The transpressive left-lateral Sierra Madre de Chiapas and its buried front in the Tabasco plain (southern Mexico)

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Abstract: The Sierra Madre de Chiapas evolved in the vicinity of the triple junction between the Cocos, North America and Caribbean plates. The Sierra Madre de Chiapas tectonics reflects positive topographic growth along its main core and a northwards-directed collapse through a free border related to the Gulf of Mexico. Major exhumation and topographic growth occurred during the middle–late Miocene (16–10 Ma). Evidence for this deformational event is provided by fault activity, major stratigraphic unconformities along the Sierra Madre de Chiapas and the Tabasco coastal plain (i.e. southern Gulf of Mexico), major salt-related motion, northward progradation of the sedimentation and northward migration of the buried deformational front. During the Neogene, strike-slip deformation and its related exhumation migrated landwards from the western edge of the Chiapas massif complex to the Chiapas Sierra. Horizontal displacement along the main strike-slip faults in the Chiapas Sierra has been indirectly estimated to be between 30 and 43 km during the last 6–5 Ma, implying 0.5–0.8 cm a−1 of lateral accommodation. These values suggest that a significant amount of the motion transferred by the Caribbean and North American plates is currently being accommodated along the Chiapas area.

Supplementary material: A geological map of the Sierra Madre de Chiapas is available at www.geolsoc.org.uk/SUP18507.

The Sierra Madre de Chiapas is located in southern Mexico in the vicinity of the triple junction between the Cocos, Caribbean and North American plates (Fig. 1). The tectonic evolution of this mountain range within the frame of the triple junction has been matter of debate. Most models emphasize the importance of strike-slip tectonics (e.g. Guzmán-Speziale & Meneses-Rocha 2000; Andreani et al. 2008). Andreani et al. 2008a,b, suggesting that exhumation along the Sierra Madre de Chiapas may have resulted from a transpressive component of deformation resulting from significant changes in the trends of the major crustal faults. The interacting tectonic structures that were responsible for strain partitioning in the region probably include the east–west Polochic–Motagua fault system and a series of NW–SE faults in the Sierra Madre de Chiapas region (Figs 1 and 2). An alternative model (Mandujano-Velázquez & Keppie 2009) suggests that the Sierra Madre de Chiapas exhumation may be related to the orthogonal subduction of the Tehuantepec ridge system (Fig. 1), which produced rapid relief growth (i.e. with a 2–2.5 Ma time span) with negligible strike-slip components. In this context, uncertainties related to the architecture of the mountain chain include (1) the timing and magnitude of exhumation, and (2) the role of the Polochic–Motagua fault system and its eventual transfer of motion to the Sierra Madre de Chiapas.

This study investigates the tectonic processes responsible for the construction of the Sierra Madre de Chiapas and its buried northern prolongation beneath the Tabasco coastal plain (i.e. the southernmost prolongation of the Gulf of Mexico). Morphotectonic interpretation of synthetic aperture radar-derived digital elevation models and fieldwork was performed to understand the tectonic processes along the chain. Also, the buried extension of the chain was imaged by using seismic reflection lines and wells. The seismic and well data presented here are part of an extensive dataset of more than 5000 km of 2D–3D composite seismic lines and stratigraphic markers obtained from about 100 wells (PEMEX). In addition, recently published geodynamic, kinematic and thermo-mechanical models (Lyon-Caen et al. 2006; Andreani et al. 2008a,b; Brichau et al. 2009; Ratschbacher et al. 2009; Authemayou et al. 2011) offer new insights into the complex tectonic deformation of the Sierra Madre de Chiapas within the frame of the triple junction evolution.

Plate tectonics and geological setting

The Eocene to Recent evolution of the Sierra Madre de Chiapas is closely related to the evolution of the triple junction between the Cocos, Caribbean and North American plates (Fig. 1). There is no consensus on the tectonic history of the northern part of the Caribbean plate in the triple junction area (i.e. the so-called Chortis block). A thorough review of the Chortis block reconstruction models has been presented by Mann et al. (2007) and Morán-Zenteno et al. (2009). Two groups of models are usually proposed: (1) the traditional ‘mobile’ models, which suggest a southward displacement (more than 1000 km) since the Eocene along a transform boundary between the Caribbean and North American plates (Schaaf et al. 1995; Pindell et al. 2006; Silva-Romo 2008;
Ratschbacher et al. 2009); these models are based on the lithological similarities found between the displaced blocks in Mexico and Guatemala and also on the magnetic anomalies observed at the Cayman trough (i.e. Mann & Burke 1984); (2) the ‘exotic Pacific’ model, which places the Chortis block in the Pacific Ocean (i.e. to the SW of its current position; Keppie & Morán-Zenteno 2005). Most of this controversy is due to the diffuse architecture of the triple point. As suggested by Guzmán-Speziale et al. (1989) and Authemayou et al. (2011), the triple junction geometry is ambiguously defined mainly because the Polochic–Motagua fault system does not clearly continue beyond its known surface trace, hence apparently it does not intersect the Middle America trench (i.e. there is no trench offset).

The studied area consists of six physiographic regions (Fig. 2): (1) the Chiapas massif complex, bounded to the SW by the Tonalá shear zone; (2) the Central Depression; (3) the High Sierra; (4) the East Front; (5) the North Front. For the sake of simplicity, we will refer to units (3)–(5) as the Chiapas Sierra. The sixth region corresponds to the Tabasco coastal plain. Although there is agreement that the middle–late Miocene orogenesis represents the main period of topographic growth at the Sierra Madre de Chiapas, one to six tectonic events are believed to drive chain evolution (i.e. Carfantan 1986; Quezada-Muñeton 1987; González-Lara 2005). Most of the proposed tectonic phases have been linked to abrupt stratigraphic changes, chiefly marine to continental transitions, and have been assumed to be a consequence of the uplift and erosion of the Chiapas massif complex.

