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Notes

Cenozoic tectonics of the Nicaraguan depression, Nicaragua, and Median Trough, El Salvador, based on seismic-reflection profiling and remote-sensing data

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ABSTRACT

Lakes Nicaragua and Managua are the two largest lakes in Central America, and they cover a combined area of ~9000 km^2 of the presently active Nicaraguan depression and Central America volcanic front. As part of the Subduction Factory focus area of the U.S. National Science "Margins" program, ~1925 km of shallow geophysical data were acquired over Lakes Nicaragua and Managua in May 2006 to establish their late Quaternary structural and stratigraphic history and to better constrain regional models for active tectonics in western Nicaragua, the Gulf of Fonseca, and the Median Trough in El Salvador. In order to investigate regional, upper-crustal deformation resulting from forearc sliver transport and/or slab rollback of the Cocos plate, these new data were integrated with: relocated earthquake epicenters, earthquake focal mechanisms, high-resolution digital topography from the National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM), published global positioning system (GPS) vectors, onland geologic maps, previous maps of lake bathymetry and bottom sediment types, a previously unpublished regional aeromagnetic data set, and multichannel seismic-reflection profiles from the Gulf of Fonseca and Pacific Ocean. These new data sets have improved bathymetric, bottom sediment, and recent fault maps for both Nicaraguan lakes and can be used as new constraints on the regional geology and tectonics. Three regional structural cross sections across the Nicaraguan depression indicate that the basin is a highly asymmetrical half-graben bounded to the southwest by northeast-dipping, oblique-slip normal faults. Late Oligocene to Holocene extension resulted in footwall uplift along the elevated and folded area of the Nicaraguan Isthmus, and the area of greatest subsidence occurs on the footwall block underlying Lake Nicaragua in the southeast. A similar but younger pattern of footwall uplift adjacent to the downthrown footwall block is present to the northeast beneath Lake Managua and the Gulf of Fonseca. We interpret this structural pattern as a time-transgressive rift opening, where the oldest extension (late Oligocene–early Miocene) began in the southeast and migrated to the northwest. GPS data indicate that this earlier phase of intra-arc normal rifting is presently being superimposed by arc-parallel, right-lateral shear related to the northwestward transport of the Central America forearc sliver.

INTRODUCTION

Tectonic Setting

The western boundary of the Caribbean plate is a broad zone of deformation that includes the Middle America Trench and the Central America volcanic front (Molnar and Sykes, 1969). Relatively young (<25 Ma) oceanic crust of the Cocos plate (Protti et al., 1995; Barckhausen et al., 2001) subducts beneath much older continental and oceanic plateau crust of the Caribbean plate in a northeasterly direction at rates of 73–90 mm yr^{-1} (Dixon, 1993; DeMets, 2001) (Fig. 1). The distribution of earthquake epicenters and hypocenters defines the Benioff zone of the subducting Cocos plate, which extends to a depth of ~220 km beneath the volcanic front in El Salvador, Nicaragua, and Costa Rica (Burbach et al., 1984; Protti et al., 1994) (Fig. 2). Slab dip along strike of the Middle America Trench ranges from a more shallow dip (32°–40°) beneath Costa Rica—due to subduction of the thicker and more buoyant Cocos ridge—to steeper dip (75°–80°) beneath central Nicaragua, and to a shallower dip (40°–60°) beneath northern Nicaragua and the Gulf of Fonseca (Figs. 2B–2E) (Protti et al., 1994). An elongate zone of crustal seismicity (<33 km depth) is concentrated within ~25 km of the Central America volcanic front and is produced by either shallow crustal faulting and/or volcanic processes related to the large volcanoes defining the Central America volcanic front (Montero and Dewey, 1982; La Femina et al., 2002) (Fig. 3). Focal mechanisms within this zone of shallow seismicity have been previously interpreted as showing strike-slip motion along the volcanic front consistent with either northeast-oriented, arc-parallel, left-lateral strike-slip motion (White, 1991) or, alternatively, northwest-oriented, arc-transverse, right-lateral strike-slip motion (La Femina et al., 2002) (Fig. 1).

Global positioning system (GPS) results suggest a large-scale counterclockwise rotation of the Central America forearc region as it detaches along a right-lateral strike-slip fault zone coincident with the narrow zone of arc-parallel seismicity parallel to the Central America volcanic front (Turner et al., 2007). Faster GPS velocities with respect to the stable Caribbean are measured southwest of the Central America volcanic front, indicating that the Central America volcanic front is roughly aligned with a major, right-lateral shear zone (Fig. 4). Previous workers have proposed that the Central American forearc region detached from the Caribbean plate along the Central America volcanic front as a "forearc sliver" (Fitch, 1972; Jarrard, 1986) that is currently being transported relative to the Caribbean plate in a northwesterly direction at a velocity of 14 ± 5 mm yr^{-1} in Nicaragua and 8 ± 3 mm yr^{-1} on the Nicoya Peninsula, Costa Rica (Lundgren et al., 1999; DeMets, 2001; Norabuena et al., 2004; Turner et al., 2007).

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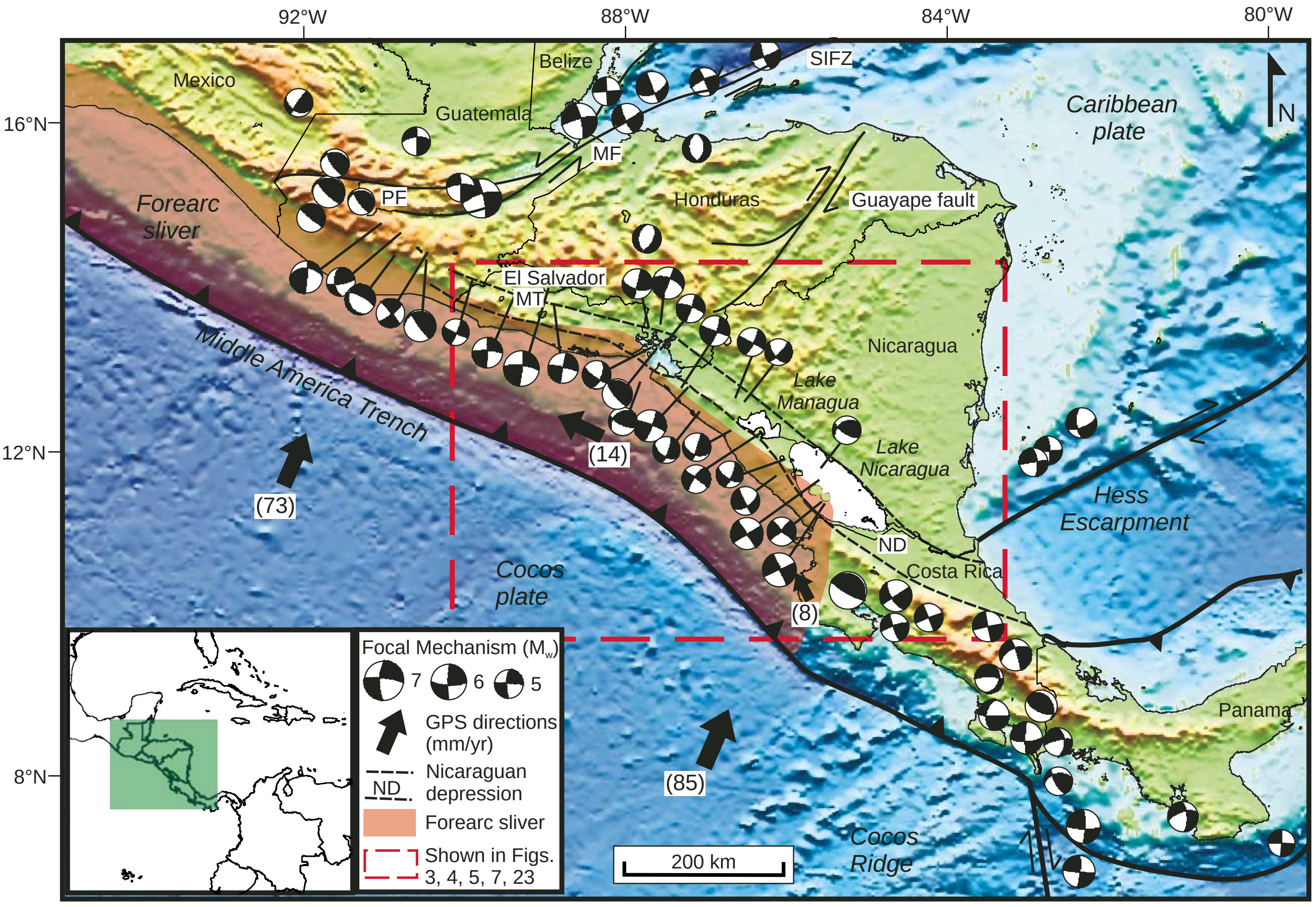


Figure 1. Tectonic setting of Central America displayed on satellite topography and bathymetry from Sandwell and Smith (1997). Subduction of the Cocos plate beneath the Caribbean plate occurs along the Middle America Trench. Global positioning system (GPS)–based plate velocities are relative to a fixed Caribbean plate, and focal mechanisms are from the Harvard Centroid Moment Tensor (CMT) catalog for all events from 1976 to 2007. Northwestward arc-parallel translation of the Central America forearc sliver (red shading) occurs at 7–8 mm yr^{-1} on Nicoya Peninsula of Costa Rica (Norabuena et al., 2004) and 14 mm yr^{-1} in Nicaragua (DeMets, 2001). The boundary between the Caribbean and North American plate occurs along the left-lateral strike-slip Swan Islands fault zone (SIFZ), Polochic fault (PF), and Motagua fault (MF).

Tectonic Geomorphology of the Nicaraguan Depression and Median Trough

A prominent, 40- to 70-km-wide, continuous, late Quaternary depression, which parallels the Central America volcanic front, extends ~1000 km from the Caribbean side of Costa Rica in the southeast to the northern Gulf of Fonseca in El Salvador (Case and Holcombe, 1980; Mann et al., 1990) (Fig. 5). This feature, known as the Nicaraguan depression, is most prominent in Nicaragua, where it is occupied by two shallow but extensive lakes (Nicaragua and Managua) and forms a large marine embayment of the Pacific Ocean in northern Nicaragua and El Salvador (Gulf of Fonseca) (McBirney and Williams, 1965) (Fig. 5B). This depression continues northwest of the Gulf of Fonseca as the Median Trough of El Salvador and Guatemala, which is less geomorphically prominent than the Nicaraguan depression (Carr, 1976; Weyl, 1980). Near the Nicaragua–El Salvador border, the floor of the Median Trough becomes filled with Quaternary lahar deposits, and the active volcanic centers are located near the southwestern boundary fault of the depression (McBirney and Williams, 1965; Weyl, 1980) (Fig. 5).

Objectives of This Paper

The objectives of this paper are to integrate existing geologic data with newly acquired geophysical and sediment core data from the Nicaraguan lakes and the Gulf of Fonseca to provide better constraints on the Oligocene to Holocene tectonic evolution of the volcanic front arc and forearc of Nicaragua and El Salvador. The Nicaraguan lakes and Gulf of Fonseca are critical areas to evaluate regional tectonic models because they provide complete sedimentary records of late Quaternary structural and stratigraphic events in the areas adjacent to the active Central America volcanic front.

PREVIOUS WORK ON THE TECTONIC DEVELOPMENT OF THE NICARAGUAN DEPRESSION

Geologic mapping by McBirney and Williams (1965) and structural analyses by Weinberg (1992) in the area of the Nicaraguan depression

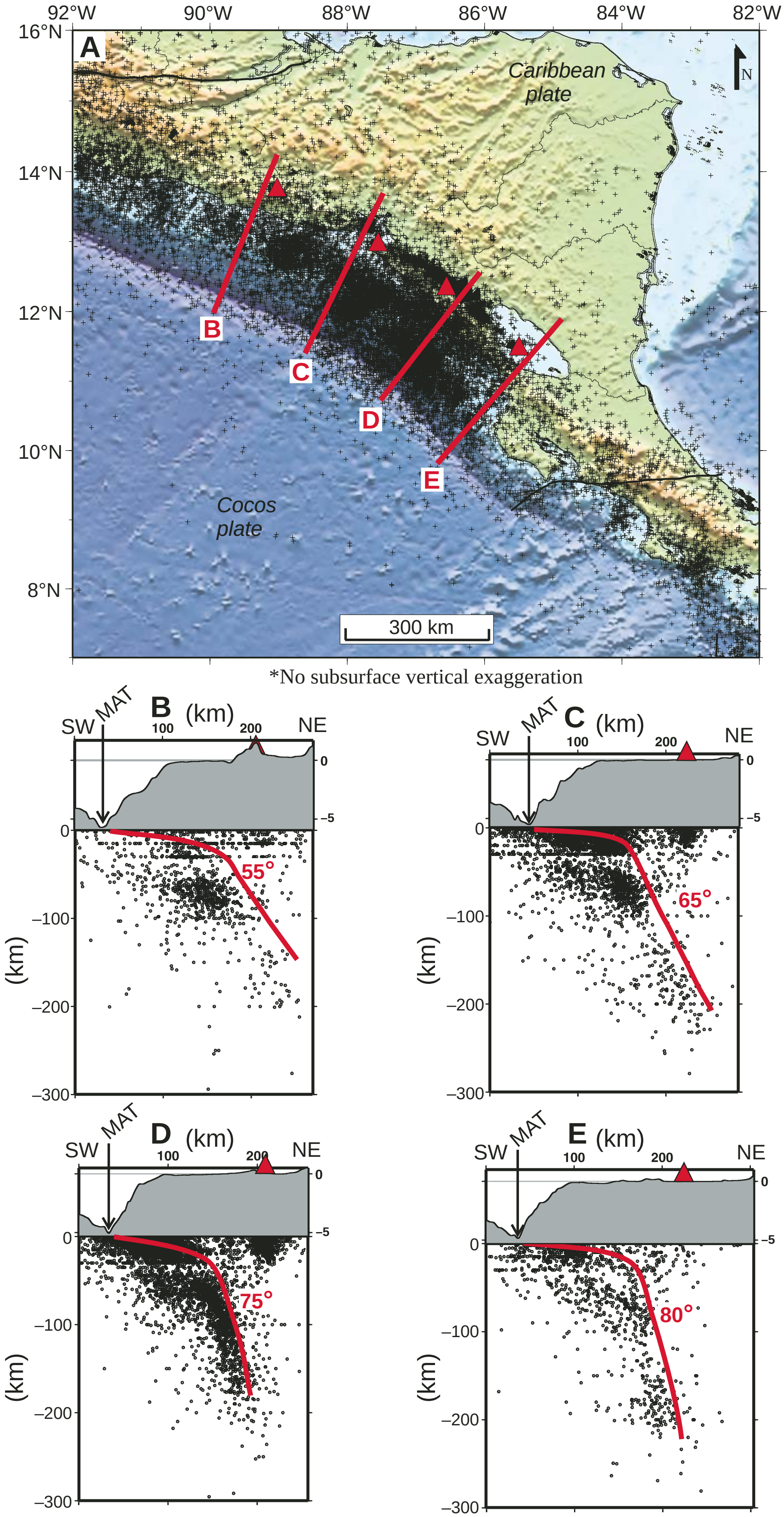


Figure 2. (A) Earthquake locations are from the National Earthquake Information Center (NEIC) and, in Nicaragua, were recorded by the local Nicaragua network from 1995 to 2003 operated by the Instituto Nicaraguense de Estudios Territoriales (INETER). (B–E) Earthquake profiles are perpendicular to the Middle America Trench (MAT) and extend to the interior volcanic highlands of Central America. These profiles merge all earthquakes within a 50-km-wide swath along each transect. Seismic activity beneath the volcanic front in Nicaragua is more evident because of more data from local stations of the Nicaraguan seismic network. These shallow crustal earthquakes commonly occur within the upper 30 km of the crust and are concentrated within ~25 km of the active Central America volcanic front (CAVF).

suggest that the area was affected by three main tectonic phases: Miocene convergence, Pliocene extension, and Pleistocene to present transtensional deformation (Fig. 5).

Miocene Convergent Phase

According to Weinberg (1992), the first phase of deformation affecting the Nicaraguan depression occurred in the late Miocene–early Pliocene and created a series of northwest-trending, 20–30-km-long wavelength, open folds formed in response to trench-perpendicular shortening (Fig. 5). Offshore folds are truncated by an angular unconformity estimated to be of Pliocene age, which correlates with a eustatic sea-level drop, according to published sea-level curves (Ranero et al., 2000). These large folds are mainly located in the Sandino forearc basin, which extends from the shelf area of the Pacific Ocean across the highlands of the Nicaraguan Isthmus to the southeastern margin of the Nicaraguan depression (Ranero et al., 2000). The Rivas and San Cayetano anticlines are the most prominent examples of Miocene convergence on the Nicaraguan Isthmus (Weinberg, 1992) (Fig. 5).

