# Magmatic intrusion west of Three Sisters, central Oregon, USA: The perspective from spring geochemistry

William C. Evans
U.S. Geological Survey, Menlo Park, California 94025, USA
Matthijs C. van Soest
Isotope Geochemistry Center, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
Robert H. Mariner
Shaul Hurwitz
Steven E. Ingebritsen
Charles W. Wicks Jr.
U.S. Geological Survey, Menlo Park, California 94025, USA
Mariek E. Schmidt
Department of Geosciences, Oregon State University, Corvallis, Oregon 97370, USA

## ABSTRACT

**A geochemical investigation of springs near Three Sisters volcanoes was conducted in response to the detection of crustal uplift west of the peaks. Dilute, low-temperature springs near the center of uplift show $^3He/^4He$ ratios $\geq 7R_A$ ($R_A$ is the ratio in air), and transport in total ~16 MW of heat and ~180 g/s of magmatic carbon (as $CO_2$). These anomalous conditions clearly reflect the influence of magma, but they seemingly predate the onset of the present uplift and derive from a previous event. Episodes of intrusion may thus be more common in this area than the age of eruptive vents would imply.**

**Keywords:** Three Sisters, Oregon, springs, gases, intrusions.

## INTRODUCTION

Cascade Range volcanoes threaten population centers on the west coast of North America and are monitored for signs of unrest (Dzurisin et al., 1997). Wicks et al. (2002) used images made by satellite-based interferometric synthetic aperture radar (InSAR) to show that a broad area on the west side of Three Sisters volcanoes had begun to rise by as much as 4–5 cm/yr beginning in 1998, an episode of inflation they attributed to intrusion of 0.006 $km^3$/yr of magma at ~6.5 km depth. Because such small, aseismic episodes of uplift would have escaped detection until recently, the frequency of these events and the likely outcome of this event are difficult to assess. This study of springs was conducted because rising magmas may release gases and heat into overlying groundwater.

There are no known fumarolic vents or hot springs on the Three Sisters, but low-temperature springs are abundant on the western flank of South Sister, especially in the Separation Creek drainage where the uplift is centered (Fig. 1). Every spring sampled here in 2001 and 2002 contained magmatic carbon, and several had mantle-like helium isotope ratios near $8R_A$ (van Soest et al., 2002; $R_A$—ratio in air). Finding such high values in dilute (total dissolved solids [TDS] $<$ 200 mg/L), low-temperature springs is, to our knowledge, unprecedented. The isotopic data appeared to provide evidence for gas release from an ongoing intrusion, but we argue instead that they identify an area where previous basaltic intrusion has occurred recently, if not frequently, in the past. The geochemical study thus provides some needed perspective on the current uplift.

## AREAL GEOLOGY AND HYDROLOGY

The youngest lavas within the broad zone of uplift are the silicic Rock Mesa and similar nearby rhyodacitic domes and flows on the southeast and northeast flanks of South Sister (Fig. 1B), dated to 1500–2000 yr B.P. (Scott et al., 1999). Throughout the Quaternary Period, however, the most voluminous and frequently erupted lavas in the central Oregon Cascade Range have been mafic (Taylor et al., 1987; Sherrod and Smith, 1990). Hundreds of mafic vents have formed along lineaments generally parallel to the axis of a broad north-trending extensional graben that confines the Quaternary arc, and these lineaments are particularly numerous near Three Sisters (Hughes and Taylor, 1986; Conrey et al., 2002). Holocene basaltic vents are found just north and south of Three Sisters, but vents to the west, near the center of uplift, are of Pleistocene age (Taylor et al., 1987).

Magmatic heat is evident in hot springs that discharge 15–30 km west of Three Sisters (Fig. 1A). Ingebritsen et al. (1994) used isotopic evidence and heat-flow data to conclude that gravity-driven flow of hot water transports ~20 MW of heat from the Three Sisters area to low elevations in the western Cascades. They inferred aquifer residence times of $10^2$–$10^4$ yr for these neutral-chloride fluids that contain almost no carbon but have $^3He/^4He$ ratios of 4–$5R_A$.

