Metamorphic reworking of a high pressure–low temperature mélange along the Motagua fault, Guatemala: A record of Neocomian and Maastrichtian transpressional tectonics

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A B S T R A C T
The Guatemala suture zone is a major east–west left-lateral strike slip boundary that separates the North American and Caribbean plates in Guatemala. The Motagua fault, the central active strand of the suture zone, underwent two major collisional events within a system otherwise dominated by strike–slip motion. The first event is recorded by high-pressure/low temperature (HP/LT) eclogites and related rocks that occur within serpentinites both north and south of the Motagua fault. Lawsonite eclogites south of the fault are not significantly retrograded and give 40Ar/39Ar ages of 125–116 Ma and Sm–Nd mineral isochrons of 144–132 Ma. Eclogites north of the fault give similar Sm–Nd isochrons (131–126 Ma) but otherwise differ in that they are strongly overprinted by a lower pressure assemblage and, along with associated HP/LT rocks, give much younger 40Ar/39Ar ages of 88–55 Ma indicating a later amphibolite facies metamorphic event. We propose therefore that all serpentine hosted eclogites along the Motagua fault formed at essentially the same time in different parts of a laterally extensive Lower Cretaceous forearc subduction system, but subsequently underwent different histories. The southern assemblages were thrust southwards (present coordinates) immediately after HP metamorphism whereas the northern association was retrograded during a later collision that thrust it northward at ca. 70 Ma. They were subsequently juxtaposed opposite each other by major strike slip motion. This model implies that the HP rocks on opposing sides of the Motagua fault evolved along a plate boundary that underwent both dip slip and strike slip motion throughout the Late Cretaceous as a result of oblique convergence. The juxtaposition of a convergent and strike slip system means that HP/LT rocks within serpentinites can be found at depth along much of the modern Guatemala suture zone and its eastward extension into the northern Caribbean. Both sets of assemblages were exhumed relatively recently by the uplift of mountain ranges on both sides of the fault caused by movement along a restraining bend. Recent exhumation explains the apparently lack of offset of surface outcrops along a major strike slip fault.

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1. Introduction

Serpentinite belts exposed on land and containing high pressure/low temperature (HP/LT) metamorphic rocks were interpreted originally as occupying the suture zone between two tectonostratigraphic terranes (Hess, 1965; Maekawa et al., 2004) and to reflect the closure of ocean basins as part of the Wilson Cycle (Wilson, 1960). Most sutures were assumed to be perpendicular to convergent directions since major dip slip motion is required to form HP rocks. However, many modern compressional terrane boundaries are not perpendicular to convergent directions, but oblique and so older serpentinite belts may also reflect oblique convergence at the time they formed. We propose that two HP/LT bearing serpentinite belts that occur parallel to each other across the Motagua fault in Guatemala, Central America are examples of a suture that evolved through oblique convergence. 40Ar/39Ar ages from HP/LT rocks within the serpentinites (Harlow et al., 2004) give Early Cretaceous age south of the fault...
and Late Cretaceous age north of the fault, which indicate that the exposed serpentinites were juxtaposed by strike slip movement along the Motagua fault. Here we present Sm–Nd geochronology from eclogites that show the original recrystallization of the eclogites on both sides occurred at the same time during the Early Cretaceous, which indicates that the two belts shared an early history of convergence and subduction. A common early history, but a different subsequent history involving both large magnitude strike slip and dip slip movement suggests that the Motagua fault is part of a boundary that has undergone oblique convergence since the early Cretaceous.

2. Regional setting

The Guatemala suture zone is presently part of a major left lateral strike slip boundary between the North American plate to the north (locally known as the Maya block) and Caribbean plate (locally, the Chortís block) to the south (Fig. 1). The present displacement rate along the Guatemala suture zone is estimated at about 21 mm/year (DeMets et al., 2007) and the total displacement since the Early Cretaceous, which indicates that the two belts shared an early history of convergence and subduction. A common early history, but a different subsequent history involving both large magnitude strike slip and dip slip movement suggests that the Motagua fault is part of a boundary that has undergone oblique convergence since the early Cretaceous.

