

BASALT MAGMA INTERACTION WITH HARZBURGITE AND THE FORMATION
OF HIGH-MAGNESIUM ANDESITES

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Abstract. The interaction of basalt melt with mantle harzburgite at low pressure might result in silica enrichment of the melt by assimilation of orthopyroxene. Experimental tests of this hypothesis show that silica-rich liquids (56 wt %) are produced by melt-orthopyroxene reaction at 1200° to 1250°C. These silica-rich liquids are enriched in Na₂O and K₂O over that found in the starting basalt melt which indicates that the alkalis diffused against a concentration gradient into the silica-rich liquid. The liquids produced in this way are chemically similar to high-magnesium andesites or boninites.

Introduction

After a primary magma is produced by melting of the mantle, the amount of chemical change that it undergoes while in transit to the Earth's surface, will depend on how fast it is transported and how much it interacts with the surrounding mantle and crust. A magma that rises slowly and re-equilibrates along the way will have a different chemistry than one that moves rapidly to the surface. Assimilation of orthopyroxene or clinopyroxene (with 52 to 60 wt % SiO₂) in the mantle by basalt magma could increase its silica content. High silica may be accompanied by alkali enrichment, and one example of this is found where quartz is incorporated in basalt.

Sato [1975] described alkali-rich coronas around quartz xenocrysts in andesite and basalt, and found that Na and K, and possibly Ca diffused from the host magma into the SiO₂-rich corona against their concentration gradient. Sato then reproduced the alkali-enrichment by melting quartz in a powdered olivine basalt. Watson [1982] also showed that the quartz-rich liquid around melting quartz spheres in an oceanic tholeiite concentrates the alkalis. The alkalis appear to be partitioned between immiscible liquids, although the two liquids will mix and only remained separated by the slow diffusion of silica.

The experiments of Sato [1975] and Watson [1982] dealt with the reaction of basalt with quartz or silica-rich crustal material, but no previous attempt has been made to evaluate the reaction of basalt with mantle minerals with high silica content (56 to 59 wt %), even though this reaction has been observed in natural rocks. Phonolitic liquids have been observed surrounding symplectic orthopyroxene in harzburgite xenoliths in basaltic lavas [Fisk, 1983; Fisk and Ford, 1984], and ultramafic xenoliths in silica undersaturated lavas from Samoa have dissolved to form alkali-rich liquids [Wright, 1985]. The reactions

just described are between alkali basalts and silica-rich minerals which are the extreme case because of the large difference of silica content of the host magma and the xenolith, but these reactions should also exist between basalt and orthopyroxene. Evans [1985] suggested that metasomatic, alkali enrichment occurs at the contact between basalt and peridotite and basalt liquid is the metasomatizing agent. In this case, orthopyroxene decomposes by reaction with basalt and leaves an alkali-rich liquid in a dunite. Dick (personal communication) sees evidence for the interaction of basalt and mantle in alpine-type peridotites and suggests that this process may dominate the chemistry of erupted lavas.

Starting Material and Experimental Procedure

These experiments examine the interaction of basalt magma with harzburgite, a major constituent of the upper mantle. Harzburgite, K22-P1, from 0.63 km below the Moho in the Samail ophiolite [Hopson et al., 1981] was chosen for the experiments. It is composed of 74% olivine (Fo_{90.91}), 24% orthopyroxene (En_{90.91}), with a grain size of about 3mm and 2% chromite [Boudier and Coleman, 1981; Pallister and Hopson 1981], and except for variation in the chromite composition, it is mineralogically and chemically similar to the other harzburgites in this 9 km thick section of the ophiolite. Much of the harzburgite in this section is serpentinized, but K22-P1 is one of the least hydrated samples, consisting of about 15% serpentine. This does not effect the experimental results because the harzburgite is dehydrated at the start of each experiment. Crucibles 5 mm high, 10 mm in diameter (average weight 1.5 g) were cut from the harzburgite and 50 mg of powdered basalt was placed in it.

The starting composition of this basalt (DSDP Leg 37, 332 B29-2, 9-12) [Sigurdsson, 1977] is given in Table 1. This MORB has high MgO content and high liquidus temperature, only olivine on the liquidus and it is considered a primitive magma. Reaction between a high-temperature magma and mantle is more likely than between low temperature magma and mantle [Huppert and Sparks, 1985].

