ferrodiorites were late-stage products of fractional crystallization of an anorthositic (leuconorite) magma. However, whereas quartz and alkali feldspar were important interstitial phases in the leuconorite parent, these phases did not occur in the ferrodiorites. Wiebe [7,8] postulated that these phases were absent in evolved ferrodiorites due to separation of an immiscible granitic liquid containing the quartz and alkali feldspar. Indeed, anhydrous granitic pillows do occur and are likely contemporaneous with ferrodiorite pillows on Tunungayualuk Island [7,8]. Furthermore, plagioclase and pyroxene phenocrysts in these granitic pillows have major-element compositions comensurate with ferrodiorite pillows. Rb-Sr isotopic systematics of contemporaneous granitic and ferrodioritic pillows from Tunungayualuk Island [9,10] are broadly consistent with the immiscibility relationship (Fig. 3). Ferrodiorites with relatively low Fe lie along a trend of increasing Fe, Ba and initial $^{87}\text{Sr}/^{86}\text{Sr}$ suggesting combined crustal assimilation and fractional crystallization of a parental leuconorite magma [9,10]. However, high-Fe ferrodiorite pillows and anhydrous granitic pillows plot off of this trend at much lower Rb/Sr and higher Rb/Sr ratios, respectively. The high-Fe ferrodiorite pillows also exhibit higher $\text{Na}_2\text{O}/\text{K}_2\text{O}$ and $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$ values and P_2O_5 , TiO_2 , MgO , and MnO contents and lower K_2O , Na_2O , and Al_2O_3 contents than coexisting anhydrous granitic pillows, while maintaining similar Mg#s and MnO/FeO values [11], consistent with their relationship as complementary immiscible liquid pairs.

LUNAR ANORTHOSITES -- Anorthosites on the Moon can be subdivided into three types: 1) Ferroan -- characterized by high-Ca plagioclase (An_{92-96}) evolved mafic mineral compositions ($\text{Mg}\# = 40-70$), and primitive incompatible trace-elements; 2) Magnesian -- exhibiting variable (yet still high-Ca) plagioclase compositions (An_{83-96}), primitive mafic mineral compositions ($\text{Mg}\# = 65-92$), and evolved incompatible trace-elements; and 3) Alkali -- comprised of relatively low-Ca plagioclase (An_{65-86}), evolved mafic minerals ($\text{Mg}\# = 35-70$), and evolved, albeit quite variable, incompatible trace-elements [12].

Ferroan anorthosites likely were precipitated from a global magma ocean early in the Moon's history (prior to 4.4 Ga; [13]) and are comprised of extremely calcic plagioclase. Therefore, ferroan anorthosites are not likely analogs for terrestrial massif anorthosites, although they may share genetic similarities with rare Archean anorthosites [e.g., 14]. Magnesian anorthosites are mineralogically more primitive than terrestrial massif anorthosites. **Lunar Alkali Suite anorthosites most closely resemble terrestrial massif anorthosites in terms of mineral chemistry.** The currently favored model for Alkali Suite anorthosite genesis is the precipitation from an evolved quartz monzodiorite-like liquid [15]. How, and if, this liquid fits into a scheme of SLI is not known. Lunar granites are known to be the crystallization products of the complementary acidic liquid of SLI (e.g., [16-20]), however, the complementary basic liquid has been elusive. Neal and Taylor [20] suggested that the phosphate phases seen in lunar highlands rocks represent a portion of the complementary basic liquid of SLI. However, the place of SLI in the evolution of anorthosites on the Moon is still unknown. Further work is needed in the areas of chemical modelling and experimental petrology in order to answer these questions.

REFERENCES: [1] Roedder, E. (1951), *Amer. Mineral.* 36, 282-286; [2] Watson, E.B. (1976), *Contrib. Mineral. Petrol.* 56, 119-134; [3] Morse, S.A. (1982), *Amer. Mineral.* 67, 1087-1100; [4] Lindsley, D.H. (1991), In *IGCP 290: Proterozoic Anorthosite Massifs*, abstract; [5] Roedder, E. (1979), In Yoder, H.S. (editor) *The Evolution of the Igneous Rocks*, 15-57; [6] Lindsley, D.H. (1994), *GCA*, submitted; [7] Wiebe, R.A. (1978), *Can. Jour. Earth Sci.* 15, 1326-1340; [8] Wiebe, R.A. (1979), *Jour. Petrol.* 20, 239-269; [9] Simmons, E.C. et al. (1980), *Trans. Amer. Geophys. Union* 61, p. 410; [10] Snyder, G.A. and Simmons, E.C. (1985), *Trans. Amer. Geophys. Union* 65, p. 305; [11] Naslund, H.R. (1983), *Amer. Jour. Sci.* 283, 1034-1059; [12] Snyder, G.A. et al. (1994) *GCA*, submitted; [13] Carlson, R.W. & Lugmair, G. (1988), *EPSL* 90, 119-130; [14] Myers, J.S. (1988), *Prec. Res.* 38, 309-323; [15] Snyder, G.A. et al. (1994), *LPSC XXV*, this volume; [16] Hess, P.C. et al. (1975), *PLSC* 6th, 895-909; [17] Rutherford, M.J. et al. (1976), *PLSC* 7th, 1723-1740; [18] Taylor, G.J. et al. (1980), In Papike, J.J. & Merrill, R.B. (editors), *Proc. Lunar Highlands Crust*, 339-352; [19] Shih, C.-Y. et al. (1985), *GCA* 49, 411-426; [20] Neal, C.R. and Taylor, L.A. (1989), *GCA* 53, 529-541.

