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NATURE AND ORIGIN OF PRIMITIVE MAGMAS AT SUBDUCTION ZONES

PREFACE

In an effort to air issues surrounding the genesis of primitive magmas at subduction zones, a Special Session was held during the joint annual meeting of the Geological Association of Canada and the Mineralogical Association of Canada in Victoria, British Columbia, in May 1995. The natural setting of Victoria was an ideal locale to attract participants from far and wide. Eighteen oral and eight poster presentations were made, including a keynote address by P.J. Wyllie; both modern and ancient intra-oceanic and continental arcs were represented, mainly from around the Pacific Rim.

Many participants agreed to contribute the papers that constitute this volume. These contributions, which follow the same order as at the meeting, start with the southwestern Pacific arc systems of New Zealand – Kermadec – Tonga and Papua – New Guinea, and move on through the Philippines and Japan, to eventually reach the Cascade Range and Mexico. Ancient arc environments are described from British Columbia and Newfoundland, and examples from south-central Alaska and Argentina are compared and contrasted. Perhaps not surprisingly, the Cascade arc was covered more extensively. The articles in this volume are summarized briefly below so that the reader may quickly grasp some of the principal petrogenetic issues relevant to each.

Why the focus on primitive magmas? How are they defined?

Primitive arc-magmas are the least fractionated members of their magmatic series, and thus offer the best opportunity to gain insight into their source materials and the partial melting process that gives rise to arc volcanism. Our aim was to highlight the diversity of primitive arc-magmas, and some of the key petrogenetic issues and interpretations surrounding their genesis.

Most authors provide a definition of what they understand to constitute a "primitive" magma. Although the criteria used are common to practically every study, namely the abundances of the strongly compatible elements Mg, Ni and Cr, Mg# [100Mg/(Mg + Fe^{2+})], and olivine composition, there is no overall consensus on limiting values. In the majority of cases, primitive lavas have olivine compositions ≥ Fo_{86} and MgO contents ≥ 8 wt.%, and the lower limit for compatible trace-elements, where specified, is variable: 100–150 ppm for Ni and 200–300 ppm for Cr. The cutoff for Mg# exhibits a relatively wide range, from 58 to 67 (total iron taken as Fe^{2+}). Note that all of these values would commonly be considered too low to be representative of magmas that last equilibrated with mantle peridotite. Thus many examples of primitive arc-magmas appear fractionated to some degree. Uncertainty in the oxidation state of iron contributes to the range of Mg# and olivine composition adopted, and **Luhr** raises the point that even if a common value were accepted, it would not adequately do justice to the pristine Fe^{3+}:Fe^{2+} ratio of all the primitive lava-types found at subduction zones. **Luhr** also reminds us that attempts to arrive at such values are strongly flavored by what one considers appropriate for a lherzolite source; but what if the source for some of the more exotic primitive magma-types (*e.g.*, lamprophyres) is predominantly pyroxenite?

In addition to the rules-of-thumb noted above, most authors are clearly more comfortable concluding that they are in fact dealing with *liquid* compositions if the rocks are nearly aphyric. By contrast, **Della-Pasqua** and **Varne** take the bold step of concluding that ankaramitic rocks with up to 37 vol.% clinopyroxene and 13 vol.% olivine represent true melt compositions. There seems no inherent reason to us why porphyritic lavas need to be so carefully avoided in petrological studies. The best approach is surely to sample them and carefully determine if the high contents of phenocrysts are indeed due to accumulation (*cf.* Russell & Snyder). **Conrey**, **Sherrod**, **Hooper** and **Swanson** apparently also concur and test olivine phenocrysts in porphyritic

Cascade lavas for $Mg–Fe^{2+}$ equilibrium with bulk-rock compositions.

