Reports

Effect of Water on the Composition of Partial Melts of Greenstone and Amphibolite

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Closed-system partial melts of hydrated, metamorphosed arc basalts and andesites (greenstones and amphibolites), where only water structurally bound in metamorphic minerals is available for melting (dehydration melting), are generally water-undersaturated, coexist with plagioclase-rich, anhydrous restites, and have compositions like island arc tonalites. In contrast, water-saturated melting at water pressures of 3 kilobars yields strongly peraluminous, low iron melts that coexist with an amphibole-bearing, plagioclase-poor restite. These melt compositions are unlike those of most natural silicic rocks. Thus, dehydration melting over a range of pressures in the crust of island arcs is a plausible mechanism for the petrogenesis of islands arc tonalite, whereas water-saturated melting at pressure of 3 kilobars and above is not.

TONALITE IS A COMMON INTRUSIVE rock in modern and ancient island arcs (*1–3*). Results from experimental, geochemical, and field studies suggest that tonalitic melts can form at crustal depths by partial melting of hydrated metamorphic rocks in the arc basement (*4–6*). We have investigated partial melting of natural arc basement rocks (greenstones and amphibolites) under two sets of conditions designed to model natural end-member scenarios for the involvement of water in the melting process: (i) experiments with no water added model a closed system in which all available water comes from the dehydration of metamorphic minerals (largely amphibole and epidote) in the rocks (dehydration melting); and (ii) experiments in which water has been added in sufficient quantity to insure that any melts formed are water-saturated. The second set of experiments models a system in which external water is available (for example, through hydrothermal circulation).

As starting materials we used five basaltic and andesitic greenstones and amphibolites collected from the Smartville complex of northern California, a deeply eroded ancient arc system. Water contents in these samples are estimated from ignition loss and modal abundance of hydrous minerals to be from 0.5 to 2.0 weight percent. The experiments were done in gold capsules in internally heated pressure vessels (*7*). We ran four sets of experiments, two in the closed system (1 and 3 kbar, 900° to 1000°C, no water added) and two water-saturated (1 and 3 kbar, 850° to 1000°C, water added). In the water-saturated experiments, distilled water was typically 20 to 30 weight percent of the charge, and water was invariably present on opening the capsules. Run times were 3 to 7 days; most were 100 hours. Oxygen fugacity is estimated from coexisting Fe-Ti oxides to have been one to two orders of magnitude above the Ni-NiO buffer. Oxide minerals are typically euhedral and do not appear to be relict grains. Loss of Fe to the gold capsules was negligible. The experiments were not reversed, and some mineral zoning and variability in mineral compositions in individual charges were noted, particularly at the lower temperatures in the closed system runs. Melt compositions, however, tend to be consistent throughout an individual charge, and change systematically with increasing temperature. These observations suggest that equilibrium was approached (*8*). Melt and mineral phases were identified with backscattered electron imaging and analyzed with a rastered, 5-nA, 15-kV beam on a Cameca Camebax microprobe. Loss of Na, especially from glasses, was unavoidable, but was minimized by low beam current, short counting times for Na, and by counting Na first. Special precautions were taken to keep the beam off the analyzed spot until the analysis had actually begun. However, Na loss from glasses is estimated at between 10 and 30%.

The closed system experiments at 1 and 3 kbar yielded melts that coexist with an anhydrous, plagioclase-rich restite (plagioclase + clinopyroxene + orthopyroxene + magnetite ± ilmenite ± apatite). For a given starting composition, the 1- and 3-kbar runs yielded similar melt and mineral compositions (Fig. 1) and melting percentages. Plagioclase makes up between 40 and 60% of the restite. The water-saturated experiments at 3 kbar yielded melts that coexist with an amphibole-bearing restite that lacks orthopyroxene and is poor in plagioclase (amphibole + clinopyroxene + magnetite ± plagioclase ± ilmenite ± apatite). Modal plagioclase ranges from 0 to 50% of the restite in these charges and decreases systematically as the run temperature and melt percentage increase. The 1-kbar, water-saturated runs contain amphibole and lack orthopyroxene at temperatures up to 950°C and tend to have mineral modes low in plagioclase at temperatures above 900°C. The contrast in mineralogy between the closed system (generally water undersaturated) and water-saturated runs is directly related to water content. As has been shown by earlier workers, high water contents favor the stabilization of amphibole (*9*) and the destabilization of plagioclase with respect to mafic mineral phases (*10*).

