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Notes

Quantifying crustal thickness variations in evolving orogens: Correlation between arc basalt composition and Moho depth

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ABSTRACT

A compilation of geochemical data from >50 active volcanoes where seismically defined Moho depth measurements are available, representing most volcanic arcs around the world, indicates a relation exists between crustal thickness (Moho depth) and the trace element composition of basalts. The best correlation exists for maximum light/heavy rare earth element (REE) ratios, and we use maximum Ce/Y ($R^2 = 0.90$) to show the exponential function with increasing depth, to 50 km. Application to New Zealand, part of the eastern Gondwanan margin through much of the Phanerozoic, shows that higher Ce/Y ratios in arc basalts correspond to two periods of recognized crustal thickening, plus an additional event at ca. 240 Ma, which links New Zealand to the Gondwanide Orogeny. Conversely, low Ce/Y ratios in basalts correlate with periods of recognized extension in eastern Gondwana. Very high Ce/Y ratios in ca. 120 Ma rocks imply an unusually thickened (~50 km) arc crust, consistent with independent geological estimates of crustal thickness at that time. The correlation shows that crustal thickness variations during orogenesis can be conservatively estimated to within ± 3 km.

Keywords: Arc magmatism, tectonics, crustal thickness, REE ratios, New Zealand.

INTRODUCTION

A consensus has emerged over the last decade that arc magmatism is generated by decompression melting in the mantle wedge, augmented by fluid and/or magma additions from the subducting slab (e.g., Pearce and Peate, 1995; Tatsumi and Eggins, 1995). The slab contribution elevates the large ion lithophile elements (LILE), such as Ba, Rb, K, Sr, and Pb, whereas the wedge contribution is dominated by compatible high field strength elements (HFSE), such as Zr, Ti, Hf, Y, and heavy rare earth elements (HREE). This chemical “decoupling” between LILE and HFSE produces the characteristic, spiked normal mid-oceanic ridge basalts (N-MORB), normalized multi-element patterns of volcanic arc basalts (Fig. 1) and forms the basis of the consensus model.

A second-order observation is that the trace element patterns steepen as the thickness of the arc increases (Fig. 1A), particularly for the REE. This is predictable according to the consensus model, because the melt column continues to decompress (and melt) as it rises further beneath thinner arcs. Accordingly, the HFSE pattern beneath thin (oceanic) arcs should approach the flat “MORB-like” patterns of ocean floor basalt, whereas steeper “oceanic island basalt (OIB)-like” patterns should develop under thick continental arcs where the degree of wedge melting is lowest. This is consistent with the findings of Plank and Langmuir (1988), who noted a correlation between crustal thickness and major element composition of arc basalts. Because volcanic arcs are an integral part of many orogenic systems, correlations between arc basalt compositions and Moho depth have the potential to provide a semi-

quantitative estimate of how much an orogen thickens (or thins) during contraction and extension.

We expand on the Plank and Langmuir (1988) observation by examining the trace element variation in active volcanic arc suites, specifically where the Moho depth has been independently defined through seismic refraction measurements. Over 50 volcanoes from all major arc systems, representing >1100 basalt analyses, were examined utilizing the Geochemistry of Rocks of the Oceans and Continents (GEOROC) database and other published information (GSA Data Repository Table DR1¹). Use of X-ray fluorescence (XRF) or inductively coupled plasma-mass spectrometry (ICPMS) data does not significantly alter the results discussed below, nor does inclusion of phenocrystic samples. Geochemical data were restricted to rocks in the range 44 to 53 wt% SiO₂, with MgO values >4 wt% and LOI <4 wt%. Rocks from the Aeolian arc were excluded, because they form a distinctly different, silica-undersaturated, K-rich (shoshonitic) group. All samples were plotted on N-MORB normalized multi-element diagrams (Sun and McDonough, 1989) to determine chemical coherency for each volcanic suite, and anomalous patterns were excluded.

