Lithosphere erosion and crustal growth in subduction zones: Insights from initiation of the nascent East Philippine Arc

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ABSTRACT

The Philippine Trench marks a nascent plate margin where subduction initiation is propagating from north to south. Magma compositions in the East Philippine Arc record thinning of arc lithosphere as it is eroded from below. Lithosphere is thicker beneath the younger, southern part of the arc, causing basaltic magma to stall and fractionate garnet at high pressure. In the mature, northern section, basaltic magma differentiates at shallower levels, at pressures where garnet is not stable. Local variations in lithosphere thickness suggest that thinning is rapid and may be piecemeal. Fluctuations in arc lithosphere thickness throughout the history of this margin appear to control spatial and temporal variations in magma fluxes into the arc crust. Varying fractionation depths of hydrous basalt may help to explain the andesitic composition of bulk continental crust.

Keywords: subduction initiation, arc lithosphere erosion, crust growth, adakitic magmatism, high-Mg# andesite.

INTRODUCTION

Subduction provides a key driving force for plate tectonics, produces the most extreme material differentiation in the solid part of Earth today, and is believed to have played an important role in generating the continents. While there are numerous studies of mature systems, examination of subduction initiation is inhibited by the paucity of suitable examples. Studies that do exist focus mainly on fossilized nascent margins and have been used to classify two initiation mechanisms (Stern, 2004). Induced initiation occurs where convergent motion forces one piece of (proto-arc) lithosphere to override another (the protoslab). Spontaneous initiation results from foundering of the protoslab prior to onset of convergent motion. During the Cenozoic, induced initiation appears to have been more common than spontaneous events, yet the latter have a higher probability of leaving a geological record (Stern, 2004). Therefore, direct observations of the rocks produced by young arcs are biased toward spontaneous subduction initiation.

The scarce and valuable insights available from real margins have been complemented by increasingly sophisticated numerical models of where and how initiation occurs. One of the clearest predictions of most subduction initiation models is large-scale, and possibly rapid, thinning of the overriding plate during the earliest stages of subduction (Andrews and Sleep, 1974; Hall et al., 2003; Gurnis et al., 2004; Arcay et al., 2006) to produce mature margins in which arc lithosphere consists largely of crust (Rowland and Davies, 1999). This prediction is hard to test and determinations of time scales for the processes involved are difficult because much of the geology in fossilized nascent margins has been obscured by subsequent plate motions and volcanism.

The Philippine Trench marks a nascent plate margin produced by induced subduction initiation (Cardwell et al., 1980; Hall, 1987). It has propagated southward since the middle-late Miocene, trailing in its wake the East Philippine Arc. This study examines the geochemical record of lithosphere maturation carried by East Philippine Arc magmatism and the consequent implications for (1) the geochemistry of arc magmatism, and (2) development of continental crust.

MAGMATIC DIFFERENTIATION IN THE EAST PHILIPPINE ARC

The Philippine Sea plate subducts westward at the Philippine Trench between 18°N and 2°N (Fig. 1A). The trench is currently propagating southward, and its tip located northeast of Halmahera (Hall, 1987). This is consistent with southward decreases in the ages of (1) initial East Philippine Arc magmatism (Ozawa et al., 2004), and (2) initial movement on the Philippine fault, which partitions oblique compression across the margin (Barrier et al., 1991; Quebral et al., 1996).

The most southerly East Philippine Arc activity of any significant volume is Pliocene to Quaternary magmatism in Surigao, NE Mindanao (Fig. 1A). Magmatism occurred in and around a graben or half-graben structure that has a sharp west margin against the Philippine fault (Macpherson et al., 2006). Pliocene lavas with typical arc geochemistry are found in the center and east of the peninsula. These are succeeded by adakitic and high-Mg# andesitic rocks in the west. All Surigao magmatism was produced by differentiation of hydrous basaltic melt that originated in the mantle wedge. In Mindanao, isotopic data demonstrate that adakitic chemistry, which is often attributed to slab melting (Defant and Drummond, 1990), is a consequence of differentiation—either crystallization of basaltic melt or remelting of basaltic rock—at depth in the presence of garnet (Dreher et al., 2005; Macpherson et al., 2006). Following early adakitic magmatism (Ozawa et al., 2004), recent magmatism in the north East Philippine Arc is dominantly medium-K, calc-alkaline basaltic andesite to rhyolite (Castillo and Newhall, 2004; Andal et al., 2005; McDermott et al., 2005; Du Frane et al., 2006).