Stratigraphic constraints

The basement mainly comprises Permian granodiorites (270–240 Ma, Pantoja et al. 1974; Weber et al. 2008; Briclau et al. 2009; Ratschbacher et al. 2009) of the Chiapas massif complex, which is locally affected by low- to medium-grade metamorphism. Basement crops out at the Chiapas massif complex and has been reached by boreholes in the Tabasco coastal plain and the Yucatan platform (PEMEX, unpublished data). Interfingering Jurassic (Callovian) red beds and salt deposits overstep the basement and were deposited during the main opening phase of the Gulf of Mexico (Carfantan 1986; Meneses-Rocha 2001). Salt deposits are widely distributed beneath the Sierra Madre de Chiapas and have been drilled as far south as the Ixtapa pull-apart basin and the Central Depression (Meneses-Rocha 2001). Most of the Cretaceous section consists of limestones and dolomites deposited in a marine carbonate platform setting. Important sedimentary facies variations occurred during the Tertiary. The Palaeocene marks the onset of terrigenous siliciclastic deposition. Shallow-water platform, slope turbidite and deep basalinal deposits define the Palaeocene units. The Eocene–Oligocene units predominantly consist of continental clastic deposits and minor shallow water deposits and carbonates. The Oligo-Miocene section represents the onset of pure continental-type sedimentation and it has been directly related to uplift and subsequent erosion of the Chiapas massif complex (Carfantan 1986; Meneses-Rocha 2001). However, zircon U–Pb single grain dating confirmed that most of the pre-deformational sedimentary input (i.e. Palaeocene to Eocene) along the North and East fronts was most probably sourced from a Grenville-type basement (Briclau et al. 2009), which probably corresponds to the Oaxaca basement or to the Guichicovi complex, both located to the NW (Weber & Hecht 2003). U–Pb results indicate that the observed increase of continental terrigenous material towards the Chiapas Sierra during the Neogene is not solely related to the uplift of the Chiapas massif complex.

North of the Polochic–Motagua fault system, subduction-related magmatism is represented by middle to late Miocene granitic intrusions emplaced along the Chiapas massif complex, whereas Plio-Quaternary volcanism occurred along the zone located between the Central depression, the High Sierra and the
North Front, where the active El Chichón volcano is emplaced (i.e. García-Palomo et al. 2004; Mora et al. 2007). The distribution of magmatic rocks documents an eastward migration of the volcanism from the Chiapas massif complex (vicinity of the Tonalá shear zone) to the Chiapas Sierra during middle–late Miocene times.

Orogenic architecture and strike-slip fault systems

NW–SE strike-slip faulting is one of the main driving forces for the topographic growth of the Sierra Madre de Chiapas. Guzmán-Speziale & Meneses-Rocha (2000) proposed that strike-slip motion is transmitted from the Polochic–Motagua fault system to the Sierra Madre de Chiapas within a ‘fault-jog’ (i.e. restraining bend) system, which includes strike-slip motion along at least six major faults. The resultant shortening is mainly accommodated along the core of the massif and its eastern front. The undisturbed continuity, linearity and considerable length (50–250 km) of the major strike-slip faults suggest a basement control (Fig. 2). Indeed, several previous studies integrated the strike-slip faults of the Sierra Madre de Chiapas within the transform boundary kinematics related to the Gulf of Mexico opening (e.g. Pindell et al. 2000). Furthermore, Plio–Quaternary intrusions and volcanoes located at releasing extensional zones suggest that basement is involved (Meneses-Rocha 2001). The majority of the faults studied here show narrow deformation zones (20–300 m wide) governed by a significant variety of tectonic styles. In some cases the narrowness of the deformational area and the poor quality of the outcrops, showing highly brecciated and reworked rocks, prevents a clear geometric and chronological characterization of the deformation. Major strike-slip faulting occurs mainly to the east of the Central Depression and the High Sierra (Fig. 2). Two major systems, comprising five major left-lateral strike-slip faults, accumulated strike-slip motion within the core of the belt. For convenience, and because of the unidentified motion transfer and/or connections at subsurface levels, we have divided the strike-slip faults into two
major systems (Figs 2 and 3), the Tuxtla–Malpaso fault system and the High Sierra fault system. In addition, evidence for strike-slip deformation is observed at the Tortuguero trend and the fold-and-thrust belt located at the East Front.

The Tuxtla–Malpaso fault system

The Tuxtla–Malpaso fault system is a left-lateral strike-slip system that bounds the Chiapas Sierra to the west. This fault system is the most prominent tectonic feature of the entire Sierra Madre de Chiapas.
recent activity along the whole extent of the Tuxtla–Malpaso fault system. Near Tuxtla Gutierrez (Point 2, Fig. 3a) the Tuxtla fault scarp is c. 300 m high and bounds Tertiary sediments to the west and carbonates to the east. At this site, deformation is expressed by metre-scale vertical slip surfaces and fault-parallel folds located within a 200–300 m wide deformational zone developed within the Cretaceous carbonate sequence. The width of the deformation zone decreases abruptly towards the south, extending along a narrow 20–30 m recumbent fold at the mouth of the Sumidero River (Point 3, Fig. 3a). At Point 6 the Tuxtla fault shows a 10–20 m high scarp that separates Palaeocene terrigenous sediments from Cretaceous carbonates. This configuration led some researchers to propose that the Tuxtla fault was active during Palaeocene sediment accumulation (Carfantan 1986). However, 200–300 m from the trace of the fault, the contact between the Upper Cretaceous and Palaeocene sedimentary units occurs along a weak angular discordance. It is difficult to assess whether this weak unconformity resulted from tectonic deformation. Palaeocene units are mainly represented by turbiditic and basinal deposits showing internal deformation related to gravitational processes rather than to an established tectonic regime. Further north (Point 7, Fig. 3a), the fault trace is defined by a 40–50 m high scarp. At this site, the Palaeocene strata adjacent to the scarp show no evidence of synsedimentary deformation.

The Malpaso fault limits the Ixtapa pull-apart basin to the west (Fig. 3a). The main depocentre of the pull-apart basin is defined by 5000–6000 m of Mio–Pliocene sediments (Meneses-Rocha 2001). Northward depocentre migration may have involved at least 11 km of left-lateral displacement since middle–late Miocene times with most of the Malpaso fault activity occurring since 6–5 Ma (Meneses-Rocha 2001). Indeed, the main tectonic unconformity along the Sierra Madre de Chiapas occurs at the northern section of the Ixtapa pull-apart basin (Point 4, Fig. 3a). The angular unconformity separates highly deformed middle–upper Miocene sediments from horizontal-bedded Pliocene units. The clearest morphological features of the Malpaso fault are located at the Chicoasen dam (Point 5, Fig. 3a). The deformed zone extends over 300–400 m within Cretaceous carbonates and includes detachment folds (box-shaped folds), oblique and vertical striated fault planes, and reverse and normal faults all showing evidence of horizontal strain components. We suggest that this structural assemblage represents a flower structure.