A GLOBAL CORRELATION

Most of the basalts are subalkaline, and most lie in the low-K and medium-K fields (Gill, 1981). The majority belong to calcalkaline suites, fol-

lowing the original definition (Peacock, 1931). Representative basalts from volcanoes with differing Moho depths show variable LILE abundance, but HFSE and light rare earth element (LREE) abundances systematically increase with depth, evident as progressive steepening of the multi-element patterns and increasing HFSE content relative to Y (Figs. 1 and 2C). The hallmark positive Sr and negative Nb anomalies of arc basalts are generally more subdued with increasing Moho depth. Y (Fig. 2C) and the HREE (Fig. 1A) show little variation with depth, and almost all samples plot between 0.4 and 1.0 × N-MORB. This shows that the variation relates to Ce enrichment, not Y depletion.

The steepening multi-element patterns of Figure 1A indicate that the LREE/HREE ratios within each suite increase with increasing Moho depth, which is best illustrated as Ce/Y (Fig. 2A). Y is used as a proxy for the HREE because more data are available compared with Yb, but a similar result is evident using La/Yb (Fig. 2B). The most striking result is the limiting, maximum ratio attained with increasing Moho depth (Fig. 2D). Examination of Figure 2A also shows that the curve is defined by maximum Ce/Y for all the specified MgO content intervals (Fig. 2D), including the most primitive basalts (MgO >12 wt%). Excluding the maximum Ce/Y ratios of Iwate, Towada, and Klyuchevskoy volcanoes (see below), which are clearly offset to low values (Fig. 2D), the maximum Ce/Y ratio is an exponential function ($y = 0.3029e^{0.0554x}$) with correlation coefficient of 0.90.

A 95% confidence band was calculated for the exponential function using GraphPad Prism, which is adapted from the generalized nonlinear regression analysis of Cox and Ma (1995). The band was defined by polynomials calculated as a function of the confidence interval required. Figure 2D shows the two derived equations ($y = 0.2352e^{0.04956x}$ and $y = 0.3706e^{0.06123x}$), which in combination can be used to calculate error limits at any Moho depth. For specific Moho depths, the 95% confidence intervals are: 10 ± 3.1 km, 20 ± 1.8 km, 30 +0.9/–1.5 km, 40 +0.7/–0.9 km, and 50 +1.3/–1.4 km. The calculations assume no error in Moho depth, but where measured, seismic refraction and reflection profiles generally coincide within ±2 or ±3 km. Such errors slightly increase the confidence band, and we consider that ±3 km is a conservative but more realistic estimate of the 95% confidence limit, because >90% of data points fall within this band.