Pliocene Extensional Phase

A second phase of deformation—northeast-southwest Pliocene extension—is the tectonic event most likely responsible for the opening of the Nicaraguan depression and Median Trough as an elongate basin extending from El Salvador to Costa Rica (Weinberg, 1992). Weinberg

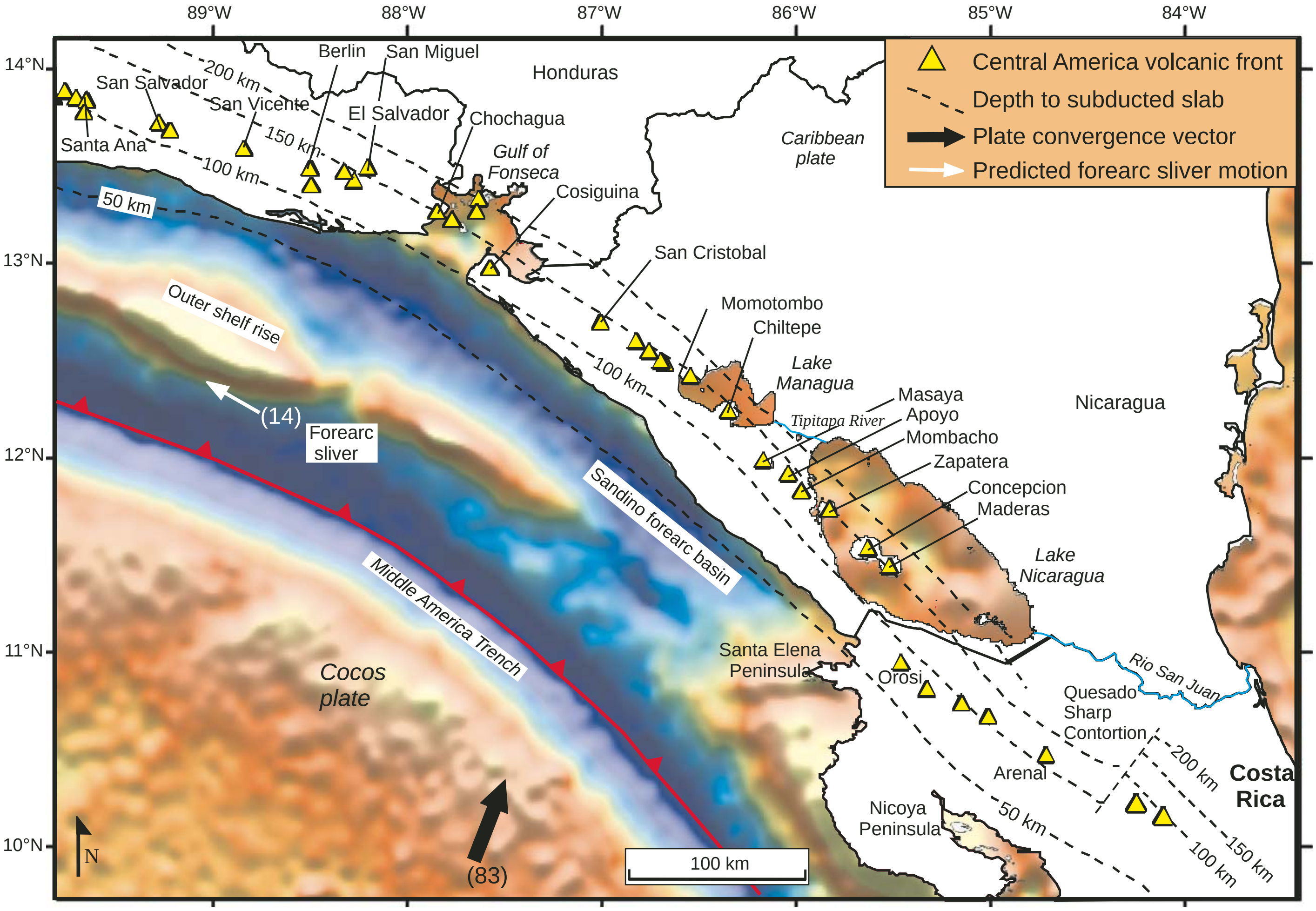


Figure 3. Geosat marine gravity map showing the change in strike of the Middle America Trench, the outer shelf rise, Sandino forearc basin, major Quaternary volcanoes, and trends of Lakes Managua, Nicaragua, and Gulf of Fonseca, which occupy the Nicaraguan depression. Major stratovolcanoes along the Central America volcanic front are marked by yellow triangles. The trend of the Central America volcanic front shows discrete, right-lateral offsets that range in length from 15 to 25 km. Slab contours from Syracuse and Abers (2006).

(1992) proposed that this extensional event may have initiated from an increase in dip of the subducting Cocos slab, a decrease in plate convergence rate, and a reduction in coupling between the Central America forearc and the subducting Cocos plate. According to Schellart (2005), decreased plate velocities or convergence rates will induce slab rollback, or subduction hinge-retreat in a seaward direction, which will in turn produce backarc or intra-arc extension in the overriding plate. During periods of high plate convergence rates, such as those presently calculated for the Cocos plate (up to 90 mm yr^{-1}), rollback of subducting slabs may alternate with phases of subduction hinge-advance to produce episodic pulses of backarc or intra-arc extension. The Nicaraguan depression–Median Trough is an intra-arc basin, rather than a backarc basin, because some of the major stratovolcanoes of the Central America volcanic front are present within the elongate basin rather than to the southwest of them (Taylor, 1995).

The steeper dip of the subducted Cocos slab beneath Nicaragua (75°–80°) supports the interpretation that slab rollback may drive extension of the overlying Caribbean plate along the Nicaraguan depression (Protti et al., 1995; Barckhausen et al., 2001; Rupke et al., 2002) (Figs. 2B–2E). Changes in Cocos slab dip resulting from slab rollback processes can also be inferred from the episodic trenchward migration of the Central America volcanic front since late Oligocene–early Miocene time to its present location within the Nicaraguan depression and Median Trough (Ehrenborg, 1996; Balzer, 1999; Plank et al., 2002) (Fig. 5B).

Nicaraguan Depression Structural Models

The large-scale structure of the Nicaraguan depression has long been a source of controversy due to the lack of subsurface data. There have been several previous models to explain the origin of the depression and its along-strike extension northward into the Median Trough in El Salvador and southward into Costa Rica. The first group of models proposes that the Nicaraguan depression formed either as a symmetrical graben (Cruden, 1988) or asymmetrical half-graben (McBirney and Williams, 1965; Carr, 1976; Weinberg, 1992). Regional extension is attributed to backarc extension and slab rollback in the same direction as northeast-southwest Cocos-Caribbean subduction (Fig. 6A).

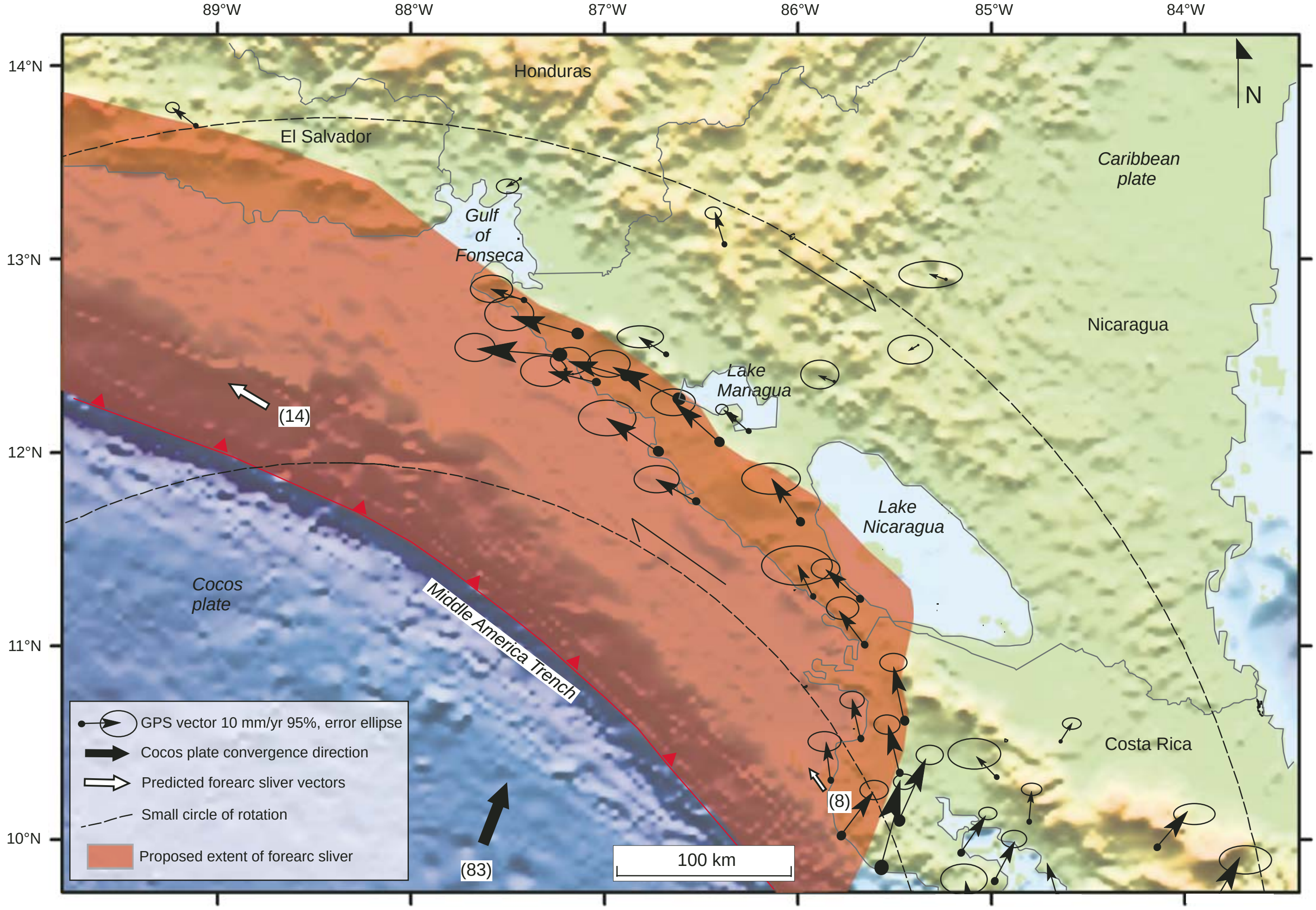


Figure 4. Global positioning system (GPS) plate convergence vectors from DeMets (2001) superimposed on bathymetry and topography from Sandwell and Smith (1997). GPS vectors in Nicaragua are from Turner et al. (2007), and vectors in Costa Rica are from Lundgren et al. (1999) and Norabuena et al. (2004). Most vectors show a uniform pattern of trench-parallel motion of a forearc sliver at 14 ± 5 mm yr^{-1} in Nicaragua and 8 ± 3 mm yr^{-1} in Costa Rica relative to a fixed Caribbean plate. Small circles of rotation are based on the Euler pole (8.9°N, 88.4°W) from Turner et al. (2007).

A different structural model, applied to the Lake Nicaragua segment of the Nicaraguan depression, suggests that the depression was formed by large-scale folding produced by northeast-dipping subduction (van Wyk de Vries, 1993; Borgia and van Wyk de Vries, 2003). In this shortening model, Lake Nicaragua occupies a large syncline between topographically positive areas formed by folding and thrusting to the west of the basin and uplifted Tertiary volcanic rocks to the east (Fig. 6B).

Early Pleistocene to Holocene Transtensional Phase

Weinberg (1992) proposed that the third and present-day phase of early Pleistocene to Holocene deformation affecting the Nicaraguan depression is a right-lateral transtensional regime localized along the Central America volcanic front. This phase resulted in multiple fault families trending both parallel and transverse to the trend of the depression and the Central America volcanic front. Previous workers have interpreted the complex pattern of faults produced during this Pleistocene transtensional period in different ways.

Transform Fault Model

Previous studies of faults in the Nicaraguan depression–Median Trough indicate the presence of a family of northeast-striking faults trending at a high angle to the Central America volcanic front (Carr et al., 1973; Carr, 1976; Carr and Stoiber, 1977). Carr (1976) proposed that tears in the subducting Cocos slab localized transverse faults in the forearc and volcanic arc of the overriding Caribbean plate. Many of these tear-related crustal faults were proposed to be active and strike-slip in character. Dewey and Algermissen (1974) proposed that this transverse fault family was “transform-like” in character and produced strike-slip offsets in the linear trend of the Central America volcanic front (Fig. 7A). They interpreted the transverse, strike-slip faults as ridge-ridge transform faults contained within a secondary backarc spreading zone that was undergoing active northeast-southwest extension. The catastrophic Managua earthquake of 1972 (M = 6.2) occurred on the Tiscapa fault, one of these transverse, northeast-striking, left-lateral strike-slip faults (Brown et al., 1973). In this transform fault interpretation, stratovolcanoes of the Central America

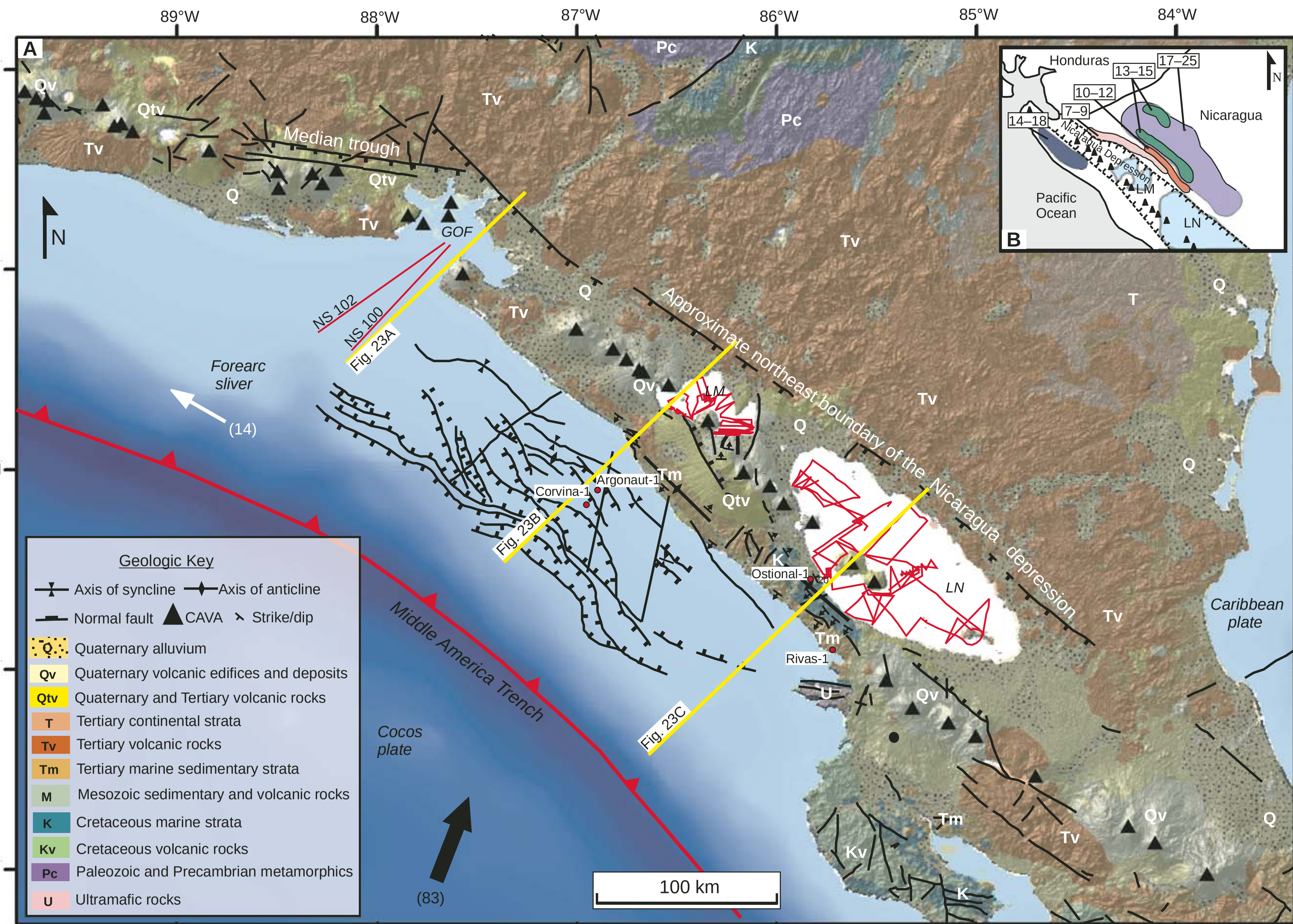


Figure 5. (A) Geologic map of the study area overlain on Shuttle Radar Topography Mission topography processed by Jarvis et al. (2006) and bathymetry by Sandwell and Smith (1997). Onland geology and structure are based on mapping from Case and Holcombe (1980), offshore structure is by Instituto Nicaraguense de Energia (1995), and well locations are from Ranero et al. (2000). (B) Map of dated volcanic deposits based on dates collected from Ehrenborg (1996) and Plank et al. (2002) showing the pattern of trenchward migration of the Central America volcanic front through the Tertiary. The present position of the active Central America volcanic front is located within the low-lying, elongate, and asymmetrical Nicaraguan depression. LM—Lake Managua, LN—Lake Nicaragua.

