

High-magnesian andesite from Mount Shasta: A product of magma mixing and contamination, not a primitive mantle melt

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ABSTRACT

It has been proposed that high-Mg andesites (HMAs) from the Mount Shasta area may represent near-primary mantle melts, carrying signatures of slab melt interaction with the Cascadia mantle wedge. We present strong evidence that their formation involved mixing of dacitic and basaltic magmas and entrainment of ultramafic crystal material, and thus they cannot represent primitive magmas. The rocks contain (1) low-Mg# (65–72) clinopyroxene (cpx) and orthopyroxene (opx) phenocryst cores containing dacitic melt inclusions, and (2) high-Mg# opx and olivine xenocrysts, all of which are rimmed by euhedral overgrowths of cpx or opx similar in Mg# (87) to skeletal olivine phenocrysts. Textural relations indicate that ultramafic xenocrysts reacted with dacitic liquid, after which the contaminated magma mixed with basaltic liquid to produce a hybrid HMA bulk composition. High Mg, Cr, and Ni derive from the latter inputs, whereas high Sr/Y and overall adakite affinity is inherited from the dacite end member, which is arguably crustal in origin. We suggest that open system processes may be more important in the petrogenesis of HMAs than generally recognized, and that their magnesian compositions do not necessarily imply that they are primitive mantle melts.

Keywords: high-magnesian andesite, primitive magnesian andesite, Mount Shasta, mixing, adakite, arc volcanism.

INTRODUCTION

High-magnesian andesites [HMAs, synonymous with primitive andesite of Kelemen et al. (2005) and primitive magnesian andesite of Grove et al. (2002)] have been considered as important magma types in many volcanic arcs despite their rare occurrence (Yogodzinski and Kelemen, 1998; Kelemen et al., 2003, 2005). Their origin has been attributed to equilibration of slab-derived melts with the ultramafic mantle wedge (cf. Kay, 1978) or melting of strongly hydrated mantle wedge peridotites (cf. Rapp et al., 1999; Grove et al., 2002). These interpretations are based in part on geochemical characteristics of HMAs, including high Mg# (>60), high Cr and Ni concentrations, Sr-Nd isotopic similarities to mid-ocean ridge basalt, and unusually elevated Sr/Y and La/Yb ratios that could be attributed to high-pressure melting of garnet-bearing rocks (e.g., eclogite or wet garnet peridotite), and the assumption that such rocks are mantle-derived melts (Fig. 1). Such compositional features in so-called adakitic rocks have been widely interpreted as evidence for melting of subducted slabs or mantle domains previously infiltrated by slab melts or fluids (Martin et al., 2005). Alternatively, their telltale selective enrichment of light rare earth elements and Sr could be produced in deep crustal domains via melting or fractionation in the presence of garnet and/or amphibole coupled with negligible plagioclase (cf. Smith and Leeman, 1987; Ducea and Saleeby, 1998; Garrison and David-

son, 2003). Because HMAs have been invoked as important mantle contributions to formation of continental crust (i.e., to circumvent the so-called andesite problem; Rudnick and Fountain, 1995; Müntener et al., 2001), it is important to resolve controversies regarding their origin.

Here we present detailed petrographic information for an important occurrence of HMA near Mount Shasta (Anderson, 1973; Baker et al., 1994; Grove et al., 2002). These rocks have chemical characteristics (~58% SiO₂, ~8% MgO, ~500 ppm Cr, ~120 ppm Ni) typical of many HMAs worldwide (e.g., Tatsumi and Ishizaka, 1982; Kay, 1978; Kelemen et al., 2005; Martin et al., 2005). We find that these rocks represent hybrid magmas (as suggested by the early work of A.T. Anderson; cf. references herein) and question their relevance to mantle compositions and processes.

