

THE EARLY SILICEOUS COMPONENT OF PLANETARY CRUSTS: EXPERIMENTAL PETROLOGY OF THE TONALITE-TRONDHJEMITE ROCK SERIES. Bradford S. White¹, Sieger van der Laan², Peter J. Wyllie¹. (1) Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, 91125; (2) Hawaii Institute of Geophysics, 2525 Correa Rd, Honolulu, HI, 96822.

There are two approaches to understanding the processes that lead to the formation of planetary crusts. The first is to determine the geology and geochemistry of rocks in the field and try to develop a consistent petrogenetic scheme to account for their occurrence. This approach has been extensively pursued on Moon and Earth, and remotely so on Mars. Another method is to establish the phase relationships of these rocks and their possible sources under various conditions of pressure, temperature, volatile content, etc., and apply the results to a petrogenetic model that is also consistent with isotope and trace-element geochemistry. This technique has been applied to the relationship between planetary mantles and basalts, and the formation of andesites and more siliceous rocks in subduction zones. Observations of rocks from Archean terranes on Earth reveal that the most prominent types are komatiites, tholeiites, tonalites and trondhjemites (grey gneisses), potassic granites (pink gneisses), and rare syenites. Early magmatic activity was dominated by the production of basalts which were subsequently followed, and intruded by, large volumes of the tonalite-trondhjemite series magmas. Approximately 80% of nine Archean cratons are composed of rocks that are chemically of tonalite-trondhjemite affinity (1).

Hypotheses for the origin of the tonalite-trondhjemite series fall into four categories: [1] Partial melting of eclogite or garnet (Ga) granulite source materials with basaltic composition (e.g. 2, 3), [2] partial melting of amphibolite with or without Ga (1, 4), [3] fractional crystallization of basaltic magma (5), and [4] direct partial melting of the mantle as has been implied by Sr isotopes (6). Mechanism [3] can be excluded because these Archean terranes consist of a bimodal distribution of basalt and tonalite-trondhjemite and if fractional crystallization were operative we would expect to find more intermediate compositions in the field. A highly fractionated REE pattern (HREE depletion) and the high SiO₂, low MgO content of Archean tonalite-trondhjemite discriminates against peridotite as a source rock during partial melting (7). Thus petrogenesis of the voluminous Archean tonalite-trondhjemite series can be viewed as fusion of a broadly basaltic protolith, controlled by a set of intensive parameters that have yet to be adequately constrained by precise determinations of the heterogeneous phase relations.

Given the importance of tonalite-trondhjemite in the formation of planetary crusts, we have used the inverse approach to study three rocks spanning the series. The T-XH₂O phase relations of the Nûk gneiss ($\approx 71\%$ SiO₂, all % by wt.) at 15 kbar have been reported elsewhere (8), and at 10 kbar in this volume. In this contribution we combine these results with those for an epidote-bearing tonalite ($\approx 55\%$ SiO₂) from an Idahoan tonalite-trondhjemite suite. These two rocks are representative of the compositional range of the Archean suites. Forthcoming results for a third sample, another epidote-bearing tonalite ($\approx 67\%$ SiO₂), are consistent with the interpolated phase relations between the two end-member compositions.

For the tonalite at 15 kbar, the vapor-undersaturated liquidus sweeps down in temperature along a curved path from $\approx 1250^\circ\text{C}$ at 0% H₂O to $\approx 960^\circ\text{C}$ at 15% H₂O where it intersects the plane of H₂O saturation. At low H₂O contents (<3%) plagioclase (Pl) is the first phase to appear on the liquidus, followed at slightly lower temperatures by clinopyroxene (Cpx). At intermediate H₂O (3-6%) Cpx replaces Pl as the primary liquidus phase, with Ga following at lower temperature. With increasing H₂O Ga crystallized first, followed by Cpx up to $\approx 10\%$ H₂O, and amphibole (Hb) out to the saturation plane. Plag and Ga are also primary liquidus phases of the Nûk gneiss at 15 kbar, however Hb, and then epidote appear on the liquidus at high H₂O contents. For the tonalite at 10 kbar Pl is still first to appear on the liquidus followed again by Cpx; this relationship holds out to 5% H₂O. From 5 to 11% H₂O Cpx replaces Pl,

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followed very closely by Hb and Ga. The Ga stability field is greatly reduced at 10 kbar and closes off above 10% H₂O and Hb replaces Cpx as the first phase to appear. For H₂O > 10%, Hb is the sole mineral to crystallize between 950 and 780°C where Pl first becomes stable. These phase relations for tonalite at 10 kbar parallel those for the Nûk gneiss where Pl, Cpx, and Hb appear respectively with increasing H₂O content. However Ga is not present at all in the Nûk gneiss at 10 kbar, and quartz and biotite appear between the liquidus and the solidus at 10 and 15 kbar but are not observed for the tonalite. Based on their work at 15 kbar, Johnston and Wyllie (8) inferred that a triple-saturation point between Ga, Pl, and Hb existed between 10 and 15 kbar, defining the low-pressure stability of Ga on the vapor undersaturated liquidus. The new results show that two triple points, one between Ga, Pl, and Hb, and another between Ga, Hb, and Cpx set the depth limit corresponding to ≈14 kbar for Ga on the liquidus of trondhjemite. For tonalite a triple saturation point for Ga, Hb, and Cpx also lies at ≈14 kbar.

A T-XSiO₂ section taken through the system at 15 kbar and 5% H₂O reveals the near liquidus phases for the full compositional range at this depth and volatile content. Beginning at the low SiO₂ end, the first liquidus phase to appear changes from Cpx, to Ga, to Pl, and finally to Quartz with increasing SiO₂. Hb is within 100 °C of the liquidus for all compositions except the least silicic. At 10 kbar the first phase to appear is Pl on the silica-poor side, replaced by Cpx for the compositional range 56% < SiO₂ < 73%. Hb is within 100 °C of the liquidus over the full composition range. The mineral assemblages described above specify the residue left behind by these magmas as they separate from their source after partial melting, and provide a basis for the development of internally consistent petrogenetic models.

These results are in accord with petrogenetic hypotheses summarized earlier by previous workers (8). Because of their highly fractionated REE patterns, Archean tonalite-trondhjemite must have had garnet or amphibole in their source residue (9). For the generation of trondhjemitic melts at 15 kbar abundant H₂O must be available (>5%) to produce the necessary liquidus phases, which suggests melting of a hydrous Ga granulite or lower crustal amphibolite. In the absence of H₂O, higher pressures are required because of the positive slope on Ga-Pl stability boundary. This same scenario is also plausible for the less silicic tonalites. Ga or Hb only appear near the liquidus at H₂O > 5%, and the Ga-Cpx boundary on the vapor-undersaturated liquidus also goes to lower H₂O with increasing pressure, implying that anhydrous eclogite may provide a suitable source rock under dry conditions. At 10 kbar both magmas have near-liquidus Hb at H₂O > 5%, pointing to a wet amphibolitic source. For high and low pressures, H₂O need not be unusually abundant if the partial melt fraction is not a large percentage of the whole. Thus generation of the tonalite-trondhjemite series of early crustal genesis appears to represent various degrees of partial melting of a basaltic protocrust in the form of a hydrous amphibolite to garnet granulite up to ≈15 kbar, or anhydrous melting of eclogite at higher pressures. Jahn *et.al.* (7) point out that remelting of the original tonalite-trondhjemite sequence can lead to a second stage of tonalite-trondhjemite magmas with the same highly fractionated REE pattern.

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