Striae and other kinematic markers along fault planes are scarce. Left-lateral kinematic markers obtained at the deformational zones of the Tuxtla and Malpaso faults (Points 2 and 5, Fig. 3a) constrain two horizontal NE–SW- and ENE–WSW-directed compressive strains, respectively (Fig. 3b). Strain tensors show good correlation with fault trend; in particular, a left-lateral component for the deformation associated with the Malpaso fault. In contrast, most of the measured striated planes for the Tuxtla fault show an east–west direction, which is oblique to the trend of the main fault. Moreover, nodal planes obtained from the inversion of kinematic data yielded east–west- and north–south-directed subvertical planes. Where measured, fault planes failed to constrain the Tuxtla fault kinematics and are considered as either secondary structures related to the main fault or associated with a westward prolongation of the east–west High Sierra fault system.

The northernmost topographic expression of the Tuxtla–Malpaso fault system is coincident with a group of folds arranged in an en echelon array (i.e. the Cerro Pelón trend; Figs 2 and 4a). The overall structure consists of two main double-verging ramp anticlines within Jurassic–Cretaceous units and a central syncline within the Oligocene–Miocene succession. In map view (Fig. 4a), folds are segmented, trending parallel next to the fault and becoming more oblique further east. The axial planes of the Amate and Cerro Pelón anticlines (Fig. 4a) show a marked sigmoidal morphology. Seismic lines traversing the Cerro Pelón trend show that the antiforms may be controlled by shallow dipping (30–40°) reverse faulting, a geometry typical of restraining step-over systems (McClay & Bonora 2001). Although both ramps probably merge at depth, it is difficult to constrain whether the deep fault may be related to the Tuxtla or the Malpaso fault. The Cerro Pelón anticline is a recumbent fold with overturned limb strata in unconformable contact (probably a faulted contact) with the less deformed Miocene sediments (Fig. 4b). When present, the Cretaceous platform sediments are displaced more than 3000 m between the summits of anticlines and the drilled sections at the buried coastal plain. This area accommodates the greatest deformation of the entire Sierra Madre de Chiapas. Seismic lines and well data confirm that syntectonic sedimentation occurred from middle–late Miocene times and most probably from 6–5 Ma onwards. Thermochronological data (Britchau et al. 2009) suggest that the evolution of the Tuxtla–Malpaso fault system occurred in two main periods: the middle
Miocene (c. 16–10 Ma) and late Miocene–Pliocene (6–5 Ma). The former period is probably related to the onset of regional exhumation, whereas the latter may represent the onset of major local transpressive deformation resulting from strike-slip activity.

The High Sierra fault system

The High Sierra fault system has a dominant east–west trend. It includes three major faults, which from south to north are the San Cristóbal, Tenejapa and Tectapan faults (Figs 2 and 3a).

The San Cristóbal fault (Figs 2 and 3a) is c. 150 km long and trends east–west, followed by a gentle switch to a WNW–ESE direction towards its western tip, showing marked releasing and restraining step-overs in map view (Point 8, Fig. 3a). It is difficult to constrain whether the San Cristóbal fault connects directly to the Tuxtla–Malpaso fault system at the Ixtapa pull-apart basin depocentre. To the east, it clearly connects to the north–south-trending Leyla–Velázquez and Santiago–Guelatao anticlines, where strike-slip motion is absorbed by thrusting and folding (Fig. 3a). The anticline axis indicates an east–west shortening, which is consistent with a left-lateral motion of the San Cristóbal Fault. North of the town of San Cristóbal de las Casas (Fig. 3a), surface deformation comprises conspicuous vertical fault planes that deform and cut the Cretaceous carbonates. Both parallel and conjugate secondary structures to the main San Cristóbal fault were measured. Kinematic markers obtained at this site (Fig. 3b) indicate an ENE–WSW maximum compression axis. There is a good relationship between the trend of the fault, its left-lateral motion and the obtained tensor. Recent fault activity is supported by the presence of Pleistocene volcanic domes in this area (0.85 Ma for the Huitepec volcanic dome; Damon & Montesinos 1978; Fig. 3a).

The Tenejapa fault is a c. 100 km long structure. Striae inversion, obtained from the main east–west-directed fault plane, yielded a NE–SW-directed shortening for a left-lateral motion (Fig. 3b). The Tenejapa fault is associated with the development of a north–south-striking antiform (i.e. the Oxchic antiform, Fig. 3a) along the central segment of the fault. Fault extension eastwards of the Oxchic antiform probably indicates an eastwards propagation of the fault subsequent to the antiform formation. On the other hand, the western tip of the fault corresponds to a releasing bend where transient motion is probably being absorbed (Point 9, Fig. 3a). We did not observe any morphological evidence to suggest whether the Tenejapa fault connects with the Tuxtla–Malpaso fault system. The amount of offset accumulated along the Tenejapa fault has been estimated at c. 5 km, as deduced from displaced morphological markers (Meneses-Rocha 2001).

The Tectapan fault extends over c. 130 km and shows a complex geometry that is probably due to variable erosion of the poorly consolidated Tertiary clastic sediments. Towards the west, it connects with the Tuxtla–Malpaso fault system along small-scale step-overs. The Nazareth antiline (Fig. 3a) defines the zone where fault motion is absorbed (Fig. 3a). The north–south-trending Nazareth antiline refolds the NW–SE-trending Simojovel fold within a fold-and-thrust belt located at the eastern front (see the next section). Similarly, inflection points at sigmoid-shaped folds of the fold-and-thrust belt mentioned above are aligned with the eastern continuation of the Tectapan fault (Fig. 2). These crosscutting relationships suggest that the Tectapan fault activity post-dated or was at least synchronous with the fold-and-thrust belt formation. Few kinematic markers could be obtained along fault planes owing to pervasive brecciation along the faults. Slip markers are mainly horizontal and constrain a NE–SW-directed main compressional stress coincident with a left-lateral motion (Fig. 3b).

The East Front

The East Front is located between the antiforms associated with the tips of the High Sierra fault system and the western border of the Yucatan platform (Figs 1 and 2). This area comprises two sections showing different morphologies. To the south, the East Front corresponds to a fold-and-thrust belt system, which plunges further south below the Peten basin in Guatemala (Fig. 2). To the north, the morphological expression of the front is coincident with sigmoidal elongated basins and topographic highs arranged in a linear manner along the Tortuguero trend.

