Bookshelf faulting in Nicaragua

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ABSTRACT

Oblique subduction at a high rate of convergence along much of the Middle America Trench results in northwest-directed trench-parallel block motion. Accommodation of this motion along northwest-striking dextral strike-slip faults has been postulated; however, in Nicaragua such faults are not well developed. We suggest instead that this motion is accommodated by bookshelf faulting that includes northeast-striking left-lateral faults. We present earthquake epicenter and focal mechanism data and mapped fracture and fault data consistent with this model. Trenchward migration of the volcanic arc since the Miocene and reactivation of northeast-striking Miocene structures may have led to the development of this arc- and trench-normal fault system.

Keywords: bookshelf faulting, block rotation, Nicaragua, neotectonics, seismic hazards.

INTRODUCTION

Trench-parallel motion of crustal blocks or slivers in response to oblique subduction has long been recognized as an important aspect of crustal deformation (Fitch, 1972; Jarrard, 1986). In general, motion of these blocks, located between the subduction zone and volcanic arc, is likely to be significant in areas of rapid subduction and high obliquity, especially where coupling between subducting and overriding plates is high (Beck, 1991; McCaffrey, 1992). In Central America, where present-day subduction of young (younger than 25 Ma) lithosphere of the Cocos plate beneath the Caribbean plate occurs along the Middle America Trench at a rate of ~8 cm/yr (Dixon, 1993; DeMets et al., 1994; DeMets, 2001), obliquity varies due to changes in strike of the trench, from essentially zero in southern Costa Rica to more than 15° in Nicaragua (Barckhausen et al., 2001). DeMets (2001) used slip vectors of subduction-zone earthquakes and a new model for Cocos-Caribbean motion to estimate trench-parallel motion of the forearc at a rate of 14 ± 5 mm/yr.

Despite this relatively high rate of motion, the crustal structures that accommodate forearc motion in Nicaragua remain unclear. In Sumatra, probably the best described example of forearc sliver transport, a major strike-slip fault parallel to the trench and located within the thermally weak volcanic arc accommodates the majority of trench-parallel motion (Fitch, 1972; McCaffrey, 1992; Sieh and Natawidjaja, 2000). However, such a mechanism does not appear to be appropriate for Nicaragua. While focal mechanisms of forearc crustal earthquakes are consistent with right-lateral motion on northwest-striking (i.e., trench parallel) faults (Molnar and Sykes, 1969; White, 1991; Fig. 1), such faults are not well expressed; northeast-striking faults are more common (Carr, 1976; Carr and Stoiber, 1977). Because of the well-known ambiguity in focal mechanism interpretation, the latter faults are also consistent with the focal mechanism data, provided that they are left lateral rather than right lateral. In this paper we present new seismic data collected by the Instituto Nicaragüense de Estudios Territoriales (INETER) local seismic network, and summarize focal mechanism and mapped fracture and fault data from the literature. These data suggest that trench-normal faults play an important role in accommodating trench-parallel motion of the forearc in Nicaragua via vertical axis block rotation. We describe a model to explain why such faults, which at first glance appear to be mechanically less favorable, may have developed, and discuss geological and seismic hazard implications.

NEOTECTONICS OF CENTRAL AMERICA AND NICARAGUA

Pleistocene-Holocene deformation in Central America includes three active fault trends: N45°–65°W right-lateral strike-slip faults, N30°–45°E left-lateral strike-slip faults, and N15°W–N10°E normal faults (Carr, 1976; Weyl, 1980; Manton, 1987; Weinberg, 1992). In a dextral shear zone these fault trends are consistent with Reidel and anti-Reidel shear, and east-west extension, respectively. Northwest-striking right-lateral faults are parallel to the arc, and have been mapped in El Salvador, Guatemala, and Costa Rica (Carr, 1976; Manton, 1987; Marshall et al., 2000). However, in Nicaragua this fault trend is not well developed and northeast-striking faults dominate in the forearc and arc (Carr, 1976; Weyl, 1980), offset northwest-striking right-lateral faults in the arcs of El Salvador, Guatemala, and Costa Rica (Carr, 1976; Marshall et al., 2000), and are associated with segment breaks along the Central American volcanic arc (Stoiber and Carr, 1973; Carr, 1976). The approximately north-striking faults show normal to oblique offset, bound north-striking grabens, such as the Managua graben (Fig. 2), and are associated with the alignment of volcanic vents (McBirney and Williams, 1965; Weinberg, 1992). These faults accommodate ~8 mm/yr of east-west extension in northern Central America (Guzman-Speziale, 2001). The spatial and temporal distribution of earthquake focal mechanisms and epicenters suggests that active faults are confined to within 25 km of the volcanic arc and that seismic events are characterized by slip on multiple, parallel fault planes (Brown et al., 1973; Molnar and Sykes, 1969; White, 1991; this study, Figs. 1–3). Elongate damage zones from historical earthquakes indicate that all three fault trends are active along the arc (Carr and Stoiber, 1977; White and Harlow, 1993).