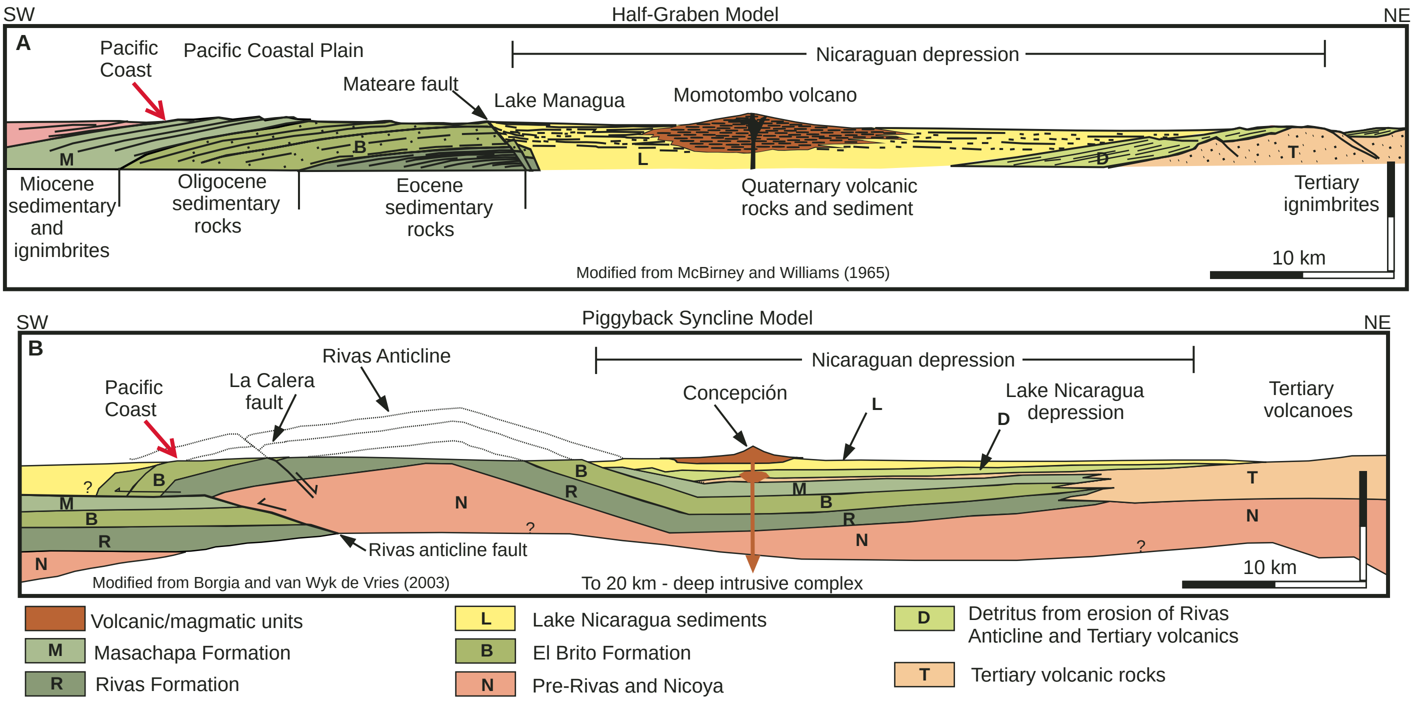


Figure 6. Previous tectonic models for structural deformation of the Nicaraguan depression. (A) McBirney and Williams (1965) first described the depression as a half-graben bound to the southwest by the Mateare normal fault northwest of Managua. (B) Borgia and van Wyk de Vries (2002) proposed that folding occurred along the Lake Nicaragua segment during a convergent phase linked to subduction of the Cocos plate. In this model, the Nicaraguan depression occupies a piggyback basin bound to the west by the Rivas anticline and to the east by the uplifted interior highlands of Nicaragua.

volcanic front are considered to be part of an active rift zone fed by upwelling magma from the region of intermediate-depth earthquakes produced by the subducted Cocos slab beneath Nicaragua (Fig. 7A). The transform fault model also predicts the occurrence of transverse, shallow strike-slip earthquakes localized at distinct offsets along the Central America volcanic front (White, 1991).

Pull-Apart Model

Seismologists interpreted the concentrated belt of shallow seismicity parallel to the Nicaraguan depression as a zone of active right-lateral shear coincident with the trend of the Central America volcanic front (Fig. 2) (Molnar and Sykes, 1969; White, 1991). One fault family within the Nicaraguan depression consists of right-lateral, arc-parallel, strike-slip faults trending N45°-65°W in Nicaragua and N85°E in El Salvador and paralleling the elongate belt of concentrated, crustal seismicity (Carr, 1976; Weyl, 1980; Manton, 1987; Weinberg, 1992) (Fig. 7B). These arc-parallel faults are geomorphically prominent in Guatemala and El Salvador, but they are not as well developed along the Nicaragua–Costa Rica segment of the Central America volcanic front. Most workers assume that this family of arc-parallel strike-slip faults accommodates large-scale right-lateral shear associated with the northwestward migration of the Central America forearc sliver at rates ranging from 7 to 8 mm yr^{-1} in northern Costa Rica to 14 mm yr^{-1} in northern Nicaragua (Lundgren et al., 1999; DeMets, 2001; Norabuena et al., 2004).

Conceptually, the main arc-parallel strike-slip fault bounding the Central American forearc sliver would likely form along the thermally weakened and thinned crust of the volcanic front; strike-slip faulting may create pull-apart basins at transverse offsets in the volcanic front (Genrich et al., 2000). These pull-apart basins would be typically bounded by transverse normal faults that may localize the eruption of large stratovolcanoes as predicted in experimental studies (Girard and van Wyk de Vries, 2005) (Fig. 7B).

Basin-bounding faults form the third observed fault family in the Nicaraguan depression, consisting of N15°W-N10°E–striking normal faults bounding north-south–oriented grabens, including the prominent Managua graben (Fig. 7B). Many faults in this orientation produce prominent alignments of volcanic craters, including the Nejapa-Miraflores volcanic alignment to the west of Managua (McBirney and Williams, 1965) and prominent faults like the Aeropuerto and Cofradía faults east of Managua (Cowan et al., 2002).

Alternatively, many of these deep localized basins in northern El Salvador and Honduras may result from east-west extension driven by larger-scale rifting of the triangular corner of the northwestern Caribbean plate (Guzman-Speziale, 2001) (Fig. 1). The interplay between east-west rifting of the Caribbean plate and transtensional faulting of the Median Trough and Nicaraguan depression is not well understood because the two sets of rifts are adjacent to one another and are opening in roughly the same direction (Fig. 1).

Bookshelf fault model. La Femina et al. (2002) interpreted the pattern of shallow earthquake distribution and associated focal mechanisms along the Nicaraguan depression as evidence for left-lateral transverse or “bookshelf faulting,” which accommodates the northwestwardly, strike-slip transport of the Central America forearc sliver (DeMets, 2001) (Fig. 7C). The bookshelf fault model predicts distributed left-lateral faulting on a set of parallel, northeast-striking, left-lateral faults. Rotation of transverse crustal blocks occurs in the

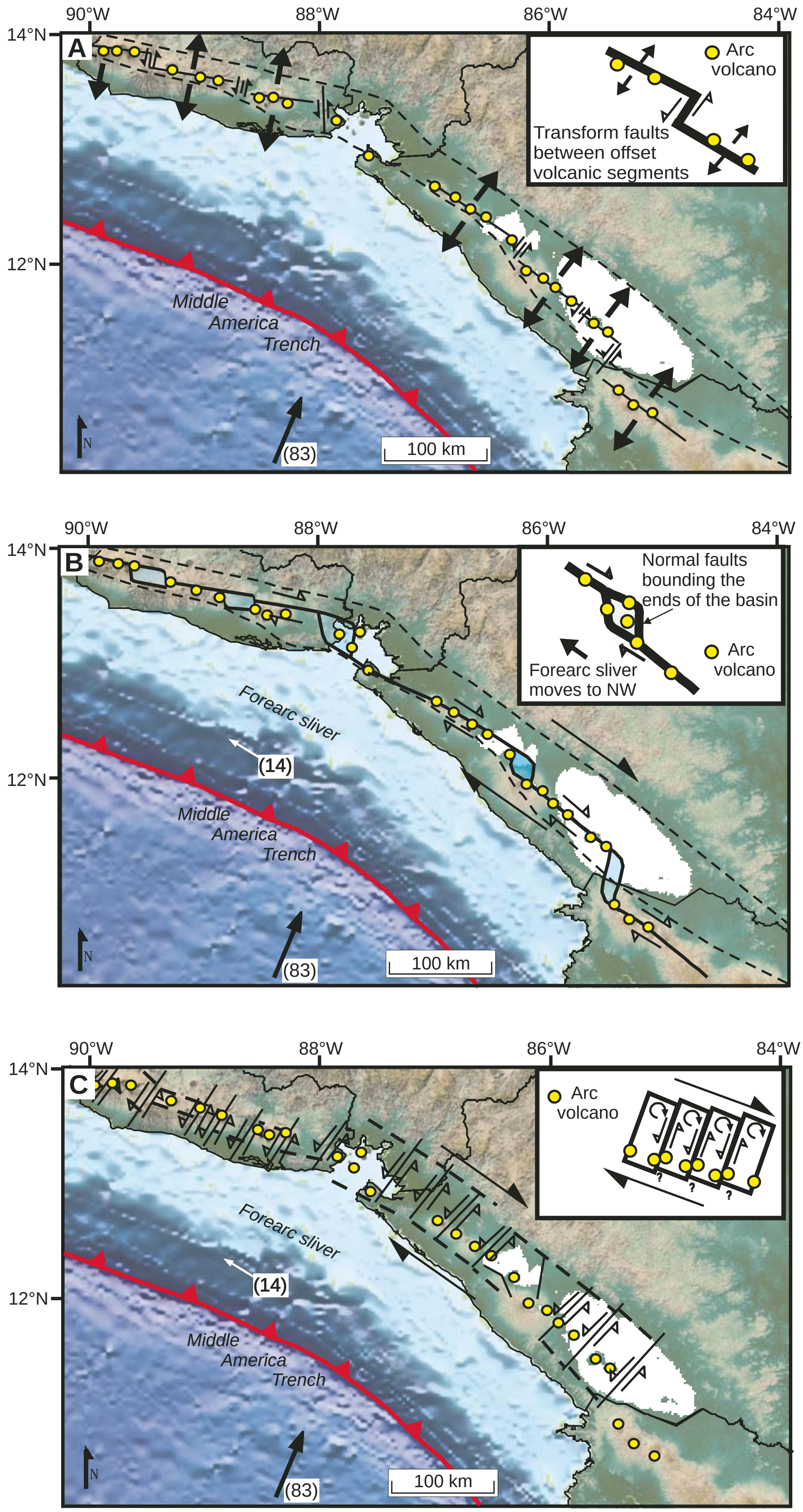


Figure 7. Previous tectonic models for the Nicaraguan depression: (A) The transform fault model was first proposed by Dewey and Algermissen (1974) to explain the segmented offsets of the Central America volcanic front by ridge-ridge transform faults. (B) The pull-apart model suggests northwestward transport of the Central America forearc sliver, which detaches from the western Caribbean plate due to right-lateral shear concentrated along the thermally weakened Central America volcanic front. Extension becomes localized at fault stepovers, resulting in pull-apart structures. (C) The bookshelf faulting model suggested by La Femina et al. (2002) explains right-lateral transport of the Central America forearc sliver by a series of rotating crustal blocks bounded by parallel, left-lateral faults.

same manner that collapsing books on a shelf can produce an overall right-lateral translation, and this mechanism is acting on the Central America forearc sliver (La Femina et al., 2002). In the bookshelf model, the alignment of volcanoes along the Central America volcanic front is predicted to show left-lateral offsets at crustal block boundaries (Fig. 7C). However, almost all apparent offsets of the Central America volcanic front show right-lateral offsets (Fig. 5).

PREVIOUS GEOLOGIC STUDIES OF THE NICARAGUAN DEPRESSION AND MEDIAN TROUGH

Studies of Lakes Nicaragua and Managua

Limited geophysical or sediment core data have been collected from the Nicaraguan lakes or the Gulf of Fonseca. The first major survey of the Nicaraguan lakes was by Swain (1966), who collected 62 cores from Lake Nicaragua and 7 cores from Lake Managua to investigate the possibility of past marine incursions into the lakes from either the Caribbean Sea or Pacific Ocean. Results from this survey produced the first and only published bathymetric map for Lake Nicaragua (scale 1:24,000, contour interval 5 m) (Swain, 1966). Coring indicated that a uniform diatomaceous layer blanketed the bottoms of both lakes and was used to propose that neither lake had any recent connection to either the Caribbean Sea or Pacific Ocean. An unpublished bathymetric map for Lake Nicaragua was completed in 1972 by the Nicaraguan Hydrographic Department of the Instituto Nicaraguense de Estudios Territoriales (INETER) (scale 1:400,000; contour interval 1 m). INETER also produced an unpublished bathymetric map of Lake Managua in 1979 (scale 1:50,000; contour interval 1 m). We have digitized and incorporated all of these previous bathymetric and bottom sediment maps into our database.

To our knowledge, the only previous geophysical data collected on the Nicaraguan lakes were in 1998 in a small area of Lake Nicaragua near Ometepe island using a 1-in.^{3} air gun and a single-channel hydrophone streamer (N. Wattrus, 2007, personal commun.). Results from this survey were handicapped by their inability to achieve any seismic penetration due to either thick volcaniclastic sediments near the lake bottom or by the presence of impenetrable methane gas.

Gulf of Fonseca

To our knowledge, there were no previous geologic or geophysical surveys in the Gulf of Fonseca prior to the NicStrat survey by K. McIntosh in 2004 (RV *Maurice Ewing* cruise EW0412) (Fig. 5). This survey acquired high-resolution multichannel seismic-reflection, gravity, and magnetic profiles across the Central America volcanic front and into the center of the Gulf of Fonseca (McIntosh and Fulthorpe, 2005).

Satellite Imagery

We used high-resolution remote-sensing satellite images to examine the geomorphic expression of faults, lineaments, drainages, stratal dips, and other surficial features in the region. Frischbutter (2002) previously used remote-sensing and seismological data from the Managua area to develop a kinematic model for the tectonic evolution of the "Managua graben." Several previous studies (Martinez-Diaz et al., 2004; Corti et al., 2005; Agostini et al., 2006) have mapped right-lateral strike-slip fault zones in El Salvador using remote-sensing data combined with field studies.

Well Data

The only onshore well with a sedimentary record of the Nicaraguan depression is a geothermal well drilled near the northern end of Lake Managua on Momotombo volcano (M. Traña, 2006, personal commun.). This well penetrates ~2 km of strata through the depression and is thought to have penetrated the Oligocene–Miocene–age Masachapa Formation, a marine, clastic formation that has been studied in outcrops on the western limb of the San Cayetano anticline along the Pacific coast of Nicaragua (Weinberg, 1992) (Fig. 5). We were unable to locate the location, well log, or other reports that documented this well.

There have been several oil exploration wells drilled along the Pacific coast and in the near-shore area. Their locations are shown on the map in Figure 5, and well logs have been reproduced from a well compilation by Ranero et al. (2000). We were not able to locate the original well data and relied entirely on the compilation by Ranero et al. (2000).

Seismological Studies

Previous studies involving earthquake relocations and focal mechanism solutions in the Nicaraguan depression have focused on either subduction-related intermediate to deep earthquakes formed by the Benioff zone of the subducted Cocos plate or crustal-depth earthquakes that form a belt of earthquakes parallel to the Central America volcanic front (Figs. 1 and 2A). Profiles of subduction-related seismicity exhibit along-strike changes in slab dip of the Cocos plate and a sharp break in the subducted Cocos slab at the Quesada sharp contortion (QSC) near the southeastern end of Lake Nicaragua in northern Costa Rica (Protti et al., 1995) (Fig. 3). Studies involving upper-crustal seismicity aligned along the thermally weakened volcanic arc have largely been driven by the possibility of the recurrence of destructive earthquakes along the axis of the Nicaraguan depression and the Median Trough, including the 1986 San Salvador earthquake (M = 5.7) in El Salvador and the 1972 Managua earthquake (M = 6.2) (Genrich et al., 2000).

Potential Fields and Studies of Crustal Structure

Magnetotelluric and gravity data were collected and analyzed by Elming and Rasmussen (1997) to develop a two-dimensional (2-D) model for the crustal structure of the western margin of Nicaragua. They proposed that the Pacific coast is an accreted terrane and estimated ~2.5 km of vertical fault offset along a 300-km-long, arc-parallel normal fault to form the Nicaraguan depression. Walther et al. (2000) also used gravity anomalies combined with wide-angle seismic data to develop a 2-D crustal-scale velocity model for the western margin of the Caribbean plate in Central America. They proposed that a previous, upper Cretaceous–Paleocene trench became inactive due to the attempted subduction of a buoyant oceanic plateau. As a result of this "choking" event, the location of the current Middle America Trench jumped seaward of the accreted oceanic plateau. These Cenozoic changes in trench position allowed the Central America volcanic front to migrate in the Quaternary to its present position in the Nicaraguan depression (Fig. 3B).