The major element compositions of the 1- and 3-kbar closed system and 3-kbar water-saturated partial melts for two of the starting compositions (478 and 557, Table 1) are

Table 1. Compositions of starting materials and natural and synthetic tonalites. (A) 478, greenschist facies metabasalt starting material. (B) 557, greenschist facies meta-andesite starting material. (C) Partial melt of 478, 3 kbar, 950°C, no added water. (D) Partial melt of 478, 3 kbar, 900°C, water-saturated. (E) Glass from partially Kilauea tholeliite, 5 kbar, 825°C, water-saturated (*7*). (F) Average tonalite, Tholo plutonic series (Fiji) (*2*). All compositions normalized to 100%, volatile free. LOI, loss on ignition for the two starting compositions.

Component	A	B	C	D	E	F
SiO_2	52.99	57.56	73.07	71.07	72.1	72.4
TiO_2	1.76	0.61	0.67	0.34	0.2	0.43
Al_2O_3	15.44	15.53	13.92	17.77	17.6	14.1
FeO	11.91	8.09	3.59	1.85	1.50	3.06
MnO	0.22	0.17	0.10	0.10	0.03	0.07
MgO	5.34	5.57	0.83	0.47	0.20	0.89
CaO	9.30	9.28	3.40	4.33	4.63	3.2
Na_2O	2.58	2.57	3.43	3.43	2.5	4.6
K_2O	0.16	0.44	0.85	0.38	1.2	1.0
P_2O_5	0.29	0.18	0.15	0.25	0.01	0.07
LOI	0.49	1.56				

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contrasted in Fig. 1. In both samples, amphibole and epidote are the major water-bearing phases. The 1- and 3-kbar, closed system experiments for each starting composition yielded melts with similar compositional ranges. In contrast, for these two starting compositions and all others examined, there is a complete lack of overlap in the major element chemistries of the closed-system melts and the 3-kbar water-saturated melts. The water-saturated melts are strongly enriched in Al and variably, but markedly, depleted in Fe and K (and Mg and Ti as well) with respect to the closed system melts. Melts from the 1-kbar water-saturated experiments (not shown in Fig. 1) have compositions intermediate between the closed system and 3-kbar water-saturated melts (Fig. 2).

Most of the compositional differences can be directly attributed to the destabilization of plagioclase with respect to mafic phases in the water-saturated system. This destabilization results in high melt Al content and low melt Fe, Ti, and Mg contents, both through dilution and, perhaps, because of enhanced stability of mafic minerals. There is no evidence that these compositional changes are related to enhanced Fe-Ti oxide stability in the water-saturated system. The modal Fe-Ti oxide content of the closed-system charges and 3-kbar water-saturated charges is the same (7.9 and 7.6 weight percent, respectively). In any event, the differences in melt Al content between the water-saturated and water-undersaturated systems are too great to be caused by enhanced stability of magnetite or any other mafic phase, and can only be attributed to diminished plagioclase stability in the saturated system. The diminished K content of the water-saturated melts probably reflects the stabilization of amphibole in the restite. Increasing water pressure increases the compositional differences between the water-saturated and closed systems (Fig. 2). This result is consistent with that of Helz (*11*), whose water-saturated crystallization experiments on basaltic compositions at 5 kbar yielded melts that are even more aluminous and iron-poor than those in our 3-kbar water-saturated experiments (Table 1) and with experimental studies on plagioclase stability cited earlier (*10*). The results of Spulber and Rutherford (*12*) indicate that silicic melts in other geologic settings (oceanic plagiogranites and Icelandic rhyolites) can also be generated by fractionation or partial melting or both of basalts at water pressures less than the total pressure and are consistent with our results.