EVIDENCE FOR NORTHEAST-STRIKING LEFT-LATERAL FAULTS IN NICARAGUA

In Nicaragua, northeast-striking faults have been mapped within the forearc, volcanic arc, and highland regions (Carr and Stoiber, 1977; Weyl, 1980; Weinberg, 1992; van Wyk de Vries, 1993; Cowan et al.,

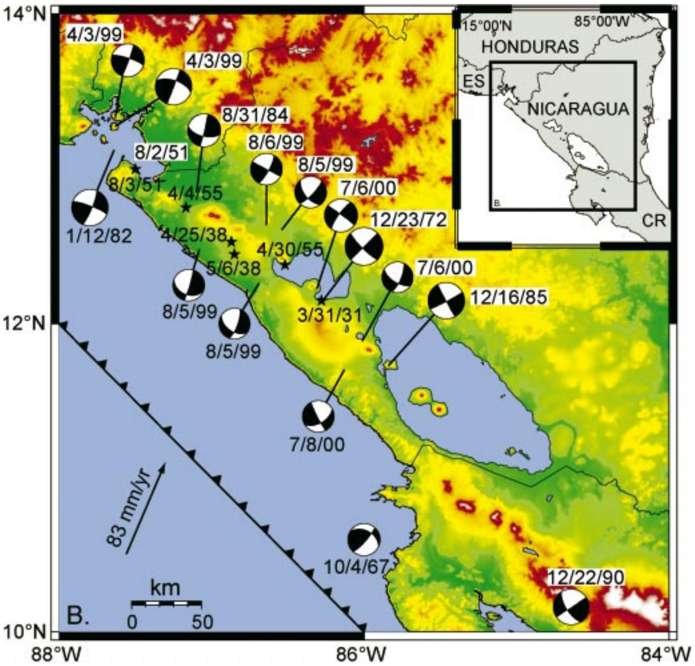

Figure 1. A: Location map of Nicaragua and study area. B: Digital elevation model of western Nicaragua with focal mechanisms of historical strike-slip earthquakes from Molnar and Sykes (1969), White (1991), and Harvard centroid moment tensor catalog. Stars mark locations of destructive earthquakes (White and Harlow, 1993). Numbers located next to focal mechanisms and stars are dates of events given in month-day-year notation. ES—El Salvador; CR—Costa Rica.