LITHOSPHERIC THINNING IN A NASCENT ARC

In most island arcs, low-pressure crystal assemblages dominate the chemical evolution of magma. This can be observed in ratios of middle to heavy rare earth elements (REE, e.g., Dy/Yb), which remain stable or, more commonly, decrease as differentiation proceeds because distribution coefficients (Kd) are greater for middle than for heavy rare earth elements ($Kd_{MREE} > Kd_{HREE}$), suggesting little or no role for garnet (Davidson et al., 2007). This scenario applies for the present north East Philippine Arc and for central and east Surigao (Fig. 2A). In contrast, Dy/Yb correlates positively with SiO_2 in adakitic rocks from west Surigao (Fig. 2A) due to garnet fractionation, which results in $Kd_{MREE} < Kd_{HREE}$ (Macpherson et al., 2006). Garnet crystallizes from hydrous basaltic magma at pressures greater than 1.2 GPa or ~35 km depth (Müntener et al., 2001). This is significantly greater than the 25 km Moho depth deter-

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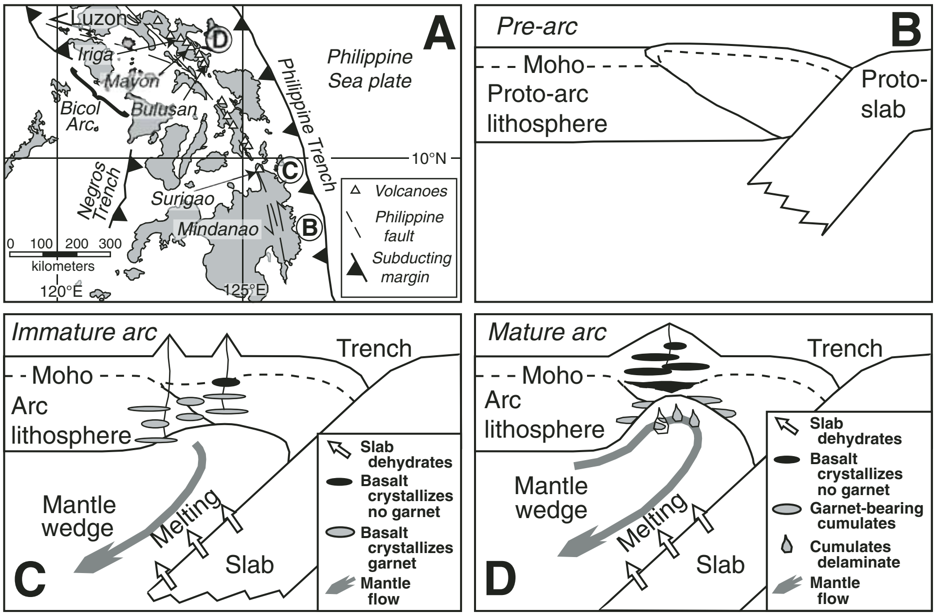

Figure 1. A: East Philippine Arc (EPA) showing location of volcanic centers discussed. Circled letters refer to schematic cross-arc sections in panels B–D, which illustrate thinning of East Philippine Arc lithosphere and its role in determining differentiation depth in nascent, induced subduction zone. B: Pre-arc: subduction of Philippine Sea plate has begun beneath amalgamated proto-arc lithosphere but magmatism has not. C: Immature arc: upwelling of basaltic magma is impeded by lithospheric mantle, and so differentiation occurs beneath Moho, generating garnet-rich cumulates (gray). D: Mature arc: erosion of lithospheric mantle leads to basalt differentiation at shallower levels (black) with garnet-free assemblage. Earlier-formed, garnet-bearing cumulates may return to mantle via lithosphere erosion as mantle flow develops and mantle lithosphere is eroded.