Fig. 1. Generalized map of the Motagua Valley of Guatemala showing distribution of major strike slip faults, thrust faults (lines with barbs), serpentinites, and eclogite sample localities from Carrizal Grande (A), Río Belejía (B), and Quebrada de los Pescaditos (C). Adapted from Francis et al. (submitted for publication). Inset: Tectonic map of the northwestern Caribbean and location of the study area (rectangle). Faults are P — Polochic, M — Motagua, and J — Jocotán. Together they comprise the Guatemala suture zone.
However the results that will be presented below indicate that both suites of HP/LT rocks formed at the same time and so the juxtaposition model would require that two HP/LT terranes of identical age were juxtaposed by large-scale strike slip displacements. We propose a geometry that can explain this apparent conundrum further along in this manuscript.

3. Serpentinites

All serpentinites and serpentinite mélanges are tectonic slices bounded by thrust faults or by steep E–W strike slip faults (Francis, 2005). The thrust faults have been interpreted as “flower structures” (Beccaluva et al., 1995; Giunta et al., 2002), but the cross-cutting strike slip faults and dip slip faults discussed above suggest that they are not contemporaneous with Tertiary strike slip motion along the Motagua ault (McBirney, 1963; McBirney et al., 1967; Donnelly et al., 1990; Francis, 2005; Tsujimori et al., 2006a; Francis et al., submitted for publication). The serpentinites that contain HP/LT blocks occur immediately north and south of the Motagua fault and are considered components of the El Tambor complex. Radiolaria from cherts within the El Tambor have a Late Jurassic age (Chiari et al., 2002). The serpentinites south of the Motagua fault are presumably of similar age, but their relationship to the El Tambor complex is less clear. Lower temperature chrysoilite-lizardite-bearing serpentinites occur over a wider area in the Guatemala suture zone ranging from selvages in the El Tambor formation just south of the Motagua fault to the Juan de Paz serpentinite (Muller, 1979) just north of the Motagua fault and the extensive Santa Cruz and Baja Verapaz ultramafic complexes further north of the Motagua fault. These serpentinites contain no HP/LT blocks though some contain some amphibolites. They are assigned an Early Cretaceous age based on fossils from the Santa Cruz serpentinites (Rosenfeld, 1981). It appears that low temperature serpentines and associated ophiolitic rocks north of the Motagua fault, particularly those adjacent to the Polochic fault, are younger (Early Cretaceous) than the amphibolite serpentinites of the El Tambor in the immediate vicinity of the fault (Late Jurassic).

4. Eclogites and associated rocks

Eclogite sample localities are shown in Fig. 1. Eclogites, jadeitites, albities, and other HP/LT rocks are usually found as boulders in the rivers that drain antigorite-bearing serpentinite bodies (Fig. 1) and flow into the Motagua River. Eclogites south of the Motagua fault were collected from river drainages below the village of Carrizal Grande. Eclogite north of the Motagua fault were collected along Quebrada de Los Pescaditos about 5 km south of San Buenaventura and from Rio Belejeyá about 5 km west of Granados. Detailed petrography of these samples is presented in Appendix A or for samples ACG-01 and ACG-17, by Tsujimori et al. (2006a,b).

Trace and major element geochemistry and Li, Sr, and Nd isotopic patterns of eclogites, peridotites, serpentinites, and jadeitites indicate that the eclogite protoliths from both sides of the fault originated at a mid-ocean ridge and subsequently were metamorphosed and metasomatized in a mantle wedge above a subduction zone (Beccaluva et al., 1995; Sorensen et al., 2006; Simons et al., submitted for publication). Petrographic and thermobarometric studies of the eclogite mineral assemblages indicate they are of the “blueschist” or “Franciscan” type, typical of subduction complexes (Ernst, 1988). Eclogites south of the Motagua fault range from pristine to mildly retrograded. They contain garnet + omphacite (± jadeite) + lawsonite (several generations) + rutile ± quartz ± phengite ± apatite ± titanite ± chlorite ± sulfide and show prograde metamorphic textures. P–T equilibration conditions are estimated at 300–480 °C and 1.1 to 2.6 GPa (Tsujimori et al., 2006a). Retrograde features, where developed, occur as reversely zoned garnet rims associated with secondary omphacite + lawsonite + titanite ± phengite ± glaucophane ± albite + quartz ± apatite ± sulfide assemblages estimated to have formed at P ≈ 1.4 GPa and T ≈ 400 °C (Tsujimori et al., 2005, 2006a). An even younger blueschist overprint consists of glaucophane + lawsonite + chlorite + titanite + quartz ± phengite. Tsujimori et al. (2006a) estimate that the P–T trajectory of these assemblages lies along a geotherm of ≈ 5 °C/km, comparable to the coldest geotherms from subduction zones worldwide.