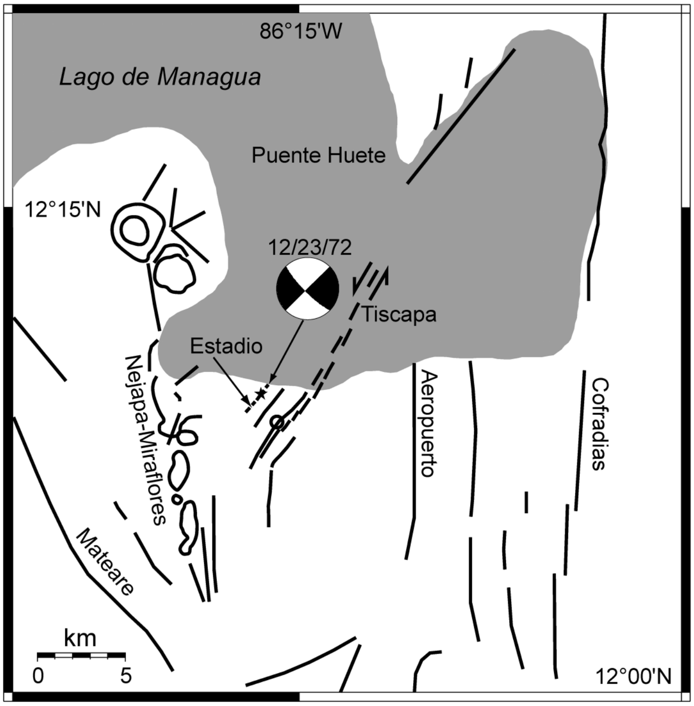

Figure 2. Map of Quaternary faults within Managua graben and Nejapa-Miraflores volcanic alignment. Faults are from Brown et al. (1973), Weyl (1980), and Cowan et al. (2000). Focal mechanisms are from White (1991) and Harvard centroid moment tensor catalog. Black star is epicenter of March 31, 1931, earthquake.

2000). Stoiber and Carr (1973) and Carr and Stoiber (1977) discussed the segmentation of the Central American volcanic arc along northeast-trending transverse structures located at right steps in the volcanic arc and between volcanic complexes. In Nicaragua, right steps in the arc are located at the Gulf of Fonseca, Managua, and southeastern Lago de Nicaragua (Carr and Stoiber, 1977; Fig. 4). These right steps may be caused by lateral variations in magma production, resulting from bending of the subducting slab (Carr et al., 1982). Weinberg (1992) suggested that northeast-trending structures formed during an earlier Miocene phase of deformation have been reactivated.

Focal mechanisms and epicenter distributions of earthquakes during the past century correlate well with these transverse structures and segment breaks (Molnar and Sykes, 1969; White, 1991; White and Harlow, 1993; Figs. 1 and 4). The Estadio and Tiscapa faults, northeast-striking left-lateral faults located within the Managua graben, ruptured during the devastating 1931 and 1972 Managua earthquakes (Brown et al., 1973; Ward et al., 1974; Cowan et al., 2000; Fig. 2). The 1972 event was characterized by surface rupture along three additional faults parallel to the Tiscapa fault (Brown et al., 1973). White and Harlow (1993) attributed the 1982 Gulf of Fonseca earthquake to slip on a near vertical left-lateral fault plane (Figs. 1 and 2). Maldonado-Koerdell (1966) and Carr and Stoiber (1977) both placed a northeast-trending fault through the Gulf of Fonseca. Following van Wyk de Vries (1993), Cowan et al. (2000) mapped the northeast-striking La Pelona, La Paz Centro, and Ochomogo fault zones (Figs. 3 and 4), located at breaks in the volcanic arc; the latter two zones are seismically active (Figs. 1 and 3). Van Wyk de Vries (1993) suggested that the 1985 Lago de Nicaragua M_w 6.1 earthquake was caused by slip in the Ochomogo fault zone (Fig. 3B).

Earthquakes in 1999 and 2000 further demonstrate the existence of active northeast-striking left-lateral strike-slip faults within the volcanic arc. M_w 5.2 and M_w 5.1 earthquakes preceded the August 5, 1999, eruption of Cerro Negro by several hours (Fig. 3A). Aftershock sequences of these earthquakes correlate well with mapped faults of the La Paz Centro fault zone (van Wyk de Vries, 1993; Cowan et al., 2000; Fig. 3A). A similar pattern of earthquake epicenters located in the La Paz Centro fault zone was presented by McNutt and Harlow (1983). M_w 5.4 and M_w 6.0 earthquakes with left-lateral focal mechanisms preceded the Cerro Negro eruption and earthquake swarm by four months and were located in the Gulf of Fonseca (Figs. 1 and 4). On July 6, 2000, an earthquake swarm caused surface ruptures along several northeast-trending faults, northwest of Laguna de Apoyo and east-southeast of Masaya (INETER, 2000). Fracture data demonstrate that the trends of surface ruptures are consistent with slip along northeast-trending faults (INETER, 2000; Fig. 3B). This spatial correlation of mapped faults and fractures, focal mechanisms, and aftershock sequences demonstrates that recent seismicity in Nicaragua has been caused by slip on northeast-striking left-lateral faults normal to the volcanic arc, rather than northwest-striking right-lateral faults parallel to the arc.