Reconnaissance stream sampling revealed a chloride concentration above background ($>$0.5 mg/L) in Separation Creek in 1990, nearly a decade prior to the onset of uplift (Ingebritsen et al., 1994). Subsequent sampling through 1998 (Iverson, 1999) showed that perennial springs in the drainage are slightly anomalous in temperature and chloride, up to 5 °C and 20 mg/L, respectively, above normal cold springs in the region.

## 2001 AND 2002 FIELD STUDIES

The discovery of ongoing uplift prompted new and expanded investigations of spring geochemistry[1] in 2001 and 2002. To check for magmatic volatiles from the suspected intrusion, water samples were

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[1] GSA Data Repository item 2004011, Tables DR1–DR6, spring locations and chemical analyses, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

*Geology;* January 2004; v. 32; no. 1; p. 69–72; DOI 10.1130/G19974.1; 3 figures; Data Repository item 2004011.

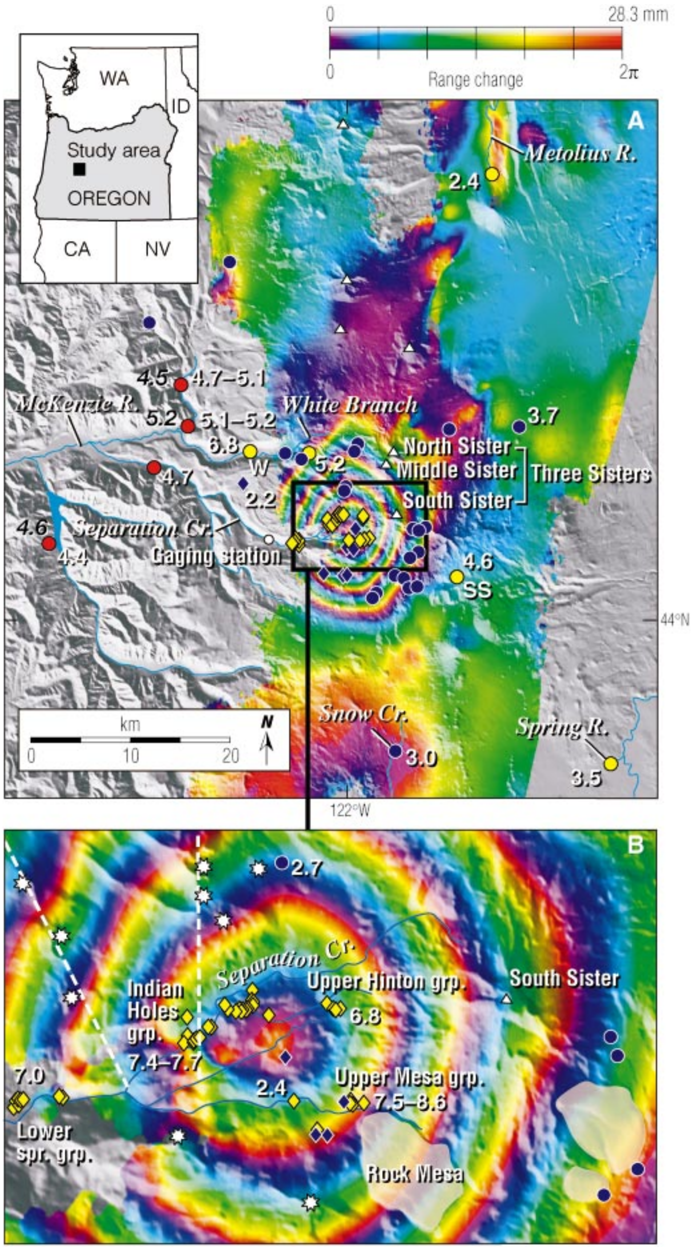

**Figure 1. A: Sampled springs and interferometric synthetic aperture radar (InSAR) interferogram showing cumulative uplift through September 2001. Diamonds are springs that feed into Separation Creek; circles are springs (and one well) outside that drainage. Low-temperature springs with $Cl^-$ > 0.6 mg/L are yellow, those with $Cl^-$ < 0.6 mg/L are blue; hot springs ($Cl^- \approx$ 1000 mg/L) are red. Well (W) and high total dissolved solids soda spring (SS) are marked. White numbers near springs are $^3He/^4He$ values (air corrected using $^{22}Ne$) measured in 2001–2002. Black numbers are 1980s $^3He/^4He$ data (UNOCAL—used with permission) for hot springs, which showed no obvious response to uplift. Triangles show volcanic peaks at crest of arc. B: Springs in upper Separation Creek drainage, including those sampled in 1998 by Iverson (1999). Four spring groups where closely spaced orifices (diamonds) show gradients in temperature and chloride are labeled. Shaded areas—Holocene rhyodacites; stars—Pleistocene mafic vents with lineaments from Hughes and Taylor (1986).**