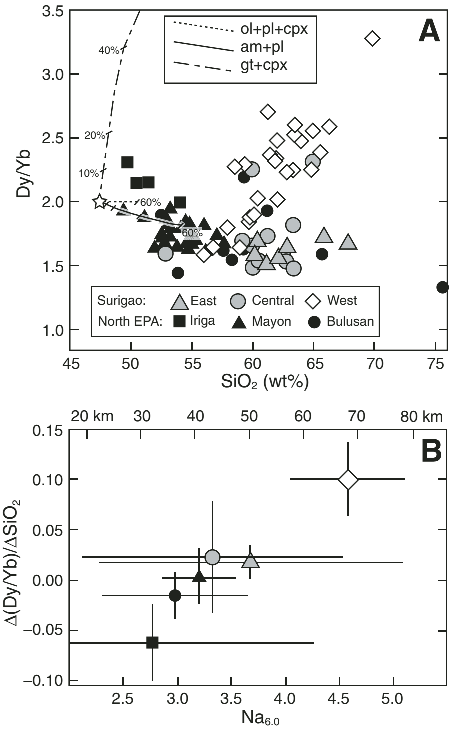

Figure 2. A: Dy/Yb versus SiO_2 for East Philippine Arc (EPA) lavas (data sources in text). Correlations with SiO_2 indicate that differentiation is primary control on Dy/Yb, which increases when garnet crystallizes and decreases when garnet is absent. Differentiation models (showing % crystallization) are from Davidson et al. (2007). gt—garnet; ol—olivine; pl—plagioclase; cpx—clinopyroxene; am—amphibole B: $\Delta(Dy/Yb)/\Delta SiO_2$ (plotted with 2SE uncertainty) is a proxy for mean differentiation depth of each suite and is determined from linear regression of slopes in panel A. This is compared with $Na_{6.0}$, which Plank and Langmuir (1988) showed to be a proxy for crustal thickness, as illustrated on top axis, using 21 arcs worldwide. Uncertainty for $Na_{6.0}$ is 95% confidence limit on regression of Na_2O versus MgO to 6 wt% MgO.

mined for Surigao from gravity data (Dimalanta and Yumul, 2003). Contrasting MREE/HREE ratios between adakitic and typical arc suites in other locations have also been used to suggest that both types are produced by fractionation of wet basalt at different depths (Chiaradia et al., 2004; Rodriguez et al., 2007).

There is too much uncertainty in partition coefficients and the chemistry of potentially fractionating phases to use them directly to quantify absolute differentiation depths in the East Philippine Arc, but relative differentiation depths can be determined from the gradient of Dy/Yb versus SiO_2; $\Delta(Dy/Yb)/\Delta SiO_2$. This represents the contrast between bulk distribution coefficients for MREE and HREE during differentiation. Positive values represent a greater role for deep (garnet-present) differentiation, while negative values reflect shallow (garnet-absent) differentiation. This approach requires the solid assemblage to have remained constant within each suite, but this is a reasonable assumption in view of the coherence of the data for each suite (Fig. 2A). The East Philippine Arc data show a decrease in $\Delta(Dy/Yb)/\Delta SiO_2$ from (1) west Surigao to (2) central and east Surigao to (3) north East Philippine Arc (Fig. 2B). This is interpreted as reflecting a decreasing role for garnet and, therefore, decreasing mean depths of differentiation from arc initiation to maturity.

Major-element systematics are consistent with a role for sub-Moho and/or garnet-present differentiation in young, southern East Philippine Arc magmatism. Western Surigao rocks possess high-Mg# values relative to their SiO_2 values. Garnet pyroxenites from the Sierra Nevada, which represent possible deep-arc cumulates, possess relatively low-Mg# values with respect to SiO_2 and so could drive residual melt to high Mg# at high SiO_2 (Fig. 3). Furthermore, differentiated, silicic magma produced beneath the Moho may acquire high Mg# as it interacts with peridotite during transport toward the surface (Rapp et al., 1999). Rocks from central and east Surigao also display elevated Mg# but to a lesser extent than their western equivalents.

Together, the trace- and major-element variations suggest that basaltic melt was more likely to stall at deeper levels when the arc lithosphere was immature but that basaltic melts can more readily reach the crust as the arc lithosphere matures. In the south East Philippine Arc, where the arc is youngest, the evidence for deep differentiation is strongest. In the longer-lived north East Philippine Arc, however, widespread, present-day low-$\Delta(Dy/Yb)/\Delta SiO_2$ and low-Mg# magmatism have succeeded early adakitic magmatism (Ozawa et al., 2004). Within Surigao, there is evidence for more localized variations in arc lithosphere thickness. Beneath central and east Surigao, the lithosphere was sufficiently thin during the Pliocene for differentiation to produce magma with moderate $\Delta(Dy/Yb)/\Delta SiO_2$ but high Mg#. High-$\Delta(Dy/Yb)/\Delta SiO_2$, Pleistocene, adakitic magmatism in the west records the earliest stages in development of this thin-spot toward the back arc, as predicted by numerical models (Arcay et al., 2006).