The metabasites north of the Motagua fault zone are mostly garnet amphibolites that contain clinoczoisite and pargasite–hornblende amphibole with rare omphacite and abundant clinoczoisite and amphibole inclusions in garnet. The rare omphacite inclusions suggest initial eclogite-facies crystallization. The clinoczoisite and amphibole inclusions suggest a later high pressure amphibolite facies metamorphism with a garnet crystallization temperature of 500–600 °C at a pressure of ~1.2–1.5 GPa (Harlow et al., 2008). An even later assemblage of clinoczoisite + albite + quartz + actinolitic amphibole indicates a subsequent greenschist overprint. True eclogite was found by us recently in the western reaches of the mélangé zone north of the Motagua fault (Fig. 1) though they contain primary clinoczoisite instead of lawsonite. The primary assemblage of garnet + omphacite, + phengitic muscovite + rutile + clinoczoisite, + glaucophanic to pargasitic amphibole ± quartz suggests a higher temperature (500–600 °C) of formation than the southern eclogites. This eclogite assemblage is moderately to strongly overprinted by a clinoczoisite + actinolitic amphibole ± paragonite ± biotite + titanite + albite + quartz ± apatite ± sulfides assemblage suggesting subsequent recrystallization at comparable temperatures (T ≈ 550–600 °C, Tsujimori et al., 2004; Harlow et al., 2008). The secondary assemblages were initially interpreted as retrograde assemblages formed during decreasing pressure and temperature conditions (Harlow et al., 2004), but are now believed to have formed during a later metamorphism. Thus the northern eclogites underwent a later greenschist to amphibolite facies recrystallization event whereas the southern eclogites did not. These distinct P–T histories are supported by 40Ar/39Ar phengite and/or amphibole dates with southern eclogites giving ages of 125–116 Ma while northern eclogites and associated rocks give ages of 88–55 Ma (Harlow et al., 2004).

5. Results

Sm–Nd analytical procedures are described in Appendix B and the data are presented and discussed in detail in Appendix C. Six of the most meaningful results (out of eight samples analyzed) are plotted on Fig. 2. The Sm–Nd ages considered reliable have low error (low MSWD), contain more than one garnet analysis, or an analysis of an additional phase besides garnet and clinopyroxene (i.e., phengite, apatite). The most precise ages from south of the Motagua fault are the 132.1 ± 6.5 Ma age from MVE02–6–3 (Fig. 2A) and the 143.9 ± 9 Ma from ACG-03 (Fig. 2B). The latter age becomes 140.6 ± 3.4 Ma (MSWD = 0.54) if the first garnet analysis (64 ratios, low intensity) is excluded. This age is considered relatively robust, despite the lack of a whole rock analysis because three phases were analyzed. The results from sample MVE02–14–6 are more equivocal. Five garnet separates were analyzed with each analysis plotting at a different location (Fig. 2C). The resultant scatterchron (MSWD = 83) age of 133 ± 14 Ma is obviously an average. The final two garnet analyses attempted to separate and date the darker garnet core from the lighter rim by color. However the pink rim (+2 clinopyroxenes and 2 whole rock samples) gives an older age (130.2 ± 1.6 Ma) than the redder core (123.8 ± 1.9 Ma) and the oldest age is obtained from the second analysis of a bulk garnet sample (144.7 ± 1.6 Ma). The scattered ages are provisionally interpreted as reflecting the span of garnet growth, suggesting this growth began at ca. 145 Ma and ended roughly twenty million years later at ca. 124 Ma.
The ages considered reliable from north of the fault are from two relatively weakly overprinted eclogites. They are 130.7 ± 6.3 Ma from MVE04-44-7 from Quebrada de Los Pescaditos (Fig. 2D) and the 125.0 ± 7.8 Ma age from MVE06-5-3 from Río Belejeyá (Fig. 2E). The 125.0 ± 7.8 Ma (MSWD = 1.3) age from Río Belejeyá (Fig. 2E) is considered particularly robust. Analysis of the quartz- and albiterich fraction yielded a point that occupies an intermediate position on the mineral isochron diagram, something that is rare in eclogite analyses and gives confidence in the isochron. The fraction probably contained hydroxylapatite based on its abundance in thin section (Appendix A).

