Calcite twinning constraints on late Neogene stress patterns and deformation mechanisms in the active Zagros collision belt

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ABSTRACT

Mechanically induced calcite twins in veins and host rocks of Late Cretaceous to Miocene age in Iran have been used to determine regional Arabia-Eurasia collisional stresses. A late folding stress regime with a compression oriented 025° (±15°) has been identified across the Zagros belt and the southern Iranian Plateau. This late Neogene stress pattern agrees with the current stress field determined from the focal mechanisms of basement earthquakes and suggests that the Hormuz salt décollement poorly decouples the basement and cover stress fields. Our data show that the collisional state of stress has been relatively constant since ca. 5 Ma. The magnitudes of the stresses obtained from the twinning analysis are unexpectedly low, and, to a first approximation, they are constant across the Zagros simply folded belt. This result supports an overall mechanism of buckling of the detached Zagros cover. Internal viscous-plastic processes help to relieve stress within this cover, thus lowering its seismogenic potential. Beyond these regional implications, this study underlines the potential of paleostress analyses in constraining both the tectonics and the mechanics of ancient and active foreland fold belts.

Keywords: Arabia-Eurasia collision, Zagros, calcite twinning, differential stresses, buckling.

INTRODUCTION

The Zagros belt results from the collision between Arabia and central Iran, beginning in Miocene times and continuing today (e.g., Stocklin, 1968). Global positioning system (GPS) studies suggest that about one-third of the Arabia-Eurasia shortening (~7 mm yr^{-1}) is taken up in the Zagros (Vernant et al., 2004) (Fig. 1A). The Zagros belt was built by folding of a 6–8-km-thick Phanerozoic cover detached from the Precambrian basement by the 1–2-km-thick early Cambrian Hormuz salt layer (Colman-Sadd, 1978). Earthquake focal depths (e.g., Talebian and Jackson, 2004), balanced cross sections (e.g., Blanc et al., 2003), and critical wedge modeling (Mouthereau et al., 2006) indicate that the basement is also involved in the collisional shortening.

Current understanding of the kinematics and structural evolution of fold-and-thrust belts has greatly benefited from the analyses of small-scale stress-strain indicators such as calcite twins (e.g., Ferrill and Groshong, 1993; Craddock and van der Pluijm, 1999). However, to date, only a few studies have attempted to define both the orientations and the magnitudes of the stresses across an active fold belt for which the plate kinematics setting and the seismotectonic stress are well constrained (e.g., Taiwan: Lacombe, 2001). In addition, apart from work in the Jura (France) (Becker, 2000), there is a paucity of available information on the stress field above and below the décollement in salt-based fold belts like the Zagros. In this study, we investigate the late Neogene stress pattern across the Zagros belt and in the southern Iranian Plateau, i.e., on both sides of the inactive Arabia–central Iran suture, by carrying out a stress inversion of calcite twin data. Special attention is paid to the timing of the twinning strain relative to fold-and-thrust belt development. By comparing stress patterns in both the detached cover and the basement, we provide further constraints on the way Arabia-Eurasia convergence has been accommodated within the Zagros belt.

GEOLOGICAL SETTING

The Iranian Plateau has a long tectonic history, starting in Paleozoic times and ending in the Late Cretaceous–Paleocene with the accretion of the Sanandaj-Sirjan zone (Fig. 1B). The Miocene marine Qom limestones unconformably overlie the older geological units; they were deposited before the plateau was uplifted to its present-day elevation in response to the collision with Arabia. In the Zagros belt, the High Zagros hinterland domain has been thrust up onto the simply folded belt (Figs. 1B and 2). The late Tertiary evolution of the Zagros foreland basin was marked by deposition of Oligocene-Miocene shallow-marine Asmari-Jahrom limestones and of the Miocene synorogenic clastic sequence of the Gachsaran, Mishan, and Agha Jari Formations. The growth strata of the upper Agha Jari Formation indicate that folding occurred ca. 7–3 Ma across the entire simply folded belt. In the Pliocene–Pleistocene, the Bakhtyari conglomerates were deposited unconformably above the folded strata. Basement seismicity, active faulting and fold amplification near the mountain front, and GPS deformation patterns (Fig. 1C) indicate that the collisional shortening is still ongoing.