collected in preevacuated glass tubes for analysis of dissolved inorganic carbon (DIC $= CO_2 + HCO_3^- + CO_3^{2-}$) and carbon isotopes (Evans et al., 2002). Samples of water (and gas bubbles when present) were collected in copper tubes for analysis of helium isotopes (van Soest et al., 2002).

Carbon isotopes (Fig. 2A) show mixing between biogenic carbon with near-modern $^{14}C$ values and magmatic carbon lacking $^{14}C$. James et al. (1999) used $^{14}C$ depletion in DIC to show that groundwater transports magmatic carbon from the crest of the arc to high-discharge cold springs many kilometers to the east. Our data from some of these same springs are included in Figure 2A. The plot shows that magmatic carbon predominates in most springs in the Separation Creek drainage, so much so that the magmatic $\delta^{13}C$ value can be reasonably well constrained at $\sim -9$‰. This value is near the $-9.8$‰ found in the soda spring southeast of South Sister (Fig. 1A), an unusual feature that bubbles $CO_2$ of presumed magmatic origin.

The highest $^3He/^4He$ ratio ($8.6R_A$) occurs next to Rock Mesa, but overall, there is no areal correlation between high ratios and Holocene lavas (Fig. 1B). Magmatic degassing rather than simple rock leaching is thus the apparent helium source. Ratios $>4R_A$ all occur in springs with anomalous chloride, but beyond that show no relationship to chloride concentration or spring temperature, and instead show a clear pattern of decline with distance away from the center of uplift (Fig. 2B).

Many $^3He/^4He$ ratios near the center of the uplift are $\geq 7R_A$ and within the range found in mid-oceanic ridge basalt (MORB), typically given as $7–9R_A$ (Farley and Neroda, 1998). This suggests that the intrusion responsible is a mantle melt largely unaffected by crustal contamination, and a basaltic composition is favored by the strong predominance of mafic over silicic vents near the center of uplift. The springs with $^3He/^4He$ ratios in the MORB range have an average $C/^3He$ of $9 \times 10^9$, compared to MORB, which is characterized by an average $C/^3He$ ratio of $2 \times 10^9$ and average $\delta^{13}C$ value of $-6.5$‰ (Sano and Marty, 1995). Assuming that $C/^3He$ of $9 \times 10^9$ and $\delta^{13}C$ of $-9$‰ reflect the intrusion, a likely source magma is mantle-derived basalt, somewhat enriched in isotopically light carbon from sedimentary organic material in the subducted Juan de Fuca plate.

Chemically, the springs in the Separation Creek drainage are mixed-cation waters with bicarbonate as the major anion (Tables DR1–DR6; see footnote 1). The weak temperature and chloride anomalies, and their strong correlation within individual spring groups, are shown in Figure 2C. Sulfate concentrations, and a clear increase in $SO_4^{2-}/Cl^-$ with elevation, are shown in Figure 2D.

## CONCEPTUAL MODEL

A conceptual model that incorporates the new data into previous models (Ingebritsen et al., 1994; Iverson, 1999) is shown in Figure 3. High-elevation recharge percolates below the upper flank of South Sister and is heated to boiling. Much of the hot water then follows long, deep flow paths to the hot springs 15–30 km to the west, but some leaks upward, mixing into the overlying cold groundwater and causing the small temperature and chloride anomalies. Dikes or faults associated with the north-trending vent lineaments may provide the permeable pathways for vertical groundwater flow.

