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## Genesis of high Mg# andesites and the continental crust

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**Abstract** The continental crust has an andesitic composition with high Mg/(Mg+Fe) and Ni contents which may be too high to have formed by differentiation of basaltic magmas. Instead, mantle-derived, high Mg# andesites (HMA) may form a substantial component of the crust. HMA may be produced by partial melting of previously depleted, subsequently metasomatised mantle peridotite. However, they are more likely produced by reaction between ascending melts and mantle peridotite. HMA are less common than basalts among lavas in modern island arcs, but may have been more common in the past, may be produced in specific environments (such as “ridge subduction”), may be more common among plutonic rocks in the lower and middle crust than among lavas at the surface, and may be selectively preserved during later erosion and subduction processes.

### Introduction

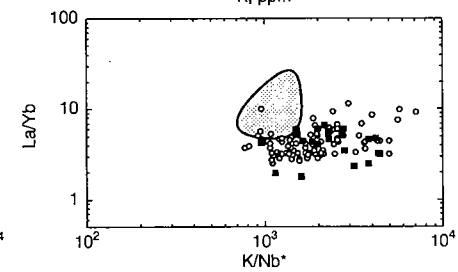
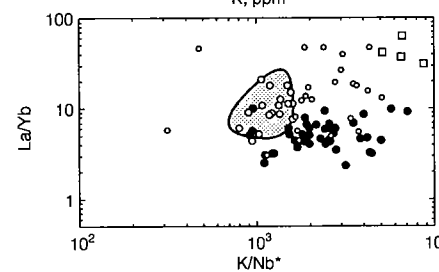
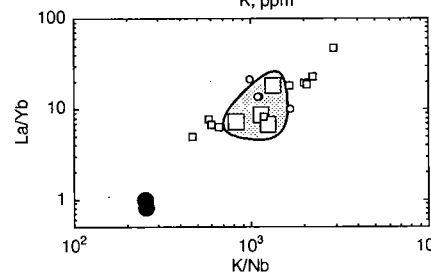
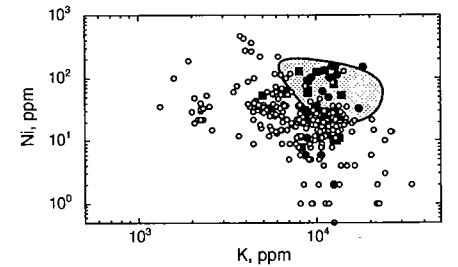
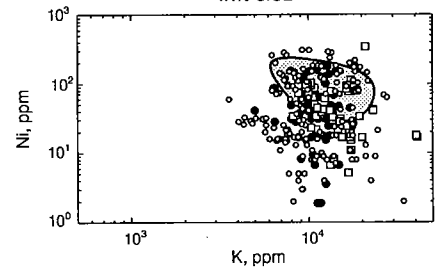
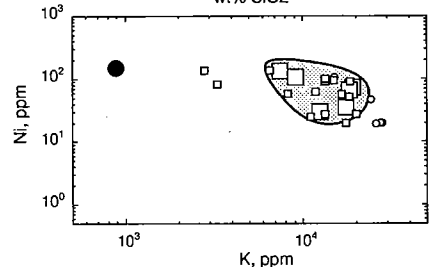
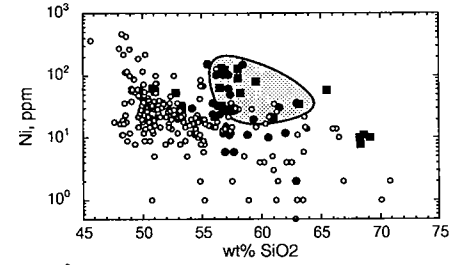
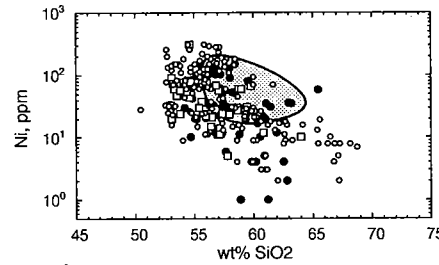
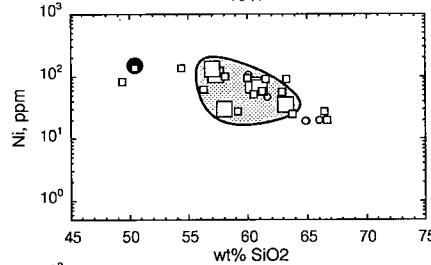
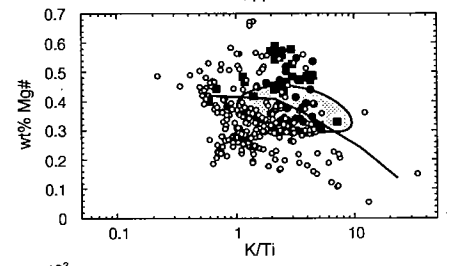
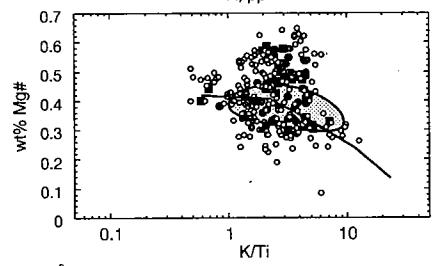
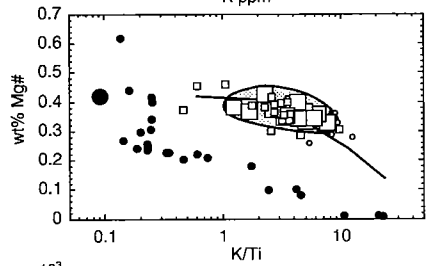
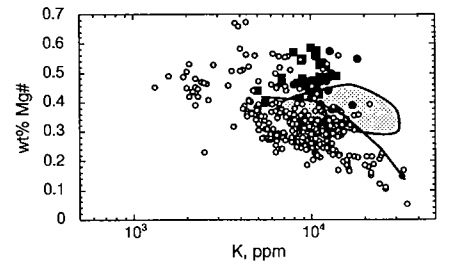
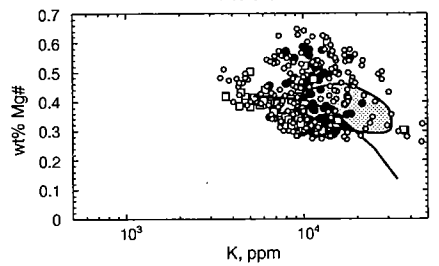
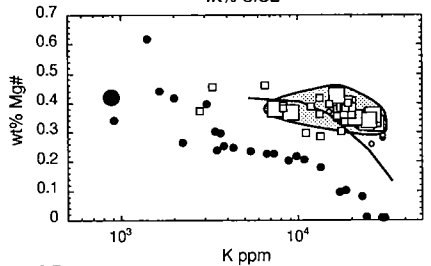
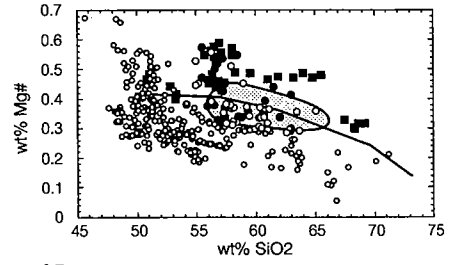
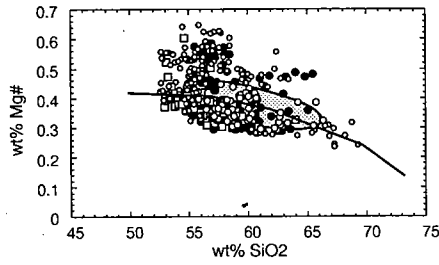
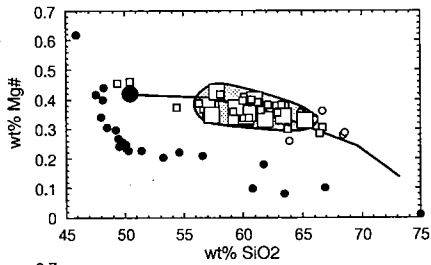
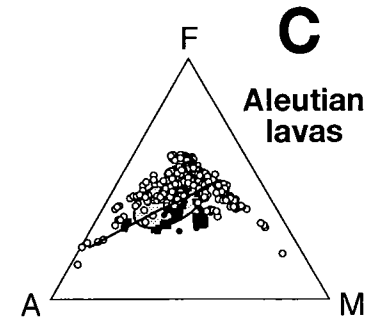
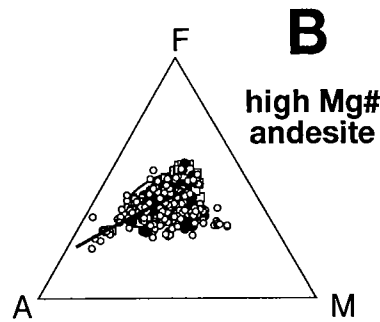
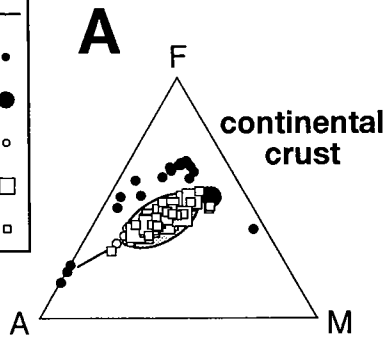
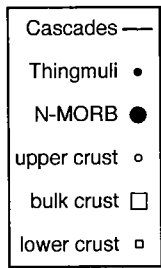
The bulk composition of the continental crust has been estimated to have 55–65 wt% SiO<sub>2</sub>, 4 to 7 wt% combined Na<sub>2</sub>O and K<sub>2</sub>O, molar Ca/(Ca+Na) of 0.4 to 0.6, and wt% Mg/(Mg+ total Fe as Fe<sup>2+</sup>) or Mg# 0.34 to 0.42 (e.g. Weaver and Tarney 1984; Taylor and McLennan 1985), the same as that of a calc-alkaline, high-Mg# andesite. Figure 1 A presents estimates of the composition of the continental crust based on averages of exposed rocks, especially in cratons, averages of shales and loess deposits representative of the clastic flux from the cratons, and averages of analyses of lower crustal xenoliths and high-pressure metamorphic terranes. The data are compared to the composition of oceanic crust as represented by mid-ocean ridge basalt (MORB), and to the Thingmuli volcanic series of Iceland (Carmichael 1964).