The fold-and-thrust belt shows closely spaced fault-related folds with highly segmented sigmoidal axes. Some outcropping folds are highly overturned, suggesting that thrust ramps may reach shallow levels. Outcropping series are mainly Cretaceous carbonates within the antiforms and pre-deformational Palaeocene–Eocene sediments within the highly attenuated synforms. There is no evidence of significant syntectonic sedimentation. Deformed units are parallel and isoline showing no internal unconformities. The proximity of the Yucatan platform, probably acting as a buttress, prevents the eastward progradation of the deformation front. Indeed, no Oligocene to Miocene Yucatan carbonates are involved in the deformation of the fold-and-thrust belt system. As previously suggested, crosscutting relationships between the north–south folded terminations of the High Sierra fault system and the NW–SE-trending folds of the East Front suggest that tectonic activity of the latter predates or was coeval with the strike-slip faulting observed along the High Sierra fault system.

To the north, the so-called Tortuguero trend is a linear zone, clearly recognizable in topography and seismic data (Fig. 5). It reveals marked topographic and structural differences with respect to the fold-and-thrust belt. These differences include the following: (1) deformation is highly linear and is not related to closely spaced thrust faults; (2) it is topographically higher than the fold-and-thrust belt; (3) it bounds two areas marked by important high positive (Tumbala thrust) and high negative (Macuspana basin depocentre) gravimetric anomalies (PEMEX, unpublished data).

Pervasive left-lateral strike-slip faulting affects the northern tip of the emerged area of the Tortuguero trend (Fig. 5a and d). Faults are preferentially east–west oriented, although some roughly north–south-oriented minor faults were also observed. Kinematic markers constrain NE–SW-directed shortening. The spatial relationships between the main trend and small-scale fault planes are similar to those obtained for the Tuxtla fault (see the section on the Tuxtla–Malpaso fault system above). Indeed, we consider that measured strike-slip faults may correspond either to secondary structures related to the main Tortuguero trend (influenced by the east–west-oriented faults of the High Sierra fault system) or to the influence of the Macuspana basin normal faults, which trend roughly perpendicular to the Tortuguero trend.

Along the coastal plane, seismic profiles reveal a highly linear zone showing vertical structures outlined by an upward inflection of reflections and shale diapiric activity (Line 1, Fig. 5c). The linearity of diapiric emplacements suggests that they are fault-controlled. This implies a northward prolongation of the Tortuguero trend, beneath the Tertiary sediments of the Tabasco coastal plain. Internal unconformities suggest continuing deformation subsequent to the main middle–late Miocene event. Apatite fission-track (AFT) thermal modelling from a single detrital sample obtained at the junction between the fold-and-thrust belt and the Tortuguero trend yielded a main exhumation-related cooling age of 10–7 Ma (Bricnau et al. 2009), suggesting continuing deformation at the East Front coeval with a major exhumation of the whole Sierra Madre de Chiapas.
The North Front

The North Front is the emergent area located between the Tectapan fault and the buried section of the chain, located to the north of the piedmont area (Fig. 6a). It is commonly accepted that the main periods of trap formation and hydrocarbon migration along the south Gulf of Mexico (i.e. Tabasco coastal plain) are coeval with major periods of deformation along the Sierra Madre de Chiapas (i.e. González-Posadas et al. 2004; Soto-Cuervo et al. 2004; Chavez-Valois et al. 2009). However, the timing of deformation and the mechanism controlling the transmission of the deformation from the chain to the coastal plain remain ambiguous. The emergent area shows a distribution of clastic Tertiary sediments arranged along NW–SE- to NNW–SSE-directed open to tight folds (Fig. 6a). These folds are at high angles with respect to the roughly east–west northernmost folds of the East Front. The difference in fold-axis direction probably resulted from rotation linked to strike-slip activity between the Tuxtla–Malpaso fault system and the Tectapan fault. Minor strike-slip deformation along the North Front is constrained by shallow seismicity, showing a left-lateral component (Guzmán-Speziale & Meneses-Rocha 2000), and by kinematic markers along the 6 km long Chapultenango fault (Figs 2 and 3b). Exhumation along the emergent North Front may have started at 11–10 Ma as constrained by AFT ages (Brichau et al. 2009).

Three chronostratigraphic markers are regionally recognized in wells and seismic lines at the Tabasco coastal plain (Figs 6 and 7): (1) the top of the Cretaceous, which shows strong reflection owing to the upwards transition from Cretaceous carbonates to clastic sediments; (2) the middle–late Miocene marker, defined by gently to highly developed unconformities (including the top of the salt, where the oldest onlapping and downlapping sediments are middle–late Miocene in age; Line 5, Fig. 6); (3) the top of the early Pliocene, which shows weak reflection but can be easily recognized within the seismic lines and wells.

The seismic lines of Figure 6 illustrate the presence of a Mesozoic basin floored by Jurassic salt. The oldest piece of evidence of deformation is related to deep unconformities beneath the Late Cretaceous marker (Lines 3 and 4; Fig. 6). The overall structure of the buried section of the chain corresponds to a wedge of Tertiary sediments thinning to the east (Lines 2 and 3, Fig. 6). The wedge architecture probably corresponds to a classical wedge-shaped foreland basin related to crustal thickening further west and is most likely to be related to a Laramide front (see the section 'Palaeocene–Eocene deformation' below). Internal deformation on the wedge is related to pinch-outs of the Palaeocene–Eocene series above the Cretaceous platform units. Palaeocene to middle–late Miocene deformation is thus constrained by salt-related discrete depocentre formation (Line 5, Fig. 6) and more regional depocentre formation (as constrained by two-way travel-time
Fig. 6. (a) The North Front and location of seismic lines shown in this study. Violet areas correspond to zones where salt-related deformation is severe. Dashed lines denote buried structures. (b–d) Time-migrated composite seismic lines (2D and 3D surveys) and well control along the buried section of the North Front. Time surfaces of the late Cretaceous and middle–late Miocene markers are shown in Figure 7. (e) NNW–SSE section at the western coastal plain in areas significantly affected by salt tectonics. Oldest onlapping and downlapping sediments at the top of the salt are middle–late Miocene in age, which indicates that massive salt motion took place during this time. Ancient depocentres are imaged to 4.5 s TWTT.
contour lines; Fig. 7b). Late Oligocene–Eocene units locally seal ancient depocentre formations. Pre-middle–late Miocene deformation along the Tabasco coastal plain is most likely to be related to early periods of salt motion and defines a period of margin destabilization with a tectonic transport probably directed towards the Gulf of Mexico.