Sample MVE04-44-6 from Quebrada de Los Pescaditos generated an age of 166 ± 22 Ma (Fig. 2F). The scatter (MSWD = 6.6) is produced by the positions of two clinopyroxenes above and two whole rocks below the best-fit line. We suspect fluid-introduced crustal Nd lowered the \(^{143}\text{Nd}/^{144}\text{Nd}\) ratios of the whole rock and, to a lesser extent, the clinopyroxenes, thereby producing scatter and steepening of the best-fit line to produce an unrealistic old age.

The four most credible ages are essentially Early Cretaceous (Neocomian) and give an average of 132 Ma and a weighted average of 136 ± 11 Ma. However, all ages probably "average" a period of eclogite-facies recrystallization that, based on the age span for garnets from MVE02-14-6 (Fig. 2C), may have lasted 20 million years or more. The ages appropriately post-date the formation of the youngest ocean floor lithology found south of the Motagua fault, the Late Jurassic El Tambor ophiolite (Chiari et al., 2002), suggesting similar age crust was subducted to form the eclogites. The Sm–Nd ages are also consistent with the \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of 116–125 Ma determined from the southern eclogites, but are much older than the \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of 88–55 Ma from eclogites and related rocks north of the fault (Harlow et al., 2004).

6. Discussion

6.1. An apparent conundrum resolved

The Motagua fault is active today based on offset terraces and the 1976 magnitude 7.5 earthquake (Schwartz et al., 1979). Nevertheless, Donnelly et al. (1990) estimated the total displacement along the Motagua fault as only 20 km appearing to create a conundrum of why large scale strike slip motion along the Guatemala suture zone (≥1100 km according to Rosencrantz and Mann, 1991) did not send these HP/LT rocks hundreds of kilometers in opposite directions. The solution may be that the Motagua fault became the active strand of the Guatemala suture zone relatively recently, consistent with recent plate tectonic reconstructions that show the Motagua fault was not active until the Early Pliocene, 4 Ma ago, and that most of the Post-Cretaceous motion along the present Guatemala suture zone was carried by the Polochic and Jocotán Faults (Rogers and Mann, 2007). If the estimated ≈21 mm/yr displacement rate of the Guatemala suture zone occurred solely along the Motagua fault for only the last 4 Ma, the total displacement of ≈84 km is greater than the apparent displacement of 20 km estimated by Donnelly et al. (1990), but within the displacements inferred from the outcrop distribution in Fig. 1.

However, as already noted, stretching lineations in mylonites are parallel to the Motagua fault suggesting significant long-term left-lateral displacement under metamorphic conditions (McBirney, 1963; McBirney et al., 1967; Donnelly et al., 1990; Francis, 2005; Tsujimori et al., 2006a,b; Francis et al., submitted for publication). In addition, the Motagua fault is associated with trans-extensional basins containing the Eocene or older beds of the Subinal Formation suggesting left-lateral movement for at least 30–40 Ma. The most important observation,
however, is that the P–T–t histories of the eclogites on opposite sides of the fault are significantly different, despite forming initially more or less at the same time. The lower Cretaceous history differs in that the southern eclogites record lawsonite eclogite formation along a very cold subduction trajectory (−5 °C/km) whereas the northern eclogites record a warmer lawsonite-free trajectory (−7 °C/km). But the most striking difference is the ca. 70 Ma greenschist/amphibolite-facies overprint recorded by the northern eclogites, but not the southern eclogites. These observations argue that eclogites from different initial locations were indeed juxtaposed by large-scale strike slip motion as originally suggested by Harlow et al. (2004). But the question remains as to why HP/LT terranes, initially far apart and with different histories, would have a common Early Cretaceous origin.