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All the estimates of the composition of the lower, upper and bulk crust lie along a “calc-alkaline” magmatic trend, similar to the modern High Cascades lava trend (Carmichael 1964; White and McBirney 1979), and the variation trend of the Peninsular Ranges batholith observed by Larsen (1948). The calc-alkaline trend for continental compositions is well constrained, since it includes careful averages for large, representative parts of the upper crust (e.g. Shaw et al. 1967), and recent compilations for lower crustal samples (e.g. Rudnick and Presper 1990). Also, since the crust does not include significant ultramafic material, but does include large amounts of silicic, granitic rocks, it must be more silica-rich than basalt – i.e. it is andesitic.

In this paper, a calc-alkaline, high Mg# andesite is simply defined as an andesitic lava with Mg# >0.3 and less than 10 wt% MgO. Figure 1 B illustrates that high Mg# andesite (HMA) lavas with compositions similar to the continental crust are found in many contemporary arcs. Although some of these are from arcs on continental margins, others are from island arcs (Aleutians, Marianas) without older, underlying continental crust. Although the definition of HMA adopted above is very broad, involving only Si, Mg and Fe concentrations, there is strong similarity in major, minor and trace element characteristics between typical HMA and the crust in several important respects. (1) Both continental crust and typical HMA are light rare earth element (REE) enriched, with La/Yb greater than 3. (2) Similarly, they have more than 6000 ppm K, and K/Ti greater than 1. (3) Both are depleted in the high field strength elements Nb and Ta relative to light REE, K and Ba. For example, they have K/Nb >500, much larger than in mid-oceanic ridge basalts (MORB). (4) Both have Ni contents from 20 to 200 ppm. These similarities can be seen in more detail in Fig. 1 of Kelemen et al. (1993), where individual trace element patterns for all Aleutian HMA from the compilation of Kay and Kay (1994) are shown, along with estimated trace element concentrations in the continental crust. The combination of these major and trace element characteristics in lavas is believed to be unique to HMA



in subduction-related magmatic arcs. It is inferred that the similarity between HMA and continental crust is not a coincidence, and indicates the operation of similar processes in their formation. As a result, it has been proposed by some workers that continental crust formed as a result of arc magmatism (e.g. Taylor 1967), and thus that subduction-related magmatism has been an important crust forming process since the early Archean (e.g. Nisbet 1987).

However, average arc crust forming today may not be andesitic. Some experimental evidence suggests that calc-alkaline andesites cannot be generated by partial melting of peridotite at mantle pressures beneath arcs (e.g. Nicholls 1974). Some HMA have compositions ( $Mg\# > 0.6$  and  $Ni > 100$  ppm) which are consistent with equilibration mantle olivine ( $\pm$  pyroxenes) and thus they could represent mantle-derived liquids. Indeed, Tatsumi (1982) has shown that a natural HMA is in equilibrium with olivine+two pyroxenes with mantle compositions under  $H_2O$ -undersaturated conditions. However, experimental studies of liquids formed by direct partial melting of mantle lherzolite have not produced HMA (see following sections). In addition, many HMA have  $Mg\#$ s and  $Ni$  contents too low to be in equilibrium with mantle olivine. Note that throughout this paper,  $Mg\#$ s are calculated assuming all Fe is FeO. Gill (1981) estimated that typical arc andesites have primary  $Fe_2O_3/FeO$  ratios of about 0.3, reflecting oxygen fugacities slightly higher than the NNO oxygen buffer. Significantly higher  $Mg\#$ s would be calculated for HMA and the continental crust if this ratio were adopted. However, many HMA and the continental crust would still have  $Mg\#$ s too low to be in equilibrium with mantle olivine.

**Fig. 1A–C** Comparison of the compositions of the continental crust (A), high- $Mg\#$  andesite lavas (B), and volcanic rocks observed in the Aleutian island arc (C). Triangular plots at the top of each column are traditional AFM diagrams, in weight proportions, with  $A=Na_2O+K_2O$ ,  $F=FeO+0.9 Fe_2O_3+MnO$ , and  $M=MgO$ . In rectangular plots,  $wt\%Mg\# = wt\%MgO/(wt\%MgO+wt\%FeO+0.9 wt\% Fe_2O_3)$ . **A** Estimates of the composition of the continental crust, compared to the composition of normal mid-ocean ridge basalt (Hofmann 1988; Sun and McDonough 1989), the compositions of the Thingmuli lava series in Iceland (Carmichael 1964), and the Cascades lava trend of Carmichael (1964). The compiled continental data include 12 upper crustal estimates, 16 bulk crustal estimates, and 17 lower crustal estimates, from Shaw et al. (1967), Dupuy et al. (1979), Weaver and Tarney (1983, 1984), Taylor and McLennan (1985), Rudnick and Presper (1990), additional references listed in the Appendix, and compiled estimates from sources cited within these references. **B** High  $Mg\#$  andesites, ( $n > 300$ ) including selected samples from the Aleutians (Kay 1978; Gust and Perfit 1987; Kay and Kay 1993; Yagodzinski et al. 1994; and Appendix), shown as filled symbols, and the Marianas (Appendix), shown as open squares. Additional samples from Papua New Guinea, southern Japan, Baja California, western Mexico, Panama, Chile, and the Cascades are shown as open circles (Arculus et al. 1983; and Appendix). **C** Aleutian lava compositions – more than 350 samples (as for B, plus Appendix). High  $Mg\#$  andesites (between 54 and 65 wt%  $SiO_2$ ,  $Mg\# > 0.29$ ) from Kay and Kay (1993) and Yagodzinski et al. (1994), are shown as filled circles and filled squares, respectively

Andesites are less abundant than basaltic magmas among volcanic and volcanoclastic rocks in arcs (e.g. Kay and Kay 1994). Figure 1 C presents lava compositions from the Aleutian intra-oceanic island arc. Although there are some HMA, it is clear that a substantial proportion of the observed lavas are basaltic. In addition, many andesitic to dacitic lavas have lower  $Mg\#$  and  $Ni$  than the continental crust. A compilation for the Marianas arc (not shown) produces the same result. Experiments have demonstrated that some andesites may be formed by crystal fractionation from basaltic magmas (e.g. Sisson and Grove 1993), though these generally have  $Mg\#$ s lower than continental crust. As a result of mass balance calculations, it has been proposed that HMA, with  $Mg\#$ s greater than or equal to continental crust, may also be formed by crystal fractionation from basalt (e.g. Grove and Kinzler 1986). An arc crustal section in south central Alaska (DeBari and Sleep 1991) may have an average composition of olivine tholeiite.

On the basis of these observations, many workers have concluded that the net flux through the Moho in arcs is basaltic, and that andesitic magmas are formed by differentiation processes (crystal fractionation, anatexis, assimilation of older crust, magma mixing) in the crust.

Three inferences introduced above, that the continental crust formed as a result of arc magmatism, that the continental crust is andesitic in composition, and that the net magmatic flux through the Moho in arcs is basaltic, form an apparent paradox. Hypotheses which can resolve this paradox can be grouped into six main categories.

#### (1) Continents are not andesitic, but basaltic

The silicic composition of the upper crust may be “balanced” by a considerable proportion of ultramafic rock. Ultramafic material is relatively rare in the crust, above the seismic Moho, but could be present as ultramafic “cumulates” below the seismic Moho (e.g. Kay and Kay 1985). If so, the crust should have the composition of liquids derived by crystal fractionation from mantle-derived, basaltic magmas.

#### (2) Basaltic crust+ recycling via delamination

HMA may have formed by crustal differentiation of mantle-derived, basaltic magmas. The mafic, crystalline residue of differentiation might be transformed into eclogite during subduction of continental crust as a result of plate collision. Eclogite, being denser than upper mantle peridotite, might then return to the mantle (“delaminate”), leaving only andesitic differentiates in the crust (Kay and Kay 1991).

#### (3) Basaltic crust+ recycling via subduction

HMA may have formed by differentiation of mantle-derived, basaltic magmas. Subduction of basaltic com-

ponents of the crust, directly or as sediments and chemical components added to altered oceanic crust, might result in selective preservation of an andesitic bulk composition.

#### (4) Continental crust did not form in arcs

A different mode of crustal accretion formed continental crust in the Archean (e.g. deWit et al. 1992). Such hypotheses invoke formation of thick basaltic to ultramafic crust, followed by intracrustal melting, and are thus similar to (2) and (3).

#### (5) Assimilation or mixing, +recycling

HMA may have formed by assimilation or mixing of earlier formed granitic rocks in mantle derived, basaltic or ultramafic magmas (e.g. McBirney et al. 1987). The mafic residues of granite formation must have been returned to the mantle, as in (2) or (3).