Fault Trenching and Paleoseismology

One of the first and most comprehensive fault mapping and trenching surveys of the Nicaraguan depression was completed by Woodward-Clyde Associates (1975) in the aftermath of the 1972 Managua earthquake. This group made numerous fault excavations of fault scarps in the environs of the city of Managua to identify a family of north-northeast–striking active faults. More recent fault trenching by Cowan et al. (2002) across the north-northeast–striking Aeropuerto fault shows 0.3–0.9 mm yr^{-1} of vertical slip rate and possibly up to 5 mm yr^{-1} of left-lateral strike-slip motion.

Models Relating Regional Stress and Strain to Volcanoes and Faulting

Lagmay et al. (2000) related volcanic morphology to the regional tectonic stress field of Nicaragua. They related the occurrence of surficial faults and fissures on volcanic edifices in Nicaragua to principal strain axes and to the relative motions of underlying basement faults (Nakamura, 1977; Moriya, 1980; Siebert, 1984). Subsequent analog modeling by van Wyk de Vries and Merle (1998), Lagmay et al. (2000), and Girard and van Wyk de Vries (2005) has suggested a close relationship between volcanic deformation and the localization of pull-apart basins along the Central America volcanic front in Nicaragua. Results from Cailleau et al. (2007) used changes in Coulomb failure stress on strike-slip faults between Nicaraguan volcanic centers to explain transverse faulting along the Central America volcanic front. They suggest that stress is transferred from the mechanically weak volcanic centers to the mechanically strong crust separating the volcanic centers to produce earthquakes along northeast-striking left-lateral strike-slip faults.

DATA ACQUISITION AND PROCESSING

Data Sets

Two different geophysical data sets collected by The University of Texas at Austin Institute for Geophysics (UTIG) in 2004 and 2006 were used in the analysis of the Nicaraguan depression in the lake areas and Gulf of Fonseca. These data include ~1925 km of shallow geophysical data collected during the 2006 NicLakes survey of Lakes Managua and Nicaragua (principal investigators: McIntosh and Mann) and ~163.5 km from the 2004 NicStrat high-resolution seismic survey in the Gulf of Fonseca (principal investigators: McIntosh and Fulthorpe). Both surveys were collaborative efforts between UTIG and INETER.

NicLakes Seismic Acquisition and Processing

The 2006 NicLakes survey includes 48 lines of high-resolution multichannel seismic-reflection data in Lake Nicaragua and four multichannel seismic-reflection lines in Lake Managua. The seismic receiver was a 74.1-m-long, 24 channel analog streamer manufactured by Beam Systems, Inc., of Pearland, Texas. The source was a 5–20 in.^{3} Bolt 600B air gun controlled by a Bolt FC120 air gun firing box. Data were recorded with a 1 s record length using SGOS by Geometrics software and processed using Paradigm Geophysical's Focus® software.

The processing of seismic data from both lakes was challenging as a result of insufficient acoustic penetration. This problem was most likely related to thermally or biogenically induced gas-charged sediments, which are a common problem in lake settings (Davy, 1992). The processing sequence included: (1) static correction; (2) a 40–60–400–500 trapezoidal band-pass filter capturing the target frequencies of ~220 Hz; (3) trace editing due to faulty hydrophones; (4) velocity analysis; (5) normal moveout (NMO) correction; (6) automatic gain control; and (7) a t^2 gain function. The surface-related multiple attenuation technique (SMAC in Focus®) was applied to prestack shot gathers to remove kinematically predicted multiples by computing several terms of Taylor expansion (Verschuur, 1991; Verschuur et al., 1992).

Subbottom Profiler Acquisition and Processing

The subbottom profiler lines were collected using a 3.5 kHz transceiver manufactured by DPS Technology, a 2 kW MASSA TR 1075A transducer, and Digital USB o/p. Data were recorded primarily using commercially available DR GEO data acquisition software with a record length of 90 ms, a 22,050 Hz sampling frequency, and target frequencies at ~3000–4000 Hz. Due to complications during the cruise, six profiles in Lake Managua were acquired using commercially available Audacity® data acquisition software. The processing sequence for these lines included: (1) a direct current (DC) bias removal; (2) a 1500–2200–5000–6000 Hz trapezoidal band-pass filter; (3) deconvolution; and (4) automatic gain control. The deconvolution was multichannel, minimum-phase, band-pass, spiking deconvolution applied to seismic traces according to the Wiener-Levinson algorithm with a 35 point operator length and 800–5000 Hz band-pass filter (Yilmaz, 2000).

Sidescan Sonar Data

A high-resolution Imagenex Model 872 "Yellowfin" sidescan sonar unit was used to acquire high-resolution sonar images of the lake floor of Lake Managua. Because of equipment malfunction, the sidescan sonar was not available for the Lake Nicaragua survey. The acquisition tool, or "fish," was towed at ~1 m depth, and data were recorded on a laptop operating Yellowfin acquisition software. The extremely shallow water depths (often <5 m) limited the lateral extent of the coverage.

NicStrat Seismic Acquisition and Processing

We also used two lines of high-resolution multichannel seismic-reflection data from the 2004 NicStrat survey in the Gulf of Fonseca in this study. The acquisition parameters and processing sequence for the Gulf of Fonseca seismic data were developed by researchers at UTIG. These profiles were collected with three 45 in.^{3} GI air guns, towed at 2.5 m depth and with 12.5 m shot spacing. The receiver was a 2100-m-long, 168 channel streamer with 12.5 m channel spacing, recording 4.0 s of data with 1.0 ms sampling rate. The dominant frequencies captured were between 30 and 140 Hz with resolution to ~5 m. These data were processed in two phases: (1) standard poststack Kirchoff time migration; and (2) a more sophisticated prestack time-migration routine that also included the SMAC (Focus®) multiple attenuation technique.

DATA SETS AND SYNTHESIS

The data synthesized in this tectonic study of Central America extends ~700 km across northern Costa Rica, Nicaragua, and El Salvador (Fig. 1). Integrated data sets used in this study include the 2006 NicLakes shallow geophysical data in Lakes Nicaragua and Managua, offshore Nicaragua multichannel seismic data from the 2004 NicStrat survey, earthquake distributions from the National Earthquake Information Center (NEIC) database center and the Nicaraguan local network (Fig. 2), earthquake focal mechanism solutions from the Harvard Centroid Moment Tensor (CMT) catalog (Fig. 1), Shuttle Radar Topography Mission (SRTM) topographic images, an aeromagnetic data set acquired by Superior Oil Associates west of Lake Nicaragua, and a marine depth soundings chart from the Gulf of Fonseca collected by the Defense Mapping Agency Hydrographic Topographic Center.

These data sets were integrated using ArcGIS and IVS-3D Fledermaus software to create a three-dimensional model of the entire region that allowed "fly-throughs" in three dimensions. The following section is divided into the major segments of the Nicaraguan depression–Median Trough including: (1) the El Salvador segment; (2) the Gulf of Fonseca segment; (3) the Lake Managua and Marabios Cordilleran segment; and (4) the Lake Nicaragua and northern Costa Rica segment.

Fault Segments of the El Salvador Right-Lateral Strike-Slip Fault Zone

The Benioff zone along this segment of the Cocos-Caribbean subduction zone has a relatively shallow dip (~55° as shown in Fig. 2B) and a slight oblique convergence angle of ~2°–3°, based on the plate convergence direction from DeMets (2001) (Fig. 1). The main zone of active displacement in the Median Trough occurs along the right-lateral El Salvador strike-slip fault zone, which is geomorphically prominent and has been well studied in central El Salvador (Martinez-Diaz et al., 2004; Corti et al., 2005; Agostini et al., 2006). Mesoscale fault orientations measured along the El Salvador strike-slip fault zone are consistent with their interpretation as Riedel shears (170°–180°–striking population), anti-Riedel shears (130° population), and shear and tensional fractures (110° population) (Corti et al., 2005). Previous studies on the El Salvador fault zone have divided the fault into the San Vicente segment, Berlin segment, and San Miguel fault segment to the east of San Miguel volcano (Fig. 8A). There has been little work on the El Salvador fault zone outside these geomorphically prominent and well-studied segments.

On the basis of remote sensing, we propose two additional segments of the El Salvador fault zone, the Santa Ana and San Salvador segments of western El Salvador, and a new structural interpretation for the San Miguel segment (Fig. 8B). All segments of the El Salvador fault zone parallel an elongate zone of crustal earthquakes as shown in Figure 8C.

Santa Ana Fault Segment

Defined in Figure 8A, this strike-slip segment extends ~65 km from Rio Paz along the western Guatemalan border to the Santa Ana volcano in

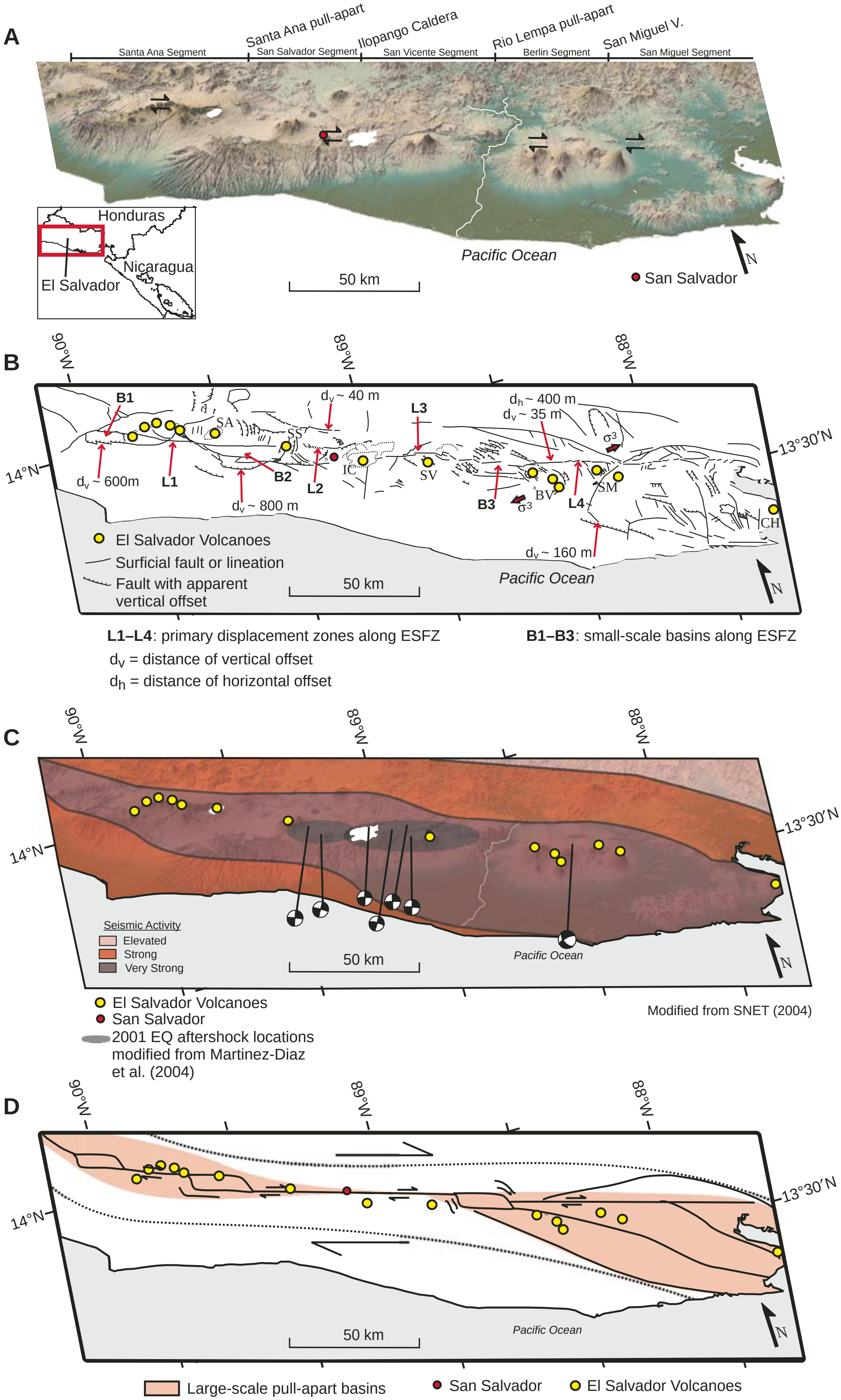


Figure 8. (A) Oblique view on Shuttle Radar Topography Mission topographic map of the El Salvador fault zone (ESFZ) extending from the Gulf of Fonseca to the western border of El Salvador. (B) Interpretation of the El Salvador fault zone based on the SRTM topography and satellite images from LANDSAT and Google Earth. SA—Santa Ana volcano, SS—San Salvador volcano, SV—San Vicente volcano, BV—Berlin volcano, SM—San Miguel volcano, CH—Chochagua volcano, IC—Illopongo caldera. (C) Map from Servicio Nacional de Estudios Territoriales SNET (2004) displaying the distribution of seismicity across El Salvador. Focal mechanisms are from the Harvard Centroid Moment Tensor (CMT) catalog for all events from 1976 to 2007. The main aftershocks from the February 2001 San Salvador earthquake occurred primarily along the San Salvador and San Vicente segments of the El Salvador fault zone (Martinez-Diaz et al., 2004). (D) Proposed transtensional pull-apart model from this paper. Two main deformation zones are characterized by large-scale pull-apart basins along a straight right-lateral strike-slip fault passing through Ilopango caldera. Within the large pull-apart basins, there are several smaller-scale pull-apart basins. Late Quaternary volcanic deposits likely obscure many recent faults.

the east (labeled SA in Fig. 8B). There is no recent seismicity associated with this fault segment; however, several fault lineaments offset Quaternary deposits and drainages (Fig. 8A). In the west, there is ~600 m of apparent vertical fault offset defining a linear mountain front that tilts Neogene strata to the southwest and forms a young basin to the north (labeled B1 in Fig. 8B). This basin originally drained to the north along several valleys, but these drainages are now diverted to the northwestern Rio Paz by an unnamed east-west–trending, right-lateral fault (Fig. 8A). This unnamed fault (labeled L1 in Fig. 8B) also strikes eastward through cinder cones near Santa Ana stratovolcano. The cinder cones are cut by closely spaced east-west–striking faults that project eastward from Santa Ana volcano (Fig. 8B). Santa Ana volcano exhibits north-northwest–striking faults bounding the northeastern edge of the complex, suggesting regional extension in a direction of ~65°, consistent with the proposed regional extensional direction of Corti et al. (2005) (Fig. 8B). East of Santa Ana volcano, another unnamed basin occupies this area of the Median Trough at a 10-km-wide trenchward step in the volcanic front between the Santa Ana segment and the San Salvador segment (labeled B2 in Fig. 8B). This unnamed basin exhibits west-northwest–striking faults and is bounded to the south by a steep, fault-bounded uplift with ~800 m of vertical relief.

San Salvador Fault Segment

The region bounded by Ilopango caldera and San Salvador volcano (labeled IC and SS, respectively, in Fig. 8B) is called here the San Salvador fault segment of the El Salvador fault zone. The San Salvador segment is characterized by several active fault zones that cut through Holocene volcanic deposits localized within a broad, topographic basin (Fig. 8A). This part of the basin is bounded to the south by south-dipping Tertiary volcanic rocks that exhibit apparent fault-related, topographic relief of ~800 m along the adjacent Median Trough (Fig. 8A). The northern basin boundary is controlled by a fault that is ~25 km long with ~40 m of vertical topographic relief (Fig. 8B). A fault between the southern and northern faults shows negligible vertical offset and an unknown horizontal component (labeled L2 in Fig. 8B). This middle fault projects directly from San Salvador volcano into Ilopango caldera, which represents the eastern end of the San Salvador segment and lies directly on the trend of an east-west strike-slip fault (Fig. 8B). Aftershocks from the February 2001 (M = 6.6) earthquake are located along this fault segment, form a cluster of earthquakes trending approximately east-west, and are consistent with an east-west, right-lateral rupture plane along this fault, as indicated by focal mechanism solutions (Martinez-Diaz et al., 2004) (Fig. 8C). This recent seismic activity suggests that this part of the segment is seismically active and currently accommodating right-lateral strike-slip motion as predicted by the Central America forearc sliver model (DeMets, 2001).