The apparent lack of consensus in determining what constitutes a primitive magma is to some degree artificial. The urge to utilize as many "primitive" compositions as possible in order to understand spatial variability in the geochemical data-set often leads to compromise about what is acceptable in any particular study. Thus in some cases, lavas that are "least fractionated" are taken as primitive. The price of this approach could be severe, since complex processes of differentiation are well documented in arc environments (*e.g.*, Smith *et al.*, Gamble *et al.*), and fractionating assemblages could maintain nominally basaltic compositions while incorporating small amounts of incompatible-element-enriched and radiogenic crustal material that may be mistaken for source heterogeneity (*cf.* DeBari). These considerations underscore the value of a comprehensive geochemical database with which to carefully evaluate such potential hazards.

Contents of this thematic issue

The first series of papers deals with the classic island-arc environments in the southwest Pacific, which historically have been at the forefront in the development of integrated petrological and tectonic models. From a database of over 500 chemical compositions, **Smith, Worthington, Price** and **Gamble** recognize the relative scarcity of primitive magmas in the various tectonic settings of the southern Taupo (New Zealand) – northern Kermadec – southwest Papuan arcs, and relate this to a plethora of high-level processes of differentiation (FEAR: fractionation, eruption, assimilation and recharge). Accordingly, they highlight the compositions of parental lavas of low-K to high-K suites that are least FEARed. They show that basaltic lavas in the Kermadec arc emplaced on young crust are most depleted in incompatible elements, whereas high-Mg, high-K lavas in the enigmatic tectonic setting of the Papuan arc are most enriched. All parental magmas exhibit typical subduction-zone trace-element patterns on multi-element diagrams. The authors go on to tackle the thorny problem of identifying the dominant mechanism of differentiation, identified as crystal fractionation, and note that the most voluminous primitive (high-Mg) magmas appear to have erupted in an extensional tectonic setting.

Gamble, Christie, Wright and **Wysoczanski** describe the mineralogy and geochemistry of primitive mafic lavas from Clark volcano, including some unusually K- and Mg-rich basalts that appear unique in the New Zealand – Kermadec arc system. The latter rocks, high-K calc-alkaline basalt and absarokite, have elevated abundances of *LILE* and *LREE*, and more radiogenic isotopic compositions than more typical, predominantly low-K, high-Al basalts and basaltic andesites at Clark volcano and elsewhere in the Kermadec arc. The authors present trace-element and isotopic evidence to suggest fluid-fluxing of the mantle source for these K-rich magmas, and contamination by subducted sediments. They consider that these unique magmas represent small-volume, near-slab melts extracted rapidly from depth, whereas the more typical Kermadec magmas are "pooled" melts, containing variable but larger contributions from less contaminated sub-arc sources and substantially modified by high-level processes of differentiation.

Della-Pasqua and **Varne** tackle the origin of primitive ankaramitic lavas erupted from volcanic centers in the Sunda and Vanuatu arcs by examining melt inclusions trapped in olivine and clinopyroxene phenocrysts. Do these bulk-rock compositions represent sub-arc liquids, or are they accumulates enriched in clinopyroxene? The reconstructed compositions of melt inclusions in olivine bear the same chemical traits that distinguish the natural ankaramites, namely high CaO (>13 wt.%) and CaO/A_2O_3 > 1, but are decidedly lower in SiO_2. This discrepancy forces the authors to consider two possible origins: 1) generation of natural ankaramites by high-pressure (>50 kbar) partial melting of lherzolite to initially produce komatiite-like melts that are subsequently modified by olivine fractionation, or 2) $CO_2–H_2O$-fluxing of lherzolite at depth to produce the less siliceous trapped melts, which subsequently react with overlying peridotite to become more like the natural ankaramitic bulk-compositions.

Danyushevsky, Carroll and **Falloon** report on an unusual plagioclase-phyric high-Ca boninite from the North Tongan fore-arc and conclude that the existence of phenocrysts of very calcic plagioclase need not imply a high H_2O content or high CaO/Na_2O in the melt, as existing models of plagioclase-melt equilibria would predict. Measurements of melt-inclusion H_2O contents are substantially lower than values predicted with existing models for melts in equilibrium with plagioclase more calcic than An_{90}. The authors conclude that existing models of plagioclase-melt equilibria are inadequate to predict plagioclase compositions under conditions of low $f(H_2O)$.