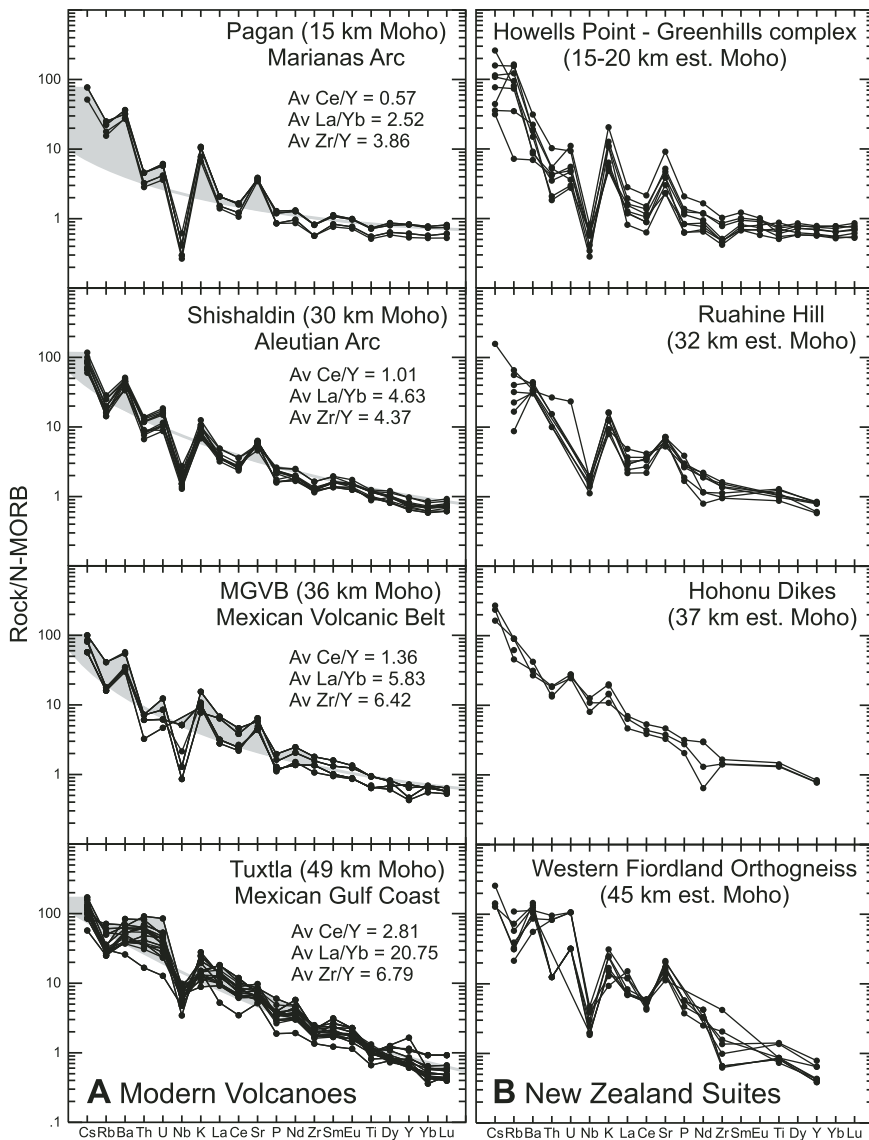


Figure 1. A: Normalized mid-oceanic ridge basalt (N-MORB) multi-element plots for representative modern volcanic basaltic suites where Moho depths have been measured by seismic refraction. Shaded region represents slab flux contribution. Steeper, smoother patterns with increasing depth superficially resemble oceanic island basalt. **B:** Representative basaltic suites from New Zealand have a similar spectrum of chemical variation as (A), which suggests that Moho depths probably varied to a similar extent from the modern-day circum-Pacific orogenic systems.

Partial melting has a first-order effect on changing arc basalt composition (Plank and Langmuir, 1988), but because the maximum Ce/Y curve is independent of MgO content (Fig. 2D), fractionation and/or contamination at the Moho must be involved. Crustal additions are not a major influence because $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ variations within and between arcs do not correlate with Ce/Y ratios, nor with Moho depth (Data Repository [see footnote 1]). A detailed explanation of how these processes affect the composition of arc basalts, and petrological implications, will be presented elsewhere.

Exclusion of Iwate, Towada, and Klyuchevskoy from the correlation curve (Fig. 2D)

highlights the caution that needs to be taken when assessing crustal thickness. The volcanoes have tholeiitic fractionation trends, which are largely produced by early removal of plagioclase relative to pyroxenes in anhydrous magmas (e.g., Grove and Baker, 1984). Plagioclase preferentially sequesters Ce, thus limiting Ce/Y variation during fractionation. By contrast, water in calc-alkaline arc magmas suppresses plagioclase crystallization (e.g., Sisson and Grove, 1993) allowing Ce/Y to increase to a limiting value during open-system fractionation. Hence, calc-alkaline volcanic suites should always be used in preference to tholeiitic suites; the latter can be identified by marked Fe enrichment,