DISCUSSION

Northwest-directed dextral shear must be accommodated along the Central America volcanic arc (DeMets, 2001). In Guatemala and El Salvador, accommodation of trench-parallel motion appears to take place on both northwest-striking right-lateral faults and northeast-striking left-lateral faults. However, the latter offset the former by as much as 10 km, suggesting that only the latter is currently active (Carr, 1976). In Nicaragua there is little evidence for northwest-striking right-lateral faults. We suggest instead that the ~14 mm/yr of dextral shear calculated by DeMets (2001) is accommodated by bookshelf faulting, involving clockwise rotation of blocks separated by northeast-striking left-lateral faults (Fig. 4). Northwest-striking faults may also bound the blocks, as is the case in El Salvador and Guatemala (Fig. 4); however,

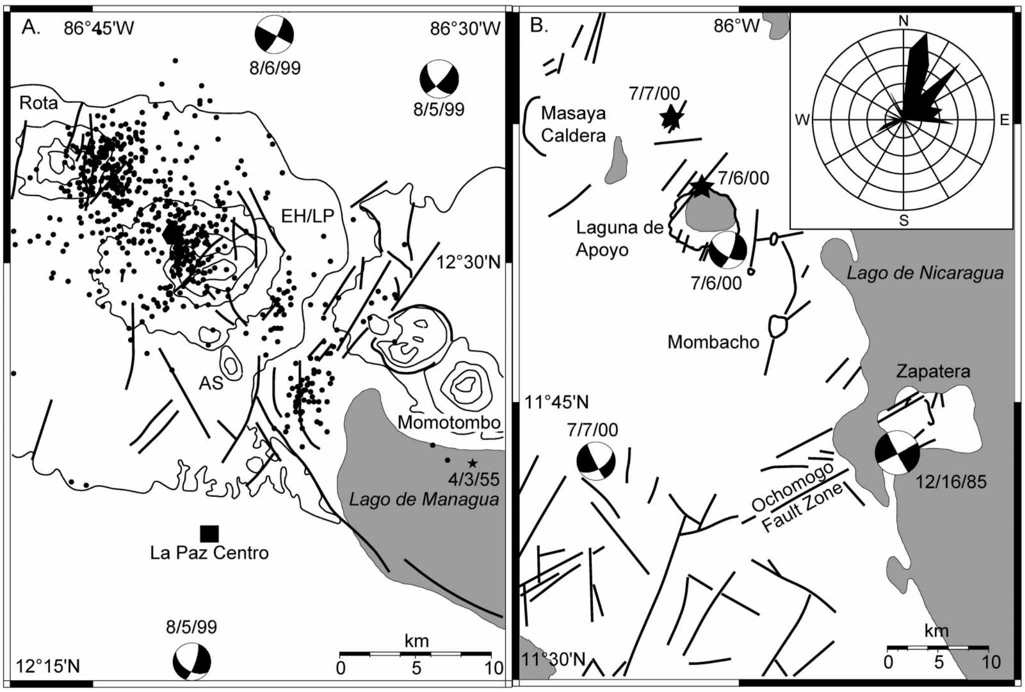

Figure 3. A: Map of La Paz Centro fault zone modified from van Wyk de Vries (1993), Cowan et al. (2000), and Badilla et al. (2001). Earthquake epicenters between August 6 and 11, 1999 (black dots; this study), and focal mechanisms (Harvard centroid moment tensor catalog) of August 5 and 6, 1999, earthquakes, demonstrate correlation between seismicity and mapped faults of La Paz Centro fault zone. Cerro Negro volcano is black hexagon. Abbreviations: AS, Laguna de Asososca; EH/LP, El Hoyo–Las Pilas volcanic complex. B: Map of Masaya, Laguna de Apoyo, and Mombacho segments of volcanic arc and Ochomogo fault zone. Inset is rose diagram of fracture trends measured after July 6 and 7, 2000, Laguna de Apoyo earthquakes (Instituto Nicaragüense de Estudios Territoriales [INETER], 2000). Faults are from Weyl (1980), INETER (2000), and Cowan et al. (2000). Black stars are epicenters. Focal mechanisms are from Harvard centroid moment tensor catalog.

the fact that these are not observed in Nicaragua may indicate that they are obscured by recent volcanic cover. East-west extension within individual blocks may also occur, accommodated on north-northwest–trending structures. For example, an ~10 km north-northwest–trending fracture opened during the 1999 seismic swarm and eruption of Cerro Negro, and recent seismicity observed along a north-northwest–trending fault near Apoyeque volcano.