San Vicente Fault Segment

Although focal mechanisms within this segment are consistent with both the bookshelf and east-west shear zone–pull-apart model, we prefer to interpret the aftershock sequences from the 2001 San Salvador earthquake (Fig. 8C) as a continuous, east-west–striking right-lateral strike-slip fault zone (labeled L3 in Fig. 8B) extending from San Salvador volcano in the west to Rio Lempa in the east (Martinez-Diaz et al., 2004). The eastern end of the San Vicente fault segment is marked by the Rio Lempa pull-apart basin, described in detail by Martinez-Diaz et al. (2004). The Rio Lempa is one of the main drainages crossing the El Salvador fault zone, and it shows a prominent ~10 km right-lateral offset within the Rio Lempa pull-apart basin. The Rio Lempa pull-apart basin (labeled B3 in Fig. 8B) formed at a major trenchward stepover in the volcanic front and shows extensional features consistent with the regional extension direction proposed by Corti et al. (2005).

Berlin Fault Segment

Along this ~45 km segment of the El Salvador fault zone, the primary displacement zone (labeled L4 in Fig. 8B) strikes parallel to and just north of the Central America volcanic front in eastern and central El Salvador and exhibits ~35 m of apparent down-to-the-south vertical displacement (Corti et al., 2005). The Berlin segment extends from the Rio Lempa pull-apart structure to San Miguel volcano in the east (Fig. 8A). Work by Corti et al. (2005) shows a late Pleistocene–Holocene horizontal slip rate for the Berlin segment of ~11 mm yr^{-1} and 400 m of mapped lateral offset of drainage patterns. This segment does not exhibit a conspicuous parallel belt of shallow seismicity, such as that found along the San Vicente segment, but the Berlin segment does lie within a more diffuse zone of crustal seismicity described by Servicio Nacional de Estudios Territoriales (SNET) (2004) (Fig. 8C). Following Corti et al. (2005), we propose that this fault segment may be aseismically creeping or locked.

San Miguel Fault Segment

East of San Miguel volcano, the El Salvador fault zone becomes diffuse, and there is a 30–40 km trenchward right-step in the Central America volcanic front to Chochagua volcano (labeled SM and CH in Fig. 8B). The arc-parallel, main trace of the fault zone projects along the eastward continuation of the Berlin segment of the El Salvador fault zone into the northern extent of the Gulf of Fonseca. Stratovolcanoes cluster near the intersection of two main faults: one volcanic cluster parallels the east-west–oriented El Salvador fault zone; the other cluster parallels a northwest-southeast–striking fault exhibiting ~160 m of apparent vertical displacement with adjacent Tertiary-aged beds dipping seaward (Fig. 8A). The San Miguel segment marks a major change in the overall strike of the El Salvador fault zone, from mainly east-west–striking fault segments in El Salvador to northwest-southeast–striking fault segments along the Central America volcanic front in Nicaragua.

Faulting in the Gulf of Fonseca Region

The Gulf of Fonseca, which is surrounded by Nicaragua, Honduras, and El Salvador, is a shallow (<20 m depth) marine embayment of the Nicaraguan depression located landward of a major change in trend of the Middle America Trench (Fig. 9A). Chochagua volcano (labeled CH in Fig. 9B) and the El Salvador fault zone define the western shores of the Gulf of Fonseca, and Cosiguina volcano forms its southeastern shore (labeled CGV in Fig. 9B). The Gulf of Fonseca occupies a tectonic transition zone between the east-west–trending El Salvador fault zone and the northwest-southeast–trending Central America volcanic front in Nicaragua (Fig. 9B). Our bathymetric map of the Gulf of Fonseca is based on depth soundings digitized from a map by Hradecky et al. (2001) of the Defense Mapping Agency Hydrographic Topographic Center and was georeferenced with other data and used for three-dimensional (3-D) visualization.

Surficial Deformation

In Nicaragua, the volcanic front makes a 15-km-wide step from the Marabios Range to Cosiguina volcano. A 25-km-wide zone of highly deformed Tertiary volcanic rocks lies within the fault stepover area, which is consistent with localized shortening in a strike-slip restraining bend (labeled F1 in Fig. 9B). This deformed zone extends northwestward near Cosiguina stratovolcano where two major faults on the southern volcanic edifice horizontally offset drainage patterns by ~100 m (labeled F2 and F3 in Figs. 9B and 10). These faults project into the Gulf of Fonseca and align with isolated bathymetric highs (~5 m) displayed on the

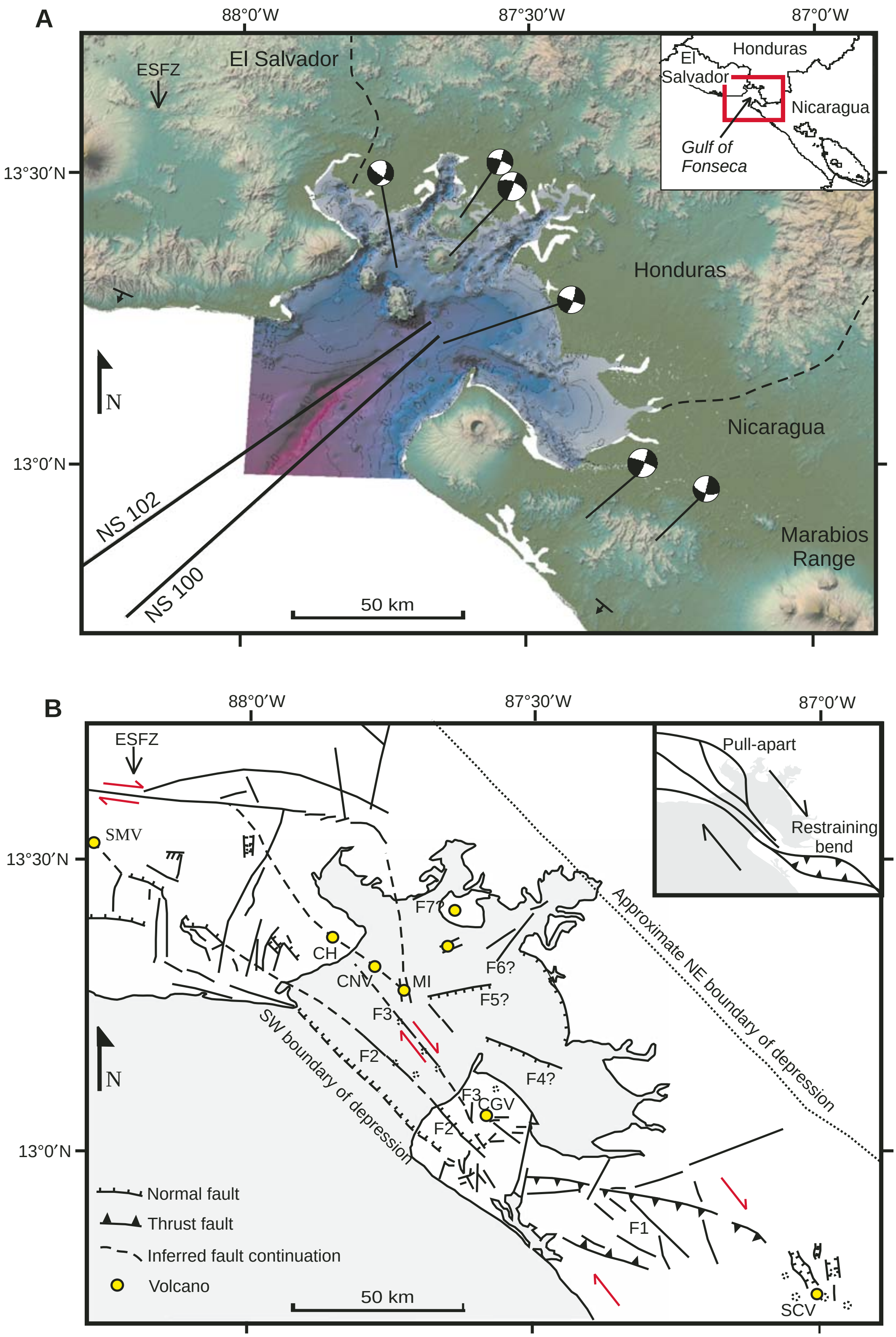


Figure 9. (A) Gulf of Fonseca showing focal mechanisms from the Harvard Centroid Moment Tensor (CMT) catalog, Shuttle Radar Topography Mission imagery, and bathymetry digitized from the Defense Mapping Agency Hydrographic Topographic Center (1996, scale 1:5000). Subsurface geology was integrated using two multichannel seismic-reflection lines collected during the EW0412 NicStrat cruise by McIntosh and Fulthorpe (2005). (B) Structural interpretation based on Case and Holcombe (1980), SRTM and Landsat images, and subsurface faults mapped on reflection lines NS102 and NS100 (Figs. 11 and 12). F1 represents a large restraining bend as the forearc sliver boundary curves from Cosiguina volcano (CGV) to the Marabios Range, beginning with San Cristobal volcano (SCV). F2 and F3 are two large faults with significant vertical offsets on late Quaternary deposits of the Cosiguina volcano; both faults project into the Gulf of Fonseca near Meanguero Island (MI), Conchaquito volcano (CNV), and Chochagua volcano (CH). Both faults align with linear highs on bathymetric maps and subsurface faults seen on seismic-reflection lines. F4–F7 are lineaments in the Gulf of Fonseca that we interpret as either faults or fluvial channels incised during lowstands of sea level. The inset map shows a tectonic interpretation for the Gulf of Fonseca area where the proposed forearc sliver boundary changes its strike between faults of the Median Trough in El Salvador and faults of the Nicaraguan depression in northern Nicaragua. ESFZ—El Salvador fault zone, SMV—San Miguel volcano.

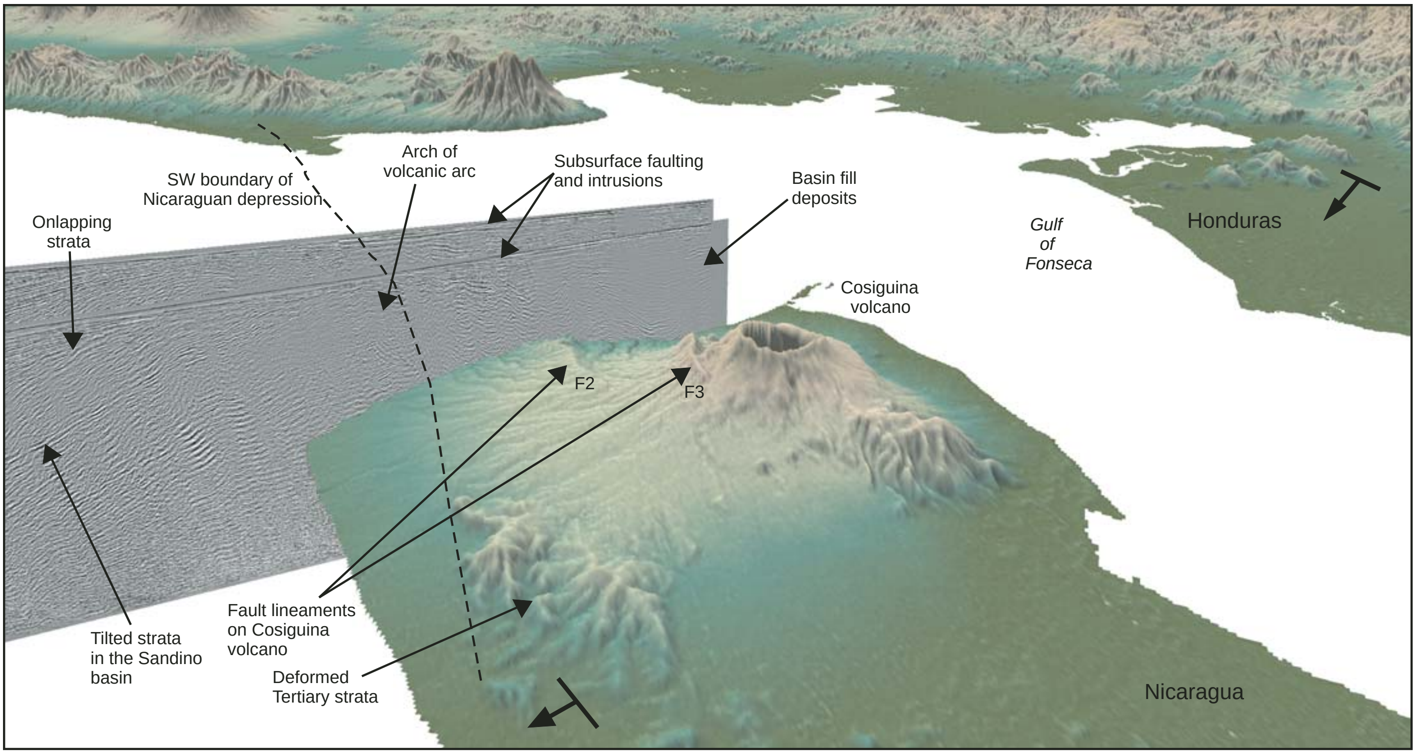


Figure 10. Oblique view of the Gulf of Fonseca displaying Shuttle Radar Topography Mission imagery and multichannel seismic-reflection profiles. Seismic-reflection lines in the offshore Sandino basin exhibit onlapping strata indicating an uplift event of pre-Miocene age (Stephens et al., 2007). Locally uplifted onland strata southwest of Cosiguina volcano are indicative of restraining bend deformation along a curving strike-slip segment as shown schematically on the inset in Figure 9B. Several fault lineaments (F2 and F3) trend from the inferred restraining bend area into Cosiguina volcano; these faults produce scarps with significant vertical throws that affect drainages on the flanks of the volcanic edifice. The fault lineaments project into the Gulf of Fonseca and correlate with several linear bathymetric highs along with faults and intrusive features seen on seismic profiles.

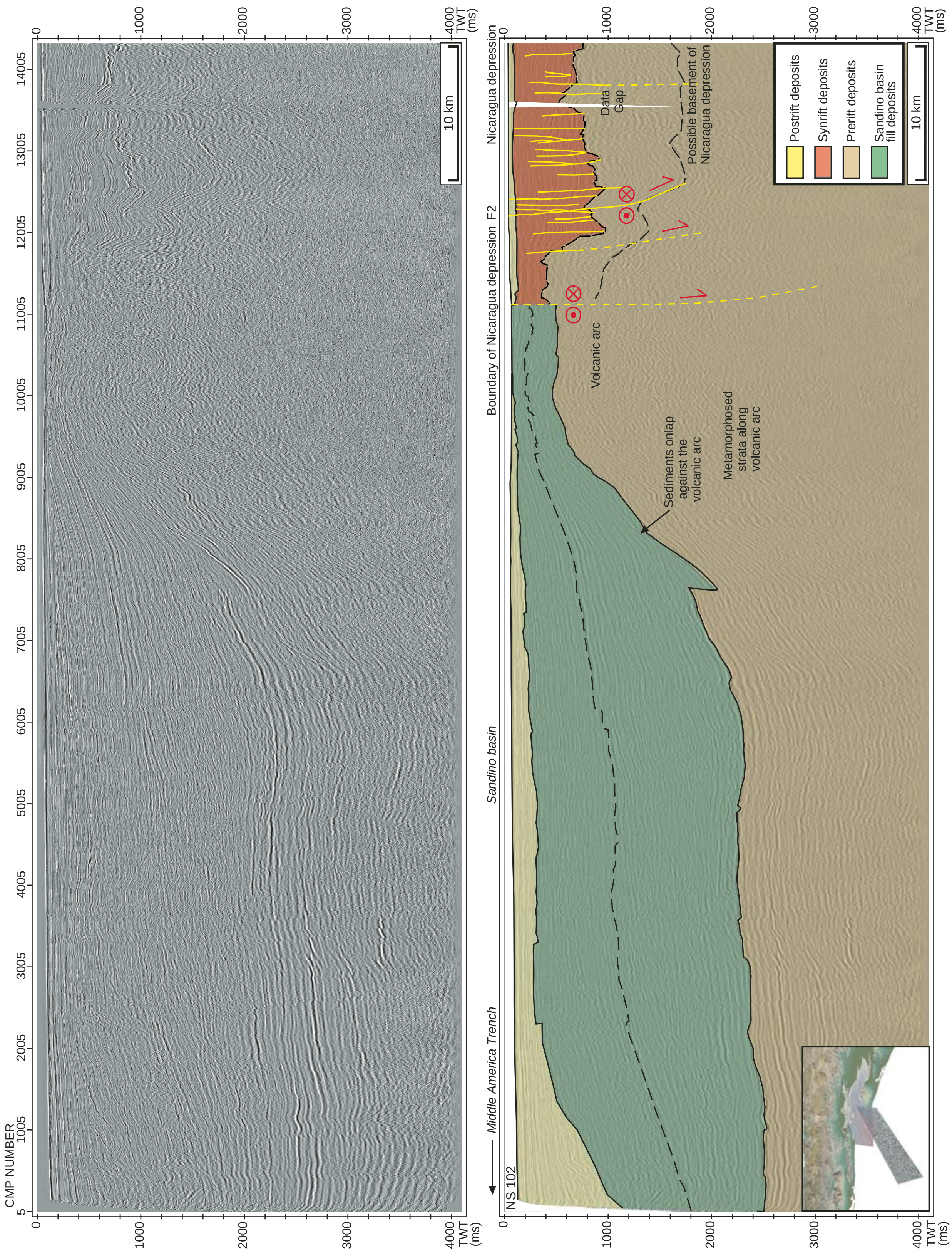
three-dimensional bathymetry grid. The smaller volcanoes and islands in the Gulf of Fonseca are collinear with Chochagua volcano and also align with the localized bathymetric highs. Based on our bathymetric compilation, several other lineaments radiate outward from the center of the Gulf of Fonseca and may represent either faults or fluvial incisions created during sea-level lowstands (labeled F4–F7 in Fig. 9B).