The NW–SE-directed folds located next to the piedmont extend further north beneath the significant package of sediments at the flat Tabasco plain. Prolongation of the Sierra Madre de Chiapas beneath the plain is particularly expressed by the shallow location of the middle–late Miocene unconformity next to the piedmont and by its deepening towards the north (Fig. 7c). The evidence of a middle–late Miocene age for the main folding stage includes (Figs 6 and 7): (1) onlapping units at the top of the folded middle–late Miocene marker; (2) planar and concordant axial surfaces for the deep and shallow folded units; (3) abrupt increase in salt mobility. Seismic Line 4 is roughly parallel to anticline axes and shows a northward progradation of sediments on top of the middle–late Miocene marker. During the growth of the Sierra Madre de Chiapas, northward progradation was enhanced by increasing subsidence owing to stacking, folding and thrusting within the Sierra Madre de Chiapas further south. The basin progressively moved northwards towards the Gulf of Mexico from middle–late Miocene to early Pliocene, probably as a result of the increasing growth of the Chiapas fold belt and the presence of the deep Gulf of Mexico acting as a free boundary for the mountain belt.

**Discussion**

**Palaeocene–Eocene deformation**

Palaeocene–Eocene deformation and coeval depocentre formation at the Tabasco coastal plain are likely to be related to early periods of salt motion. U–Pb analysis of single zircons on Palaeocene–Eocene terrigenous rocks cropping out at the North and East fronts defined a northwards provenance of sediments (Brichau et al. 2009). Indeed, 0.8–1 G a clusters suggest that Palaeocene–Eocene sedimentary units are mostly sourced from basement exposures such as the Grenvillian Oaxaca block, or the Guichicovi complex (Weber & Hecht 2003), most probably eroded during the Laramide orogeny (Nieto-Samaniego et al. 2006). Sediment overloading had to be significant to reset the AFT and U–Th/He systems (Brichau et al. 2009), implying a minimum of 2–3 km of overburden. As observed in many other passive margins little or no tectonic input is needed to produce gravitational collapse and deformation can start immediately after deposition if there is an adequate driving force. Along the northern margin of the Gulf of Mexico major periods of gravitational failure are controlled by elastic margin progradation, which resulted in differences in the vertical stress and salt motion (Rowan et al. 2004, and references therein). Salt mobility may explain the discrete, weak and episodic deformation along the Tabasco coastal plain, prior to the major middle–late Miocene orogeny. Salt activity seems to be concentrated at both borders of the Sierra Madre de Chiapas (i.e. Tabasco coastal plain and Peten basin), suggesting that these areas probably acted as free borders with respect to the chain formation. In contrast, more confined salt deposits observed in the central part of the chain have little or no effect on the chain architecture.

**Sierra Madre de Chiapas topographic growth**

The 300–400 km long Tonalá shear zone and the 200–300 km long Tuxtla–Malpaso fault system are major crustal faults, whose Neogene activity is constrained by tectonic, seismological and volcanic activity. Thermochronological evidence suggests that uplift of the Chiapas massif complex probably began at 35–25 Ma (Brichau et al. 2009; Ratschbacher et al. 2009). However, major coeval unconformities along the chain are absent, an aspect earlier suggested by Frost & Langenheim (1974) and Quezada-Maldon (1987). Major transient deformation did not occur along the Tonalá shear zone until middle–late Miocene time (12–9 Ma) as expressed by the age of volcanic intrusions, the low-temperature thermochronological record and magnetic-derived rotations (Wawrzyniec et al. 2005; Brichau et al. 2009; Ratschbacher et al. 2009). Location of strike-slip motion along the Tonalá shear zone may have resulted in the major period of transpression and related topographic growth along the Sierra Madre de Chiapas (Fig. 8). This is supported by: (1) the major unconformity observed near the Ixtapa pull-apart basin; (2) the major middle–late Miocene unconformity at the Tabasco plain and the rapid increase in salt mobility; (3) the age of folding at the North Front and at the fold-and-thrust belt at the East Front; (4) clusters of AFT and U–Th/He cooling ages at 16–9 Ma widespread in the Chiapas massif complex and Chiapas Sierra (Brichau et al. 2009); (5) U–Pb dating of syntectonic sediments at the Ixtapa pull-apart basin, which yielded a younger population of 15–10 Ma (Brichau et al. 2009). The fold-and-thrust belt front architecture is parallel to the major left-lateral faults and accommodation zones between the Polochic–Motagua fault system and the Tuxtla–Malpaso fault system (i.e. east–west folding parallel to the Polochic–Motagua fault system in the south and roughly NW–SE folding parallel to the Tuxtla–Malpaso fault system further north; Figs 1 and 2). This parallelism defines the link between fold-and-thrust belt formation and the left-lateral strike-slip systems. Furthermore, coeval ages obtained for the onset of exhumation between the shear zone and the fold-and-thrust belt system (Brichau et al. 2009; Ratschbacher et al. 2009) suggest that the two systems may be structurally linked.

The middle–late Miocene event coincides with a major deformational period observed throughout the triple junction area and the Gulf of Tehuantepec. Major middle–late Miocene deformational processes have been identified along the Nicaragua rise, the Mexican ridges, in the Veracruz basin and in some restricted areas in the Sierra Madre del Sur (Jennette et al. 2003; Keppie & Morán-Zenteno 2005; Nieto-Samaniego et al. 2006; Alzaga-Ruiz et al. 2008; Andreani et al. 2008a,b; Le Roy et al. 2008; Rangin et al. 2008; Roure et al. 2009). Salt migration related to orogenic construction is at the origin of important middle–late Miocene petroleum plays at the Tabasco area and off Campeche (i.e. Ambrose et al. 2003; Guzmán-Vera & Calderon-Barrera 2004; Mitra et al. 2005; Chavez-Valois et al. 2009). Furthermore, important changes in deformation style at the Polochic–Motagua fault system may have been taking place since middle–late Miocene times (Authemayou et al. 2011). Although related to different tectonic scenarios, the middle–late Miocene represents the onset of important deformation throughout the west and south borders of the Gulf of Mexico, South Mexico and North Guatemala areas.