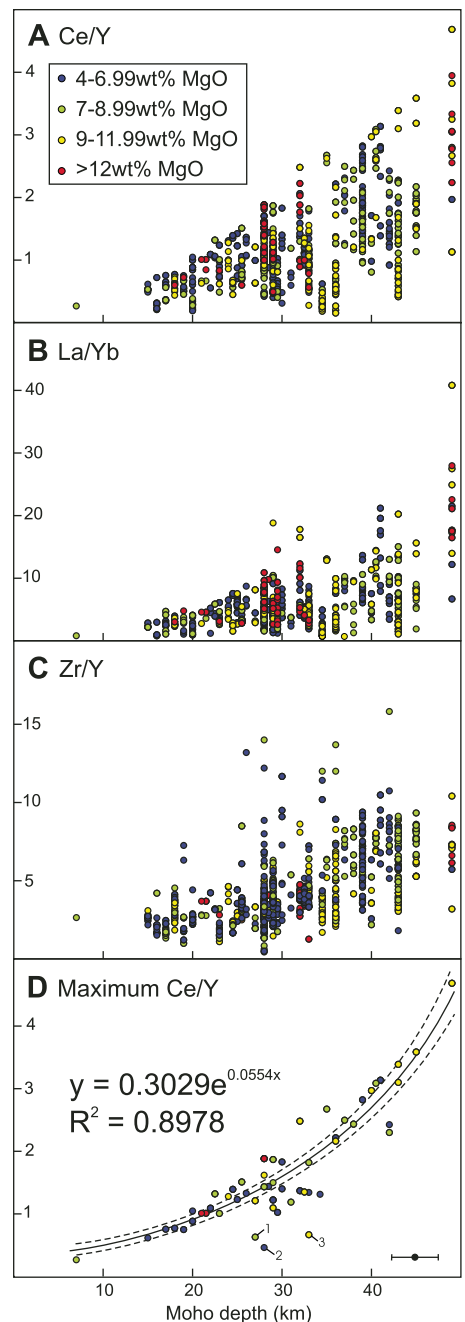


Figure 2. Plots showing relationship of Ce/Y with Moho depth in arc basalts, color coded for MgO content. **A:** Complete Ce/Y variation relative to MgO content, a proxy for degree of fractionation. Red circles are the most primitive magmas, least modified by fractionation. **B:** Plot showing that a similar variation exists with Moho depth for other light rare earth elements (La) and heavy REE (Yb). **C:** Zr/Y ratios show average increase with Moho depth, although maximum values are variable. **D:** Maximum Ce/Y value for each volcanic suite, plotted as a function of Moho depth. General seismic refraction error of ± 3 km is shown. Exponential correlation coefficient (R^2) has volcanoes 1–4 omitted. See text for details. Dashed lines show 95% confidence band. 1—Iwate, 2—Towada, 3—Klyuchevskoy. 1 and 2 are from Hohshu arc; 3 is from Kamchatka.

negative Eu anomalies (Arculus, 2003), and no Nb or Sr anomalies. Also, many alkaline, silica-undersaturated, shoshonitic basalts derived from enriched lithospheric mantle, such as the Aeolian arc, yield anomalously high Ce/Y (>4) and cannot be used. Bearing in mind that the maximum Ce/Y ratio gives the estimated thickness for any volcanic suite, it is the highest analyzed value that provides a minimum thickness estimate of the crust during emplacement. Ideally, ~10 samples from each mafic suite are required to obtain a reliable maximum ratio.

APPLICATION TO OROGENS

Magmatic arcs are an integral part of accretionary orogens, in contrast to collisional orogens such as the Himalayas, which are almost amagmatic. The Phanerozoic circum-Pacific orogens are a good example, never having experienced continent collision. The protracted magmatic history of accretionary orogens makes them amenable to assessing crustal thickness variations through time. We have chosen New Zealand as the test case, because it is a small, but representative part of circum-Pacific orogenesis.

NEW ZEALAND GEOLOGY

New Zealand was part of the long-lived active margin of eastern Gondwana, until the Late Cretaceous. The South Island preserves most of the Mesozoic/Paleozoic geology and is divided into three geological zones reflecting ongoing west-directed (present coordinates) subduction. The Western Province is part of Paleozoic Gondwana and the Eastern Province comprises Permian to Cretaceous oceanic arc, forearc, and trench fill sequences (Mortimer, 2004, and references therein). The intervening central zone is the Median Batholith, built upon the western zone. This study focuses on synplutonic basaltic dikes and gabbros from the Median Batholith (Table DR2 [see footnote 1]), with most of the geochronological data from Mortimer et al. (1999) and Price et al. (2006).