Figure 1 outlines a model for progression from deep- to shallow-level differentiation in the nascent East Philippine Arc. In south Mindanao, the proto-arc lithosphere is composed of accreted ophiolitic and older arc terranes (Quebral et al., 1996). The Philippine Trench is well defined, and the slab can be traced into the mantle (Cardwell et al., 1980), but there is negligible East Philippine Arc magmatism there. During this pre-arc stage (Fig. 1B), hydration of the mantle wedge and/or flow of hot mantle into the wedge is not sufficient to cause subduction-

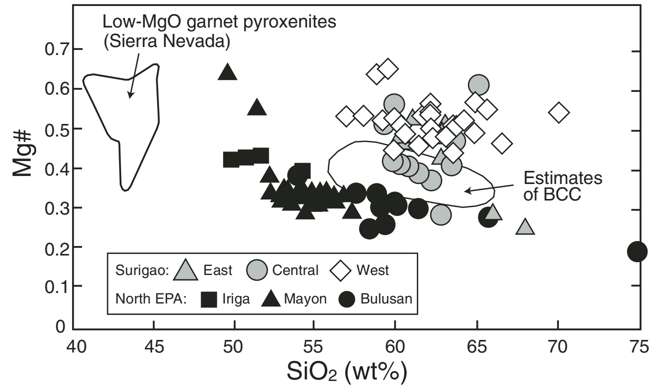

Figure 3. Mg# (Mg/[Mg + Fe^{II}]) versus SiO_2 for East Philippine Arc (EPA) lavas. Fields are shown for various estimates of bulk continental crust (BCC; Kelemen, 1995) and for low-MgO garnet pyroxenites from Sierra Nevada (Lee et al., 2006), which represent possible deep-arc cumulates.

related magmatism. In the immature margin, as epitomized by Surigao (Fig. 1C), the slab induces flow in the mantle into which it also releases fluids. These processes weaken and erode the mantle lithosphere and produce hydrous basaltic magma in the mantle wedge. The remaining lithospheric mantle retards vertical migration of the basalt, causing it to stall within the garnet stability field. The strength of geochemical signatures of deep differentiation, e.g., elevated $\Delta(Dy/Yb)/\Delta SiO_2$ and Mg#, in evolved, silicic magma will depend on the exact depth of differentiation. As the arc becomes mature, mantle flow becomes more vigorous (Billen and Hirth, 2005). This combines with increasing fluxes of fluid and heat from the mantle wedge to further erode arc lithosphere (Arcay et al., 2006), so that basaltic magma is more likely to reach the crust and differentiate shallower than the garnet stability field (Fig. 1D). This will produce the more typical arc lava suites observed in the northern East Philippine Arc. Earlier formed, garnet-bearing cumulates will be delaminated as lithospheric mantle is eroded.

The greatest age measured for north East Philippine Arc magmatism, 6.6 Ma (Ozawa et al., 2004), provides a maximum estimate for the time required to remove most of the mantle lithosphere in the mature segment. This sample displays adakitic traits (e.g., high Sr/Y, low Y, and high Ni) that, by analogy with Surigao, we attribute to deep differentiation with the lithospheric mantle. However, the shorter distances that separate adakitic from more typical arc lavas in many parts of the East Philippine Arc suggest that lithosphere erosion may occur substantially faster.

In an attempt to place further constraints on the thickness of East Philippine Arc lithosphere, which in mature arcs is believed to equate with the thickness of the crust (Rowland and Davies, 1999), $\Delta(Dy/Yb)/\Delta SiO_2$ is compared to $Na_{6.0}$, which has been noted to correlate positively with crustal thickness (Plank and Langmuir, 1988). $Na_{6.0}$ is the Na_2O content that would have been present in a melt containing 6 wt% MgO. Plank and Langmuir (1988) attributed $Na_{6.0}$ variations to different degrees of mantle melting, but the concentration of sodium, and other incompatible elements, may be highly sensitive to deep fractionation (Lee et al., 2006). The low MgO contents of East Philippine Arc rocks places large uncertainties on the $Na_{6.0}$ values, yet the correlation with $\Delta(Dy/Yb)/\Delta SiO_2$ is striking (Fig. 2B).