CALCITE-TWIN ANALYSIS METHOD

Mechanical e-twinning readily occurs in calcite deformed at low temperature. Calcite twinning requires a low critical resolved shear stress of 10 ± 4 MPa, which depends on grain size (e.g., Rowe and Rutter, 1990) and internal twinning strain and has only a small sensitivity to temperature, strain rate, and confining pressure. Since calcite twin data are basically strain data, Groshong's (1972) strain gauge technique is commonly used to produce a strain ellipsoid, while differential stresses are given by Jamison and Spang's (1976) technique. However, in order to allow comparison with seismotectonic stresses, we use Etchecopar's method of inverting calcite twin data (Etchecopar, 1984; see details in Lacombe, 2001), which simultaneously computes stress orientations and differential stresses. This method applies to small twinning strain that can be approximated by coaxial conditions, so orientation of twinning strain can be correlated with paleostress orientation (Burkhard, 1993). The inversion process takes into account both the twinned and the untwinned planes, the latter of which are those of the potential e-twin planes that never experienced a resolved shear stress value of sufficient magnitude to cause twinning. The inverse problem consists of finding the stress tensor that best fits the distribution of twinned and untwinned planes. The orientations of the three principal stresses $\sigma1$, $\sigma2$, and $\sigma3$ are calculated, together with the Φ ratio [$\Phi = (\sigma2 - \sigma3)/(\sigma1 - \sigma3)$] and the peak differential stresses ($\sigma1 - \sigma3$). If more than ~30% twinned planes in a sample are not explained by a unique stress tensor, the inversion process is repeated with the uncorrelated twinned planes and the whole set of untwinned planes. Where polyphase deformation has occurred, this process provides an efficient way of separating superimposed twinning events.

MICROSTRUCTURAL SETTING AND STRATEGY OF SAMPLING

Sampling was carried out away from fault zones, mainly in the straight limbs of the major folds (Fig. 1B), where road cuts provide fresh exposures. Fifteen samples were collected in the Zagros belt, and three samples were collected in the southern Iranian Plateau. The sampled rocks

Geology, March 2007; v. 35; no. 3; p. 263–266; doi: 10.1130/G23173A.1; 2 figures; 1 table.