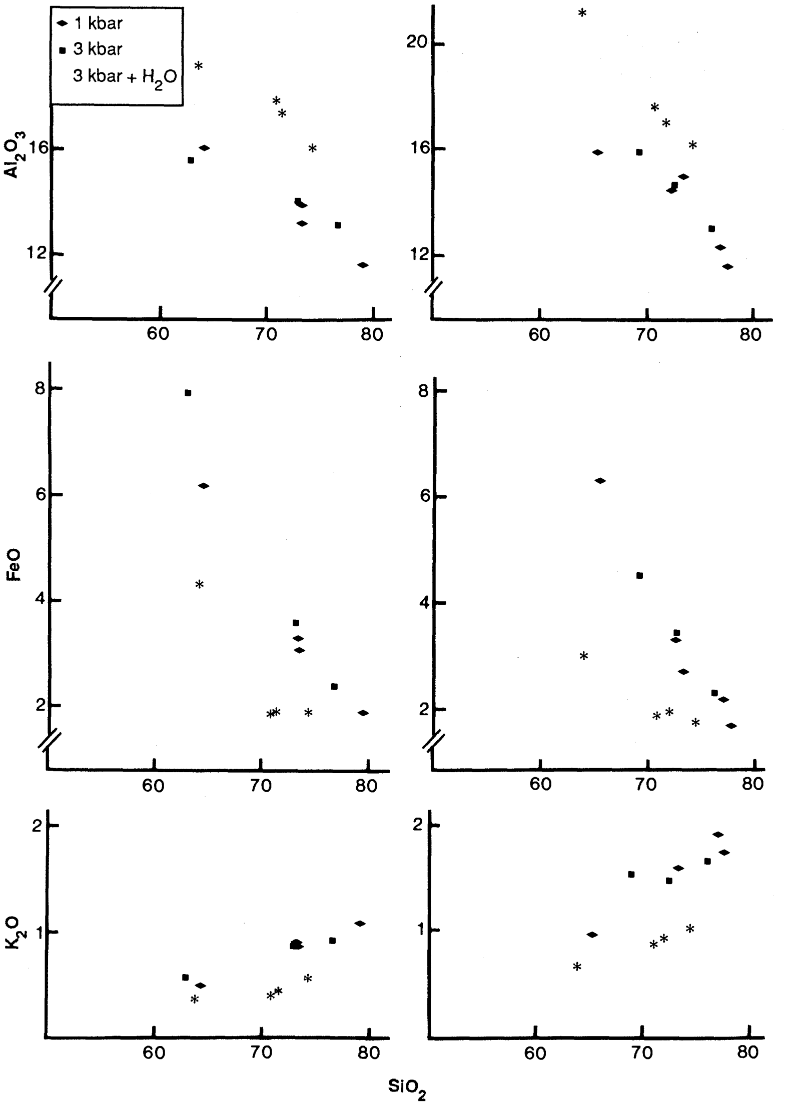

Fig. 1. Plots of Al_2O_3, K_2O, and FeO versus SiO_2 for all experiments on starting compositions 478 (left) and 557 (right) (analyses in Table 1). The compositions of 1- and 3-kbar closed system experimental melts are similar, but are significantly different from those of the 3-kbar water-saturated melts. Similar variations also characterize the other three compositions studied. All compositions normalized to 100%, volatile-free.

The major element chemistry [especially the Al content (Fig. 2)] of the closed system melts for all five of our starting compositions is similar to that of several suites of island arc tonalites (Table 1). In contrast, analyses from the island arc tonalite suites do not plot in the field defined by the compositional range of melts from the 3-kbar water-saturated experiments on an Al versus Si plot, and only one analysis (out of 74) plots in the field on an Fe versus Si plot (Fig. 2). The melts generated during water-saturated experiments at 5 kbar are also unlike natural island arc tonalite compositions (*11*) (Table 1). The 1-kbar water-saturated experiments yielded some melts similar in composition to the more iron-poor and aluminum-rich members of the natural island arc tonalite suite. Overall, however, the compositional overlap between the natural data set and the 1-kbar water-saturated melts is small (Fig. 2).

Tonalite melts can, of course, be generated or modified by processes other than crustal melting. Relatively mafic tonalites (SiO_2 = 60 to 63 weight percent) have been shown to have liquidus temperatures too high to have been generated by crustal melting (*13*); the agreement between our experimental results and the natural island arc tonalite data set tends to be poorest at low values of SiO_2 (Fig. 2). Fractionation of basalt or retention of restite minerals in silicic tonalite melts can account for the occurrence of mafic tonalites, as can mixing of basalt with crustal contaminants. One such crustal contaminant might be silicic tonalite melts like those generated in the closed system experiments.