Evidence for a separated vapor phase is seen only in the higher-elevation springs. Latent heat from steam condensation together with scrubbing of $H_2S$ can explain the steeper slopes of the temperature versus $Cl^-$ curves and the higher $SO_4^{2-}/Cl^-$ ratios in the upper spring groups (Figs. 2C, 2D). The highest elevation springs, upper Hinton, are richest in DIC by a factor of three compared to all other springs, reflecting the fact that $CO_2$ is not scrubbed out as easily as the more soluble and reactive $H_2S$. It is noteworthy that the evidence gleaned from subtle anomalies in dilute springs no more than 5 °C above background favors a model of South Sister quite similar to that invoked for more active volcanoes, where high-chloride springs, acid-sulfate seeps, and variable $CO_2/S$ ratios in summit fumaroles or plumes provide much more dramatic evidence of phase separation, scrubbing, and lateral outflow of brines (e.g., Giggenbach, 1997; Symonds et al., 2001).

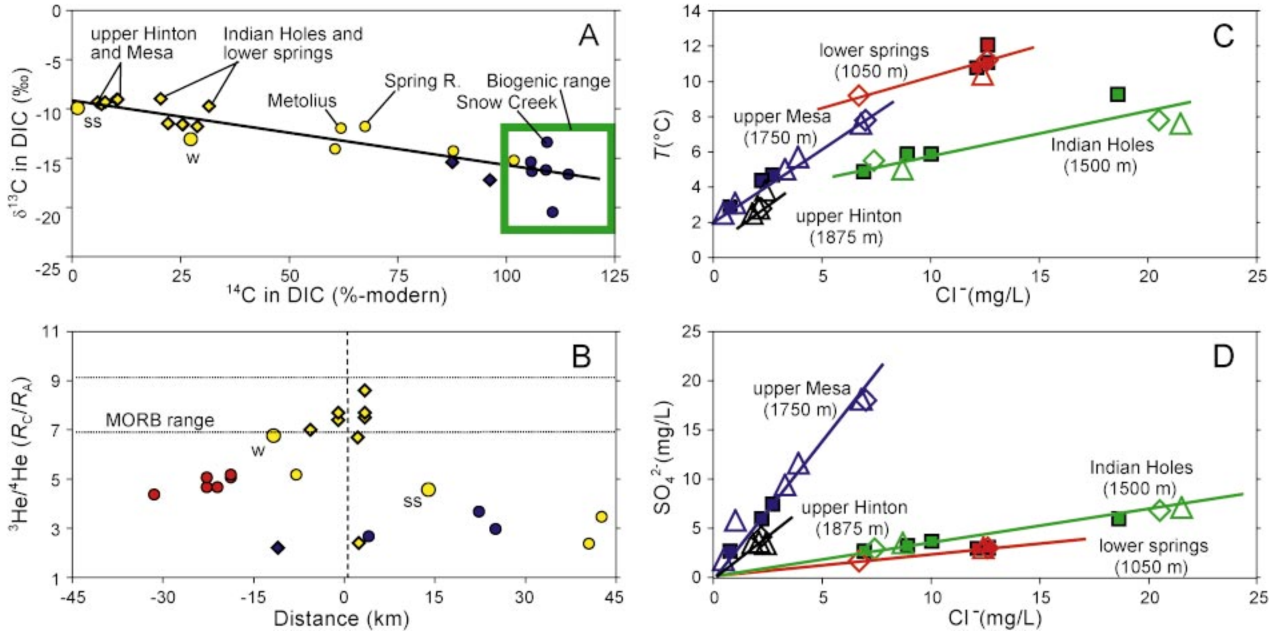

**Figure 2. Selected geochemical data (see text footnote 1). A: Carbon isotopes of dissolved inorganic carbon (DIC) with regression line (symbols as in Fig. 1). Metolius, Spring River, and Snow Creek Springs were studied by James et al. (1999). B: Air-corrected $^3He/^4He$ ratios vs. radial distance from center of uplift (symbols as in Fig. 1). C: Temperature vs. chloride and average elevations for spring groups labeled in Figure 1. Filled squares are 1998 samples from Iverson (1999). Diamonds and triangles are 2001 and 2002 samples, respectively, from same spring groups but generally different orifices. D: Sulfate vs. chloride for samples shown in C (symbols as in C).**

## DISCUSSION

As intriguing as the patterns of helium and carbon isotopes are (Figs. 2A, 2B), the collocation of the uplift and the chloride anomaly that predates the onset of uplift (Fig. 1) is equally striking and suggests that the magmatic helium and carbon in the springs are not related to the current episode of intrusion. The springs contribute nearly all of the late summer flow of Separation Creek at the gaging site (Iverson, 1999), so stream sampling and gaging can easily reveal whether the chloride anomaly has changed in response to uplift. Four measurements in 2001 and 2002 showed that the total anomalous chloride load corrected for background is very constant at 9.7 ± 0.5 g/s, indistinguishable from the 10 g/s measured in 1990 (Ingebritsen et al., 1994).