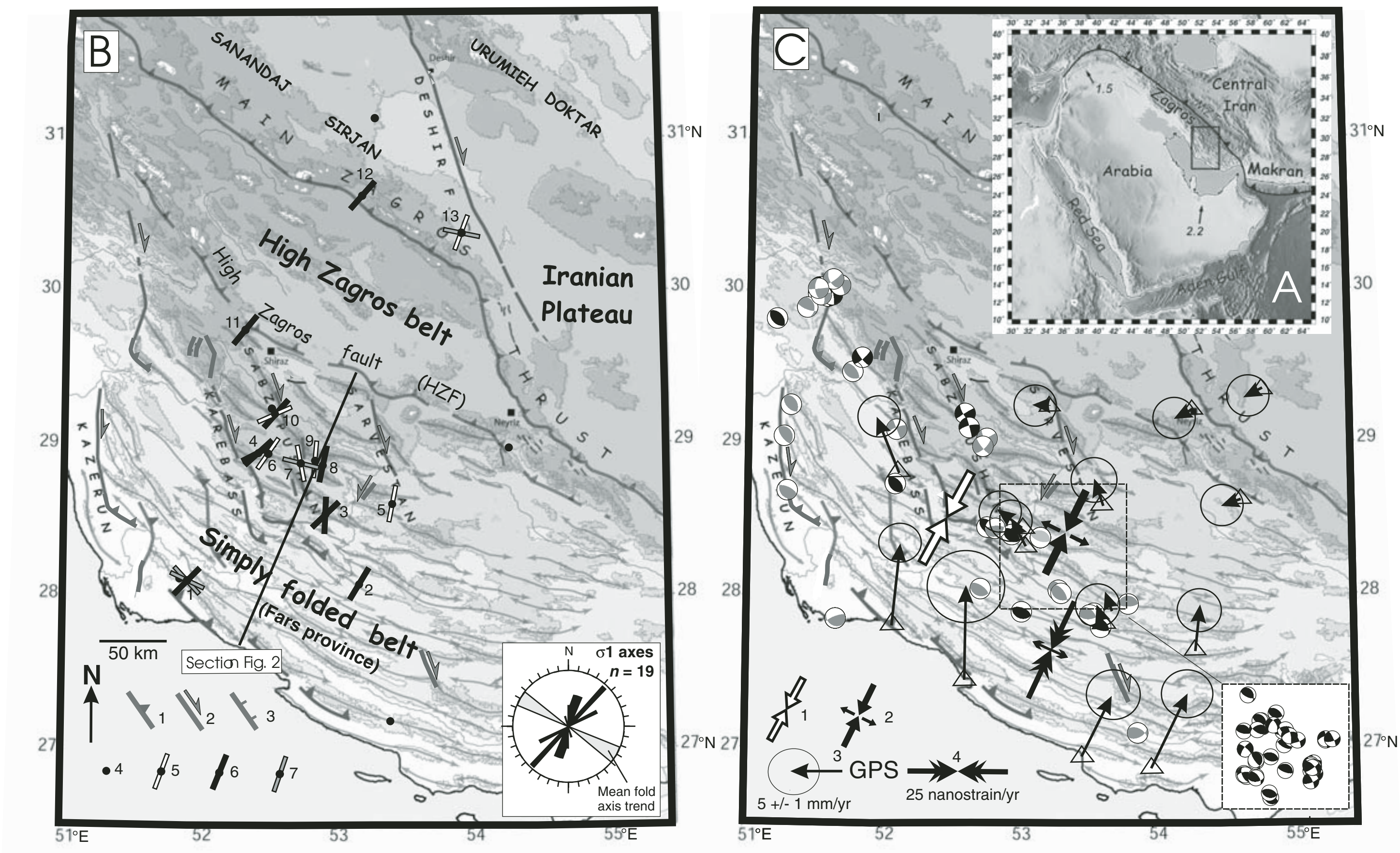

Figure 1. A: Geodynamic setting of Arabia-Eurasia collision. Global positioning system (GPS) convergence vectors after Vernant et al. (2004). Velocities in cm/yr. B: Schematic structural map of Fars. Topographic contours (GTOPO30) and shading every 500 m. Main anticline axes are reported. 1—thrust; 2—strike-slip fault; 3—normal fault; 4—sites of sampling; 5 and 6—main compressional trend, strike-slip and reverse regimes, respectively; 7—belt-parallel extensional trend. Insert: Rose diagram of local σ1 trends. C: Focal mechanisms of moderate earthquakes (Talebian and Jackson, 2004) and microearthquakes (Tatar et al., 2004: insert), and GPS velocity field. 1 and 2—Current compressional trend derived from moderate earthquakes and microearthquakes, respectively (Lacombe et al., 2006). 3 and 4—GPS velocity field relative to central Iran and related strain rate, respectively (Walpersdorf et al., 2006).

are Late Cretaceous to middle Miocene in age. In most sites, minor faults and veins were observed. Pervasive pressure solution is evidenced by widespread stylolitization. Most veins in fold limbs are perpendicular to the bedding and have a strike either perpendicular or parallel to bedding strike; they likely formed coeval with fold growth during the Miocene–Pliocene. Twinned calcite was examined within the coarse-grained matrix in host rocks and/or within veins. Thin twins are dominant in our samples, indicating that calcite deformed below 200 °C (Ferrill, 1998). Twinning strain never exceeds 3%–4%. Our reconstructions therefore meet the assumptions of low finite strain and stress homogeneity required to derive the regional paleostresses of interest. Data collected from both matrix and vein in the same sample, or from mutually perpendicular veins, were analyzed separately and/or together to check for consistency and to constrain the relative timing of separate twinning events. Five samples were discarded because the grain size was too small or because they contained gypsum. Sixteen independent and representative stress analyses were generated (Table 1).

RESULTS

Orientations of Tectonic Stresses across the Zagros Belt (Fars)

The predominant compressional trend is nearly constant throughout the simply folded belt and the southern Iranian Plateau: it is oriented 025° (±15°), at high angle to the folds (Fig. 1B). In Andersonian terms, the stress regime is either truly compressional (vertical σ3 axis) or strike-slip (vertical σ2 axis), without any obvious regional variation in the results. The computed Φ ratios are often lower than 0.3–0.4 (Table 1), indicating that the values of the principal stresses σ2 and σ3 are nearly similar and hence that σ2 and σ3 axes could easily switch between being vertical and horizontal. Some samples also reveal a component of fold-parallel extension.