The harzburgite crucible containing the basalt powder was placed in the hot zone of a vertical quench furnace at 100°C. A mixture of 74% CO₂ and 26% H₂ was introduced into the furnace and the temperature raised to 1200°C or 1250°C in three hours, and then maintained at that temperature. The higher run temperature was equivalent to the calculated liquidus temperature of the starting basalt [Roeder and Emslie, 1970]. At this temperature, the oxygen fugacity was 10^{-9.5} which maintains an accepted ratio of Fe³⁺ to Fe²⁺ in the molten basalt and suppresses the formation of oxide mineral phases. After two hours at the run temperature, the sample was removed from the furnace and quenched in air. The whole crucible

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Table 1

	1	2	3	4	5	6	7	8	9
SiO ₂	47.8	49.8	56.0	55.9	56.3	56.8	41.0	41.0	53.5
TiO ₂	0.60	0.63	0.53	0.47	0.0	0.0	0.0	0.0	1.31
Al ₂ O ₃	16.2	16.1	11.2	14.51	2.30	1.76	0.15	0.14	14.65
FeO*	8.55	8.52	8.09	6.84	6.39	5.61	11.36	12.17	8.50
MnO	0.19	0.12	0.13	0.15	-	0.15	-	-	0.15
MgO	11.4	9.99	8.92	7.14	32.5	33.7	47.6	47.2	7.45
CaO	11.3	11.9	9.02	12.3	2.08	2.57	0.26	0.34	11.27
Na ₂ O	2.11	1.99	2.74	2.30	0.0	0.0	0.0	0.0	3.06
K ₂ O	0.14	0.15	0.21	0.19	-	-	-	-	0.37
Cr ₂ O ₃	0.14	-	-	-	0.81	0.62	0.21	0.07	0.07

* Total iron as FeO.

1. DSDP Leg 37 332B-29-2 (9-12) [Sigurdsson, 1977].
2. Glass far from Opx-glass contact in 1250°C experiment.
- 3,4. Glass from 120 μm wide reaction zone with Opx in 1250° experiment.
5. Opx next to reaction zone in 1250° experiment.
6. Opx from capsule K22-pl [Pallister and Hopson, 1981].
7. Olivine from reaction zone in 1250° experiment.
8. Olivine outside reaction zone in 1250° experiment.
9. Glass from reaction zone with orthopyroxene in 1200° experiment.

and charge was cut in half and a polished thin section was prepared for microprobe analysis.

Results

Basalt liquid had formed a U-shaped meniscus in the crucible and some vesicles remained in the glass (Figure 1). The clear, light-brown glass contained no quench phases but about 1% olivine had settled to the bottom of the crucible. The contact between the glass and the olivine of the harzburgite crucible was sharp, but the liquid had corroded the orthopyroxene of the capsule (Figure 1). The orthopyroxene and glass formed a 100 to 250 μm wide symplectitic reaction zone of approximately 70% olivine and 30% glass and a trace of chromite (Figure 1). This zone appears identical to the "spongy-texture" described by Kuo and Kirkpatrick [1985] where orthopyroxene in harzburgite xenoliths dissolved faster than the olivine.

The microprobe analyses of the crucible and glass are given in Table 1. The orthopyroxene in the crucible, adjacent to the reaction zone, is the same as that of Pallister and Hopson [1981], and the glass 2 mm from the contact with the crucible is similar to the starting composition. This glass has olivine on its liquidus at 1252°C based on its FeO and MgO content, and the olivine saturation surface [Roeder and Emslie, 1970] which agrees well with the run temperature of 1250°C. The glass in the reaction zone has a 56% silica, 7 to 9% MgO and alkali contents higher than the starting basalt liquid (Table 1). The olivine in this zone (Fo₈₈) is similar to olivine outside the reaction zone except for its higher Cr₂O₃ content.

Discussion

The breakdown of the orthopyroxene in contact with basalt melt at 1250°C can be described in terms of the melting of enstatite in the system

forsterite-silica [Bowen, 1928]. In this system, enstatite (59.8 wt % SiO₂, 40.2 wt % MgO) melts incongruently (decomposes) at 1557°C to form olivine and a liquid with more silica than the enstatite. In the more complex system of basalt-melt interaction with orthopyroxene, the same decompositions should take place at a lower temperature,