This dilemma is resolved if the Guatemala suture zone, and the Motagua fault in particular, follow a Lower Cretaceous convergent suture for a large portion of its length. The implication of this geometry is that eclogite-bearing serpentinites could occur at depth along much of the suture zone, but the terranes on opposite sides would have undergone different histories as a result of different initial positions in the suture followed by large lateral displacements. This geometry is not unique. For example, Cordilleran terranes, including convergent system such as the Franciscan Formation, underwent large-scale strike slip displacements (1000–3000 km) parallel to the western margin of North America throughout Late Jurassic, Cretaceous and Tertiary time (e.g., Avé Lallemant and Oldow, 1988; Umhoefer and Dorsey, 1997). Thus the terranes on opposite sides of the Motagua fault could have been originally from the same Lower Cretaceous subduction system, but were positioned far apart along strike in areas where one terrane underwent a subsequent Late Cretaceous event whereas the other did not.

6.2. Recent exhumation

An additional consequence of this geometry is that HP/LT terranes could be exposed on either side or both sides of the fault at any time at any place along the length of the Motagua fault given the operation of a suitable exhumation mechanism. The serpentinites and serpentinite mélanges shown on Fig. 1 occur amidst two ranges; the Sierra de Las Minas range to the north, uplifted to about 3000 m above the Motagua Valley and an unnamed range to the south that is uplifted by the northern eclogites, but not the southern eclogites. These observations argue that eclogites from different initial locations were indeed juxtaposed by large-scale strike slip motion as originally suggested by Harlow et al. (2004). But the question remains as to why HP/LT terranes, initially far apart and with different histories, would have a common Early Cretaceous origin.

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6.3. A strike slip/convergent tectonic model

There is strong evidence that the Chortís block originated from the west coast of Mexico and was translated towards the southeast along left lateral strike slip faults (Pindell, 1994; Mann, 2007; Pindell and Kennan, in press). Yet, the presence and metamorphic ages of HP/LT eclogites within serpentinites of the Motagua fault require two convergent events as well; Early Cretaceous subduction of the Paleo-Pacific beneath western Mexico followed roughly 60 my later by a collision of the Maya block with another terrane. Thus, any tectonic model for the evolution of these rocks requires synchronous or alternating strike slip motion and convergence. We propose a synchronous model where oblique convergence of the Farallon plate with western Mexico resulted in the formation of both a left-lateral strike slip system (the Paleo-Motagua fault zone) parallel to the plate boundary and a spatially coincident subduction system with motion normal to the plate boundary (Fitch, 1972; Avé Lallemant and Guth, 1990). Thus the event that initially crystallized the HP/LT eclogites of the Motagua fault (Fig. 3A) during the Early Cretaceous involved the subduction of the Farallon plate beneath western Mexico, as shown in Fig. 3A, or possibly a terrane outboard of Mexico. A discrete collision between the Chortís block and western Mexico is not required and portions of the Farallon oceanic crust may have survived locally along strike. The Upper Jurassic El Tambor ophiolite complex represents obducted fragments of the Farallon plate, whereas the HP/LT eclogites represent deeply subducted fragments of the Farallon plate that underwent metamorphism typical of “Franciscan”-type eclogites as they mixed with serpentinites created by the aqueous metasomatism of the mantle wedge above the subduction zone (Fig. 3A). The different Early Cretaceous P–T gradients of the northern versus southern eclogites suggest that they were generated in different places within the subduction complex and therefore underwent different P–T trajectories (Gerya et al., 2002; Gorczyk et al., 2007). A subduction complex can be active for many tens of millions of years explaining, the >20 million year interval of eclogite growth inferred from some of the Sm–Nd dates presented in Fig. 2. The P–T and chemical history within an accretionary prism can be quite complex as the eclogite protoliths are churned to different levels below the mantle wedge and as fluids of different compositions flux through at different times (Krebs et al., 2008).

A portion of this accretionary prism, with its cargo of serpentinites, eclogites, and other HP rocks, was thrust over the leading edge of the Chortís block (Fig. 3A) and isolated from subsequent convergent tectonics. The northward dip of thrust faults on the Chortís block is consistent with this model (Fig. 1). The apparent paucity of deep sea lithologies normally associated with accretionary prisms may require a system relatively starved of sediments, similar to those that occur today west of the Andes of South America. Alternatively, much of the accretionary prism may have been subducted (e.g., von Huene et al., 2004; Scholl and von Huene, 2007).