The two major recognized contractional deformation events are the Middle Paleozoic Tuhua (Cooper, 1979) and Early-Middle Cretaceous Rangitata orogenies (Bradshaw et al., 1981). The Tuhua orogeny occurred by 370–360 Ma, culminating in granite emplacement (Karamea batholith) and high-grade metamorphism (Ireland and Gibson, 1998), and the main phase of the Rangitata orogeny was penecontemporaneous with tectonic burial of the Western Fiordland Orthogneiss to depths of ~45 km, at 126–116 Ma (e.g., Daczko et al., 2002; Hollis et al., 2004).

A rapid Middle-Cretaceous change to continental extension, associated with graben development (Laird and Bradshaw, 2004), metamorphic core complex formation (Spell et al., 2000), and emplacement of the Hohonu

Batholith (Waight et al., 1998) may have begun as early as 115 Ma (Forster and Lister, 2003). Extension culminated with the opening of the Tasman Sea at 90 Ma (Gaina et al., 1998) as New Zealand drifted away from Antarctica.

NEW ZEALAND MAFIC ROCKS

Mafic rocks were collected from synplutonic dikes and coeval gabbro complexes within dated plutons. Contemporaneous emplacement was established by careful examination of contacts to determine whether mineral grains in the host pluton had been fractured during emplacement. Lack of mineral fracturing indicates that melt was present even though the magma was capable of brittle failure. Post-plutonic dikes in the Devonian Buller complex have strong similarities with the distinctive Cretaceous dikes of the Separation Point Suite, and the data sets were combined. Some gabbroic host rocks were included with synplutonic basalts, such as the Jurassic-Triassic Oraka, Pahia, and Ruahine Hill plutons from the Longwood Ranges, and the 126–116 Ma Western Fiordland Orthogneiss. Poor outcrop within the Devonian Karamea Batholith prevented recognition of dike contacts, but a distinctive geochemical data set, similar to samples from the ca. 370 Ma Riwaka Complex, is considered to reflect this Devonian magmatism. Basaltic lava flows from Howells Point and dikes from the Greenhills Complex (Spandler et al., 2003), both part of the Permian Brook Street terrane, were also similar.

Almost all samples are medium- to low-K basalts. All have spiked N-MORB normalized multi-element patterns, including positive Sr and negative Nb anomalies (Fig. 1B), typical of subduction-related basalts. The patterns confirm geological evidence that the South Island bordered a subduction zone for at least 400 Ma. A significant aspect of the patterns is their variable steepness, which is similar to that observed from modern volcanic arc basalts (Fig. 1A).

CRUSTAL THICKNESS VARIATION IN NEW ZEALAND

The spectrum of chemical variation of the South Island basalts (Fig. 1B) suggests they have experienced the full range of crustal thickness variation that the entire circum-Pacific orogenic system is now recording. A systematic pattern emerges for New Zealand basalts when maximum Ce/Y is plotted against time (Fig. 3). During the Late Devonian (370–360 Ma), Ce/Y ratios reached a maximum of ~2.0, but dropped to <1.0 in the middle Permian (270–260 Ma), then steadily increased to ~2.0 by the latest Jurassic (144 Ma). At ca. 120 Ma, maximum Ce/Y peaked at 3.7 before dropping to 2.5 at ca. 100 Ma.