Knittel, Hegner, Bau and **Satir** bring combined isotopic and trace-element studies to bear on the origin of primitive basaltic lavas erupted from numerous volcanic centers in the Macolod Corridor, a northeast-trending extensional feature transecting the Taiwan – Luzon arc in the Philippines. Simple models for garnet involvement in the source are rejected as an explanation for fractionated and cross-cutting *REE* patterns. Instead, these features and the isotope systematics of primitive lavas are interpreted in terms of the variable addition of a slab-derived melt or fluid component to the sub-arc mantle wedge.

Gust, Arculus and **Kersting** present the results of a study of parental and evolved rocks from the Honshu arc, in Japan, in an attempt to assess the impact on magma compositions of input from the lithosphere overriding the subducted slab. Although most of the samples they studied are substantially fractionated and, thus, far from being primitive, they are nevertheless able to utilize trace-element and isotopic data to conclude that the source region(s) for their samples is more refractory than a MORB source. They are also able to document distinct source-domains within the Izu–Bonin and central and northeastern Honshu arc; they speculate that these may derive from magma interaction with subcontinental lithosphere.

A series of contributions on the Cascade arc derive from an intimate knowledge of the Cascade Range developed over the years by teams of U.S. Geological Survey geologists, their collaborators, and other workers experienced in High Cascades volcanism.

Bacon, Bruggman, Christiansen and **Clynne** present a comprehensive geochemical study of mafic lavas from volcanic fields in the Cascade arc stretching from northern California to southern Washington. They recognize three distinct primitive magma-types: 1) high-Al olivine tholeiite (HAOT) with abundances of incompatible trace-elements similar to N-MORB, 2) arc (calc-alkaline) basalt and basaltic andesite with higher SiO_2 and Fe_2O_3 contents than HOAT, and exhibiting typical subduction-zone related enrichments in *LILE* and *LREE*, and relative depletions in *HFSE*, and 3) alkali basalt with a distinct intraplate

(OIB-like) trace-element signature. They relate these distinct magma-types to three end-member mantle components: 1) depleted sub-arc mantle modestly enriched in *LILE* during *ancient* subduction, 2) a *modern* hydrous (fluid or melt) subduction-related component derived from the young subducting Juan de Fuca plate, and 3) an OIB-like source domain within this subduction-modified mantle. They point out that coeval lavas representing these distinct mantle sources have erupted from vents in close proximity, and that many magmas appear to be blends of two or more of these end-member components. Drawing upon previous phase-equilibrium studies, they submit that the melts last equilibrated near the base of the crust. They conclude that the uppermost mantle beneath this part of the Cascade arc is anomalously hot, and that the locus of volcanism is coincident with an extensional tectonic regime, both factors facilitating emplacement of primitive magmas at the surface.

From a large analytical database representing mainly post-7-Ma lavas in the Cascade Range of northern Oregon and southern Washington, **Conrey *et al.*** describe the mineralogy and geochemistry of primitive lavas erupted in an extensional to post-extensional subduction-zone environment. The variation in primitive magma-types is surprisingly diverse, including low-K olivine tholeiite with N-MORB-like geochemical signatures except for weak *LILE* enrichment (essentially equivalent to the high-Al olivine tholeiites of Bacon *et al.*), within-plate basalt, olivine nephelinite, medium- to high-K calc-alkaline basalts and absarokite, and magnesian basaltic andesite in the fore-arc region. With the exception of the olivine analcimite, the absarokites are the most enriched in *LREE* and *LILE*, and also the most oxidized, judging from the composition of their olivine phenocrysts (Fo_{94}). The authors relate the origin of these diverse magma-types primarily to differences in the degree and depth of melting and the amount of H_2O contained in, or added to, the source. It is argued that the olivine tholeiites represent the hottest and driest magmas derived from the shallow upper mantle (spinel lherzolite facies), whereas the medium-K to high-K calc-alkaline basalt to absarokite series reflects a progression to cooler and wetter melts originating from subduction-metasomatized mantle (garnet–phlogopite-bearing lherzolites) at near-slab depths.