Several plate-tectonic processes coincide with the time span of Sierra Madre de Chiapas construction. These processes, some of them most probably competitive, may include: (1) Neogene migration of the Chortis block (i.e. Ratschbacher et al. 2009); (2) fast spreading on the East Pacific Rise between 18 and 10 Ma (Wilson 1996); (3) NE–SW migration of the volcanic arc activity and opening of the Nicaraguan back-arc basin from 10 to 0 Ma (i.e. McIntosh et al. 1993); (4) subduction of the Tehuantepec ridge (Mandujano-Velázquez & Keppie 2009). Further work is needed to assess whether Sierra Madre de Chiapas deformation is linked to one or several of these processes and whether the middle–late Miocene corresponds to a period of major reorganization at plate scale.
Fig. 7. Seismic-derived time-surface maps along the Tabasco coastal plain. Coloured areas limit the zones where each of the markers was constrained using seismic and well data. Uncovered areas are characterized by loss of seismic reflections owing to salt or shale presence and/or to severe deformation. (a) The top of the Cretaceous. (b) Time thickness between the top of the Cretaceous and the middle–late Miocene unconformity. (c) The top of the middle–late Miocene, which corresponds to the main unconformity observed along the Tabasco coastal plain. (d) Time thickness between the middle–late Miocene unconformity and the top of the early Pliocene. (e) The top of the early Pliocene. Lines 2–5 are shown in Figure 6.
**Strike-slip faults and relationships with the Polochic–Motagua fault system**

Recently, new kinematic, seismological and tectonic constraints have considerably improved the knowledge about the mechanism of transfer of motion from the Polochic–Motagua fault system to the Sierra Madre de Chiapas. Global positioning system (GPS) data show that the westernmost segments of the Polochic–Motagua fault system are not currently active (Lyon-Caen et al. 2006), which suggests that little or no motion is being transferred at present to the westernmost areas of the Sierra Madre de Chiapas (i.e. Tonalá shear zone). GPS models suggest that a displacement rate of 0.8–1.2 cm a⁻¹ may be transferred from the Polochic–Motagua fault system to the Sierra Madre de Chiapas at a zone coincident with the Sierra de Cuchumatanes (Fig. 2), whose high altitude and internal deformation are likely to be related to a significant tectonic deformation. The mechanism involved in this transfer of motion may include: (1) a ‘fault-jog’ or major restraining bend with motion dying at the northern limit of the Sierra Madre de Chiapas (Andreani et al. 2004), which is currently transmitted to the Chiapas area, provided current GPS data may be extrapolated to 6–5 Ma; (2) a crustal drifting block (i.e. South Mexico block) that is migrating to the plate limit (Guzmán-Speziale & Meneses-Rocha 2000); (2) a crustal setting, implying a diffuse North American–Caribbean accretion to the northern limit of the Sierra Madre de Chiapas in a shaped zone where anticlines and synclines developed as en echelon folds resulting from the left-lateral activity along the Tuxtla–Malpaso fault system. This area is believed to accommodate the transfer of motion along the step-over between the Tuxtla–Malpaso fault system and the Veracruz fault (Andreani et al. 2008b). Hypothetical rock uplift associated with a restraining step-over is difficult to estimate because vertical deformation may be absorbed across multiple structures and because of the uncertainty of the flexural response of the deformed zone (Wakabayashi et al. 2004). As suggested by Wakabayashi et al., the vertical component of fault displacement in a restraining stepover can be estimated in an idealized case of a single transverse structure as $z = x \sin[\tan^{-1}(\sin\theta \tan \delta)]$, where $z$ is the vertical component of displacement, $x$ is the strike-slip displacement, $\theta$ is the angle between the transverse structure and the fault strike, and $\delta$ is the dip of the transverse structure. We have calculated the amount of lateral displacement of the Tuxtla–Malpaso fault system as a function of the vertical offset accommodated along the Cerro Pelón area. We have considered the following: (1) an approximation of the horizontal displacement may be obtained by the addition of Wakabayashi et al.’s relationship calculated for each of the two antiforms forming the Cerro Pelón trend; (2) antiforms trend at 10° and 30°–40° with respect to the main fault trace for the western and eastern anticlines, respectively, as observed in map view (Fig. 4a); (3) the dip of the transverse structures ranges between 30° and 40° in agreement with observed seismic lines (Sánchez-Montes de Oca 2006; PEMEX, internal data); (4) there is an accommodated vertical displacement of c. 3000 and c. 4000 m with respect to the Cretaceous platform, as observed in well data and on seismic lines. Taking into account these aspects, the horizontal motion accommodated along the Cerro Pelón restraining bend ranges from 30 to 43 km. The displacement obtained here may be considered as a good approximation. This value accounts only for the amount of vertical displacement predicted from strike-slip movement through the step-over; it does not take into account the impact of regional transpression (Wakabayashi et al. 2004). Major strike-slip deformation along the Tuxtla–Malpaso fault system may have started at 6–5 Ma as indicated by seismic data, the age of syntectonic sedimentation and low-temperature thermochronology (Meneses-Rocha 2001; Sánchez-Montes de Oca 2006; Brichau et al. 2009). In the lack of other well-defined displaced features (lithological or morphological), the displacement of 30–43 km constrains 0.6–0.8 cm a⁻¹ of lateral accommodation for the 6–5 Ma main exhumation period. Taking into consideration that part of the deformation may be absorbed by the strike-slip faults and related folded tips of the High Sierra fault system, we believe that the 0.5–0.8 cm a⁻¹ accommodation along the Tuxtla–Malpaso fault system accounts for most of the current relative motion between North America and Caribbean plates that is currently transmitted to the Chiapas area, provided current GPS data may be extrapolated to 6–5 Ma. Thus, our results are in

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**Fig. 8.** Geodynamic evolution sketch of the Sierra Madre de Chiapas and surrounding areas showing the inland migration of deformation from 12–9 Ma to 6–5 Ma. Grey areas indicate the Chiapas massif complex. Continuous lines define active tectonic systems for every period; dashed lines refer to inactive tectonic systems. Blue arrows denote migration of deformation. HSFS, High Sierra fault system; SC, Sierra de los Cuchumatanes; TMFS, Tuxtla–Malpaso fault system; TSZ, Tonala shear zone. Thermochronological ages from Brichau et al. (2009).
agreement with previous studies that suggested a bulk displacement along the strike-slip fault systems of the Sierra Madre de Chiapas of c. 70 km (Meneses-Rocha 2001).