#### (6) Mantle-derived andesite magmas

The average magmatic flux through the Moho during continent-building processes may have had the composition of HMA. Since average crust has the composition of HMA, basaltic rocks in the crust must be volumetrically minor, or must be offset by a similar proportion of rocks more silicic than HMA, with high Mg#s and Ni contents. The observed abundance of basaltic lavas in modern arcs may not be representative of the composition of magmatic crust during continental accretion. For example, arc magmatism may have been dominantly andesitic in the Archean (e.g. Shirey and Hanson 1984), or andesitic crust – once formed – may be selectively preserved in the geologic record.

In this paper, these hypotheses are critically evaluated in the light of evidence from experimental petrology, studies of phase equilibria, and modelling of trace element fractionation. (1) through (4) are similar in that they call upon differentiation of basaltic magma to produce the andesitic composition of the crust. This process lacks experimental verification to date, despite investigation of crystallization and melting in a wide range of basaltic bulk compositions, pressures, and temperatures. Hypothesis (5), invoking assimilation or mixing between crustal granites and mantle-derived magmas, requires subduction or “delamination” of the residua of earlier granite formation in order to account for the composition of the continental crust. Otherwise, the net flux through the Moho remains basaltic.

Hypothesis (6) requires that, at some times, the net magmatic flux through the Moho has the composition of HMA. Since many prior papers have reviewed basaltic

differentiation and mixing processes, extra emphasis in this paper is given to the production of HMA in the upper mantle, and its implications for crustal genesis. Some HMA are in equilibrium with mantle olivine and pyroxene. However, special circumstances are required to produce HMA by direct partial melting of peridotite. In contrast, experiments and phase equilibrium calculations have shown that HMA is the natural product of melt/rock reaction in the upper mantle. Modelling also shows that the trace element characteristics of HMA and the continental crust can be produced in this way (Kelemen et al. 1993). Mg#s and Ni contents of the bulk continental crust are too low to be in equilibrium with mantle olivine. Combined melt/rock reaction and high pressure crystal fractionation of mantle-derived HMA, just below the seismic Moho, may produce modified mantle peridotites, ultramafic “cumulates”, and more evolved HMA liquids which rise to form the crust.

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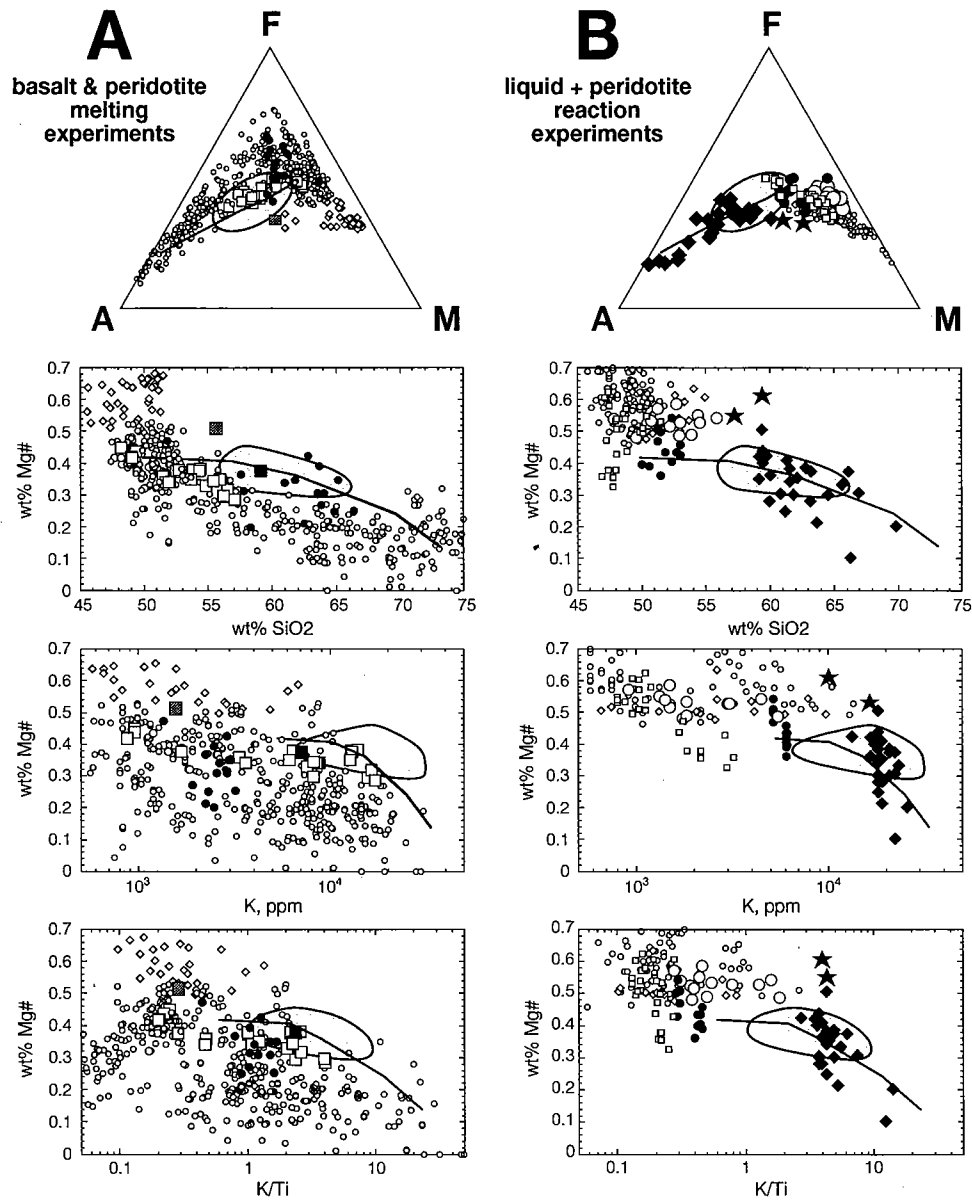
### Crystallization and melting in basaltic bulk compositions

Low pressure crystal fractionation of basaltic magmas, or anatexis of basaltic rocks, does not produce HMA as a derivative liquid. As proposed by Fenner (1929), crystallization of ferromagnesian silicates, with Mg#s higher than coexisting melts, drives derivative liquids to lower Mg#s. Fractionating solid phases have a high silica content, similar to coexisting melts, so that decreasing Mg# is accompanied by nearly constant SiO<sub>2</sub> in liquid products. Ultimately, increasing Fe and decreasing temperature lead to stabilization of Fe–Ti oxides. Fractionation of oxides, plus Fe-rich silicates, finally leads to decreasing Fe content, increasing SiO<sub>2</sub>, and a slight increase in Mg# of the liquid in the last stages of solidification. This type of differentiation – termed the “tholeiitic trend” – is observed in mid-ocean ridge volcanic suites and in many other basaltic volcanic series, such as the Thingmuli lavas of Iceland (Carmichael 1964), as illustrated in Fig. 1 A. Among tholeiitic liquid series, lavas with 55 to 65 wt% SiO<sub>2</sub> are volumetrically subordinate to basalt, and have Mg#s less than 0.3.

It has been proposed that “calc-alkaline” liquid lines of descent, with abundant liquids having 55 to 65 wt%

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**Fig. 2 A, B** Reported experimental liquid compositions illustrated for comparison with the average composition of the continental crust (*shaded region*) and the Cascades trend (*heavy line*). **A** Melting experiments on basaltic and mantle peridotite compositions ( $n > 450$ ). These data are for liquids approaching solid/liquid equilibrium during crystallization (or melting) of basaltic compositions. Fractional crystallization of basaltic liquids will produce evolved melts with lower Mg# and Ni content, at a given SiO<sub>2</sub> and K content, than those produced by equilibrium crystallization. Liquids formed by partial melting of mantle peridotite are from Hirose and Kushiro (1993), and Baker and Stolper (1993), both shown as *open diamonds*. Liquids formed by partial melting in basaltic compositions include those from H<sub>2</sub>O-free experiments at 1 bar to 30 kbar (Grove et al. 1982; Gust and Perfit 1987; Kinzler and Grove 1992; and Appendix), and H<sub>2</sub>O-saturated and -undersatu-



rated experiments at 1 bar to 32 kbar (Holloway and Burnham 1972; Helz 1973; Spulber and Rutherford 1983; Beard and Lofgren 1991; Rapp et al. 1991), all shown as *small open circles*. Three reported HMA liquid compositions, in substantial Fe/Mg disequilibrium with reported solid compositions, have been eliminated from the data of Holloway and Burnham (1972) and Helz (1973). Two recent studies report andesitic liquid compositions with Mg#s similar to continental crust: Sisson and Grove (1993), shown in *large squares*, and Wolf and Wyllie (1994), shown as *filled circles*. Sisson and Grove report a hornblende saturated andesite composition which falls into the continental crust "field" on the Mg# vs SiO<sub>2</sub> plot (*filled squares*), and an andesitic liquid, produced at high  $fO_2$ , with higher Mg# than the continental crust (*shaded square*). These are discussed further in the text. **B** Experiments on reaction between liquids and mantle peridotite. Data from experiments in which basaltic or silicic magma compositions and mantle peridotite were mixed and allowed to react at temperatures near the liquidus for the magma on its own composition, and near or below the solidus for the peridotite on its own composition. Hydrous tonalite/peridotite mixtures at 15 kbar (Carroll and Wyllie 1989), are shown as *filled diamonds*. Hydrous basalt/harzburge mixtures at 5 kbar (Kelemen et al. 1990), are shown as *filled*