Age of Twinning Strain and Chronology Relative to Folding

Sampling in fold limbs constrains the chronology of twinning relative to the folding. For example, one might expect that if a twin set formed during the initial phase of layer-parallel shortening and was subsequently tilted with the strata during folding, then one axis of the stress tensor should be perpendicular to bedding and the other two would lie within the bedding plane. In contrast, late or postfolding twin sets should yield two horizontal stress axes and one vertical one (assuming that the regional stress field is in that orientation), within a range of 10° uncertainty. Inspection of the attitude of the stress axes with respect to bedding indicates that in both veins and host rocks, twinning predominantly records the stresses during late-stage fold tightening. Only three samples yield an early, layer-parallel (or possibly a synfolding) NE-directed compression. This study complements earlier work concerned with the relative timing of calcite twinning strain and fold-belt development (e.g., Harris and van der Pluijm, 1998) in that it emphasizes that twinning may record not just layer-parallel shortening, as is often stated or assumed (e.g., Craddock and van der Pluijm, 1999), but also late-stage fold tightening strain.

The age of the sampled rocks (Table 1) together with the timing of twinning and vein formation relative to folding indicate that twinning strain is mainly Miocene–Pliocene in age, or even younger. There is no evidence of any distinct Paleogene tectonic stresses in the older samples.

Magnitudes of Tectonic Stresses across the Zagros Belt and the Southern Iranian Plateau

To a first approximation, peak differential stresses during the 025° compression are low and nearly constant across the simply folded belt and the southern Iranian Plateau. Except for sample 11 adjacent to the High Zagros fault, most values are within a narrow range of 40 ± 15 MPa (Fig. 2).

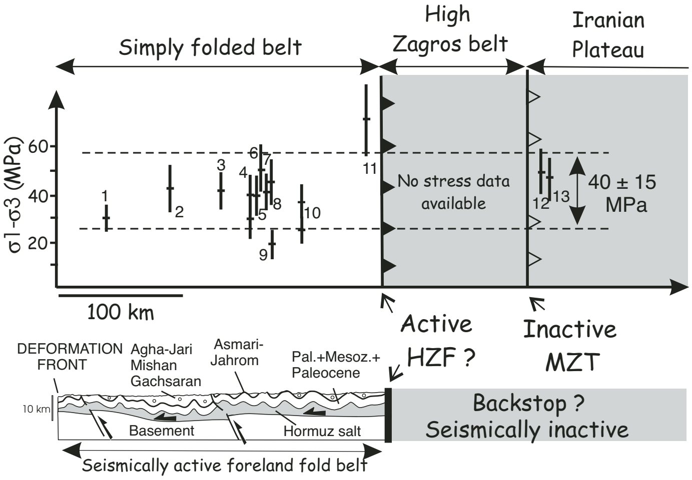

Figure 2. Schematic geological cross section across Zagros simply folded belt and differential stress magnitudes in simply folded belt and southern Iranian Plateau (sites projected perpendicularly on transect of Fig. 1B). Numbers 1 to 13 refer to sites of sampling reported on Fig.1B. HZF—High Zagros fault, MZT—main Zagros thrust.

DISCUSSION

Late Neogene Stress Regime in the Zagros (Fars) and the Accommodation of the Arabia-Eurasia Convergence

The 025° compressional trend (Fig. 1B) agrees well with the current compressional trend revealed by inversion of the focal mechanisms of basement (and of few cover) earthquakes (Lacombe et al., 2006; Fig. 1C); it is also consistent with the geodetic shortening axis (Walpersdorf et al., 2006; Fig. 1C). This implies that the regional compression was approximately constant in space (across the Zagros collision zone) and time (during the late Neogene), in agreement with the stability of the Arabia-Eurasia convergence over the last 25 m.y. (McQuarrie et al., 2003). Our study demonstrates that a reverse-strike-slip stress regime prevailed in the Zagros during the late Neogene, both in the cover and the basement. This regime accounts for the kinematics of the major faults (Fig. 1B) (Berberian, 1995) and for the combination of strike-slip and thrust-type focal mechanisms of earthquakes, whatever their magnitudes and focal depths (Fig. 1C).