GEOLOGICAL FRAMEWORK

Mount Shasta and nearby volcanoes erupted diverse magmas ranging from dacite to basaltic variants including high-alumina olivine tholeiite (HAOT), calc-alkaline basalt (CAB), and basaltic andesite (BA). Rare HMA lavas and scoria erupted from a cinder cone on the Whaleback volcano, on the north flank of Mount Shasta. Because petrologic investigations of these unusual rocks (Anderson, 1973, 1974, 1976, 1979; Baker et al., 1994; Müntener et al., 2001; Grove et al., 2002, 2003) have produced conflicting interpretations, we undertook a detailed petrographic study to resolve their origin. Large vesicular bombs were sampled from the upper tephra sequence

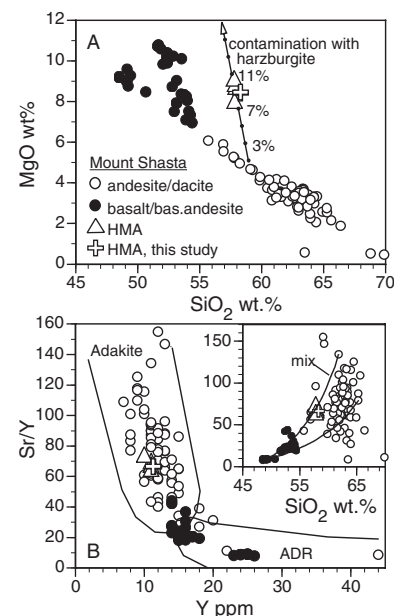


Figure 1. Compositional relationships among Mount Shasta magmas. A: MgO vs. SiO₂. B: Sr/Y vs. Y (inset shows Sr/Y vs. SiO₂). Data for basalts, basaltic andesites, and high-magnesian andesites (HMA) are from Baker et al. (1994) and this study; data for andesites and dacites are from Grove et al. (2005). Vector in A shows effect of adding harzburgite (75% olivine, 25% orthopyroxene) to common andesite. Fields in B are for adakite and for common arc andesite-dacite-rhyodacite (ADR) after Defant and Drummond (1990); inset shows bounding mixing trajectories (mix) between dacites and basalts, considering range in Sr/Y in dacites.

in well-exposed quarry exposures (S-17 locality of Anderson, 1973); these bombs and associated scoria lapilli appear identical.

The Shasta HMAs are porphyritic with ~15% phenocryst-sized minerals (the term phenocryst is used here for size only) consisting, in subequal proportions, of olivine, orthopyroxene (opx), and clinopyroxene (cpx) (cf. Anderson, 1979; Baker et al., 1994). Plagioclase is restricted to the groundmass, while larger plagioclase crystals are only reported from the basal unit of the Whaleback quarry (Anderson, 1974). Crystal clots of complexly intergrown pyroxenes of various sizes are also observed, as are ultramafic xenolithic fragments (as large as centimeter sized in hand samples); the latter could be entrained from the Trinity ophiolite, which underlies Mount Shasta (Quick, 1981).

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EVIDENCE FOR MAGMA MIXING AND CONTAMINATION

Pyroxene phenocrysts typically show disequilibrium textures and/or strong compositional zoning and comprise two main types (in subequal proportions) of different origins (Figs. 2 and 3). Type 1 pyroxenes record interactions between distinct dacitic and mafic magmas, whereas type 2 pyroxenes are entrained from mafic to ultramafic country rocks.

Type 1 includes euhedral opx and cpx crystals (~100–500 μm in size) with distinct overgrowths (<10–200 μm) on rounded and mildly resorbed, relatively unzoned low-Mg# (~65–72) cores; rim compositions have higher Mg# (85–92) (Fig. 2A). Transitions between low-Mg# cores and higher-Mg# rims are extremely sharp (2–5 μm). Compositions of melt inclusions in low-Mg# cpx resemble erupted Mount Shasta dacites (Figs. 3A, 3D). Distinct (higher Na/K) silicic glasses occur as inclusions or veins in some late-formed Fo_{87} olivines (Figs. 3B, 3D); these are interpreted as products of crystallization of intergranular melt entrapped shortly before eruption. Thus, type 1 pyroxene cores likely reflect crystal growth in dacitic melt(s) that subsequently mixed with more mafic magmas. Generally low Al_2O_3 contents (≤ 2 wt% for opx and ≤ 3 wt% for cpx) in pyroxene preclude crystallization from an aluminous (>16 wt% Al_2O_3) melt at mantle pressures (cf. Müntener et al., 2001).