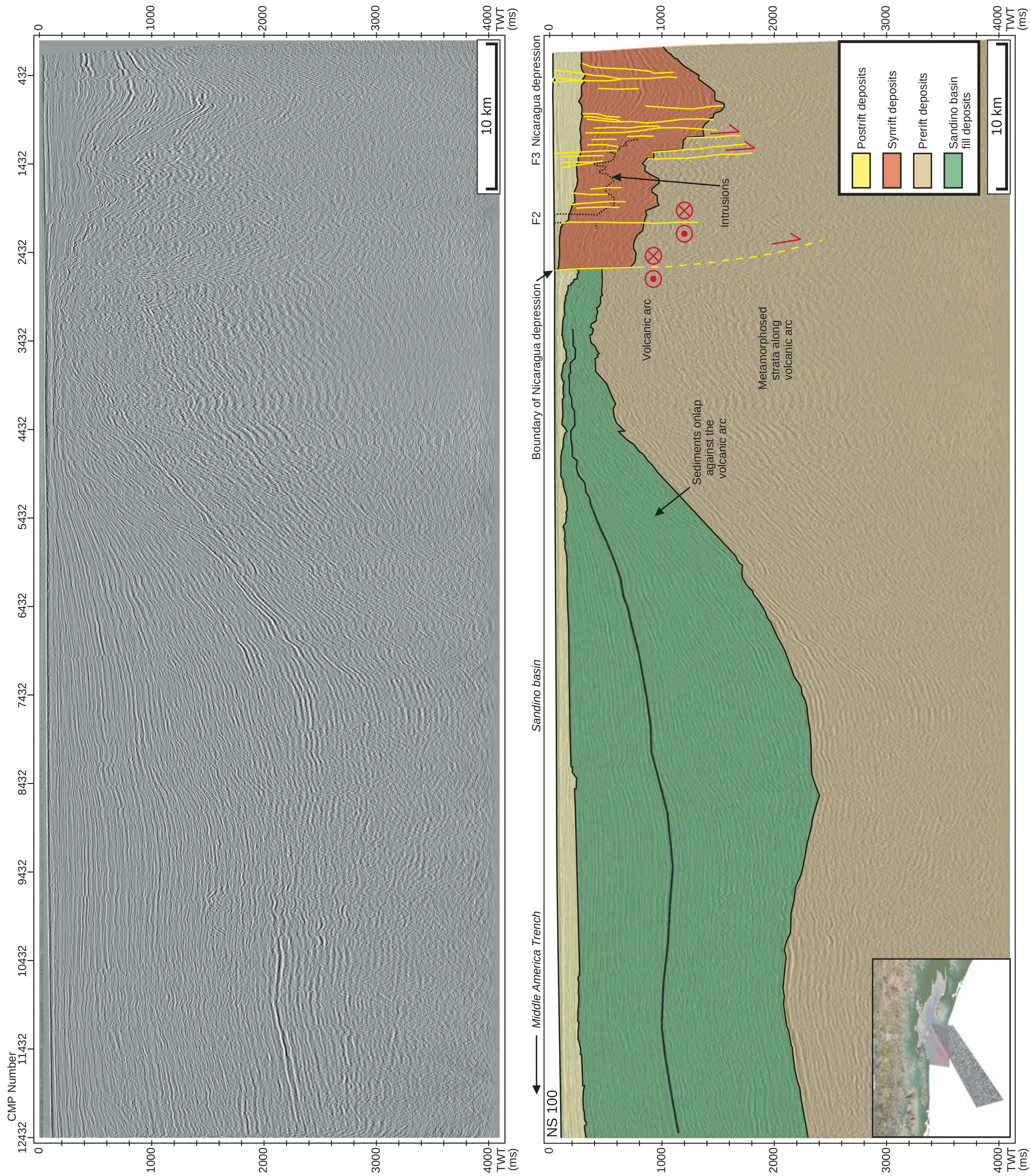
Subsurface Deformation

Several major bathymetric features in the Gulf of Fonseca (labeled F2 in Figs. 9B and 10) correlate with interpreted faults and intrusions seen on 2004 NicStrat seismic-reflection lines (Figs. 11 and 12). These seismic data suggest that an uplift occurred prior to the Oligocene, as indicated by onlapping Oligocene and younger strata in the offshore Sandino basin (Figs. 10, 11, and 12), and dates from well data described by Ranero et al. (2000) and Stephens et al. (2007). At least one major volcanic uplift occurred ca. 14–18 Ma along this segment during a major trenchward jump in the volcanic front location, as shown in Figure 3B (Ehrenborg, 1996; Balzer, 1999; Plank et al., 2002). It is unclear if this seaward jump represented the entire Central America volcanic front or whether it was a local volcanic anomaly.

The younger, onlapping strata cannot be correlated across the present-day trend of the Central America volcanic front because of local highs related to inferred shallow intrusions and the presence of active fault scarps F2 and F3 (Fig. 12) which form scarps on the seafloor and are parallel to the highest part of the volcanic ridge; moreover, there are no wells in the Gulf of Fonseca or Nicaraguan depression that can be used to constrain the age of strata imaged within the Gulf of Fonseca (McIntosh and Fulthorpe, 2005) (Figs. 11 and 12). It is also difficult to estimate the total sedimentary thickness of the depression beneath the Gulf of Fonseca because of the presence of lava flows or dense layers between 0.6 and 0.75 s two-way traveltime (TWT), as shown in Figure 11B (McIntosh and Fulthorpe, 2005).

Figure 11. (A) Uninterpreted multichannel seismic-reflection line NS102 extending from the offshore Sandino forearc basin across the Central America volcanic front to the Nicaraguan depression in the Gulf of Fonseca. TWT—two-way traveltime. (B) Interpreted line NS102. Offshore strata can be dated using ties from wells drilled in offshore Sandino basin (Ranero et al., 2000). Within the Nicaraguan depression, there are no age constraints from wells. Onlap and faulting make it difficult to correlate between the Sandino forearc basin and the Nicaraguan depression in the Gulf of Fonseca, thus limiting the age constraints for the timing of Nicaraguan depression formation. The feature labeled F2 is interpreted as a local area of inverted strata related to recent transpressional faulting. This zone of faulting correlates with aligned bathymetric highs in the Gulf of Fonseca and onland faults affecting drainages on the flanks of Cosiguina stratovolcano.


CMP NUMBER
TWT (ms)
10 km
Nicaragua depression
Boundary of Nicaragua depression F2
Sandino basin
Middle America Trench
NS 102
Data Gap
Possible basement of Nicaragua depression
Volcanic arc
Sediments onlap against the volcanic arc
Metamorphosed strata along volcanic arc
Postrift deposits
Synrift deposits
Prerift deposits
Sandino basin fill deposits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432
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F3
Nicaragua depression
F2
Intrusions
Boundary of Nicaragua depression
Volcanic arc
Metamorphosed strata along volcanic arc
Sediments onlap against the volcanic arc
Sandino basin
Middle America Trench
NS 100
Postrift deposits
Synrift deposits
Prerift deposits
Sandino basin fill deposits

Figure 12. (A) Uninterpreted multichannel seismic-reflection line NS100, 5 km from NS102 at the northeast end of the lines. In the eastern part of NS100, it is difficult to identify reflections below ~500 ms because of the presence of a strong reflector, possibly a lava flow. The eastern part of the depression shows deeper reflectors at 2000–3000 ms two-way traveltime (TWT). The most laterally continuous reflector occurs at ~1500 ms TWT, although a faint reflector may be imaged around 2250 ms TWT. (B) Interpreted line NS100. Synrift deposits of the Nicaraguan depression in the Gulf of Fonseca (green) show a maximum thickness toward the east and thin to the west, terminating near the eastern boundary of the Nicaraguan depression. F2 can be correlated with features on NS102, bathymetric highs, and faults on the flank of Cosiguina stratovolcano.

The major bounding faults of the depression, which initially formed as extensional features, may have been reactivated in a transpressional strike-slip setting related to recent forearc sliver tectonics, as suggested by the zone of young, inverted strata labeled F2 in Figure 11B.

A major change in the seismic characteristics between the Sandino basin sediments and the Nicaraguan depression sediments occurs across the crest of the structural arch that we assume represents the projection of the modern Central America volcanic front. Sedimentary fill of the Nicaraguan depression exhibit lower seismic velocities (1600–2000 m/s) and display prerift, synrift, and postrift geometries in cross section (Figs. 11 and 12). The youngest age of the prerift deposits is unknown, but the prerift section shows little lateral variation in thickness (Figs. 11B and 12B). The synrift deposits thin to the northeast and southwest, although shallow volcanic intrusions and flows may obscure deeper sedimentary reflectors (Fig. 12B). Postrift deposits exhibit minimal lateral changes in thickness, but they are also highly intruded and contain zones of fault deformation northeast of the main Nicaraguan depression-bounding fault (Fig. 11B). The fault patterns near the main fault boundary (Fig. 10) and within the depression suggest that several synthetic normal faults are parallel to the main bounding fault and merge at depth (Fig. 12B). East of the main depocenter, synrift deposits thin to the northeast. Both seismic lines exhibit an unconformity around 0.25 s TWT, suggesting that uplift accompanied recent rifting of the Nicaraguan depression in the Gulf of Fonseca.

Lake Managua and Marabios Cordilleran Segment

Lake Managua is the second largest freshwater lake in Central America, occupying a total area of ~1300 km^2. The lake level is presently ~40 m above sea level and drains to the southeast through the Tipitapa River into Lake Nicaragua (Fig. 13A). The linear Marabios Cordillera northwest of Lake Managua includes Momotombo stratovolcano at its south end and San Cristobal stratovolcano at its north end (McBirney and Williams, 1965). The western shoreline of Lake Managua is bounded by the prominent Mateare fault, which exhibits up to 900 m of apparent vertical topographic relief (Fig. 13C). The southern shoreline of Lake Managua borders the capital city of Managua, which sprawls across the flat, low-lying Managua graben (Figs. 13A and 14).

Multiple onland fault families have been mapped within the narrow but dense zone of arc-parallel crustal seismicity, as shown by the shallow earthquake distribution in Figure 13B. Within this seismic zone, aftershocks from the 1972 (M = 6.2) earthquake show dominantly northeast-directed left-lateral strike-slip motion on the Tiscapa fault (Woodward-Clyde Associates, 1975; Brown et al., 1973) (Fig. 13B). The southern shore of Lake Managua is deformed by north-south–striking normal faults, including the Aeropuerto fault (Cowan et al., 2002) (Fig. 14). The eastern lake shore is bounded by the north-south–trending Cofradía fault, which exhibits mainly east-west extension (Cowan et al., 2002) (Fig. 13C).

Data Sets

Results from the Lake Managua survey are based on 300 km of 3.5 kHz subbottom profiles, 80 km of multichannel seismic-reflection data, and 300 km of sidescan sonar collected over a period of 7 days using the chartered barge *Morrito No. 2*. The goal of the survey was to map the offshore extensions of known fault scarps in the Managua area (Woodward-Clyde Associates, 1975; Cowan et al., 2002) and any faults associated with predicted, arc-parallel, right-lateral faults or transverse faults predicted by the bookshelf fault mechanism (La Femina et al., 2002) (Fig. 7C).

Managua Faults

Most of the active faults near Managua, (i.e., those faults offsetting the lake bottom), are diffuse, have small offsets, and are difficult to correlate between our survey lines with 1–3 km spacing (Fig. 13A). For this reason, we focus our discussion on those major faults recognized in the survey and their correlations to previously mapped onshore faults.

The first fault family is a series of northeast-striking faults that extends from the Nejapa-Miraflores volcanic alignment in the west to the Aeropuerto fault in the east (Fig. 13). A smaller cinder cone, labeled C1 in Figure 13C, is found near the southern shore of Lake Managua and aligns with the northeast-striking Asososco-Acahualinca fault zone in Lake Managua, which marks the most westerly discovered fault of our survey. East of the Asososco-Acahualinca fault zone, a small fault trends for several hundred meters, exhibits ~3 m of vertical offset, and correlates with the lakeward projection of the Estadio fault (labeled EF in Fig. 13C), and 1.5 km east of the onland Estadio fault, the Tiscapa fault projects into the lake as shown by the aftershocks in Figure 13B, but does not correlate with any of the other faults that we found offsetting the floor of Lake Managua. The closest major fault to the Tiscapa fault that we mapped in Lake Managua is a 5–7-km-long fault (labeled T1 in Fig. 13C) that does not continue east of the Aeropuerto fault.

There are also several features on the lake bed that indicate lower lake levels and the presence of meandering paleostream channels (Figs. 15F and 15G). Prominent reflectors down to ~10 m depth are interpreted as stream channels when the level of Lake Managua was much lower than today (Fig. 16A). These channel deposits are adjacent to an uplifted horst block that exhibits ~3–4 m of vertical offset and trends north-south. This family of northeast-striking faults all terminates along the north-south–striking Aeropuerto fault, which bounds the Airport graben (Fig. 14).

The lakeward extension of the Aeropuerto fault correlates with the prominent lake bed fault shown in Figure 15A that exhibits about ~1 m of vertical offset and is located ~250 m from its onshore projection (Fig. 13C). Within the offshore continuation of the Airport graben, there is a high concentration of north-south–striking faults that exhibit varying amounts of apparent vertical offset (Fig. 15). The inset in Figure 13C shows the nature of closely spaced faulting near the southern shoreline of Lake Managua that offsets several apparent drainage patterns and paleostream channels on the lake bottom (Figs. 15F and 15G). There are numerous other fault-bounded horsts and grabens that show evidence for the presence of shallow gas-charged sediments (Fig. 16B).

We propose that the rapid variation in seismic penetration is a function of active faulting: gas appears to be preferentially released from the lake sediments within areas of young