Both the stress field and the deformation pattern therefore have remained unchanged in the Zagros at least since ca. 5 Ma, a key period that likely corresponds to a major reorganization of the entire Arabia-Eurasia collision (e.g., Allen et al., 2004). Long-term calcite twin data and short-term earthquake and GPS data are consistent with the idea that in the Fars, the Arabia-Eurasia convergence has been accommodated by both across-strike shortening and strike-slip faulting throughout the cover and the basement, with a minor belt-parallel extension component.

It is worth noting that the Hormuz décollement poorly decouples principal stress orientations in the cover and the basement, although the GPS strain rate is much higher than the seismic strain rate (Masson et al., 2005). The present comparison of the stress field above and below the décollement of the still-active Zagros belt complements earlier work in the Jura belt (Becker, 2000) and yields a potential analogue for ancient, salt-based fold belts.

TABLE 1. RESULTS OF STRESS TENSOR DETERMINATION BASED ON CALCITE TWIN DATA

Site	Name/Age of Sampled Formation	Host or vein or both	Strike (dip) of bedding (°)	Strike (dip) of vein from which measurements were taken (°)	Trend (plunge) of principal stress Axes (°)			Ratio between differential stresses (Φ)	Type of stress regime	Total number of data T/UT	Number of data consistent with the tensor T/UT	Estimated peak (σ1-σ3) value for pre/post folding N025° comp.
					σ1	σ2	σ3					
Zagros Simply Folded Belt (Arabian plate)												
1	Gurpi/Late Cretaceous	vein	095 (30N)	030 (81E)	214 (66)	033 (24)	123 (00)	0.40	E	48/15	28/15	—
		vein		110 (27N)	043 (32)*	301 (19)*	185 (52)*	0.50	R	75/27	37/23	30 (±6)
		vein			310 (89)	051 (00)	141 (01)	0.15	E	38/27	11/24	—
2	Gurpi/Late Cretaceous	vein	117 (12S)	030 (85E)	024 (09)	290 (26)	133 (62)	0.16	R/SS	145/71	58/66	46 (±11)
3	Mishan/Middle Miocene	vein	110 (70S)	105 (23N)	001 (03)	270 (31)	096 (59)	0.23	R	122/46	61/39	40 (±8)
		vein			232 (36)*	114 (33)*	354 (37)*	0.75	R	63/44	25/36	—
4	Asmari-Jahrom/Oligo-Miocene	host	~horizontal		226 (18)	320 (12)	082 (68)	0.40	R	113/72	43/68	40 (±10)
		host			062 (17)	160 (23)	300 (61)	0.40	R	168/72	68/65	28 (±6)
5	Mishan/Middle Miocene	vein	108 (16N)	177 (85W)	009 (12)	159 (76)	278 (07)	0.66	SS	171/66	76/58	39 (±8)
6	Gachsaran/Low.-Mid. Miocene	host	~horizontal		033 (11)	153 (69)	299 (18)	0.16	SS/R	131/43	78/37	51 (±11)
7	Mishan/Middle Miocene	host	024 (13W)		345 (11)	169 (79)	075 (01)	0.30	SS	119/52	54/44	41 (±10)
		host			039 (54)	181 (30)	282 (18)	0.30	E	68/50	28/43	—
8	Mishan/Middle Miocene	host	124 (76N)		010 (24)	277 (06)	174 (65)	0.40	R	177/66	71/62	45 (±11)
9	Mishan/Middle Miocene	host	085 (55N)		183 (10)	305 (71)	090 (15)	0.90	SS/E	51/40	20/37	20 (±4)
10	Asmari-Jahrom/Oligo-Miocene	vein	145 (66S)	Unknown	065 (28)	291 (53)	168 (23)	0.50	SS	96/61	37/50	37 (±8)
		vein			200 (54)*	067 (27)*	325 (22)*	0.19	R/SS	62/58	24/52	28 (±6)
		host			245 (01)	153 (60)	335 (29)	0.30	SS	19/18	10/18	25 (±5)
11	Pabdeh/Paleocene	host	100 (43N)		218 (12)	311 (10)	079 (74)	0.19	R/SS	80/28	40/27	71 (±13)
Iranian Plateau (Central Iran plate)												
12	Qom / Miocene	host	130 (30N)		040 (14)	134 (19)	275 (67)	0.70	R	229/44	80/39	51 (±12)
13	Qom / Miocene	vein	~horizontal	020 (85E)	193 (36)	347 (51)	093 (13)	0.20	SS	74/28	51/27	—
		host			039 (20)	173 (63)	302 (18)	0.10	SS/R	118/50	59/46	—
		both			199 (03)	300 (77)	109 (13)	0.50	SS	192/78	96/72	47 (±11)
		both			182 (77)	011 (13)	281 (02)	0.47	E	96/78	43/63	—