*circles*. In addition to these, the diagram includes data from basalt/peridotite "sandwich" experiments (Kushiro 1990; Falloon et al. 1988; and Appendix). Incompatible element and compatible element concentrations in these experiments are dominated by the initial magma composition, and may not reflect their abundance in partial melts of mantle peridotite. Relatively high concentrations of K<sub>2</sub>O and H<sub>2</sub>O, in turn, change the phase relations of melting, and thus the "sandwich" data are not the best indicators of mantle melt compositions (Johnson and Kushiro 1992; Hirose and Kushiro 1993; Baker and Stolper 1993). However, sandwich experiments provide data on reaction between melts and peridotite. Of particular interest are H<sub>2</sub>O-rich, fluid-saturated and fluid-undersaturated experiments at 16 kbar by Kushiro (1990), shown as *large, open circles*, and H<sub>2</sub>O-free sandwich experiments at pressures less than 10 kbar (Falloon et al. 1988), shown as *open diamonds*. *Open squares* are for liquids produced in olivine+basalt and orthopyroxene+basalt experiments of Kinzler and Grove (1992) and *small, open circles* are for H<sub>2</sub>O-free sandwich experiments at pressures of 10 kbar or greater. Finally, stars indicate compositions of HMA shown by Tatsumi (1981, 1982) to be in saturated with olivine and orthopyroxene ( $\pm$ clinopyroxene) with upper mantle compositions

SiO<sub>2</sub> and Mg#s higher than 0.3, can be produced by differentiation of basaltic magma at higher pressure (e.g. reviews in Grove and Kinzler 1986; Sisson and Grove 1993). Crystallization or melting of basalt at lower crustal pressures yields a solid assemblage with lower SiO<sub>2</sub>, thus increasing silica content in derivative liquids. Relatively high oxygen fugacity stabilizes Fe–Ti oxides at higher temperatures and lower total Fe contents. Relatively high H<sub>2</sub>O contents can cause crystallization of hornblende and/or biotite, which fractionate Mg#s in derivative liquids less than anhydrous ferromagnesian silicates. By substantially depressing the liquidus temperatures of silicates, but not of oxides, high H<sub>2</sub>O content also produces crystallization of oxides earlier in a differentiation series (Sisson and Grove 1993). These ideas have been supported by least-squares, mass balance calculations involving subtraction of phases constrained to experimentally observed, cotectic proportions, except for magnetite and hornblende, whose proportions were not constrained (Grove and Kinzler 1986), and by experimental production of calc-alkaline liquid compositions from a basaltic bulk composition (Sisson and Grove 1993).

However, HMA and the continental crust have higher Mg#, at a given silica concentration, than most liquids produced by experimental melting of basalt or peridotite (Fig. 2 A). No liquids with Mg#s higher than 0.33 have SiO<sub>2</sub> contents greater than 55 wt% and K concentration greater than 10,000 ppm, despite experimental investigation of basalt crystallization at pressures from 1 bar to 30 kbar, with and without high oxygen fugacity and water content. Two studies (Sisson and Grove 1993; Wolf and Wyllie 1994) have produced HMA liquid compositions. These are emphasized in Fig. 2 A, and will be discussed in the following paragraphs.

The discrepancy between mass balance models, indicating that HMA can be produced by crystal fractionation from basalt, and the observation that such liquids have not been experimentally produced, can be explained in a variety of ways. Mass balance calculations may be incorrect if the required proportions of crystallizing phases do not correspond to true cotectic phase proportions during magmatic crystallization. For example, calculations commonly require abundant Fe–Ti oxides early in the crystallization process. Estimated oxygen fugacity ( $f_{O_2}$ ) in calc-alkaline, arc magma series is higher than that estimated for tholeiitic magma series, ranging from close to the fayalite-magnetite-quartz (FMQ) buffer to one log unit higher than the nickel-nickel oxide (NNO) oxygen buffer (review in Gill 1981). It was presumed that abundant magnetite could be produced at these oxygen fugacities. However, an experimental test of basalt crystallization at  $f_{O_2}$  higher than NNO, by Grove et al. (1982), did not produce HMA, probably because increasing Fe<sup>3+</sup> abundance in the magma decreased Fe<sup>2+</sup>, so that crystallizing silicates had higher Mg#s. Fractionation of Mg-rich silicates offset the effect of Fe–Ti oxides on the Mg# of derivative liquids.

It is possible that experimental studies generally have not been conducted under the appropriate conditions to produce HMA. Wolf and Wyllie (1994) investigated H<sub>2</sub>O-undersaturated melting of an unusual, high Mg, high Ca amphibolite composition and produced several liquids with Mg#s and SiO<sub>2</sub> contents in the range of continental crust. However, as a result of the unusual bulk composition, the liquids have very low alkali contents, which makes them a poor analog for continental crust. Sisson and Grove's experiments (1993) produced a calc-alkaline liquid line of descent from a basaltic parent, under H<sub>2</sub>O-saturated conditions at 2 kbar, along the NNO oxygen fugacity buffer. The liquid trend falls at lower Mg#s than the continental crust, with one exception. The exception, a low-temperature, hornblende-saturated andesite (filled square in Fig. 2 A), is potentially of great significance. Additionally, Sisson and Grove report an HMA liquid with Mg# higher than continental crust, produced at  $f_{O_2}$  higher than NNO, from an experiment in which the oxygen buffer failed (shaded square in Fig. 2 A). Its low alkali content renders it a poor analog for crustal compositions, but the result suggests that high  $f_{O_2}$  combined with high H<sub>2</sub>O may be efficacious in producing HMA from a basaltic parent.

These results suggest important avenues for continued experimental investigation. However, liquids produced in other water-saturated and water-undersaturated melting experiments on basaltic compositions, at pressures from 1 to 32 kbar (Holloway and Burnham 1972; Helz 1973; Spulber and Rutherford 1983; Beard and Lofgren 1991; Rapp et al. 1991), lie along the same general trend as most of Sisson and Grove's data, at Mg#s lower than continental crust and the Cascades trend. This is true despite increased Mg#s in the run products due to substantial loss of Fe in many earlier experiments. It should be recalled that the average composition of the continental crust lies along the Cascades trend. Low Mg# basaltic and andesitic compositions in the crust are offset by a similar proportion of andesitic and silicic rocks with Mg#s higher than the Cascades trend and higher than Mg#s in liquids experimentally produced from basalt.

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### Mixing and assimilation in the crust

It is beyond the scope of this paper to fully explore the potential for origin of the continental crust as a result of processes such as magmatic assimilation of older crust, mechanical mixing, and magma mixing. The combination of high compatible element concentrations and high incompatible element concentrations, which characterizes HMA, is a natural result of mixing mafic and silicic compositions. For example, it has been proposed that some Archean HMA were produced by assimilation of granitic, crustal rocks in komatiitic magmas (e.g. Sun et al. 1989). The major obstacle to acceptance of the general hypothesis that mixing processes were essential in producing the continental crust is to explain the origin of the silicic end-member. In simple terms, how can conti-

mental crust be formed by assimilation of continental crust, in the continental crust? Observation of silicic lavas in Iceland (e.g. Carmichael 1964) illustrates that appropriate end-members can be produced without the action of processes specific to subduction. However, these silicic magmas have been produced in the crust, from basalt, and the net composition of the crust in Iceland must still remain basaltic. Explanation of the bulk composition of the continental crust as a result of mixing requires removal of the basaltic material residual to formation of silicic magmas.

### Formation of andesites by partial melting of peridotite

The pioneering experiments of Kushiro (1972) and Warner (1973) suggested that andesitic magmas could be produced by partial melting of mantle lherzolite under hydrous conditions. However, these experiments were in simple, Fe- and alkali-free systems. Interpretation of the results of hydrous partial melting experiments on natural lherzolite compositions has been fraught with controversy (e.g. Mysen et al. 1974), and a consensus has yet to emerge. Many workers believe that water-saturated melting is unlikely in the mantle and that water-undersaturated melting is unlikely to create andesitic liquids. Dry partial melts of mantle lherzolite at pressures of 10 kbar and greater are generally not andesitic (Jaques and Green 1980; Hirose and Kushiro 1993; Baker and Stolper 1994), as can be seen in Fig. 2 A.

However, Baker et al. (1995) have produced HMA glass compositions with up to 57 wt% SiO<sub>2</sub> by small degrees of partial melting of anhydrous mantle lherzolite at 10 kb. These liquids are rich in Na, K-rich HMA, similar in composition to the bulk continental crust, could be produced by very small degrees of melting of metasomatized, K-enriched mantle, as suggested by Kushiro (1975). Thus, H<sub>2</sub>O may not be essential in producing HMA by small degrees of partial melting in the mantle.

Tatsumi (1982) demonstrated that an HMA composition with 57 wt% SiO<sub>2</sub> (anhydrous) is saturated with olivine and two pyroxenes with appropriate, mantle compositions, at 1050 to 1150° C and 10 to 15 kbar, under H<sub>2</sub>O-rich, fluid-undersaturated conditions with 7 to ca. 15 wt% H<sub>2</sub>O in the melt. Since amphiboles have about 2 wt% H<sub>2</sub>O, a peridotite containing 10 wt% amphibole could produce a 2 wt% liquid fraction with 10 wt% H<sub>2</sub>O by melting. High K contents, high K/Ti, and light REE enrichment in HMA support the idea that very small degrees of melting are required to produce HMA and the continental crust (e.g. O'Nions and McKenzie 1988). However, Tatsumi's experiments did not produce hornblende on or near the liquidus, casting doubt upon the hypothesis that amphibole serves as a solid reservoir for H<sub>2</sub>O in the mantle source of HMA.