Borg, Clynne and **Bullen** also draw upon an extensive geochemical database to examine the compositions of primitive calc-alkaline magmas across the Cascade arc in northern California. They consider that variations in elemental and isotopic composition in the sub-arc mantle are coupled with variations in the proportion of slab-derived fluid and melt contributed to peridotites in the overlying wedge. Primitive lavas in the fore-arc are characterized by enrichments in Sr and Pb, low abundances of incompatible elements and MORB-like isotopic ratios. Their counterparts along the arc axis and toward the backarc have less pronounced Sr and Pb enrichments, weaker depletions in Nb and Ta, and higher overall abundances of incompatible elements, coupled with OIB-like isotopic compositions. The authors explain these geochemical characteristics by a two-stage model involving 1) hydrous fluxing of the mantle wedge to form amphibole-bearing peridotite enriched in Sr and Pb from slab-derived fluids and melts contaminated with subducted sediment, respectively, and 2) subsequent melting of this hydrous peridotite as it is dragged downward, creating magmas that are relatively depleted in Ta and Nb owing to preferential retention by amphibole. The gradual decay of the paired Sr–Pb (fluid–sediment) enrichment and Nb–Ta depletion in primitive magmas across the arc, and concomitant increase in levels of incompatible elements, are considered to reflect the decreasing proportion of a subduction component superimposed on fore-arc MORB- *versus* arc and backarc OIB-like mantle sources rather than variations in the degree of partial melting. In a companion paper, **Clynne** and **Borg** address the relative fertility of these mantle sources using olivine and spinel compositions in incompatible-element-depleted calc-alkaline basalt and magnesian andesite in the fore-arc, and more enriched calc-alkaline basalt and high-Al tholeiite in the arc axis and backarc region. They exploit the highly sensitive nature of spinel solid-solutions to the conditions of magma genesis and conclude that the range of mineral compositions in part requires fundamental differences in the composition of sub-arc mantle.

Luhr addresses the diverse nature of arc magmatism in a review of the mineralogy and geochemistry of primitive lavas in the western part of the Mexican Volcanic Belt that are spatially related to Plio-Quaternary rifting. Three distinct suites of primitive magmas are recognized on the basis of major and trace-element abundances and isotopic composition: 1) calc-alkaline basalts, 2) lamprophyric lavas including minettes, leucitites, spessartites and kersantites, and 3) alkaline basalts with an intra-plate-type (OIB-like) trace-element and isotopic signature. All three magma-types have erupted in close spatial proximity. The lamprophyric and calc-alkaline lavas form a mineralogical and compositional continuum, whereas the alkaline rocks represent an unrelated series. The ultimate origin of the lamprophyric suite is taken to reflect the melting of a phlogopite pyroxenite vein component in the mantle wedge formed by hybridization reactions between peridotite and melts or fluids ascending from the downgoing slab. The geochemistry of the calc-alkaline magmas reflects dilution of this vein component by melts from peridotitic wallrock. The intraplate-type magmas appear to be chemically unmodified by subduction-zone processes and are related to upwelling of asthenosphere to relatively shallow levels in the sub-arc environment.

In a comparative study of magmatic evolution within lower arc crust, **DeBari** contrasts the mineralogical and geochemical traits of ultramafic to gabbroic plutonic suites intruded into oceanic and continental crust, as exemplified by well-exposed cross-sections through the Jurassic Talkeetna arc terrane in south-central Alaska and the Ordovician Fiambalá intrusion in Argentina, respectively. The results of mass-balance calculations indicate that the compositions of parental magmas for both subduction-zone settings are low-A, high-Mg basalts that exhibit typical *LILE* enrichment and flat to slightly *LREE*-enriched *REE* patterns. Despite minor variations in fractionating mineral assemblages related to small differences in P_{total} and $f(H_2O)$, differentiation in the deep arc-crust produced residual liquids of high-A basalt composition, thereby precluding their derivation directly from the subducted slab. In contrast, the most differentiated gabbroic rocks in the continental setting of the Fiambalá intrusion display anomalous enrichments in all incompatible elements that are linked to small amounts (~3%) of crustal contamination rather than involvement of an old, enriched subcontinental mantle, as has been suggested previously for the source for such arc-related geochemical signatures. The latter evidence cautions against the common practise of using "fractionation-corrected" basaltic compositions to compensate for the scarcity of mantle-equilibrated magmas in order to evaluate chemical heterogeneity in mantle sources, particularly where a comprehensive geochemical database incorporating trace and major elements and isotopic analyses is unavailable.