We conclude, however, that many island arc tonalite magmas can and probably do form directly by dehydration melting of hydrated, metamorphosed basalts and andesites (greenstones and amphibolites) at

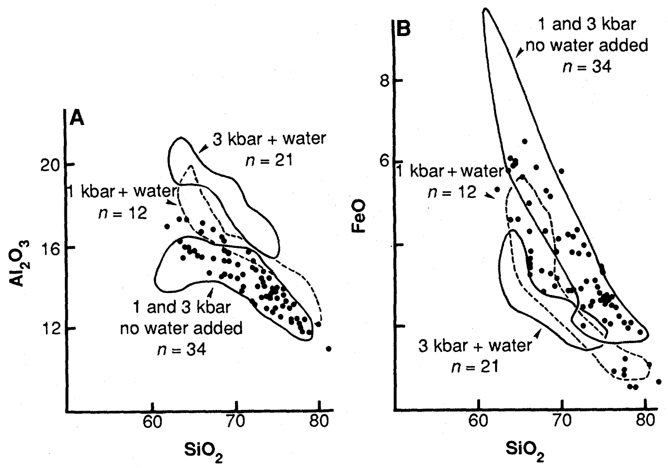

Fig. 2. Comparison of island arc tonalite compositions from Fiji, Guadalcanal, western North America, and Newfoundland (filled circles) (*2, 3, 5, 14, 16*) with experimental results. There is excellent agreement between closed system experimental melt compositions and the natural data, little agreement between the 1-kbar water-saturated results and the natural data, and virtually no overlap between the 3-kbar water-saturated experimental melts and the natural tonalites. All compositions normalized to 100%, volatile-free; *n* = number of experiments.

crustal pressures in a closed system. A likely place for such melting to occur is at or near the contact between hydrated arc crust and a hot basaltic intrusion. Local zones of melting have been observed around basaltic intrusions and elsewhere in several ancient island arc basement complexes (*6, 14*). Significant volumes of silicic magma can be generated by basalt-induced melting even of relatively mafic island arc crust (*15*), potentially enough to account for the observed abundance of island arc tonalite. Our experiments predict that dehydration melting will leave an anhydrous "granulitic" restite; rocks having the proper restite mineralogy have been described from at least one contact aureole (*6*). At water pressures as low as 1 kbar, there is significant divergence of experimental melt compositions and the natural data set, and by 3-kbar water pressure, the compositions are distinctly different. Indications from this and other studies are that the compositional gap between natural and experimentally produced melts increases as water pressure increases. Thus water-saturated melting of arc crust at pressures greater than 1 kbar is an unlikely mechanism for the formation of island arc tonalite.

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Contribution of Ultraviolet Irradiance Variations to Changes in the Sun's Total Irradiance

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The sun's total irradiance decreased from 1980 to mid-1985, remained approximately constant until mid-1987, and has recently begun to increase. This time interval covered the decrease in solar activity from the maximum of solar cycle 21 to solar minimum and the onset of cycle 22. The sun's ultraviolet irradiance also decreased during the descending phase of cycle 21 and, like the total irradiance, is now increasing concurrently with the increase in cycle 22 activity. Although only 1 percent of the sun's energy is emitted at ultraviolet wavelengths between 200 and 300 nanometers, the decrease in this radiation from 1 July 1981 to 30 June 1985 accounted for 19 percent of the decrease in the total irradiance over the same period.

DURING THE RECENT SUNSPOT CYCLE 21, changes in the sun's total irradiance and in its emission at ultraviolet (UV) wavelengths were observed simultaneously from space by a variety of independent experiments. Understanding the nature and origin of this variability is important because solar irradiance variations over longer time scales have been invoked as drivers of tropospheric change, for example, in the sea-surface temperature (*1*) and in climate (*2*), including the Maunder Minimum climate anomaly. Although the spectrum of the radiation that composes the sun's total irradiance is well known, the contribution of irradiance variations in specific spectral bands to changes in the total irradiance is less certain (*3*). These irradiance variations are of interest for solar studies as a tool for probing the physical origins of the variability. They are also of interest for climate studies because variations in the total solar irradiance measured from a satellite platform must be separated into changes in that part of the solar spectrum incident on the earth's surface and changes in the solar UV spectrum at wavelengths less than 300 nm that is absorbed in the earth's atmosphere. The UV energy emitted by the sun is known to be more variable than its visible radiation. This difference in variability suggests that, although only $\sim$1% of the sun's

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