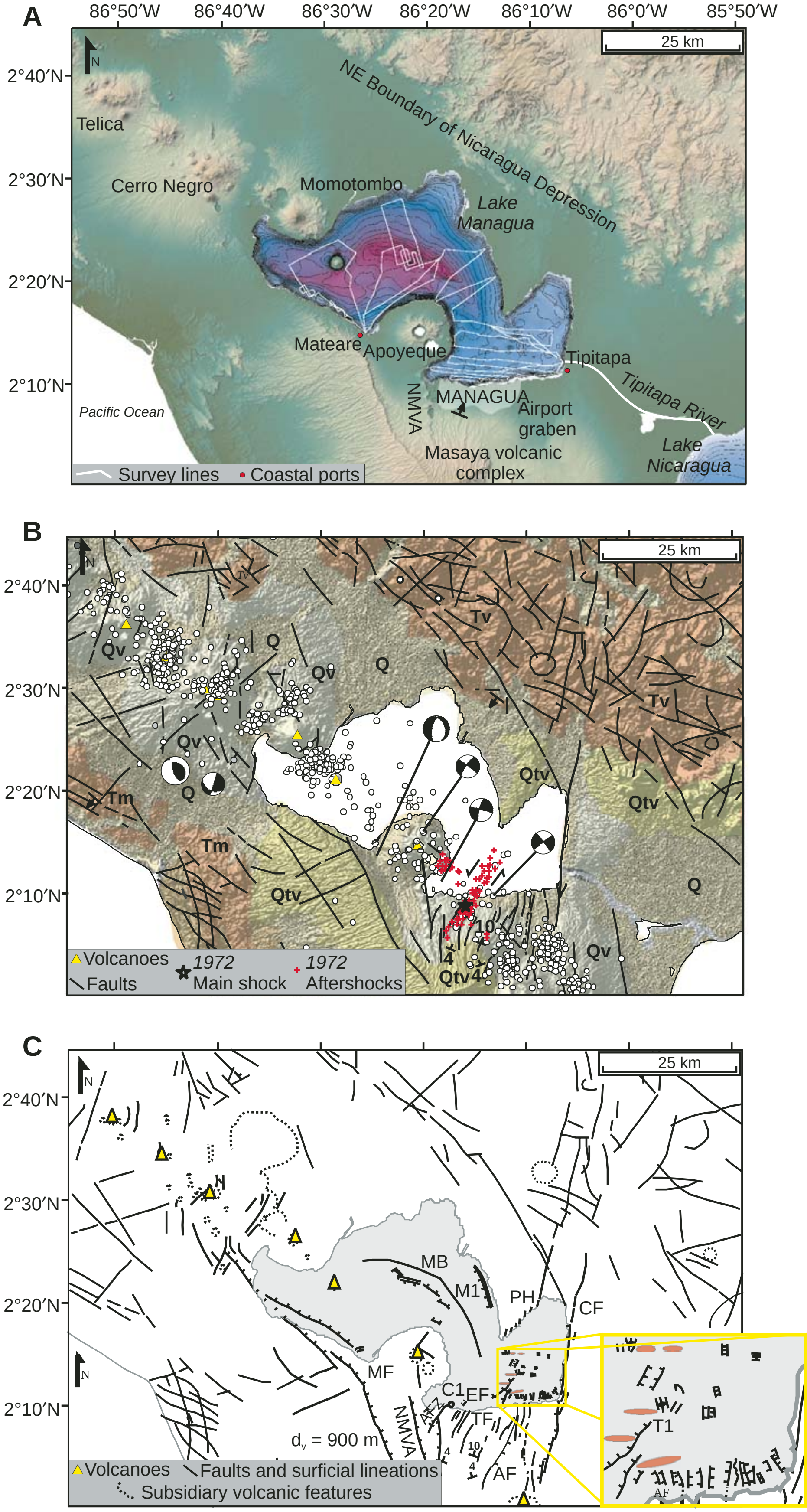

Figure 13. (A) Shuttle Radar Topography Mission imagery of Lake Managua and the Central America volcanic front in northern Nicaragua. Bathymetric data set was created from Nicaraguan Hydrographic Department of the Instituto Nicaraguense de Estudios Territoriales (INETER, 1979) and new bathymetric data collected during this survey using a subbottom profiler. (B) Geologic map from Case and Holcombe (1980) and Cowan et al. (2002) overlain on topography. Shallow earthquakes less than 33 km depth (white circles) are from the local Nicaragua seismic network operated by INETER from 1995 to 2003 and focal mechanisms are from the Harvard Centroid Moment Tensor (CMT) catalog, indicating a concentrated seismic belt along the Central America volcanic front. Aftershocks calculated from the 1972 (M = 6.2) Managua earthquake occurred along the left-lateral northeast-striking slip-plane of the Tiscapa fault (TF) and the parallel, left-lateral Estadio fault (EF). (C) Interpretation from the 2006 NicLakes survey of Lake Managua based on 38 lines of 3.5 kHz subbottom profiler and sidescan sonar, and four multichannel seismic-reflection lines. The inset is a close-up view near the southern shores showing intense faulting within the Airport graben and faults terminating against the Airport graben, including the fault labeled T1. These lines show several faults scarps on the lake bottom with vertical throws on the order of 1–7 m and an unknown component of horizontal offset. Red shading shows areas of seismic penetration that lack a prominent multiple reflector. The main results from the southern part of Lake Managua suggest that northeast-southwest–striking faults are bound to the west by the Nejapa-Miraflores volcanic alignment (NMVA) and to the east by the north-south–striking faults of the Airport graben. AF—Aeropuerto fault, CF—Cofradía fault, PH—Puente Huete fault, MF—Mateare fault, MB—Momotombito fault, AFZ—Asososco-Acahualinca fault zone.

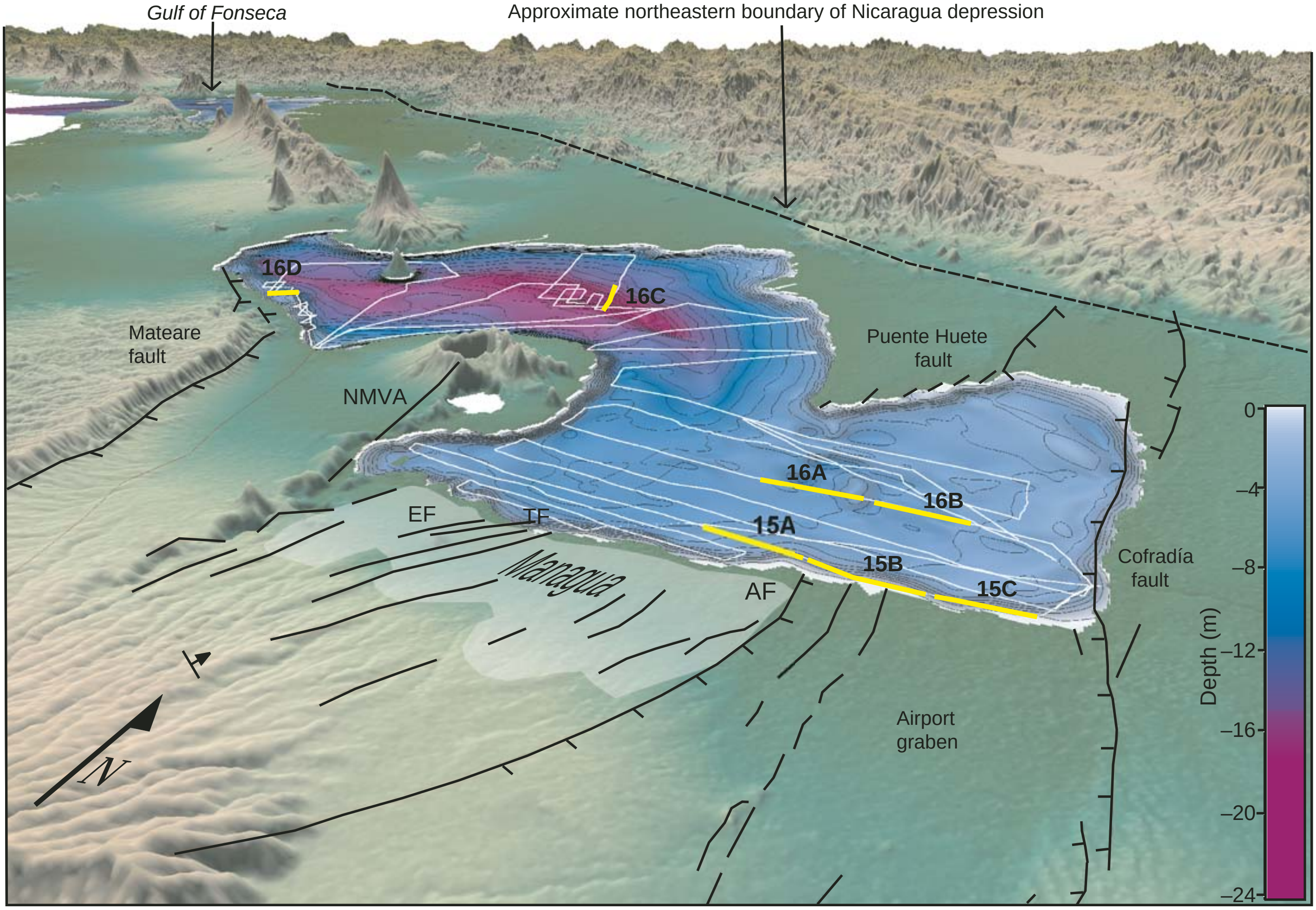

Figure 14. Oblique view of Lake Managua showing the low-lying Nicaraguan depression bounded to the northeast by the interior highlands and to the west by the Mateare fault (MF) and the axis of the Central America volcanic front. The main goals of the survey were to map the surficial expression of the Nejapa-Miraflores volcanic alignment (NMVA), Estadio fault (EF), Tiscapa fault (TF), and Aeropuerto fault (AF) into Lake Managua. Figures 15, 16A, and 16B show examples of scarps found near the southern lake shoreline indicating the large number of parallel and closely spaced faults projecting outward from the capital city Managua (Woodward-Clyde Associates, 1975). Figures 16C and 16D show vertical offsets typical of the Momotombito fault and Mateare fault, respectively.

faulting. Faulted areas are therefore depleted in concentrated gas and allow a higher degree of seismic penetration.

Momotombito Fault Zone

The central deep of Lake Managua to a maximum depth of 23 m is controlled by a single fault zone, which we have named the Momotombito fault zone (labeled MB in Figs. 13C and 16C). The Momotombito fault zone controls the arcuate shape of Lake Managua and exhibits smaller-scale normal offsets (Figs. 13A, 14, and 16C). Several other faults control the northeastern boundary of the lake, strike parallel to the Momotombito fault zone in the central part of the lake, and allow a higher degree of seismic penetration than in unfaulted areas (M1 in Fig. 13C). The northern lake edge shows evidence for prominent lake bed reflectors at depth. Two faults (M1 and MB in Fig. 13C) are interpreted as antithetic normal faults formed along the northeast-dipping Mateare fault.

Mateare Fault Zone

The onland Mateare fault, which exhibits ~900 m of topographic relief, defines the western coast of Lake Managua and extends over 50 km in length (Figs. 13C and 14). In Lake Managua, a large bathymetric fault scarp extends parallel to the onshore expression of the Mateare fault, is downdropped to the east, and exhibits ~5 m of vertical offset at the lake floor (Figs. 13A and 16D). This fault parallels the lake edge from the town of Mateare to the northwestern shoreline of Lake Managua. We interpret the absence of a prominent multiple signal near the fault zone as support for our hypothesis that escaping gas near fault zones improves the degree of seismic penetration (Fig. 16D).

Lake Nicaragua and Northern Costa Rica Segment

Lake Nicaragua is the largest freshwater lake in Central America, covering ~7700 km^2. The present lake level is ~33 m above sea level and drains into the Caribbean Sea through the Rio San Juan at the southeastern end of the lake (Fig. 17A). Over 1100 km of 3.5 kHz subbottom profiles, 600 km of multichannel seismic-reflection data, and 35 sediment cores

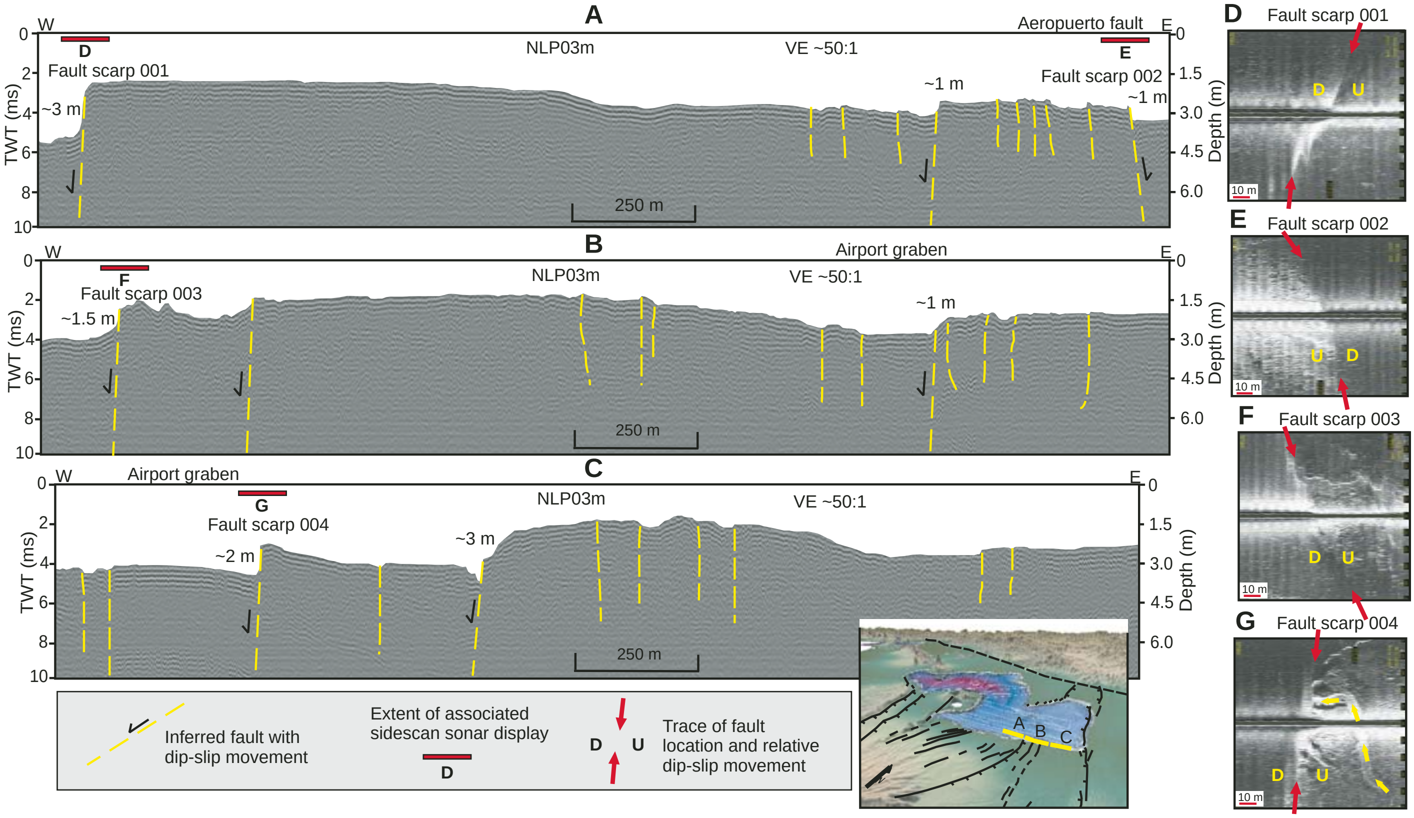

Figure 15. Subbottom profiler lines acquired using Audacity software and associated sidescan sonar images from Lake Managua. The lines show significant vertical offsets (1–7 m) in the late Holocene lake bed near the southern lake shore. (A) The easternmost offset is interpreted as the northward continuation of the Aeropuerto fault with a left-lateral sense of slip and ~1 m of vertical offset downthrown to the east. The orientation of offsets can be seen on the maps in D and E. (B) Projection of the Airport graben aligns with this intense zone of faulting on this seismic section and with the orientation of fault scarp 003 in F. (C) This seismic line crosses the strike of the Airport graben and shows several vertical offsets on the order of 2–3 m. The sidescan sonar image of these faults, shown in G, shows fluvial drainage patterns offset by a parallel set of north-south–striking faults. The downthrown side of the fault does not exhibit any fluvial incision, suggesting the fault has either been subsequently buried by younger sediments or there is a strike-slip component that has transported the block (and channel) out of view. VE—vertical exaggeration. (D) Sidescan sonar image of the down-to-the-west fault scarp 001. (E) Sidescan sonar image of the down-to-the-east fault scarp 002 which correlates with the onland expression of the Aeropuerto fault. (F) Sidescan sonar image exhibiting erosional features on the upthrown block of fault scarp 003. (G) Sidescan sonar image exhibiting paleostream channels on the upthrown block of the down-to-the-west fault scarp 004.

were acquired during the 2006 NicLakes survey to constrain the presence of through-going strike-slip faults controlling pull-apart basins (Fig. 7B) or an array of parallel, left-lateral bookshelf faults (La Femina et al., 2002) (Fig. 7C). Another goal of the survey was to identify possible faulted boundaries of the Nicaraguan depression, including the linear, southwest boundary of the Lake Nicaragua segment inferred as a fault from SRTM images and from aeromagnetic data. There was also interest in possible subaqueous volcanic features and venting associated with the volcanic front near the southern end of Maderas volcano (Fig. 17).

Results from the geophysical survey were limited due to the inferred presence of gas-charged sediments (Davy, 1992) found throughout most of the lake, as well as some mechanical problems that limited our ability to fire the air gun at the ideal pressure of 1800–2000 psi. Coring results shown in Figure 17C indicate that the bottom sediments of Lake Nicaragua are primarily composed of organic-rich, diatomaceous mud (Swain, 1966; Wulf et al., 2007). In addition, our geophysical survey discovered three major fault zones, named here the San Ramon fault zone (SRFZ), the Morrito fault zone (MFZ), and the Jesus Maria fault zone (JMFZ) (Fig. 17). While there were numerous other lake bed offsets, they were on a much smaller scale (<1 m) and were difficult to correlate between the widely spaced survey lines (all lake bottom faults seen on single lines are shown as red crosses in Fig. 17B).