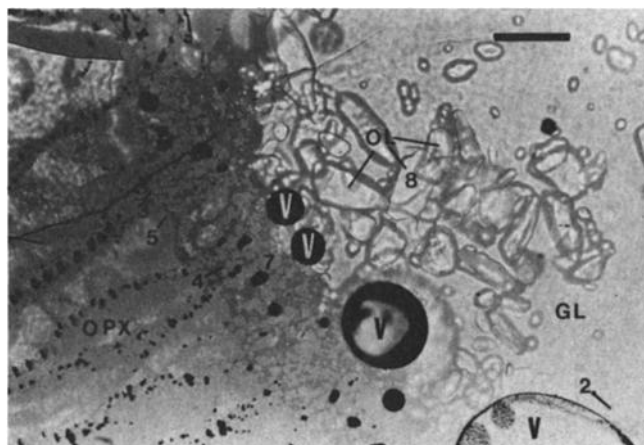


Fig. 1. Photomicrograph of experiment H7 in reflected light showing the contact between orthopyroxene (left) and glass (right), and the transition zone between them. Opx = orthopyroxene V = vesicle. Ol = olivine. Gl = glass. Numbers are analyses keyed to Table 1. Bar is 100 μm long. Transparent olivine grains cluster at the edge of the orthopyroxene. Strings of pits (black) mark cracks in the Opx along which melt has migrated. Olivine in the the glassy area of the charge is greater than 1 volume % because the olivine has settled to the bottom of the crucible; the top of the crucible is crystal-free. Rounded, non-equilibrium are due to the short duration of the run.

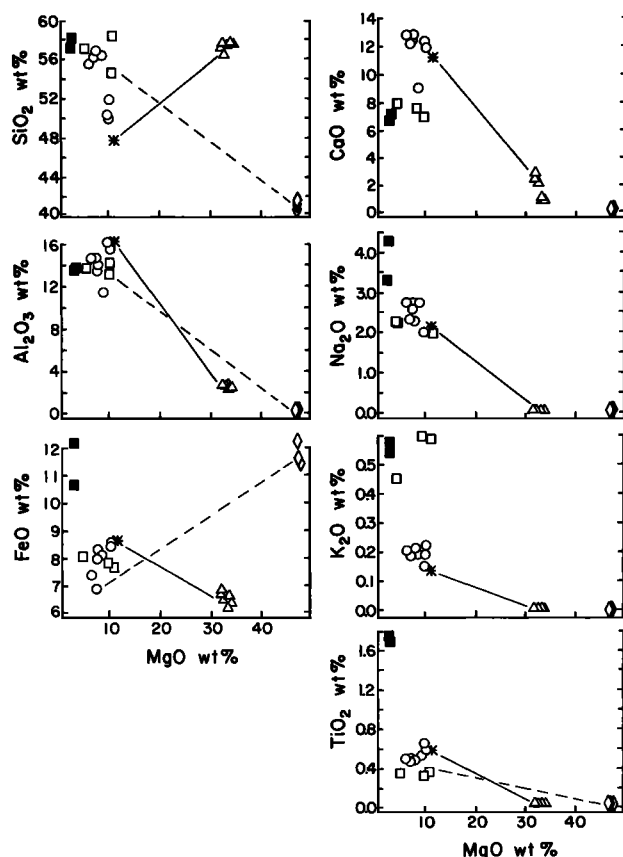


Fig. 2. Oxide variation diagrams for the experimental phases: circle - glass; diamond - olivine, triangle - orthopyroxene; asterisk - starting composition; solid square - oceanic andesites [Hart, 1971; Byerly et al., 1976]; open square - boninites [Kuroda et al., 1978]. Solid line - simple mixture of Opx and starting composition. Dashed line - olivine fractionation. Experimental liquids are nearly identical to boninites.

but the result of the reactions should be the same: the formation of olivine and a liquid more silica-rich than the orthopyroxene. The composition of the resulting liquid is complicated by the presence of basalt liquid and the diffusion of sodium and potassium from the basalt liquid into the silica-rich liquid as described in experiments by Watson [1982]. This breakdown of orthopyroxene and influx of alkalis produces liquids that are identical to some high-magnesium andesites.

Chemistry of experimental liquids

Figure 2 shows the major element chemistry of the starting basalt composition, the resulting glass compositions, and andesites from mid-ocean ridges [Hart, 1971; Byerly et al., 1976] and boninites [Kuroda et al., 1978]. The higher SiO_2 , and lower Al_2O_3 , TiO_2 , and MgO in the glass of the reaction zone, compared to the starting basalt, can be explained by crystallization of olivine (Fo_{88}) from a simple mixture of the starting basalt and orthopyroxene. The line connecting the starting composition (*) and the orthopyroxene (triangles) in Figure 2 represents possible mixtures of starting material and pyroxene. Liquids

on this line will have liquidus temperatures greater than 1250°C because of their high MgO content, and will crystallize olivine from their liquidus temperature down to at least 1250°C . The effect of crystallization of olivine (dashed line) from an arbitrary composition on the mixing line will result in an increase in all elements except iron and magnesium.