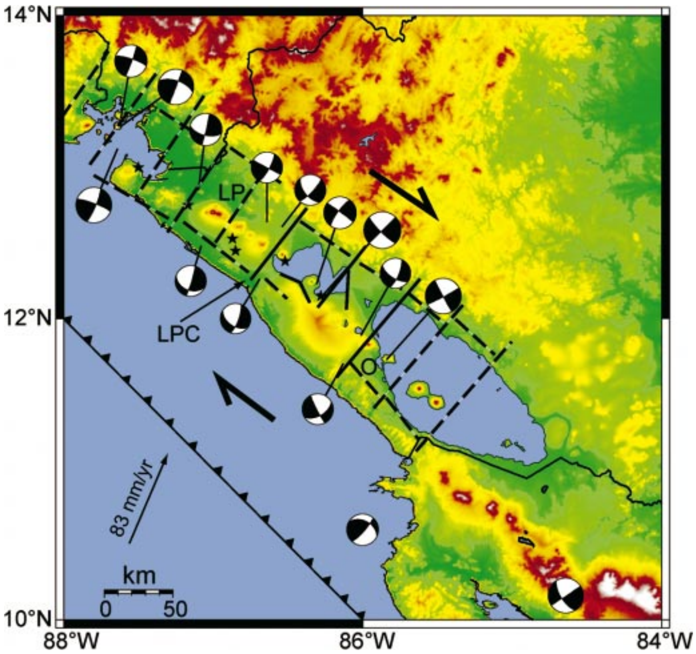

Figure 4. Schematic representation of bookshelf faulting along Central American volcanic arc in Nicaragua. Block-bounding faults are modified from Carr and Stoiber (1977). Focal mechanisms of historical strike-slip earthquakes are from Molnar and Sykes (1969), White (1991), and Harvard centroid moment tensor catalog. Stars mark locations of destructive earthquakes (White and Harlow, 1993). Abbreviations: O—Ochomogo fault zone; LP—La Pelona fault zone; LPC—La Paz Centro fault zone.

Why should bookshelf faulting develop in place of a simpler through-going strike-slip fault? Trenchward migration of the volcanic arc and/or reactivation of preexisting fractures may play a role. Phipps Morgan and Kleinrock (1991) showed that bookshelf faulting is common in propagating rift settings, such as the South Iceland seismic zone (Einarsson and Eiriksson, 1982), because as the rift propagates, it is mechanically more favorable for bookshelf faults to lengthen by the increment of propagation, rather than cut new intact rock the entire length of the transform. Perhaps trenchward migration of the volcanic arc in Nicaragua since the Miocene (Weinberg, 1992; Ehrenborg, 1996) has made it more favorable to lengthen or reactivate northeast-trending faults, rather than form a new northwest-striking fault parallel to the arc. The southernmost San Andreas fault system is also characterized by bookshelf faulting between the overlapping San Andreas and San Jacinto fault segments. Earthquake epicenters and focal mechanisms located between these major faults suggest the existence of northeast-striking left-lateral bookshelf faults (Nicholson et al., 1986). These latter faults may have been reactivated on structures from an earlier phase of deformation, to accommodate dextral shear by clockwise, vertical-axis block rotation (Nicholson et al., 1986). In Nicaragua, northeast-trending structures that initially formed during an earlier Miocene phase of deformation may have been reactivated to form the bookshelf faults (Weinberg, 1992; Ehrenborg, 1996), which in a dextral shear zone correspond with an anti-Reidel shear trend, generally the least favorable fault trend in a dextral system.

Damaging historical earthquakes, e.g., the 1931 and 1972 Managua earthquakes, occurred along northeast-striking left-lateral faults, causing more than 13 000 deaths and massive destruction. Although these earthquakes are of lower magnitude than typical plate-interface subduction-zone earthquakes, they may cause more destruction and loss of life due to proximity to population centers located within the arc and forearc. Recent earthquakes in El Salvador (e.g., the February 13, 2001, M_w 6.6 earthquake) may also be located on north-northeast–striking left-lateral faults (Hreinsdottir and Freymueller, 2001). Seismic hazard analyses for Nicaragua, as well as other sections of the Central America volcanic arc, should include hazards associated with slip on northeast-striking left-lateral faults.

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