If the relationship in Figure 2B is used to calibrate $\Delta(Dy/Yb)/\Delta SiO_2$, the results suggest that differentiation depths for the onset of arc magmatism, as typified by west Surigao adakitic rocks, are similar to those in other arcs where the crust is thicker than 60 km. This is up to 30 km thicker than crust associated with more arc-like magmatism in east and central Surigao. A conservative (i.e., old) estimate for initiation of the Philippine Trench is 10 Ma. Assuming that the trench propagated its 1600 km length at a constant rate, then subduction initiated outboard of Surigao ca. 4.5 Ma, just 1 m.y. before the oldest examples of low-$\Delta(Dy/Yb)/\Delta SiO_2$ magmatism in east and central Surigao (Sajona et al., 1994). This suggests that 1 m.y. was sufficient to remove ~30 km of mantle lithosphere. A similar rate of erosion has been determined for lithosphere removal above a thermal anomaly in the North Atlantic (Hamilton et al., 1998).

DISCUSSION AND CONCLUSIONS

Rocks with adakitic chemistry were originally, and remain widely, attributed to melting of subducted basaltic crust (Defant and Drummond, 1990). At Mindanao, however, slab melting is ruled out on isotopic grounds (Macpherson et al., 2006). The slab melting model for adakite genesis has been questioned by an increasing number of studies, e.g., Garrison and Davidson, (2003), Prouteau and Scaillet (2003), Chiaradia et al. (2004), Eiler et al. (2007), and Rodriguez et al. (2007), with most of these attributing adakitic magmatism to garnet fractionation from hydrous arc basalt magma. The corollary to this conclusion is that adakitic rocks can probe differentiation deep beneath arcs. Adakitic rocks and typical arc andesites were generated contemporaneously in both Surigao (Macpherson et al., 2006) and the north East Philippine Arc (Andal et al., 2005), indicating that the thickness of arc lithosphere varies considerably, with wavelengths of tens of kilometers. These observations may reflect localized variations in East Philippine Arc lithospheric thickness superimposed on a progression from thick, immature arc lithosphere in the south to thin, mature arc lithosphere in the north. Such local geochemical variations suggest that lithosphere erosion is piecemeal.

Changes in lithosphere thickness will play a role throughout the history of any arc. Localized variations may be preserved from initiation or may develop further as the arc lithosphere responds to changes in slab dip, convergence rate, convergence velocity, extension and the flux of fresh basalt from the mantle wedge. These factors all have the potential to affect convective flow and fluid supply within the mantle wedge and, hence, influence the stability of arc mantle lithosphere (Arcay et al., 2006). Therefore, any piece of arc lithosphere could thin or thicken during the lifetime of a subduction zone, depending on the flux of new basalt from the mantle wedge versus the removal of lithospheric mantle—and the cumulates it contains—by erosion from beneath. Thickening and thinning would be manifest as magmatic products fluctuating between those resembling the immature and mature stages of the East Philippine Arc, respectively.

Much has been learned about spontaneous initiation of subduction from suprasubduction-zone ophiolites and the early products of the Izu-Bonin-Mariana Arc (Stern, 2004, and references therein). The East Philippine Arc provides a valuable complement to existing subduction initiation models because subduction was induced when convergence was transferred from a nearby margin (Cardwell et al., 1980; Hall, 1987). Magmatic products of the East Philippine Arc suggest that piecemeal thinning of the proto-arc lithosphere occurs relatively quickly, but without the high extension rates responsible for producing the ophiolitic and/or boninite-dominated suites that characterize spontaneous initiation. Transitions from adakitic to typical arc magmatism would be an important marker for lithospheric thinning of this type.

Compositional similarities are widely used to infer that subduction-related magmatism was involved in generating bulk continental crust (BCC; Rudnick and Gao, 2005, and references therein). The closest magmatic analogue for bulk continental crust is high-Mg# andesite, such as that in west Surigao (Kelemen, 1995). These magmas are rare in modern arcs, but the East Philippine Arc suggests that high-Mg# andesite might have been more common in the past if mean differentiation depths of hydrous basaltic magma were greater than at present. High-Mg# andesites from the East Philippine Arc are not an exact match for bulk continental crust, but the major element compositions of magma from the immature and mature East Philippine Arc are complementary with respect to bulk continental crust (Fig. 3). Therefore, components of bulk continental crust may be generated at distinct times during a subduction event (or events) and combined later. Repeated thinning and thickening of arc lithosphere would drive subsequent blending of the components while also causing delamination of mafic and ultramafic cumulates, thus contributing to an andesitic composition for bulk continental crust despite a basaltic mass flux from the mantle (Kelemen, 1995; Davidson and Arculus, 2007). Thus, thickness fluctuations in arc lithosphere may provide the environment in which to build bulk continental crust (Figs. 1B–1D) as well as the components required to produce it (Fig. 3).

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