Type 2 pyroxenes vary in size (to >1 mm) and exhibit strong textural and compositional disequilibrium. They commonly include resorption channels (~10–40 μm in width) that produce a sieve-like or wormy appearance (Figs. 2B, 2C). Such crystals are either anhedral or overgrown by thin (<20 μm) euhedral rims. Backscattered electron images reveal patchy zoning in resorbed opx interiors (Figs. 2B, 2C). Where preserved, original opx compositions are magnesian (Mg# 85–88), whereas replacement patches resemble dacitic opx. Zoning patterns in type 2 pyroxenes seem to reflect reequilibration after high-Mg# opx crystals came in contact with dacitic magma, and some are overgrown by dacitic opx along fractures or other open areas. These features are attributed to infiltration of dacitic liquid (Fig. 2B) and are observed both in single and glomerocrystic opx grains; such resorbed type 2 opx crystals are interpreted as xenocrysts.

Olivines also appear to have multiple origins. Euhedral and commonly skeletal microphenocrysts (70–200 μm across) of Fo_{87} composition crystallized from the last hybrid liquid shortly prior to eruption (Fig. 3B). They contrast with sparse (~1–3 grains per thin section) large anhedral olivine crystals (to ~4 mm) with highly magnesian cores (Fo_{90-94}); many either have reaction rims of opx or overgrowths of Fo_{87} olivine. The Fo_{94} cores are notable because such compositions are rare (cf. Sobolev et al., 2005), even in

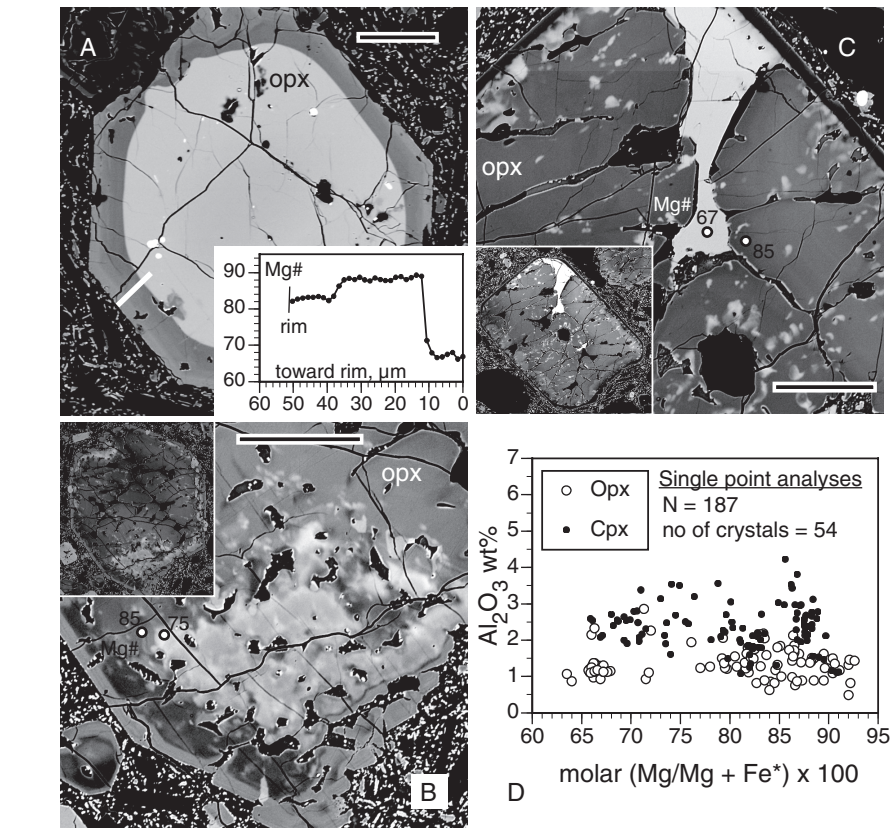


Figure 2. Representative textural and compositional complexities in phenocrysts from Mount Shasta high-magnesian andesites (HMAs). All images are backscattered electron images and scale bars are 100 μm . A: Typical type 1 phenocryst cored by low-Mg# dacitic pyroxene overgrown on anhedral interior by high-Mg# pyroxene; inset shows analysis traverse at position of white bar. Note zonation in rim from Mg# 89–92 (inside) to 83–86 (outside). B and C: Resorbed, type 2 pyroxene (high-Mg# opx) likely derived from ultramafic country rocks; insets show entire crystals. Patchy zoning of lower Mg# pyroxene is shown in B, whereas C shows later crystallization of dacitic pyroxene in former crack; both grains have narrow euhedral rims. D: Compositional spread of phenocrystic orthopyroxene (opx) and clinopyroxene (cpx), as represented by 187 point analyses on 54 mineral grains; single crystals were analyzed 2–4 times between center and rim. Microprobe data obtained in traverse mode are excluded so as to avoid biases due to high number of analysis points of few selected crystals.

ultramafic rocks; their characteristics suggest to us that these olivines are xenocrystic.