Note: As in Fig.1B, only the stress tensors related to the predominant compressional trend and to the belt-parallel extension are reported for clarity, while the stress tensors of local significance (e.g., extension at the hinge of anticlines or local stress permutations) are not. T/UT—Twinned/Untwinned planes. For stress regime: R—Reverse; SS—Strike-slip; E—Extensional.

*Pre-(syn?) folding (tilted) stress axes.

Evolution of Differential Stress Magnitudes across the Zagros Belt: Insights into Deformation Mechanisms of the Cover Sequence

Our differential stress estimates differ from previously reported stress values in fold belts, which are much higher (e.g., 90–150 MPa in the Idaho-Wyoming belt; Craddock and van der Pluijm, 1999) and show a strong decay across both the fold belt and the undeformed foreland (e.g., 100–20 MPa in the Sevier-Appalachian forelands; van der Pluijm et al., 1997). The relative homogeneity of differential stresses agrees with the homogeneously distributed shortening across the simply folded belt, where no deformation gradient toward the backstop is observed in contrast to classical fold-and-thrust wedges (Fig. 2). This supports buckling of the cover sequence over the weak Hormuz salt as the dominant regional mechanism of deformation. This interpretation differs from the thrust-related folding style commonly considered in previous studies (e.g., McQuarrie, 2004; Sherkati and Letouzey, 2004). The overall constant wavelength of folds, their nearly coeval development, and hence the first-order absence of clear propagation of deformation across the simply folded belt, and their rapid growth rates also support buckling of the cover (Mouthereau et al., 2006). Recent numerical models of buckling of a viscous (non-Newtonian)– elastic layer above a homogeneous viscous (Newtonian) matrix show that such a deformation mechanism is viable for the Zagros cover (Schmalholz et al., 2002).

In the Fars, seismicity is of low magnitude and occurs mainly in the basement, while the cover is almost devoid of large thrusts and mainly earthquake deficient. One possible explanation is the thickness of the seismogenic layer, which is too thin (10–14 km depth range; Tatar et al., 2004) to generate large earthquakes, which cannot propagate upward due to the salt layer. Our observations additionally suggest that the strata of the detached cover are buckling while internally deforming through diffusion mass transfer and calcite twinning. We argue that these viscous-plastic creep mechanisms, although unable to accommodate large strains, help to relieve stresses in the cover, keeping the stress level generally below the frictional yield required for large-scale faulting. This provides a renewed explanation for both the structural style and the low seismogenic potential of the Zagros cover.

CONCLUSIONS

Arabia-Eurasia collisional stresses have been consistently recorded by calcite twinning in the detached cover of the Zagros simply folded belt and in the southern Iranian Plateau. The late Neogene reverse-strike-slip stress regime with a 025° directed compression agrees with the current stress field derived from focal mechanisms of basement earthquakes. Calcite twinning paleopiezometry reveals an unexpected low-level and first-order homogeneity of differential stresses across the simply folded belt, which supports an overall mechanism of buckling of the cover sequence. This study highlights the potential of calcite twin analyses to yield a regionally representative simple picture of the collisional stress pattern consistent with plate kinematics, and to constrain the deformation mechanisms of the aseismic cover of an actively deforming fold belt.

ACKNOWLEDGMENTS

Field work was supported by the Middle East Basin Evolution program and the Geological Survey of Iran. A. Saïdi and S. Kargar are thanked for their friendly help during field trips. D. Stockli, D. Farris, S. Covey-Crump, and an anonymous reviewer are thanked for their constructive comments.

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Manuscript received 14 August 2006
Revised manuscript received 13 November 2006
Manuscript accepted 20 November 2006

Printed in USA