Subsequently, new oceanic crust was generated between the Chortís block and western Mexico as a result of rotation and left lateral trans-
Martens et al., 2009). These ages overlap the Ar–Ar ages of 88–55 Ma from eclogites within the northern block serpentinites. It seems inescapable that the synchronous subduction of the Chuacús, the formation of HP/HT eclogites within the Chuacús, and the thermal event that reset Ar–Ar ages and retrograded the HP/HT assemblages within serpentinites north of the fault were linked. We suggest that fragments of the Mid to Late Cretaceous seafloor (i.e., the Santa Cruz, Juan de Paz, and Baja Vera Paz ophiolites) of the basin that had separated the Chortís and Maya blocks as well as fragments of whatever portions remained of the Farallon plate were obducted onto the Maya block as the Chuacús complex began to underthrust the southern block (Fig. 3B). The southward dip of thrust faults north of the Motagua fault is consistent with this model. The leading edge of the eclogite-bearing Lower Cretaceous accretionary prism was obducted as well. As convergence continued another portion of the Lower Cretaceous HP/LT serpentinite mélange assemblages was re-subducted resulting in the greenschist/amphibolite facies re-metamorphism of the HP/LT eclogites at ca. 70 Ma (Fig. 3B) while the underlying Chuacús complex subducted to even deeper levels to form HP/HT eclogites.

7. Conclusions

High pressure/low temperature (HP/LT) eclogites within antigorite-bearing serpentinite crop out north and south of the Motagua fault, a major strand of the Guatemala suture zone that forms the boundary between the North American and Caribbean plates. The northern association differs from the southern association in petrography, P–T conditions of formation, degree of retrogression, and 40Ar/39Ar ages. However, Sm–Nd mineral isochrons from eclogites show that the initial metamorphism that created the eclogites in both terranes occurred at the same time, at ca. 140–120 Ma, probably within the same accretionary system. The Early Cretaceous exhumation of the HP/LT eclogites and associated rocks south of the Motagua fault caused them to be largely unaffected by later events. Those north of the fault, however, were subjected to a subsequent oblique collision at ~70 Ma. The disparity between P–T records on opposite sides of the fault suggest that the two terranes were separated from each other by a significant lateral distance along the Motagua fault during the Late Cretaceous collision. Their present juxtaposition across a strike slip system means that their positioning occurred since the last oblique collision at ~70 Ma. It was most likely produced by left-lateral displacement of the present Chortís block, with its Lower Cretaceous collisional remnants, to its current position adjacent to the Chuacús, although the amount of displacement is unknown. The apparent lack of strike slip displacement based on present surface exposure is therefore deceptive. Serpentinite hosting HP/LT rocks probably occur at depth along much of the modern Guatemala suture zone, but with different P–T histories on opposite sides of the Motagua fault. The two presently exposed terranes were exhumed opposite each other by recent uplift resulting from strike slip motion along a restraining bend. Thus the two terranes were juxtaposed at depth by large-scale strike slip motion along the Motagua fault, but their exposure across the fault is due to recent vertical movement and erosion. In summary, our data show that what appears to be a simple terrane boundary defined by serpentinites with HP/LT blocks is not a record of simple continental accretion but rather a more complex record of metamorphic reworking during two oblique collisional events as a
result of the oblique convergence of the Farallon and North American plates. The HP/LT metamorphic rocks in the Guatemala suture zone are like beads in a bracelet; they are not only displaced over great distances, but they are also stretched. Rocks similar to the Guatemalan HP/LT rocks occur throughout the Caribbean–North American plate boundary; and can be found eastward to Cuba and the Dominican Republic. The east–west trending southern Caribbean South American plate boundary is similarly decorated with HP/LT rocks; they have been found from Margarita Island (Venezuela) to Colombia. The oblique evolution model described here for eastern Guatemala appears to be a ubiquitous feature of these two major strike slip terrane boundaries and may apply to similar systems worldwide.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.epsl.2009.04.032.

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