EVOLUTIONARY SCENARIO

The aforementioned observations imply a complex evolutionary scenario for HMA, as follows. (1) Formation of dacitic melt(s) at crustal pressures is evidenced by dacitic opx and cpx cores. (2) Entrainment of ultramafic debris in dacite is implied by penetration or overgrowths of dacitic opx on Mg-rich xenocrysts. (3) Interaction of mafic magma with contaminated dacite is indicated by Fo_{87} olivine overgrowths and microphenocrysts, and by overgrown pyroxene rims with Mg# near 87. To test this scenario, simple models (Figs. 1A, 1B, and 3D) were constructed to reproduce the Shasta HMA bulk composition using as magmatic mixing end members representative silicic and mafic lavas from Mount Shasta—phenocryst-poor (3%) Shastina dacite #83-58 (Grove et al., 2005), and HAOT and CAB basalts (Baker et al., 1994). Compositions

of high-Mg# cores of olivine and opx xenocrysts were combined at a 3:1 ratio to approximate harzburgitic country rock (cf. Quick, 1981). HMA major element composition is closely reproduced by mixing proportions: ~33%–42% basaltic magma (depending on choice of basalt type), 60%–53% dacitic magma, and 7%–5% of harzburgitic debris (Table 1).

DISCUSSION

Use of HMA as Model Primitive Magma

Mount Shasta HMA was used as a starting composition in several experimental studies addressing arc magmatism (Baker et al., 1994; Müntener et al., 2001; Grove et al., 2002, 2003). Despite recognition of petrographic complexities (Baker et al., 1994; Grove and Shimizu, 1999), compositional modification of HMA due to contamination or magma mixing was considered minimal, and small corrections for these effects were assumed sufficient to make it a reasonable proxy for a primary magma type (e.g., Grove and