Russell and **Snyder** describe the mineralogy and geochemistry of picritic lavas in south-central British Columbia that were emplaced in an early Mesozoic island-arc setting. Their bulk compositions have been variably affected by alteration and olivine accumulation. Mass-balance and thermodynamic calculations are utilized to reconstruct the pertinent intensive parameters [T, $f(O_2)$] and compositions of the primitive liquid. The authors conclude that the freshest samples are related by olivine fractionation and have oxygen fugacities and bulk compositions comparable to many such lavas in modern arc environments. The primitive magmas are estimated to contain 15–21 wt.% MgO.

Varfalvy, **Hébert**, **Bédard** and **Laflèche** examine the whole-rock and mineral chemistry of pyroxenite dykes that cut refractory harzburgites in ophiolitic sequences exposed at North Arm Mountain, Bay of Islands, Newfoundland. Reconstructed compositions of melts coexisting with the pyroxenites (orthopyroxenite, websterite, clinopyroxenite) exhibit depletions in *HFSE* and *HREE* and enrichments in *LILE* relative to MORB, and resemble modern magnesian andesites (boninites) in southwestern Pacific island arcs. Their origin is related to a complex history of melt-wall-rock interaction in a fore-arc environment.

Concluding remarks

Many recurrent themes appear in the studies summarized above. Statistically, it seems that those regions of an arc in which small-volume eruptive centers are best developed are the most likely places in which to encounter the least fractionated arc-related magmas. This is because the widespread development of monogenetic cones and rootless vents is, more often than not, related to extensional arc environments, or at least highly fractured crust, which facilitate the passage of small-volume batches of primitive magma to the surface. The diverse nature of these products is particularly striking: olivine (high-Al – low-K) tholeiite, low-, medium- and high-K basalt and basaltic andesite, magnesian andesite (boninite), picrite, ankaramite, absarokite, olivine analcimite and a variety of lamprophyres. The geological sample is unlikely to be complete, but given the petrogenetic conclusions reached by the authors, many of these magma types either do occur, or could conceivably be generated, in both intra-oceanic and continental arc settings.

Our understanding of the sources that contribute to arc magmatism stems largely from trace-element and isotopic studies, as is evident from the preponderance of articles in this volume that utilize such geochemical approaches. It is ironic that we appear to know more about the behavior of a multiplicity of trace elements and isotopic systems in subduction-zone environments than we do about the response of the handful of mantle minerals that dictate the composition of a primary magma under various conditions of melting. Speaking personally, we predict that progress in understanding the controls of the major-element compositions of primitive magmas at subduction zones will provide the next burst of insight in the future. Geologically realistic models for magma generation, of necessity, will require more sophisticated quantitative modeling of the major elements in hydrous silicate systems. For example, the "inverse approach" to the compositions of mantle-derived melts will ultimately enable constraints to be placed on the depth of final equilibration, and hence improve our appreciation of those regions within the mantle that could have contributed to the trace-element and isotopic signatures of the primitive magmas. In many cases, it is still unclear if these signatures are telling us about the influence of ancient or modern subduction regimes on the mantle wedge. Ultimately, an integrated approach is desirable whereby we may learn what components (fluid or melt or both) are the most prevalent from arc to arc and how these components and the magmas that derive from them chemically interact with the mantle wedge during their ascent to the crust.

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For a fleeting moment in the warm May sunshine of the day following the conference, we contemplated reconvening at the next GAC–MAC annual meeting to be held in Victoria to see how far ideas concerning the genesis of primitive arc magmas have progressed!

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