THE EARLY SILICEOUS COMPONENT OF PLANETARY CRUSTS: EXPERIMENTAL
PETROLOGY OF THE TONALITE-TRONDHJEMITE ROCK SERIES. Bradford S. White1,
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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 Núk 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 ~1250 °C at 0% H2O to ~960°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 ~10%
H2O, and amphibole (Hb) out to the saturation plane. Plag and Ga are also primary liquidus
phases of the Núk 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,
followed very closely by Hb and Ga. The Ga stability field is greatly reduced at 10 kbar and
closes off above 10% H$_2$O and Hb replaces Cpx as the first phase to appear. For H$_2$O$>$10%,
Hb is the sole mineral to crystallize between 950 and 780°C where Pl first becomes stable.
These phase relations for tonalite at 10 kbar parallel those for the Núk gneiss where Pl, Cpx,
and Hb appear respectively with increasing H$_2$O content. However Ga is not present at all in the
Núk 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 $\approx$14 kbar for Ga on the liquidus of
trondhjemite. For tonalite a triple saturation point for Ga, Hb, and Cpx also lies at $\approx$14 kbar.

A T-XSiO$_2$ section taken through the system at 15 kbar and 5% H$_2$O reveals the near
liquidus phases for the full compositional range at this depth and volatile content. Beginning at
the low SiO$_2$ end, the first liquidus phase to appear changes from Cpx, to Ga, to Pl, and finally
to Quartz. With increasing SiO$_2$, 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%<SiO$_2$<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 H$_2$O 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 H$_2$O, 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 H$_2$O$>$5%, and the Ga-Cpx boundary on the vapor-
undersaturated liquidus also goes to lower H$_2$O with increasing pressure, implying that
anhdyrous eclogite may provide a suitable source rock under dry conditions. At 10 kbar both
magmas have near-liquidus Hb at H$_2$O$>$5%, pointing to a wet amphibolitic source. For high
and low pressures, H$_2$O 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 $\approx$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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