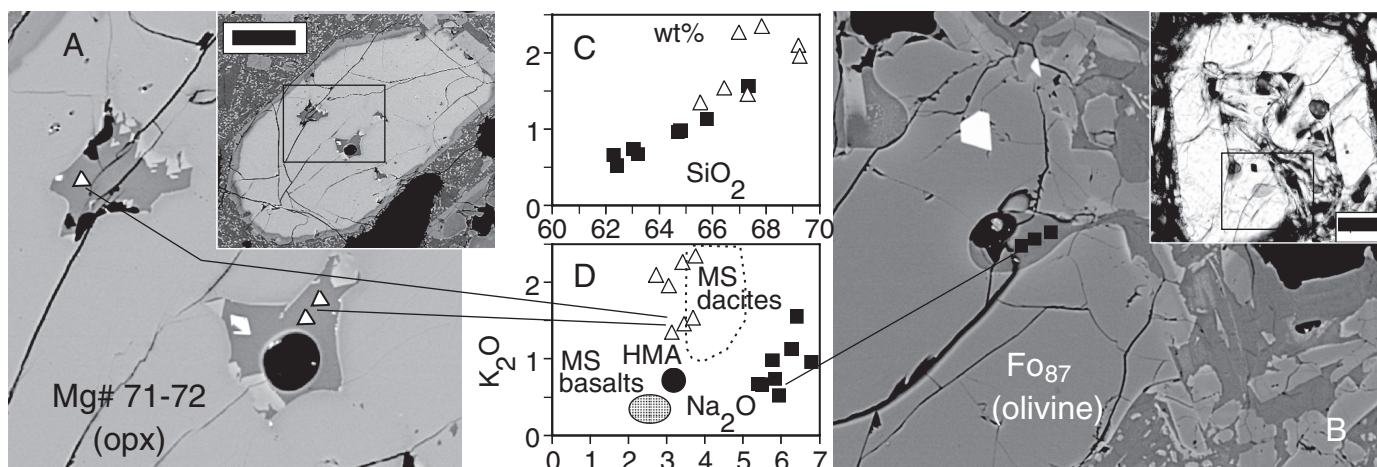


Figure 3. Selected compositional characteristics of melt inclusions in (A) dacitic (type 1) pyroxene and (B) late-crystallizing skeletal olivine. Insets show entire crystals and black rectangles enclose enlarged areas; scale bars are 100 μm . All images are backscattered electron images, except inset of B, which is transmitted light image. Note characteristic darker (high Mg#) rim of phenocryst in A inset. Data sources for Mount Shasta (MS) rocks in D are same as in Figure 1. Melt inclusions in dacitic pyroxene (triangles) overlap with Mount Shasta dacite lavas, whereas late entrapped glass inclusions or veins in Fo_{87} olivine (squares) are compositionally distinct (i.e., trondhjemitic). HMA—high-magnesian andesite; opx—orthopyroxene.

Shimizu, 1999; Grove et al., 2003). Results from these studies have led in part to consideration that generation of HMA is a “defining process of arc magmatism” (Kelemen et al., 2005, p. 602). Grove et al. (2002, 2003) developed a scenario in which HMA is a product of initially very hydrous mantle melt that progressively reacted with mantle wedge peridotite during ascent; this scenario hinges on the idea that HMA is a primitive magma segregated from the mantle.

Our findings indicate that Mount Shasta HMA is a hybrid magma for which crustal inputs dominate over the mafic melt component. Thus, HMA bulk composition is unlikely to provide reliable information concerning mantle melting, and experimental studies based on this rock as a starting material have questionable relevance regarding mantle processes.

Ingredients to Make HMA Elsewhere

In essence, the formation of HMA can be viewed as a two-step process: (1) mixing between dacite and high-Mg basalt to make andesite, and (2) addition of ultramafic crystal debris to an andesitic magma to make HMA (Table 1). The first process commonly occurs in arcs (cf. discussion for Mount St. Helens; Smith and Leeman, 1993). Contamination by ultramafic debris occurred elsewhere (e.g., Arculus et al., 1983), but may be difficult to recognize despite its significance for compositionally modifying arc magmas (Dungan and Davidson, 2004). Mount Shasta dacites and andesites commonly contain high-Mg ferromagnesian xenocrysts. In addition, centimeter-sized peridotite and orthopyroxene inclusions occur rarely in all eruptive phases at Mount Shasta (Grove et al., 2005). Mount Shasta is the only locality in the Cascades where HMAs occur, and it is here

TABLE 1. COMPOSITION OF ROCKS AND MODELS

Wt%	HMA ¹ MS1604	HMA ² 85–41*	HMA Model 1	HMA Model 2	Dacite ³ 83–58	HAOT ² 85–38	CAB ² 85–1a	Harz.
SiO_2	58.30	57.85	58.16	58.16	64.19	49.88	52.06	45.43
TiO_2	0.59	0.61	0.63	0.54	0.56	0.88	0.57	0.03
Al_2O_3	14.73	14.65	15.68	15.43	16.62	17.21	15.71	0.39
FeO^*	5.58	5.71	5.54	5.47	3.67	8.77	7.64	6.41
MnO	0.10	0.11	0.11	0.11	0.07	0.18	0.16	0.08
MgO	8.46	8.70	8.46	8.56	3.24	9.74	10.69	47.16
CaO	8.19	8.14	7.24	7.46	6.09	10.77	10.02	0.51
Na_2O	3.17	3.36	3.28	3.39	4.29	2.14	2.67	0.02
K_2O	0.76	0.73	0.77	0.75	1.12	0.30	0.38	0.00
P_2O_5	0.13	0.16	0.13	0.13	0.16	0.11	0.10	0.00
		ΣR^2	0.027	0.025				

Note: HMA—high-magnesian andesite. HAOT—high-alumina olivine tholeiite. CAB—calc-alkaline basalt. Data sources: 1—this study, 2—Baker et al. (1994), 3—Grove et al. (2005). Model 1: composition after mixing of 7% harzburgite, 60% dacite, and 33% HAOT basalt. Model 2: composition after mixing of 5% harzburgite, 53% dacite, and 42% calc-alkaline basalt. Harz—harzburgitic contaminant (75% $\text{Fo}_{83.7}$ olivine, 25% Mg# 89.6 orthopyroxene).