The zone of reaction of basalt melt and pyroxene (Figure 1) is approximately 30% glass and 70% olivine. Mass balance calculations indicated that subtracting 70% olivine from a mixture of orthopyroxene and basalt melt (1:2 ratio) will produce a new melt with the 57% SiO_2 . The calculated Al_2O_3 , TiO_2 , and FeO contents of the 30% melt described above agree with the composition of the glass found in the reaction zone (Table 1). The Na_2O , K_2O , and CaO of the mass balance calculation do not match the composition of the reaction zone glass, but their enrichment can be explained by their preference for the silica-rich liquid over the basalt liquid.

Formation of Oceanic Andesites and Boninites.

The FeO , K_2O , and TiO_2 of the experimentally produced liquids are lower than natural oceanic andesites [Hart, 1971; Byerly et al., 1976; Staudigel et al., 1982], but are similar to boninites [Kuroda et al., 1978]. The difference between the experimental run products and oceanic andesites may be due to a number of factors. First, these elements are lower in the starting basalt than in the average ocean ridge basalt, so their concentration is low in the co-existing silica-rich liquid in the experiments. Second, FeO , K_2O , and TiO_2 would increase during fractional crystallization of plagioclase, olivine, and pyroxene during cooling from 1250°C to the temperatures of andesite solidification, so the difference between the experimental liquids and the oceanic andesites may not be a problem, at least in terms of major elements. Natural boninites are quite similar to the experimentally produced glasses, except for CaO which is higher and K_2O which is lower in the experiments than in the boninites. Additional experiments at 1200°C show that K_2O is enriched by more than a factor of 2 in the boundary layer glass compared to the starting composition and produce liquids that are identical to boninites (Table 1). Na_2O , K_2O , and possibly CaO , are enriched in the reaction zone glass, and this enrichment can be explained by their partitioning between silica-poor and silica-rich liquids as seen around quartz xenoliths in basalts [Sato, 1975]. High-magnesium andesites can, therefore, be produced by the reaction of basalt magma and harzburgite at low pressure. Whether this is the primary way that they are produced may be confirmed by trace element studies on high-magnesium andesites and associated ultramafics.

The U-shaped rare earth patterns of boninites and some harzburgites [Pallister and Knight, 1981] and the low abundance of rare earths in boninites suggests a relationship to ultramafic rocks with extremely low rare earths. Oceanic andesites have light-rare earth enriched patterns and high overall rare earth content which suggests they are not derived by reaction with harzburgites.

Liquid Volume and Segregation. The experiments show that high-magnesium andesite can be produced by the interaction of magma and harzburgite at low pressure and the calculations below suggest that

large volumes of the andesite could be formed and that it could segregate. Andesite produced at 1250° would be 0.1 g/cm³ less dense than basalt [Bottinga et al., 1982] and the andesite will rise to the top of the magma chamber. One 12 hour experiment under the same conditions used for the 2 hour runs produced a thin layer of andesite at the top surface of the basalt. Cooling of this segregated liquid will further increase its Si, Na, and K content by crystal fractionation. Based on other work [Sato, 1975; Watson, 1982], this silica-rich magma will further concentrate alkalis from the adjacent basalt magma. Diorite and plagiogranite above the high-level gabbros, and below the sheeted dikes in the Wadi Kadir sections of the Samail Ophiolite could be formed in this manner [Pallister and Hopson, 1981].

Substantial quantities of basaltic andesite can be produced by this process. The cooling of 1 km³ of magma from 1250°C to 1200°C, coupled with the latent heat of crystallization of olivine in reaction with the orthopyroxene, can produce about 0.1 km³ of andesite. This assumes that the latent heats of fusion of olivine and orthopyroxene are the same and that 90% of the orthopyroxene is converted to olivine.

The formation of high-magnesium andesites described here can only occur where magma is in contact with harzburgite at low pressures. Fresh boninites were collected with harzburgite in a single dredge hauls from near the Bonin Islands [Kobayashi, 1983] showing the association of the two rock types. At high pressures (>10 kb) orthopyroxene and basalt may co-exist, so there would be no breakdown of the orthopyroxene. Magma stored within the oceanic crust will not have the opportunity to form andesites because it is not in contact with harzburgites. Eruptions on elevated regions of oceanic ridge crest, such as Iceland, will require a greater hydrostatic head, and these eruptions may be from magma chambers rooted in the mantle and, therefore, they would be more likely to have occasional andesites while in deeper ocean ridges they would be less likely. This may explain the occurrence of icelandites in Iceland [Carmichael, 1964] and the Galapagos islands [McBirney and Williams, 1969].

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