Another HMA composition investigated by Tatsumi (1981) had olivine and orthopyroxene (Opx), but not clinopyroxene (Cpx), on its liquidus at mantle pressures.

The absence of Cpx was due to high Si content combined with low Ca concentration in the liquid. This observation was in accord with the general hypothesis that many HMA have formed by melting of harzburgite previously depleted in Cpx. However, the high Na and K contents, high H<sub>2</sub>O contents, and light REE enrichment of HMA render their origin from depleted mantle peridotite unlikely. Instead, they require special source compositions. Metasomatism of a harzburgite host, adding Na, K and H<sub>2</sub>O, but not Ca, could produce such a source composition. Observation of mantle-derived, harzburgite xenoliths from South Africa, greatly enriched in K- and H<sub>2</sub>O, indicates that such compositions are present (e.g. Erlank et al. 1987). Metasomatized harzburgite xenoliths from the Luzon arc (Maury et al. 1992) are much less enriched than the South African examples. They have the chemical characteristics of harzburgites that may have equilibrated with arc magmas, but it seems unlikely that partial melting of such source rocks (with minor amounts of phlogopite) could yield volumetrically important quantities of HMA.

Since the solubility of alkalis and rare earth elements in aqueous fluids (e.g. review in Hawkesworth et al. 1993) is hundreds of times smaller than their solubility in arc magmas, supplying these "incompatible elements" to the arc magma source via aqueous fluid metasomatism requires that fluid flux to the mantle source be hundreds of times greater than magmatic flux through the Moho. Given that arc crust may be produced at rates on the order of 10 m<sup>2</sup>/yr per unit length of arc (e.g. review in Kelemen et al. 1993), subduction of oceanic crust occurs at 100 to 1000 m<sup>2</sup>/yr, and the total H<sub>2</sub>O content in subducted crust does not exceed 10 wt%, much of which is probably lost via shallow level dehydration beneath forearcs, it seems unlikely that supply of incompatible elements to a depleted peridotite source via aqueous fluid metasomatism could account for a significant proportion of the arc crustal budget for these elements.

Magmatic metasomatism (e.g. Menzies et al. 1985; Francis 1987) may better account for incompatible element budgets in the arc source. This may occur in a two step process in which mantle peridotite is chemically modified by one type of melt, and later undergoes partial fusion to produce a second type of melt, which rises to form arc crust. Conversely, magmatic metasomatism may be synchronous with production of arc magmas, in an integrated melt/rock reaction process. Chemically, these two possibilities are very similar. They are discussed in the following section of this paper.

### Formation of andesites by melt/rock reaction in the upper mantle

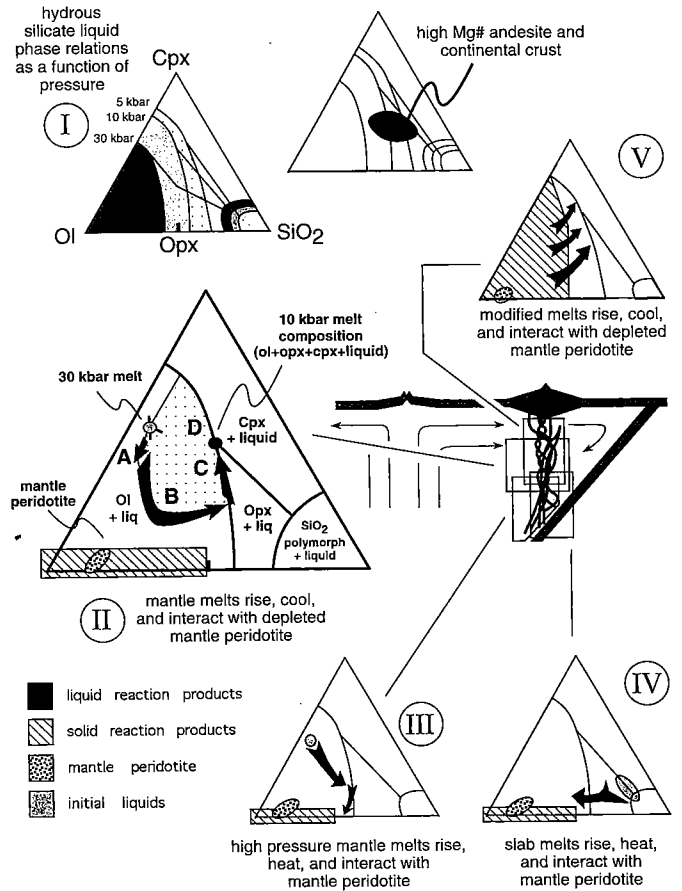
It has been proposed that calc-alkaline andesitic magmas can be produced as a result of reaction between ascending liquids and mantle peridotites (Green and Ringwood 1967; Kay 1978; Quick 1981; Arculus et al. 1983; Myers et al. 1985; Fisk 1986; Kelemen 1986, 1990). In addi-

tion, melt/rock reaction beneath arcs can account for high concentrations of Opx, light REE enrichment, and fractionation of Ti from the Ree in the sub-continental lithosphere (Kelemen et al. 1992; Rudnick et al. 1993). Initial liquids could be derived by small degrees of melting of mantle peridotite at greater depth, or by partial melting of the downgoing slab in a subduction zone. Hydrous,  $H_2O$ -undersaturated initial liquids would carry much of the incompatible element "budget" of HMA. Reaction with peridotite during ascent could substantially change the silica content of derivative liquids, and will generally produce liquids close to saturation in mantle olivine, with high Mg# and high Ni content. If reaction is extensive enough, it may cause fractionation of incompatible trace elements in the liquid as well (e.g. Navon and Stolper 1987; Kelemen et al. 1993).

### Experimental data

The general hypothesis that melt/rock reaction in the mantle can produce HMA has been experimentally verified, as illustrated in Fig. 2 B. Reaction between silicic liquids and mantle peridotite, with and without excess  $H_2O$  at 15 kbar, produced HMA with compositions appropriate for the continental crust (Carroll and Wyllie 1989). Reaction between basaltic liquids and mantle peridotite has produced basaltic andesites and andesites with Mg#s higher than the Cascades series and continental crust, under  $H_2O$ -rich conditions at 16 kbar (Kushiro 1990), and dry conditions at pressures less than 10 kbar (Falloon et al. 1988). The paucity of liquids with 56 to 59 wt%  $SiO_2$  produced by experimental reaction of basalt and peridotite illustrates a need for continuing experimental investigation. However, the experiments of Tatsumi (1981, 1982) illustrate that such siliceous liquids can be in equilibrium with mantle olivine and pyroxene compositions.

**Fig. 3** Schematic, pseudo-ternary phase diagrams on the plane olivine (Ol) – clinopyroxene (Cpx) – silica ( $SiO_2$ ), projected from spinel, for hydrous silicate liquids at upper mantle pressures. The positions of phase boundaries are based on inference from the experimental results of Kushiro (1972) and Warner (1973) in the system forsterite–diopside–silica– $H_2O$ , and on projection of experimental partial melt compositions from spinel onto the plane Ol–Cpx– $SiO_2$ , following similar methods to those for projection from plagioclase onto Ol–Cpx– $SiO_2$  from Grove et al. (1982), and projection from spinel onto the plane Ol–Cpx–Opx described by Kelemen et al. (1992). More quantitative illustrations and extended discussion of the phase relations of reaction can be found in Carroll and Wyllie (1989), Kelemen (1990), and Kelemen et al. (1992). Diagram I illustrates the effect of pressure in these systems. Decreasing pressure leads to increased stability of Ol relative to pyroxenes, so that liquids in equilibrium with Ol, Cpx and Opx at a high pressure will be initially saturated only in Ol during cooling at a lower pressure. Diagram II illustrates reaction at 10 kbar between mantle lherzolite and hydrous, picritic liquid which initially formed by a small degree of partial melting of mantle lherzolite at 30 kbar. In this example, the peridotite is just at its solidus temperature at 10 kbar. The liquid, which has risen adiabatically to this point, is above its liquidus temperature, and under-