Figure 2C shows that spring temperatures have not changed appreciably since 1998 except possibly at upper Mesa Creek, where some warmer, more chloride-rich springs were found in 2001 and 2002. The temperature-$Cl^-$ relationships in the individual spring groups—including upper Mesa Creek—have not changed, however. The invariance in total chloride load thus implies a constant advective heat output since the onset of uplift. Figure 2D also shows that the $SO_4^{2-}/Cl^-$ ratios in the spring groups have stayed constant, which rules out an increase in sulfur flux since the onset of uplift.

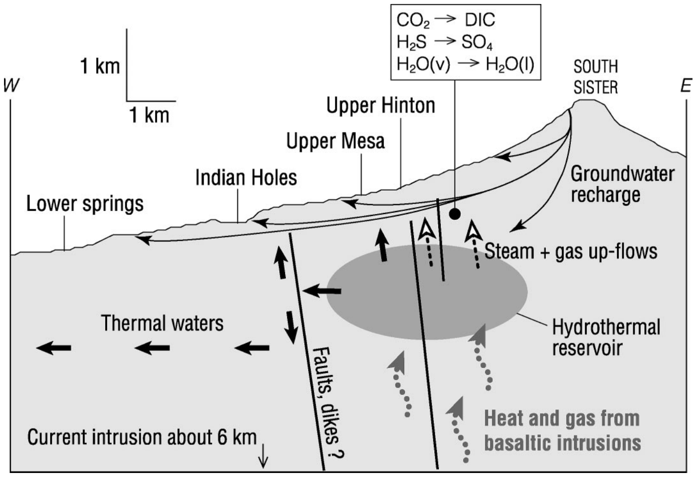

**Figure 3. Conceptual model of Separation Creek drainage showing proposed flow paths of hot and cold groundwaters, gas, and steam, and hypothetical faults or dikes that follow regional north-trending structure (Hughes and Taylor, 1986). DIC is dissolved inorganic carbon.**

A magmatic intrusion could drive a pulse of helium and $CO_2$ rapidly to the surface without a concomitant increase in heat, sulfur, or chloride, as was seen in 1989 at Mammoth Mountain volcano in California. Fumarolic $^3He/^4He$ ratios jumped ~6 months after an inferred intrusion rose to within 7 km of the surface, and $CO_2$-rich soil gases and cold springs were subsequently detected (Sorey et al., 1998). Such a scenario does not seem applicable to the Separation Creek area, as we show by calculating total magmatic carbon and heat fluxes.

The amount of magmatic $CO_2$ absorbed by groundwater can be calculated from the DIC concentration and $^{14}C$ data (see formula in James et al., 1999). Average spring water in the Separation Creek drainage contains 1.1 mmol/L of dead carbon (carbon lacking $^{14}C$). Combined with the late summer streamflow at the gaging site (3.6 $m^3/s$), this concentration equates to 180 g/s of magmatic $CO_2$. Manga (1998) developed a method to calculate heat advection by large-discharge springs that drain clearly defined areas of the Cascade arc. This method is difficult to apply in the Separation Creek drainage, but the linear temperature versus $Cl^-$ relationships (Fig. 2C) still permit rigorous calculation of the total geothermal heat anomaly in a way that avoids the problem of solar heat input (see Nathenson et al., 2003). For the spring groups on average, $Cl^-$ increases ~2.5 mg/L for each 1 °C increase in temperature. Combining this average with the total late summer streamflow (3.6 $m^3/s$) and anomalous chloride load (10 g/s) gives a total advective heat output of 16 MW for all the springs.