Crustal thickness variation (Fig. 3), calibrated from Figure 2D, suggests that New

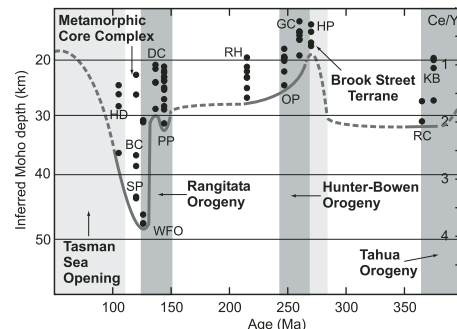


Figure 3. Heavy line shows inferred crustal thickness variation with time, New Zealand orogen, based on the maximum Ce/Y values in basaltic suites. Dark shaded regions are crustal thickening periods; light regions are extensional periods. HD—Hohonu Dike Swarm, BC—Buller Complex, SP—Separation Point Batholith, WFO—Western Fiordland Orthogneiss, DC—Darren Complex, PP—Pahia Point Dikes, RH—Rauhine Hill Dikes, OP—Oraka Point Dikes, GC—Greenhills Complex, HP—Howells Point Suite, RC—Riwaka Complex, KB—Karamea Batholith.

Zealand underwent at least three thickening phases, two of which correspond to the Tuhua and Rangitata orogenies. A third event at ca. 240 Ma corresponds to the Hunter-Bowen Orogeny in eastern Australia and to the Gondwanide Orogen of western Gondwana (Veevers and Powell, 1994). The Ce/Y ratios of ca. 240 Ma basalts in New Zealand now link this Permo-Triassic orogenic event along the entire Gondwanan margin. Like the Hunter-Bowen orogeny, it probably marks the timing of accretion of the outboard oceanic arc (Brook Street terrane) to the continental margin.

Extensional events are also evident in the data set. Ce/Y ratios of 0.5–0.8 suggest the Brook Street oceanic arc was 15–20 km thick. The arc has equivalents (Gympie terrane) in eastern Australia (e.g., Waterhouse and Sivell, 1987), which formed during backarc extension (Little et al., 1992) and culminated with outboard arc migration (Jenkins et al., 2002) along the east Gondwanan margin.

The other major extensional event was associated with rifting of New Zealand from Gondwana and opening of the Tasman Sea. Ce/Y ratios from basaltic dikes in the Hohonu Batholith suggest thinning was well under way by 100 Ma, consistent with 110–90 Ma ⁴⁰Ar/³⁹Ar ages of extension in the Papanoa Metamorphic Core Complex (Spell et al., 2000). Corroborative evidence comes from 109–112 Ma ⁴⁰Ar/³⁹Ar ages from synkinematic extensional fabrics in the Otago Schist (Forster and Lister, 2003). Numerous onshore and offshore extensional basins were initiated between 105 and 100 Ma (e.g., Laird and Bradshaw, 2004).

INDEPENDENT THICKNESS ESTIMATES OF THE CRETACEOUS ARC

The 126–116 Ma Western Fiordland Orthogneiss is considered to be the deep roots of a magmatic arc emplaced at ~8 kbar, but locally the contact metamorphic assemblages suggest emplacement at 12–14 kbar (~50 km depth) (Daczko et al., 2002). The contrasting P estimates have been reconciled by suggesting that the crust was thickened *during* emplacement of the Western Fiordland Orthogneiss (Daczko et al., 2002; Hollis et al., 2004). The high Ce/Y ratio for the Western Fiordland Orthogneiss (Fig. 3) is consistent with the barometric studies, because it suggests that the crust thickened to almost 50 km during emplacement of the Orthogneiss. Ce/Y ratios also suggest that the 120 Ma, adakitic Separation Point Batholith formed under an ~45-km-thick crust, consistent with petrogenetic/tectonic models that imply formation of adakites at the base of thickened arcs (Atherton and Petford, 1993; Muir et al., 1998). Therefore, field, geobarometric, and petrological data all corroborate the geochemical evidence from the Ce/Y ratios of Western Fiordland Orthogneiss and Separation Point batholith mafic rocks that the crust beneath New Zealand reached ~50 km thickness at ca. 120 Ma. The compatibility of results places confidence in the application of maximum Ce/Y ratios in basalts as a quantitative estimate of crustal thickness *during* the evolution of an orogen.

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