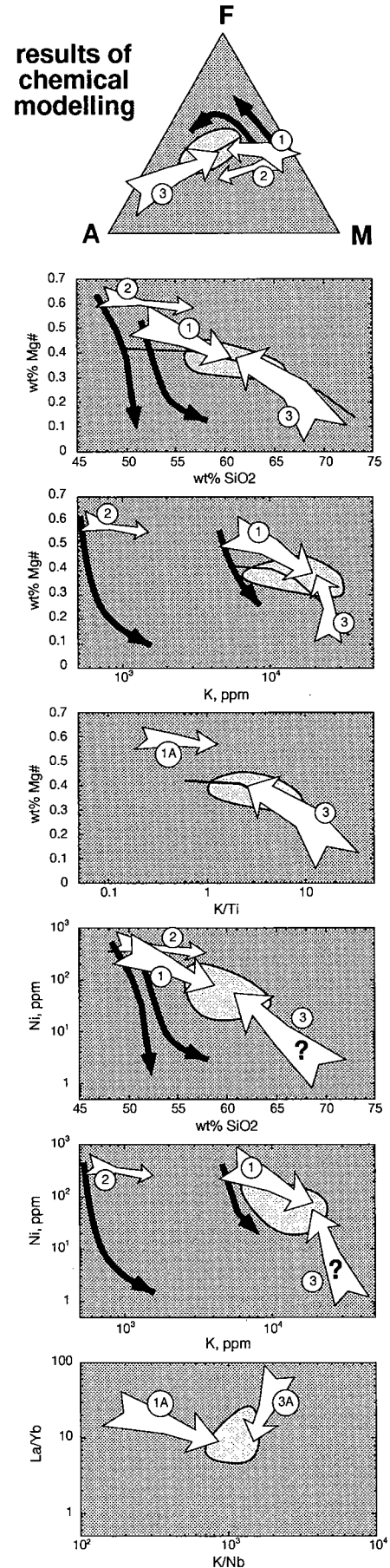


goes cooling during reaction. Initially, along path A, the super-liquidus melt dissolves peridotite. This rapidly leads to olivine saturation in the liquid. The melt now will crystallize Ol, and continue to dissolve pyroxene. One possible liquid path is shown as the vector labeled B; this is for rapid reaction and slow cooling, during which liquid mass actually increases. More rapid cooling, or slower pyroxene dissolution, would procedure derivative liquid compositions within the shaded region above B. Eventually, path B leads to saturation of the melt in Opx as well as Ol. Continued reaction and cooling will consume all Cpx and a small amount of Ol in peridotite reactants, producing decreasing liquid mass, Opx+Ol solid assemblages, and derivative liquids along path C. Finally, at D, the liquid will become saturated in Cpx; it has acquired the major element composition of a small degree, hydrous melt of lherzolite at 10 kbar, although its trace element characteristics will preserve a "memory" of its provenance in an open system. Diagrams III through V explore various other reaction paths for melts in the mantle beneath arcs. Liquids initially must rise through an inverted geotherm above the subducting slab, heating as they decompress. Higher, they pass upward into the lithosphere, and cool as they ascend. Diagram III shows the effect of decompression and heating on reaction between a hydrous, picritic mantle melt and peridotite. These reactions produce pyroxene-poor and pyroxene-free solid products, and an increase in liquid mass. If the rate of reaction is fast relative to the rate of heating and decompression, the liquid will approach Opx saturation. If the rate of reaction is slow, the liquid will remain saturated only in Ol. Diagram IV illustrates a possible reaction path for silicic, slab melts and peridotite. Reaction consumes Ol and some of the liquid, producing Opx and increasingly  $SiO_2$ -poor melts, until Ol saturation is reached. After Ol saturation, continued decompression and heating results in small amounts of Ol dissolution and increasing liquid mass. Diagram V illustrates paths followed during cooling and continued ascent of Ol+pyroxene saturated melts produced in II through IV

## Modelling of basalt/peridotite reaction

Previous papers have investigated the phase relations of reaction between ascending, basaltic magma and mantle peridotite (Kelemen 1986, 1990; Kelemen et al. 1990, 1992), as illustrated schematically in Fig. 3. As partial melts of lherzolite ascend, the effect of decompression is to render them undersaturated in pyroxenes. Initially, reaction will involve dissolution of pyroxene and crystallization of olivine. Since orthopyroxene (Opx) is more abundant in the upper mantle than clinopyroxene (Cpx), dissolution reactions will increase the silica content of the liquid, moving it toward Opx saturation, i.e. toward andesitic liquid compositions. Saturation in olivine + Opx – but not in Cpx – may be produced in this manner without partial melting of harzburgite, and without the presence of abundant amphibole in the mantle. This may account for the apparent paradox of HMA liquids which have high incompatible element contents, suggesting that they are small degree partial melts of lherzolite, but which also have high Ni contents and are not in equilibrium with Cpx or hornblende, suggesting that they are high degree partial melts of harzburgite.

Figure 4 illustrates results of thermodynamic modelling of reaction between anhydrous basaltic liquid and



**Fig. 4** Summary of results of modelling and experiments on the compositional effects of melt/rock reaction in the upper mantle. Liquid products of reaction are illustrated with *broad, white arrows*; products of closed-system, fractional crystallization of basaltic and picritic magmas are illustrated with *narrow, black arrows*. The major element trends (Kelemen 1986, 1990), were produced using the silicate liquid solution model of Ghiorso and co-workers (Ghiorso et al. 1983; Ghiorso 1985; Ghiorso and Kelemen 1987). Major element modelling was for reaction at 3 kbar, under H<sub>2</sub>O-free conditions, on the fayalite-magnetite-quartz oxygen buffer, without crystallization of a spinel phase, using only quadrilateral pyroxene compositions (Na, Ti, Al, Fe<sup>3+</sup> and Cr-free). Since Ti was excluded from all solid phases in the modelling, but is present in insignificant concentrations in mantle pyroxene and spinel, calculated K/Ti was incorrect, and is not illustrated. Ni concentration in model liquids has been calculated using the major element modelling results, and the Hart and Davis (1978) formulation for olivine/liquid Ni exchange equilibrium. Path 1 is for reaction between harzburgite and an olivine tholeiite liquid, proposed as a primary Aleutian magma by Gust and Perfit (1987). Very similar results were produced for reaction between lherzolite and a high alumina basalt liquid, proposed as a primary Aleutian magma by Myers et al. (1985). Path 2 is for reaction between harzburgite and a K-poor, picritic liquid composition. Path 1A illustrates results of trace element modelling of reaction between a depleted harzburgite in spinel peridotite facies and a K-rich, small degree melt of garnet lherzolite (Kelemen et al. 1993), using the mass balance model for melt/rock reaction developed by DePaolo (1981). Path 3 is based on experimental results and extrapolated phase equilibria from Carroll and Wyllie (1989), for reaction between hydrous, silicic liquids and peridotite at 15 kbar. The initial silicic liquid composition was similar to those of partial melts of hydrous meta-basalt at 30 kbar (e.g. Rapp et al. 1991), and thus these results approximate the effects of reaction between a slab melt and the upper mantle. Ni contents in liquid products of reaction are inferred, based on increasing approach to equilibrium with mantle olivine. Path 3A is for trace element modelling of reaction between peridotite and a small degree melt of hydrous metabasalt (Kelemen et al. 1993)

mantle peridotite at 3 kbar (Kelemen 1986, 1990). Increasing pressure decreases the maximum SiO<sub>2</sub> content of melts in equilibrium with mantle olivine. Thus, it may be argued that the low pressure used in modelling produces SiO<sub>2</sub> contents in liquids which are higher than could be produced at 10 to 20 kbar. However, the models do not incorporate the effect of H<sub>2</sub>O, which substantially increases the maximum SiO<sub>2</sub> content of olivine-saturated liquids. The experiments of Tatsumi (1981, 1982) demonstrate that SiO<sub>2</sub> content in hydrous liquids saturated in mantle olivine at 10 to 16 kbar may exceed 59 wt% under some circumstances. Similarly, the results of Kushiro (1975) and Baker et al. (1995) show that SiO<sub>2</sub> content in alkali-rich, anhydrous liquids may exceed 57 wt% at 10 kbar.

Despite the limitations of prior modelling, the general trends of major element variation produced by reaction between ascending basaltic liquid and upper mantle peridotite are clear. Dissolution of pyroxenes from mantle peridotite in olivine-saturated, basaltic liquid produces a substantial increase in SiO<sub>2</sub> content. Mg# and Ni content remain relatively high, "buffered" by exchange reactions with olivine, as compared to liquids produced by closed system crystal fractionation. When reaction is combined with decreasing liquid mass as a result of decreasing temperature, incompatible element abundance and H<sub>2</sub>O contents of liquids increase. Note that predicted liquid Mg#s, while much higher than those for closed system crystallization, are similar to those in continental crust, and lower than in magmas in equilibrium with mantle olivine. It is apparent from the results of modelling that melt/rock reaction in the upper mantle can account for the major element composition of HMA liquids.

Also illustrated in Fig. 4 are recent results of trace element modelling of melt/rock reaction in the upper mantle, described more fully in a companion paper (Kelemen et al. 1993). The trace element models are distinct from those for the major elements. The former require reaction between small amounts of liquid and large masses of peridotite. Such small melt/rock ratios are not yet amenable to thermodynamic modelling for major elements. The results of trace element modelling illustrate some general effects of the reaction process. K/Nb, will increase during extensive melt/rock reaction involving olivine, orthopyroxene, and/or spinel in depleted peridotite because these three phases all have lower crystal/liquid distribution coefficients for K than they do for Nb. La/Yb ratios may also change as a result of extensive reaction, depending on the nature of the liquid and peridotite reactants.

It is apparent from these results that reaction between ascending melts and mantle peridotite can account for the trace element characteristics of HMA. Much of this reaction probably occurs where liquids are migrating slowly by porous flow, so that they may be close to Fe/Mg equilibrium with mantle olivine throughout much of their ascent path. Mg#s in many HMA and the continental crust are somewhat lower than required for equilibri-

um with mantle olivine. This may be indicative of cooling, decreasing magma mass due to crystallization, and decreasing melt/rock reaction rates in ascending HMA magmas in the shallow mantle lithosphere just below the seismic Moho.

#### Modelling of reaction between silicic, slab melts and mantle peridotite

Whatever the origins of arc magmas (by slab and/or mantle melting), they must pass through an inverted geotherm until they reach the maximum temperature in the mantle wedge, some 1100 to 1300° C at 50 to 75 km. Such inverted geotherms are robust features in thermal models of subduction zones (review in Davies and Stephenson 1992). The inverted geothermal gradient at depth creates an otherwise unusual situation in which ascending melts must heat during decompression. Increasing liquid temperature combined with decreasing pressure provides substantial thermal energy for crystal dissolution. For example, 100 g of magma with a heat capacity of 0.3 cal/g° C, produced at 900° C and heated to 1200° C, has the thermal energy to dissolve about 100 g of peridotite, even at constant pressure (assuming for simplicity that peridotite at 1200° C has an *apparent heat of fusion* (Kelemen 1990) of 100 cal/g).