Good sample coverage probably constrains these calculated totals for carbon and heat output to within ±50%, and unless our assumption of mantle-derived basalt is in error or a large diffuse emission of $CO_2$

exists, these totals imply an intrusion rate smaller by an order of magnitude than that inferred from InSAR results for 1998 to the present (0.006 km$^3$/yr). A CO$_2$ emission rate of 180 g/s would require complete degassing of 0.0003 km$^3$/yr of mantle-derived basalt with a density of 2.65 g/cm$^3$ and an initial CO$_2$ content of 0.7 wt% (Gerlach et al., 2002; Giggenbach, 1997). The 0.0003 km$^3$/yr of basaltic magma emplaced at 1200 °C and cooling to 300 °C could also support a heat output of 40 MW, under the assumptions of a latent heat of crystallization of 420 J/g and a specific heat of 1.25 J/(g·°C) (Ingebritsen et al., 1994). This heat output is nearly equal to the combined advective heat in the Separation Creek springs (16 MW) plus the low-elevation hot springs to the west (20 MW). That the CO$_2$ emission rate is in balance with the long-term heat advection strongly suggests that the heat, carbon, and probably the helium anomalies in the Separation Creek springs derive from a previous episode of intrusion(s).

James et al. (1999) proposed that all the dead carbon in springs draining the east side of the central Oregon Cascade Range could be attributed to degassing magma, given the estimated long-term intrusion rates of 9–55 km$^3$/m.y. per kilometer of arc (Ingebritsen et al., 1989; Blackwell et al., 1990). If we take the total north-south extent of the geochemical anomaly considered here to cover ~20 km of arc length (Fig. 1), then 0.0003 km$^3$/yr of magma represents a normalized intrusion rate of 15 km$^3$/m.y. per kilometer of arc, within the long-term range. Thus, the exceptional characteristic of the Separation Creek springs relative to other springs in the region is not the total output of magmatic gas and heat, but the strong, nearly undiluted nature of the magmatic signature in some of the springs. This must reflect the proximity of these springs to the magmatic source. Other springs farther away are less dominated by magmatic carbon and have lower $^3$He/$^4$He values (Figs. 2A, 2B) because of greater dilution, input of biogenic carbon, and leaching of radiogenic $^4$He (see Mariner et al., 2003).

In-growth rates of $^4$He calculated from U and Th contents in mafic lavas from this region (Hughes and Taylor, 1986) indicate that moderately degassed magma of any Holocene age with an initial $^3$He/$^4$He ratio of 8$R_A$ could still retain a ratio of $>7R_A$. Mafic intrusions beneath South Sister, which may have triggered the rhyodacitic eruptions around the peak at 1500–2000 yr B.P., conceivably provide a long-lasting source of the volatiles in the Separation Creek springs. However, no comparable geochemical anomaly is detectable on the east side of South Sister, where enrichments in magmatic carbon and $^3$He/$^4$He ratios are not as pronounced (Manga, 1998; James et al., 1999; Fig. 1). A previous intrusion, or intrusions, located near the center of the current uplift is a more probable source.

The balance between advective heat and magmatic carbon discharge at the long-term intrusion rate is best explained if moderately frequent but relatively small scale episodes of basaltic dike intrusion occur along the north-trending lineaments on the west side of the Three Sisters and maintain the distinctive isotopic signature of magmatic gas in the springs. For example, an episode lasting ~5 yr at 0.006 km$^3$/yr would be needed every ~100 yr to sustain the present output of carbon, helium, and heat. Although north-trending vent lineaments characterize volcanism throughout the Quaternary Period, no basalts have reached the surface in the Separation Creek drainage for at least 10 k.y. (Taylor et al., 1987). Viewed in this context, the intrusion inferred to be the cause of the current uplift would have a low probability of actually erupting.

## ACKNOWLEDGMENTS

We thank M. Huebner, L.D. White, and K. Lee (U.S. Geological Survey) for analytical help and stream gaging, S. Otoupaulik (U.S. Forest Service) for logistical support in the Wilderness Area, and UNOCAL for permission to use their data. Noble gases were analyzed by RARGA (roving automated rare gas analysis) at Lawrence Berkeley National Laboratory, for which we thank B.M. Kennedy and P.F. Dobson. Van Soest was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, contract DE-AC03-76SF00098. R. Conrey and W. Hildreth provided advice and W. Scott, M. Nathenson, M. Manga, and T. Gerlach helped with useful reviews.

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Manuscript received 25 June 2003
Revised manuscript received 15 September 2003
Manuscript accepted 23 September 2003

Printed in USA