*Average of #85–41a-d; all normalized.

where the volcanic arc is underlain by a major ophiolitic body (cf. Quick, 1981).

Are conditions that produced Mount Shasta HMA exceptional, or may similar scenarios operate at other centers to produce HMAs? Some HMAs from the Aleutian Islands (including the type adakite; R. Kay, 2005, personal commun.) carry zoned phenocrysts that implicate evolved magmas as mixing components (Yogodzinski and Kelemen, 1998; Kelemen et al., 2005). Similarly, Tatsumi et al. (2006) presented petrographic evidence for mixing in HMAs from the Setouchi volcanic belt. Notably, pyroxenes from the mixed Aleutian and Setouchi HMAs contain low-Mg# cores overgrown with high-Mg# rims, as observed at Shasta. The commonly elevated Pb isotopic signatures of HMAs worldwide could be interpreted in terms of a crustal contribution (Kelemen et al., 2005). It is worth revisiting petrographic details to determine whether other HMAs have a true mantle origin.

Decoupling of Primitive and Adakitic Signatures in HMA

Magma mixing and contamination processes to generate Mount Shasta HMA may operate largely independently, and could lead to decoupling of primitive (e.g., high Mg#) versus adakitic (e.g., high Sr/Y) chemical attributes. Mount Shasta HMA (Sr/Y = 67, Y = 11 ppm) is in the category of low- SiO_2 adakites of Martin et al. (2005). Basaltic magmas at Mount Shasta have lower Sr/Y and higher Y, whereas many dacites have considerably higher Sr/Y and lower or equal Y compared to the HMA (Fig. 1). Thus the HMA could have inherited its adakitic signature from a high-Sr/Y dacitic end member, whereas its high Mg# and other primitive characteristics stem from ultramafic contamination and mixing with basaltic magma.

More fundamental questions concern the origins of the basaltic and dacitic magmatic end members, and what information, if any, they

retain regarding subduction-related processes at mantle depths. U-series isotopic data preclude significant input of a slab derived flux-component in any Shasta lavas, and imply that most analyzed lavas are products of magma mixing (Newman et al., 1986). In addition, Cascades basaltic lavas exhibit little or no enrichment of fluid mobile elements and isotopic tracers (Leeman et al., 2004), suggesting that slab contributions are small, presumably because the downgoing slab is dehydrated and stripped of fluid mobile components owing to unusually warm subduction zone conditions. It is argued that magmatism in the Cascades is fundamentally basaltic, as a result of melting within the mantle wedge primarily driven by decompression of convecting asthenosphere (Leeman et al., 2005).

CONCLUSIONS

Petrographic evidence conclusively demonstrates that Mount Shasta HMA was a hybrid magma, formed by mixing between dacitic (>50%) and basaltic (≤40%) magmas with contamination by ultramafic debris (<10%). Resorbed, high-Mg pyroxenes and the highest-Mg olivines in these rocks appear to be xenocrystic in origin (likely derived from ultramafic country rocks), and do not support a direct mantle origin. The high proportion of dacitic crustal component inferred for this HMA precludes a direct mantle derivation, and casts doubt on its relevance for understanding mantle processes and the long-term composition of the crust (Kelemen et al., 2003). As mixing between basalt and dacite to yield andesitic magmas is commonplace in volcanic arcs, we attribute the occurrence of unusual HMA magma at Shasta (and perhaps other HMA localities) to the availability of ultramafic crystal debris and/or processes that favor entrainment of such material. Furthermore, primitive versus adakitic compositional attributes of HMA magmas may be decoupled, allowing them to vary independently, depending on local circumstances.

ACKNOWLEDGMENTS

This work was supported by National Science Foundation (NSF) grant EAR-0409423 to Leeman and Chesley and by instrumentation grant EAR-0320863 to Streck and others. Streck acknowledges support from Eidgenössische Technische Hochschule (ETH) Zürich as Gastdozent during preparation of this manuscript and thanks W. Halter and C. Heinrich at the ETH and H.-J. Massone and T. Theye at the University of Stuttgart for their hospitality. Leeman acknowledges support from the NSF for time spent in preparation of this paper. We thank Jon Davidson, Mike Dungan, and an anonymous reviewer for their thorough comments.

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Manuscript received 11 August 2006

Revised manuscript received 22 November 2006

Manuscript accepted 27 November 2006

Printed in USA