Rising slab melts which are heated as they interact with the mantle will dissolve peridotite, increasing in mass, until they become saturated in hornblende, pyroxene and/or olivine. If initial saturation is with hornblende or pyroxene ( $\pm$  garnet), the fate of the liquid depends largely upon the rate of reaction vs the rate of continuing decompression and heating. If decompression and heating are slow relative to reaction rates, liquids may be consumed by reactions in which liquid+olivine form pyroxene and/or hornblende. However, if initial saturation is with olivine, or if decompression and heating are fast relative to reaction rates (due to rapid magmatic ascent or to partial armoring of magmatic conduits with hornblende or pyroxenite), then liquid mass will continue to increase. Thus, depending upon the water and alkali contents of these liquids, the rate of reaction vs decompression, and the nature of the wedge geotherm, hybrid magmas may continue to react with peridotite, heating until they reach the thermal maximum in the wedge. Under these circumstances, reaction between peridotite and siliceous melts could produce HMA, as originally proposed by Kay (1978) and illustrated in Figs. 3 and 4.

This process was experimentally investigated by Carroll and Wyllie (1989), who also illustrated the phase relations of the reactions. Major element modelling of reaction between silicic magmas and mantle peridotite at high pressure is not yet complete. Instead, the experimental and theoretical results of Carroll and Wyllie are summarized in Fig. 4. Their data show a decrease in the silica content of derivative liquids, and a sharp increase in Mg# and Mg concentration, as a result of olivine dis-

solution and of reactions such as olivine+SiO<sub>2</sub> (in liquid)=Opx. It is inferred that Ni content increases as well. K concentration remains high in experimental liquids, as does the K/Ti ratio. Variation trends for K/Nb and La/Yb in a hypothetical slab melt reacting with mantle peridotite were calculated by Kelemen et al. (1993). Slab-derived, silicic magmas have high initial K/Nb when they leave residual rutile in their source, and have high initial La/Yb due to the effect of residual garnet in their source. Reaction between these melts and mantle peridotite, under conditions of increasing liquid mass, will leave K/Nb high, but decrease La/Yb to values typical of arc magmas, as originally proposed by Ryerson and Watson (1987). The results illustrate that such a process is capable of producing the major and trace element characteristics of HMA and the continental crust.

## Conclusions

The continental crust has the composition of high Mg# andesite (HMA). This composition has rarely been produced by melting experiments on hydrous, basaltic magmas. Hypotheses for the origin of the crust as a result of crystal fractionation from basaltic magmas may not be correct, and require additional experimental verification. Crustal mixing between basaltic and granitic compositions has certainly produced some HMA (e.g. McBirney et al. 1987). In order for mixing hypotheses to account for the composition of the crust, the basaltic residue of granite formation, which must commonly exceed the mass of granite, must be removed from the crust. This could occur as a result of lower crustal delamination after eclogite facies metamorphism of the lower crust during continental collision events. However, since there is little evidence that the bulk of the continental crust has undergone high pressure metamorphism, this may be an implausible explanation.

The basaltic residue of granite formation could also be removed by selective erosion and/or subduction. Certainly, some proportion of the continental crust is returned to the mantle by subduction of sediments and chemically altered oceanic crust (e.g. DePaolo 1980; Armstrong 1981). However, recycling processes will only affect the bulk composition of the continents if the recycled components are different in composition from juvenile igneous crust. Studies of shale and loess compositions show that both contemporary and PreCambrian clastic sediments derived from the cratons are dominantly granitic (e.g. Taylor and McLennan 1985). This is particularly true for regions such as the continental cratons in which the upper crust is dominantly granitic in composition, and the lower crust is more mafic – but rarely exposed to weathering. Removal of a granitic clastic component cannot account for production of an andesitic crust from a basaltic one.

Chemical weathering might be more effective. However, Whitfield and Turner (1979) showed that both Si and Mg concentrations in river water are two orders of magnitude higher than Fe concentration. These data suggest that surficial weathering cannot produce a high Mg# andesitic crust from a basaltic protolith. If the atmosphere was more reducing in the Archean, then Fe may have been more soluble in fresh water than at present. However, both Weaver and Tarney (1983, 1984) and Taylor and McLennan (1985) estimated the Archean crust to have had a high Mg#, andesitic to dacitic composition, quite similar to the contemporary continental crust composition. Their estimates are compared in Table 1. According to these data, there have been small, secular increases in SiO<sub>2</sub> concentration, Mg# and alkali content over more than 2.5 billion years, but certainly not on a scale sufficient to convert a basaltic crust to an andesitic one. This conclusion that very little secular change in the composition of the continental crust has occurred through geologic time, is also supported by trace element and isotope data (e.g. Goldstein et al. 1984). Thus, avail-

**Table 1** Comparison of estimated compositions of Archean and present-day continental crust

	Taylor and McLennan (1985)	Taylor and McLennan (1985)	Weaver and Tarney (1983)	Weaver and Tarney (1983)	Weaver and Tarney (1983)	Weaver and Tarney (1984)
	Archean bulk crust	Bulk crust	Archean mid-crust	Archean lower crust	Post-Archean mid- & lower crust	Bulk crust
SiO <sub>2</sub>	57	57.3	66.7	61.2	59.2	63.2
TiO <sub>2</sub>	1	0.9	0.3	0.5	0.9	0.6
Al <sub>2</sub> O <sub>3</sub>	15.2	15.9	16	15.6	17.2	16.1
FeO <sup>a</sup>	9.6	9.1	3.2	5.3	6.1	4.9
MnO			0.04	0.08	0.12	0.08
MgO	5.9	5.3	1.4	3.4	3.4	2.8
CaO	7.3	7.4	3.2	5.6	5.9	4.7
Na <sub>2</sub> O	3	3.1	4.9	4.4	4	4.2
K <sub>2</sub> O	0.9	1.1	2.1	1	2.4	2.1
P <sub>2</sub> O <sub>5</sub>			0.14	0.18	0.27	
Wt%Mg#	0.37	0.38	0.30	0.39	0.36	0.36

<sup>a</sup> Total Fe as FeO

able evidence suggests that neither mechanical nor chemical weathering has produced an andesitic crustal composition from a basaltic one.

Production of andesitic magmas in the upper mantle is a viable alternative to basalt differentiation and/or crustal mixing in explaining the genesis of HMA. Direct partial melting of previously depleted, and then metasomatized, amphibole peridotite may be capable of producing some HMA, but probably cannot account for the total magmatic flux of alkalis and other incompatible elements in arcs. More conclusively, theoretical and experimental results from previous studies show that the major and trace element characteristics of HMA can be produced by melt/rock reaction in the upper mantle. However, formation of the continental crust from arc-derived HMA requires further explanation, since a large proportion of arc volcanics are basaltic, not andesitic.

In order to address this apparent contradiction, several related hypotheses are discussed below.

#### (1) HMA magmatism in the Archean

HMA may have been more commonly produced in the Archean than at present. Figure 5 A presents a compilation of Archean volcanic, plutonic, and meta-igneous rock compositions. The Archean record includes a higher proportion of HMA, compared to lower Mg# andesites, than modern arc volcanics. In addition, andesitic compositions are less common in the Archean than more silicic plutonic rocks such as tonalite (plutonic equivalent of dacite). Many of these have been interpreted as the products of anatexis of basalts (e.g. Rapp et al. 1991). Certainly, some tonalites are the result of crustal anatexis (e.g. Jahn et al. 1984), and some lower crustal rocks are residues of partial melting (e.g. Rudnick 1992). However, comparison of Figs. 2 A and 5 A shows that liquids with Mg#s as high as most Archean tonalites have not been produced by experimental melting of basalt, as noted by Evans and Hanson (1992) and Sen and Dunn (1994). Similarly, most Archean tonalites have higher Ni contents than silicic melts known to have formed by crystal fractionation from basalt. Some high Mg#, high Ni dacite magmas may have formed by differentiation of HMA (by crystal fractionation or crustal anatexis). Other high Mg# dacitic magmas may have formed in the mantle.

Defant and Drummond (1990) have emphasized that light REE enriched andesitic and dacitic magmas may be produced in arcs when hot, young oceanic crust (<30 Ma) is subducted and undergoes partial melting. Such a process may have been common in the Archean when oceanic crust was warmer and/or subduction rates were faster (e.g. Martin 1986). HMA would then result from interaction between these slab-derived melts and mantle peridotite (e.g. Carroll and Wyllie 1989). An intriguing alternative in considering melt/rock reaction in the Archean mantle is that reaction between ascending komatiite melts and peridotite produced more HMA than

reaction involving picritic or basaltic melts does today. Adiabatically ascending, komatiitic liquid would have an enormous capacity to dissolve pyroxene from upper mantle peridotite, and would thus become more silicic as a result of reaction.