Strike-slip deformation and related exhumation may have migrated eastwards from the shear zone to the Tuxtla–Malpaso fault system between 12–9 Ma and 6–5 Ma. This is supported by: (1) the current inactivity of the westernmost sections of the Polochic–Motagua fault system; (2) the age of syntectonic sedimentation at the Ixtapa pull-apart basin, Malpaso fault and Cerro Pelón areas; (3) 6–5 Ma (U–Th)/He ages defining significant exhumation at the Tuxtla–Malpaso fault system (Briand et al. 2009); (4) the migration of volcanism from the shear zone to the Tuxtla–Malpaso fault system and High Sierra fault system (i.e. Mora et al. 2007). Towards the south, in Guatemala, extension related to the activity of the Polochic–Motagua fault system has been propagating northward since late Miocene time (Fig. 8), making the triple junction increasingly diffuse as it is propagating eastward and inland within the continental crust (Ratschbacher et al. 2009; Authemayou et al. 2011). A landward migration of deformation related to the limit of the Caribbean–North American plates has been taking place throughout the system, including the Polochic–Motagua fault system and the Chiapas area, since middle–late Miocene time.

Strike-slip faults of the High Sierra fault system may each have no more than 5 km of displacement (Meneses-Rocha 2001). They fall into the category of confined intraplate strike-slip faulting (Storti et al. 2003), especially with regard to their rotational or contractional terminations. On the other hand, the Tuxtla–Malpaso fault system shows characteristics of transfer intraplate strike-slip faulting involving a more rigid tectonic escape, in agreement with the displacement rates obtained in this study. It is probable that the High Sierra fault system corresponds to a secondary accommodation zone related to the Tuxtla–Malpaso fault system.

Field and seismic evidence suggests that the junction area between the Tortuguero trend and the Macuspana basin accommodated a component of strike-slip deformation. Whether the East Front corresponds to a major restraining structure is difficult to assess with the existing data. However, the high linearity of the Tortuguero trend and the sigmoid and highly segmented character of the fold-and-thrust belt may suggest a strike-slip component for the deformation. Gravity modelling between the Tumbala thrust and the Macuspana basin revealed the existence of an important sediment accumulation beneath the Cretaceous platform (PEMEX, unpublished data), suggesting that the Tortuguero trend corresponds to a reactivated structure, probably coincident with the border of the Yucatan platform, which acted as a transfer fault during the Gulf of Mexico opening (i.e. Pindell et al. 2000). In this scenario the Tortuguero trend probably corresponds to the shallow section of a major strike-slip fault, which plunges to the SE beneath the current fold-and-thrust belt.

Conclusions

The Sierra Madre de Chiapas consists of six physiographic units constrained by different topographic expressions: the Chiapas massif complex, the Central depression, the High Sierra, the North and East fronts, and the Tabasco coastal plain. These zones record deformation related to a transpressive motion resulting from the relative motion between the Caribbean and North American plates. Palaeocene–Eocene deformation and coeval depositional formation at the Tabasco coastal plain are most probably due to early periods of salt motion triggered by major sediment stacking related to a Laramide event.

Thermochronological evidence (Briand et al. 2009) suggests that the uplift of the Chiapas massif complex probably began as early as 35–25 Ma. However, field and seismic evidence suggests that the Chiapas Sierra was not affected by this process. Major topographic growth took place at the Sierra Madre de Chiapas during middle–late Miocene (12–9 Ma). Several lines of evidence support this: (1) major unconformities related to transpressional deformation; (2) significant salt migration and sediment progradation along the coastal plain; (3) migration of the buried section of the North Front; (4) low-temperature thermochronological ages (Briand et al. 2009); (5) the age of syntectonic sedimentations.

Strike-slip deformation and related exhumation may have migrated eastwards from the shear zone to the Tuxtla–Malpaso fault system between 12–9 Ma and 6–5 Ma. Several observations support this: (1) the current inactivity of the westernmost sections of the Polochic–Motagua fault system; (2) the age of major syntectonic sedimentation at the Ixtapa pull-apart basin, Malpaso fault and Cerro Pelón areas; (3) 6–5 Ma (U–Th)/He ages defining significant exhumation at the Tuxtla–Malpaso fault system (Briand et al. 2009); (4) the migration of volcanism from the shear zone to the Tuxtla–Malpaso fault system and High Sierra fault system (see Mora et al. 2007).

Horizontal displacement along the northern section of the Tuxtla–Malpaso fault system could have reached c. 30–40 km during the last 6–5 Ma, involving 0.5–0.8 cm a⁻¹ of lateral accommodation. This rate accounts for a great part of the current relative motion between the Caribbean and North American plates that may be transmitted to the Sierra Madre de Chiapas area, as it has been constrained by GPS and kinematic models (Lyon-Caen et al. 2006; Andreani et al. 2008a, b). Although related to different processes, the middle–late Miocene appears to be one of the most developed constructional periods of relief along southern Mexico. Middle–late Miocene deformation has been observed in the Chiapas area, the Veracruz basin, the Mexican ridges and offshore Belize and Guatemala.

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References

Aiza-González, H., López, M., Roque, F. & Serrano, M. 2008. Interactions between the Laramide foreland and the passive margin of the Gulf of Mexico: tectonics and sedimentation in the Golden Lane area, Veracruz State, Mexico. Marine and Petroleum Geology, 26, 951–973.

Ambrose, W.A., Wawrzyniec, T.F. & Hofmann, D., 2008. Geologic framework of upper Miocene and Pliocene gas splay systems of the Macuspana basin. Southeastern Mexico. AAPG Bulletin, 87, 1411–1435.

Andreani, L., Pichon, X., Rangin, C. & Martínez-Reyes, J. 2008a. The southern Mexico block: main boundaries and new estimation for its Quaternary motion. Bulletin de la Société Géologique de France, 179, 209–223.

Andreani, L., Rangin, C., Martínez-Reyes, J., Le Roy, C., Aranda-García, M., Pichon, X. & Peterson-Rodríguez, R. 2008b. Neogene left-lateral shear along the Veracruz Fault: the eastern boundary of the Southern Mexico Block. Bulletin de la Société Géologique de France, 179, 195–208.

Authemayou, C., Briand, S., Geyssens, C., Simon-Labrecque, T., Gutiérrez, A., Chiquet, L. & Morán, S. 2011. The Caribbean–North America–Cocos triple junction and the dynamics of the Polochic–Motagua fault systems: pull-up and zipper models. Tectonics, doi:10.1029/2010TC002814.

Briand, S., Witt, C. & Caret, A. 2009. Thermochronology applied to the Chiapas mountains, Mexico. EOS Transactions American Geophysical Union, 89, Fall Meeting Supplement, Abstract T23C-2064.

Carpentier, J.C. 1986. Du système cordilleran Nordaméricain au domaine Caraïbe. Etude géologique du Mexique méridional. PhD thesis, University of Savoie, Chambery, France.

Chavez-Valois, V., Valdés, M., Juárez, J., Aloí, I., Mata, M., Villagrán, R. & Guerrero, M. 2009. A new multidisciplinary focus in the study of the
Tertiary plays in the Sureste basin, Mexico. In: Bartolini, C. & Roman Ramos, J.R. (eds) Petroleum Systems in the Southern Gulf of Mexico. AAPG Memoirs, 90, 155–190.

Damon, P. & MonteSingos, E. 1978. Late Cenozoic volcanism and metallogeneosis over an active Benioff zone in Chiapas, Mexico. Arizona Geological Society Digest, 11, 155–168.

DeMets, C., Gordon, R.G., Angius, D.F. & Stein, C. 1990. Current plate motions. Geophysical Journal International, 101, 425–478, doi:10.1111/j.1365-246X.1990.tb06579.x.

Frost, S. & Langenheim, R. 1974. Cenozoic Reef Biofacies: Tertiary Larger Foraminifera and Scleractional Corals from Chiapas, Mexico. Northern Illinois University Press, DeKalb.

Garcia-Palomino, A., Macias, J.L. & Espindola, J.M. 2004. Strike-slip faults and K-alkaline volcanism at El Chichon volcano, southeastern Mexico. Journal of Volcanology and Geotherm Research, 136, 247–268.

González-Lara, J.C. 2001. El Paléoceno del Chiapas (SE del México): Biotstratigraphie, Sédimentologie et Stratigraphie S yiéquente. Géologie Alpíne, Mémoire Hors Série, 36.

González-Pousadas, J., Ayeyano-López, S. & Molina, J. 2004. Strike-slip model for the Jacinto and Paredon fields of the Chiapas–Tabasco basin, South East basin, Mexico. World Wide Web address: http://www.searchanddiscovery.com/documents/abstracts/2004intl_cancun/extended/A093535.pdf

Guzmán-Speziale, M. & Meneses-Rocha, J.J. 2000. The North America–Caribbean plate boundary west of the Motagua–Polocic fault system: a fault jog in southeastern Mexico. Journal of South American Earth Sciences, 13, 459–472.

Guzmán-Speziale, M., Pennington, W. & Matumoto, T. 1989. The triple junction of the North America, Cocos, and Caribbean plates: seismicity and tectonics. Tectonics, 8, 981–997.

Guzmán-Vera, E., Calderón-Barrera, J. 2004. Direct hydrocarbon indicators and structural inversion in the south of the Macuspana basin, an addition for 2D and 3D multichannel seismic data. Géologique de France Bulletin de la Société Géologique de France, 179, 107–116.

Ratschbacher, L., Franz, L. et al. 2009. The North American–Caribbean plate boundary in Mexico–Guatemala–Honduras. In: James, K.H., Lorente, M.A. & Pendell, J.L. (eds) The Origin and Evolution of the Caribbean Plate. Geological Society, London, Special Publications, 328, 219–293, doi:10.1144/SP328.11.

Rowan, M.G., Peel, F.J. & Vendeville, B.C. 2004. Gravity-driven fold belts on passive margins. In: McClay, K.R. (ed.) Thrust Tectonics and Hydrocarbon Systems. AAPG Memoirs, 82, 157–182.

Sánchez-Montes de Oca, R. 2006. Curso Cuenca del Sureste. Unpublished report, PEMEX.

Schaff, F., Morán-Zenteno, D., Hernández-Bernal, M.S., Solís-Picardo, G., Tolson, G. & Köhler, H. 1995. Paleogene continental margin truncation in southwestern Mexico: geochronological evidence. Tectonics, 14, 1339–1350.

Silva-Romo, G. 2008. Guayape–Papalutla fault system: a continuous Cretaceous structure from southern Mexico to the Chortis block? Tectonic implications. Geology, 36, 75–78, doi:10.1130/G24032.2.

Singh, S., Roodiger, M. & Espindola, J. 1984. A catalog of shallow earthquakes of Mexico from 1900 to 1981. Bulletin of the Seismological Society of America, 74, 267–279.

Soto-Cuurio, A., Ortiz-Gonzalez, V. & Mara Oropeza, M. 2004. Present and future of the Salina del Tulai rise and its offshore extension into the Gulf of Mexico. World Wide Web address: www.searchanddiscovery.com/documents/abstracts/2004intl_cancun/extended/A91518.pdf.

Storey, F., Holdsworth, R.E. & Salvini, F. 2003. Intraplate strike-slip deformation belts. In: Storey, F., Holdsworth, R.E. & Salvini, F. (eds) Intraplate Strike-Slip Deformation Belts. Geological Society, London, Special Publications, 210, 1–14.

Wakabayashi, A., Henges, J. & Sawyer, T. 2004. Four-dimensional transform fault processes: progressive evolution of step-overs and bends. Tectonophysics, 392, 279–301.

Weber, B. & Hecht, L. 2003. Petrology and geochemistry of maﬁnogenic rocks from a Grenvillian basement fragment in the Maya block: the Guichicovi complex, Oaxaca, southern Mexico. Precambrian Research, 124, 41–67.

Weber, B., Valencia, V.A., Schaff, P., Pomer-Mera, V. & Ruiz, J. 2008. Signiﬁcance of provenance ages from the Chiapas massif complex (SE Mexico): redefining the Paleozoic basement of the Maya block and its evolution in a peri-Gondwanan wrangle. Journal of Geology, 116, 619–639.

Wilson, D. 1996. Fastest known spreading on the Miocene Cocos–Paciﬁc plate boundary. Geophysical Research Letters, 23, 3003–3006.
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