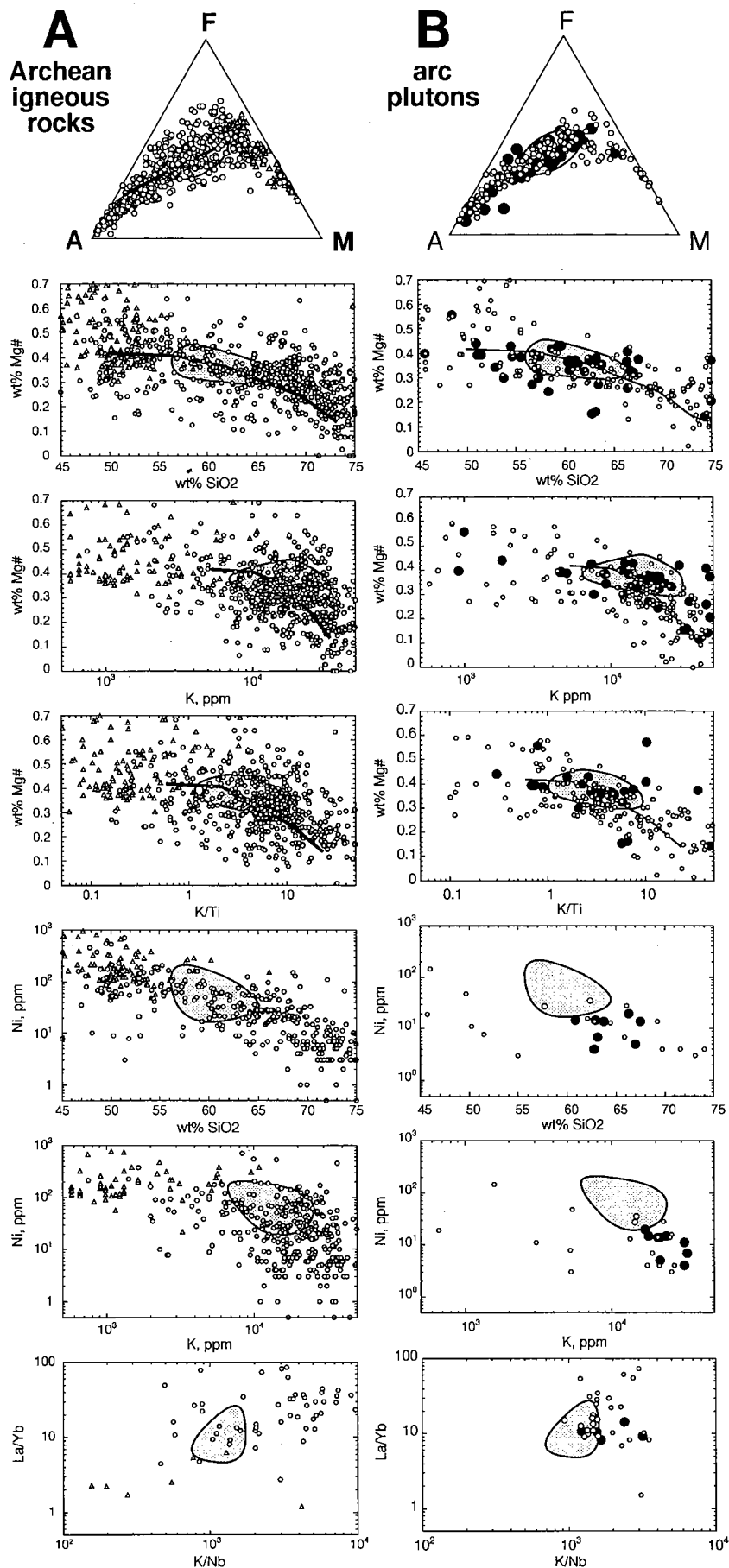
The nature of Archean plate tectonics is uncertain. On the basis of the detailed compositional similarity between continental crust and HMA, and the observation that HMA are exclusively erupted in arcs in the modern geologic environment, it has been assumed that (1) similar processes operated in the formation of continental crust and HMA, and (2) that these processes involved arc magmatism. These simple, generally uniformitarian inferences are controversial (e.g. reviews by Weaver and Tarney 1984; Taylor and McLennan 1985; Nisbet 1987; de Wit et al. 1992). In this paper, the first of these inferences has been justified on the basis of current petrologic data. The second is more difficult to support. However, whether subduction tectonics was important in the Archean or not, production of voluminous, mantle-derived HMA may be best explained as the result of reaction between upper mantle peridotite and ascending liquids. Where reaction is extensive and continues to the base of the crust, phase equilibria tend to drive magmas toward olivine-orthopyroxene saturation at relatively low pressure; i.e. they drive derivative liquids to HMA compositions.

#### (2) HMA emplaced in the middle and lower crust

HMA may be abundantly produced in the mantle but, because they are more viscous than basalts, they are mainly emplaced in the middle and lower crust. Figure 5 B illustrates that young, arc-related plutonic terrains include abundant intrusive rocks with the composition of HMA. It is particularly interesting to note the compositional contrast between silicic, high Mg# plutonic rocks in the Aleutians (filled circles in Fig. 5 B) and the dominantly basaltic Aleutian lavas with lower Mg#s in Fig. 1 C. High K contents of these plutonic rocks suggest that these are not "cumulates" which have lost a substantial liquid component by crystal fractionation. Instead, the plutonic rocks represent HMA which were emplaced in plutons rather than erupted on the surface.

Direct evidence bearing on the average composition of arc middle and lower crust is sparse. DeBari and Sleep (1991) determined a basaltic bulk composition for a cross-section of the accreted Talkeetna arc in the Chugach Mountains of south central Alaska. However, Burns (1983, 1985) reported that 30 to 40% of the Talkeetna arc terrane is composed of tonalitic plutons, which were not incorporated in DeBari and Sleep's mass balance. Addition of 30% average tonalite from Burns (1983) to the basaltic composition of DeBari and Sleep produces a high Mg# andesite composition which has 56 wt% SiO<sub>2</sub> and wt% Mg# of 0.52, i.e. an HMA composition within the field of estimates for the continental crust.

**Fig. 5 A, B** Compositions of Archean igneous rocks, and arc-related plutonic rocks, for comparison with the average composition of the continental crust (*shaded region*) and the Cascades trend (*heavy line*). **A** Archean igneous and meta-igneous rocks ( $n > 800$ ). *Triangles* are for komatiite-related suites, and *circles* for all other compiled compositions (Shirey and Hanson 1984; and Appendix). **B** Cretaceous and younger, arc-related plutonic rock compositions ( $n > 250$ ). Compositions of Aleutian samples (Appendix) are shown as *filled circles*. Other samples, shown as *open circles*, are from the New Britain arc, the Coast Ranges plutonic belt, the Ladakh batholith of northern India, the Chilliwack and Mt. Stuart batholiths of the North Cascades, and the Peninsular Ranges batholith in southern California and Baja California (Larsen 1948; and Appendix)



Another exposed arc crustal section is the Kohistan terrane in Pakistan (e.g. Bard et al. 1980; Bard 1983). Although investigators have emphasized the presence of mafic and ultramafic rocks in the basal portion of the Kohistan terrane (Jan and Howie 1981; Loucks et al. 1989, 1990; Miller et al. 1991; Miller and Christensen 1994), the mafic rocks include abundant norites and hypersthene diorites (Jan and Kempe 1973; Jan and Howie 1980). These must have crystallized from magmas which had relatively low Ca/Si ratios, which became saturated in orthopyroxene and plagioclase before clinopyroxene – i.e., they must have crystallized from andesitic magmas. In addition regional mapping and petrological investigations suggest that the middle crustal part of the Kohistan terrane includes abundant tonalite and granodiorite (Bard et al. 1980; Coward et al. 1982; Petterson and Windley 1985; Debon et al. 1987). In summary, although the data are uncertain, the bulk composition of the Talkeetna and Kohistan accreted arc sections may be andesitic rather than basaltic.

### (3) HMA production spatially and temporally discontinuous

Volumetrically important HMA may be produced in certain times and places under favorable tectonic conditions. As noted by Defant and Drummond (1990), many HMA were produced during subduction of young, hot oceanic crust (Cascades, Baja California, western Mexico, southern Chile). Perhaps ridge-trench collisions are accompanied by voluminous andesitic volcanism and plutonism that has produced most of the continental crust. Alternatively, Yogodzinski et al. (1994) propose that formation of thick, arc crust may create a density barrier, impeding magma ascent from the mantle into the crust, and leading to extensive reaction between liquids and periodotite in the upper mantle.

### (4) Selective erosion of (basaltic) volcanic rocks from the upper crust in arcs

If andesitic magmas are dominantly emplaced as plutonic rocks, subduction of sediments derived from easily eroded sub-aerial volcanic and volcanoclastic rocks may have preferentially removed basalts and preserved plutonic rocks of andesitic composition.

### (5) Selective subduction of basaltic arcs, preservation of andesitic arcs

If “normal” island arc magmatism produces basaltic crust, this dense crust may be susceptible to subduction during collision events, whereas buoyant andesitic crust would tend to resist subduction.

In general, it is inferred that the compositional similarity between high-Mg# andesites and the continental crust is not a coincidence, and that a substantial proportion of the crust is composed of HMA and their differentiates. The net magmatic flux through the Moho during accretion of the continents may have been andesitic. Most HMA may form by melt/rock reaction in the upper mantle. Evaluating this hypothesis will require substantial additional experiments to determine liquid and solid products of melt/rock reaction in the upper mantle, and the products of crystallization of HMA magmas, especially under H<sub>2</sub>O-undersaturated conditions. In addition, it will be important to characterize the composition of the middle and lower crust in island arcs, in order to test the related hypothesis that some arc crust is andesitic, not basaltic.

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## Appendix

Additional sources of data and modelling techniques, in order of citation in figure captions

Estimates of continental crust composition in Fig. 1 A

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Aleutian HMA composition in Fig. 1 B and lava compositions in Fig. 1 C

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