San Ramon Fault Zone

The San Ramon fault zone is a 25-km-long, 5-km-wide asymmetrical, fault-bounded, bathymetric depression trending approximately N45°W, parallel to the volcanic front, near Maderas volcano, that terminates near the Zanate Islands near the northeast shore of the lake (Fig. 17A). The San Ramon fault zone includes apparent normal faults bounding its southwestern margin and shallows bathymetrically to the northeast. The overall shape of the fault zone suggests a half-graben structure (Fig. 19A). Several mounds on the lake bed near the center of the San Ramon fault zone with relief of 1–2 m are interpreted as small vents possibly related to active faulting. To the southwest of the San Ramon fault zone, bathymetry suggests that igneous

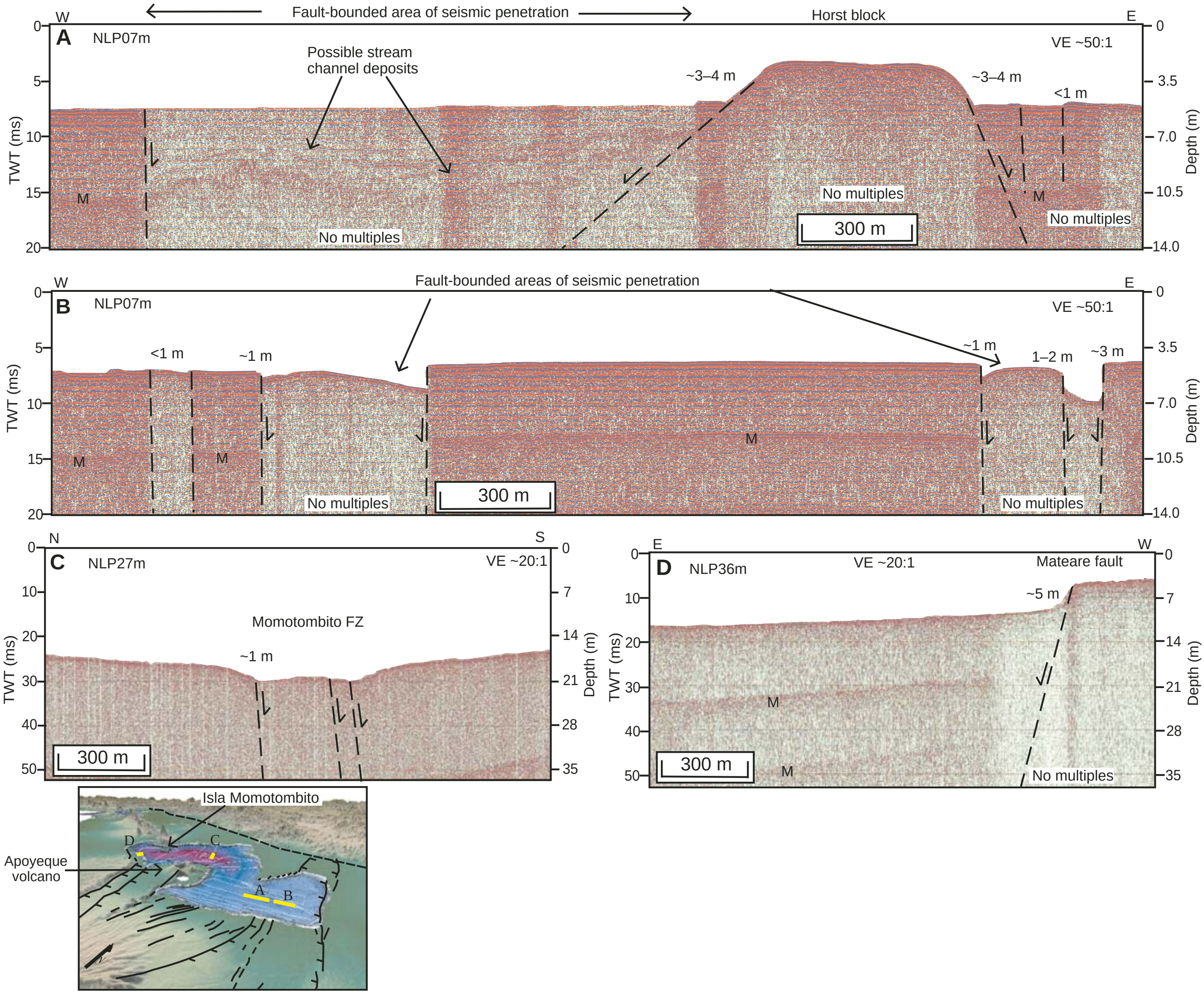

Figure 16. Subbottom profiler lines acquired in Lake Managua that achieved limited seismic penetration. (A) The fault-bounded areas of seismic penetration represent a poorly understood change in the seismic characteristics of the lake bottom. There is a drastic difference inside and outside of these "acoustic windows," which are commonly bounded on at least one side by an active fault. The only positive bathymetric feature is a horst block with a north-south trend. (B) These fault offsets in the eastern part of the lake have a unique geometry. Offsets occur along a set of faults with a convex-concave asymmetry and exhibit between 1 and 3 m of vertical offset. (C) The central deep of Lake Managua is controlled by the Momotombito fault, which terminates before reaching Isla Momotombito and before wrapping entirely around Apoyeque volcano on the peninsula in the southern part of the lake. (D) Previous workers proposed that the onshore Mateare fault represents a fault line scarp that has been eroded from a scarp located more to the northeast. However, results from this survey suggest that the scarp found along the western boundary of the lake is most likely a synthetic normal fault to the main Mateare normal fault found further onland. This lake edge fault exhibits ~5 m of vertical offset at the lake bottom and is proposed to be the southwestern boundary of the Nicaraguan depression, which also exhibits a prominent lineament on the aeromagnetic map shown in Figure 21. VE—vertical exaggeration.

basement is higher and that the downthrown block of the fault zone is on its northeastern side (Fig. 19A). The southwest fault block is characterized by subaqueous outcrops, which are similar in character to those lake floor outcrops seen near the western shore of the lake (Figs. 17B and 19B), and which exhibit westward-dipping bedding planes along the western limb of the Rivas anticline (Figs. 17 and 18). This area of lake floor outcrops and tilted beds may represent a manifestation of the northwesterly extension of Nicaraguan depression–bounding faults that form the prominent Costa Rica fault zone that offsets Quaternary volcanic deposits in Costa Rica (Fig. 18). We propose that the southwestern shoreline of Lake Nicaragua itself may represent the approximate location of the major normal fault bounding the Nicaraguan depression (Fig. 18).

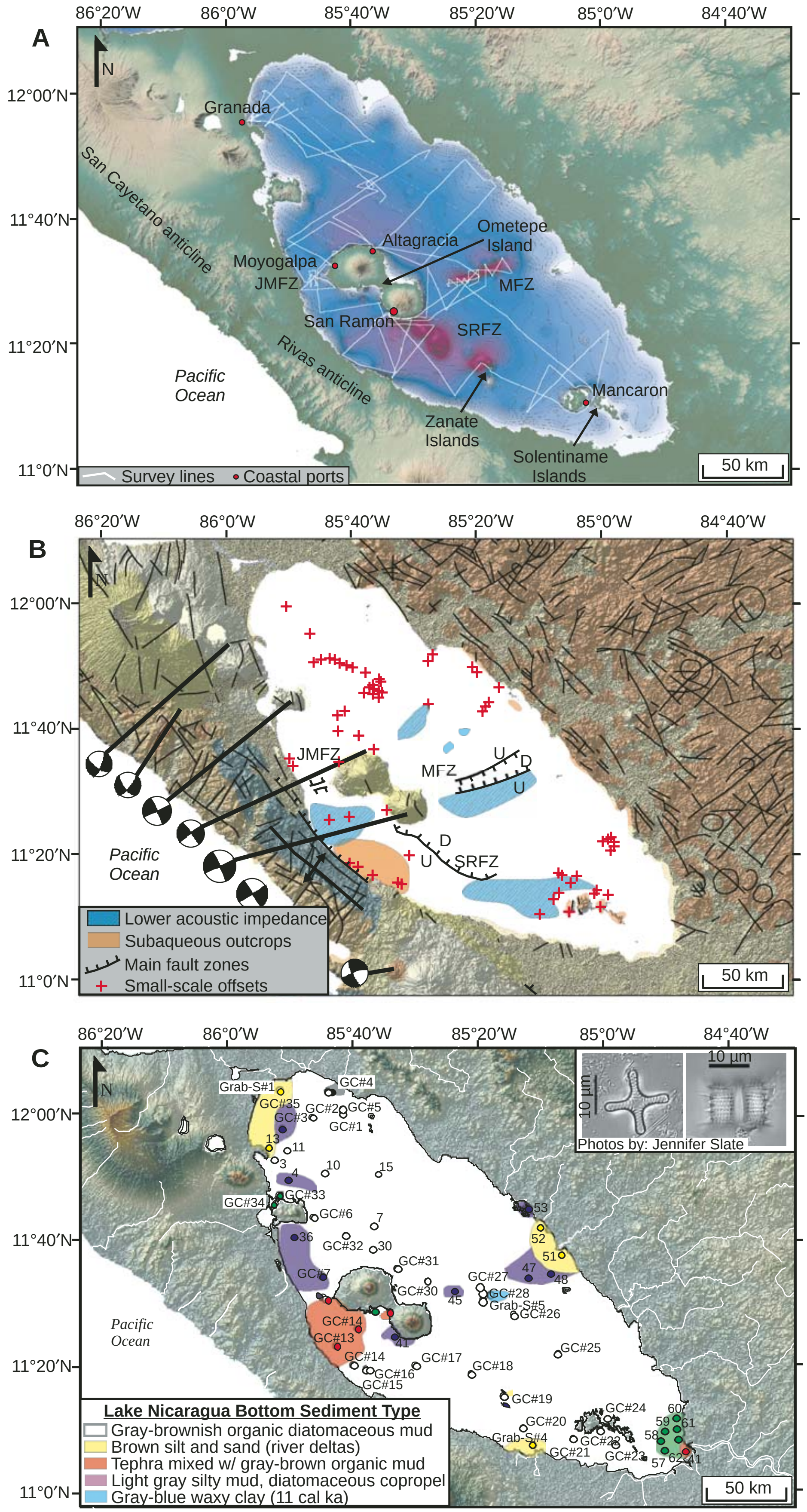

Figure 17. (A) The Shuttle Radar Topography Mission topographic image shows Lake Nicaragua bounded to the west by uplifted rocks of the Pacific coast and to the east by the interior Nicaragua Highlands. (B) Map showing geology and structure compiled by Case and Holcombe (1980) and Instituto Nicaraguense de Estudios Territoriales (INETER) with focal mechanisms from the Harvard Centroid Moment Tensor (CMT) catalog. Three main faults zones (Jesus Maria—JMFZ, Morrito—MFZ, San Ramon—SRFZ) were discovered beneath the lake, along with numerous uncorrelatable small-scale faults. (C) Bottom sediment map is compiled from 35 sediment cores collected during the NicLakes survey (Wulf et al., 2007). Bottom sediment type distribution suggests the majority of the lake bottom consists of a homogeneous, diatomaceous mud as shown in the inset (diatom photos in inset are courtesy of Jennifer Slate, Northeastern Illinois University).

Jesus Maria Fault Zone

The Jesus Maria fault zone, which is much smaller in length and width than the San Ramon fault zone, is a 4-km-long, 1-km-wide uplift exhibiting ~4–7 m of vertical offset with an unknown amount of possible strike-slip offset (Fig. 19C). The Jesus Maria fault zone has a strike of N80°W and forms a prominent uplift within the center of a broader zone of uplift between Concepcion and the western shore of Lake Nicaragua (Fig. 17A). The zone of uplift can be seen on bathymetric (Fig. 17A), gravity (Fig. 2), and aeromagnetic data presented later, and it also correlates with a peninsula that protrudes westward from Concepcion volcano.

Morrito Fault Zone

The Morrito fault zone is a 20-km-long, 5-km-wide, asymmetric depression striking approximately N80°E parallel to the Jesus Maria fault zone (Figs. 17 and 19). The Morrito fault zone terminates ~3 km off the eastern coast of Maderas, where it is covered by a wedge of volcanic deposits derived from Maderas and Concepcion volcanoes; it shallows to the east where it exhibits no surficial expression on SRTM images (Fig. 17). The areal extent of the fault zone, representing only ~1% of the total lake area, is the only area of Lake Nicaragua that allowed significant seismic penetration (Figs. 17 and 19). We propose that the southern Morrito fault boundary localizes the gas distribution in the sediment column as suggested by inferred

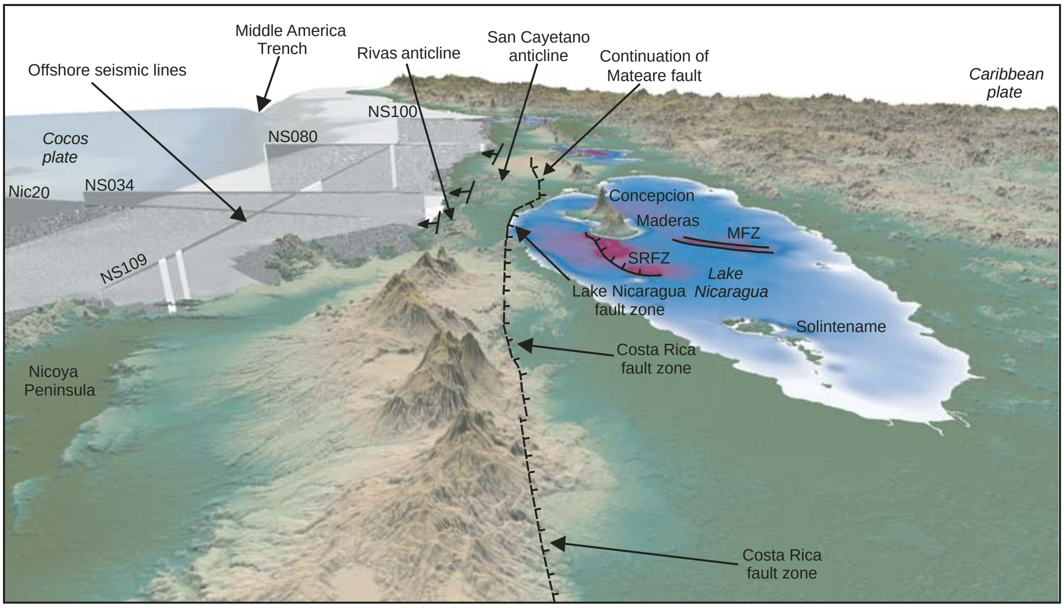

Figure 18. Inferred trace of the Costa Rica–Lake Nicaragua fault that offsets the northwestern edge of the Quaternary Central America volcanic front in Costa Rica and projects along the southwestern shore of Lake Nicaragua. This fault system exhibits ~300–800 m of vertical topographic relief in Costa Rica and forms a continuous scarp for ~50–60 km. The Costa Rica fault zone is responsible for southwesterly tilts in Quaternary volcanic deposits in the area south of Lake Nicaragua. Southwestward dips on strata protruding from the coastal plain south of Lake Nicaragua support the presence of the Lake Nicaragua fault zone near the present lake coastline. MFZ—Morrito fault zone, SRFZ—San Ramon fault zone.

areas of gas shown by the blue shading in Figure 17B. The southern boundary fault of the Morrito fault zone exhibits an apparent vertical offset of 5–7 m, as shown by reflector Ra (Figs. 20A and 20B).

Shallow gravity cores were taken across a clastic wedge covering the active fault, and they constrain the ages of its activity (Fig. 20B). Sediment core #5 and GC-29 sampled a gray-blue waxy clay dated at 11,271–11,403 cal 14C yr B.P. and whos that the thick, asymmetrical fault wedge adjacent to the fault is likely Holocene in age (Wulf et al., 2007) (Fig. 20B). Reflectors labeled Ra–Rc are the only subsurface layers imaged in the Morrito fault zone area, but they are continuous throughout the fault zone and have uniform dips down to the south (Fig. 20B).

Aeromagnetic Data

An aeromagnetic data set, acquired in 1969 by Superior Oil Company and Associates at a 1:250,000 scale and covering ~1900 km^2 of the western margin of southern Nicaragua (Fig. 21A), was digitized and gridded in the same manner as the lakes and Gulf of Fonseca bathymetric data sets. However, processing information is poorly known. The aeromagnetic data provide critical regional coverage of both lake boundaries and their structural relationships to the Pacific coastal plains and offshore Sandino basin. The main results show a series of northwest-southeast–trending fold axes that are ~15–25 km in width and generally span the entire length of the survey area (Fig. 21B). These folds and faults interpreted from aeromagnetic data correlate well with anticlines and synclines mapped in offshore seismic data (Ranero et al., 2000) and with mapped onland geology (Fig. 21B).

The aeromagnetic map helps to constrain the location of a major normal fault (called here the Lake Nicaragua fault zone) along the southwestern shore of Lake Nicaragua that trends along the approximate axis of the Rivas anticline (Fig. 21B). The northern projection of this Lake Nicaragua fault zone aligns with the continuation of the Mateare fault zone, which bounds the Lake Managua segment of the depression (Fig. 21). West of the Mateare fault, a magnetic high can be correlated with the San Cayetano anticline, which exhibits dipping strata to the west along the coastline and eastward-dipping strata further inland. These data provide evidence for a sharp structural boundary between half-grabens beneath Lakes Managua and Nicaragua and accompanying footwall uplift in the isthmus area (Fig. 21B). We propose that the Lake Nicaragua fault extends to the south as the Costa Rica fault zone, which forms a prominent scarp in young volcanic deposits (Fig. 18).

DISCUSSION

The various forms of data synthesized in this paper suggest that several tectonic variables affect the modes of deformation along the proposed Central America forearc sliver boundary within the Nicaraguan depression–Median Trough. The mechanism for crustal deformation along this major fault boundary is likely controlled by a combination of tectonic and geologic factors, including dip of the subducted Cocos plate, convergence obliquity of the subducting Cocos plate, variations in the convergence rate of the Cocos plate, and the presence of forearc structures inherited from previous tectonic events (Weinberg, 1992).

El Salvador Strike-Slip Fault Zone

In El Salvador there is a significantly shallower dip (40°–60°) of the Benioff zone of the subducted Cocos plate, which may result in an increase in the degree of coupling between the Cocos plate and Central America forearc and an increase in convergent deformation in the overriding plate (Beck, 1983). Subduction zones are categorized by their slab dip: Mariana-type sub-

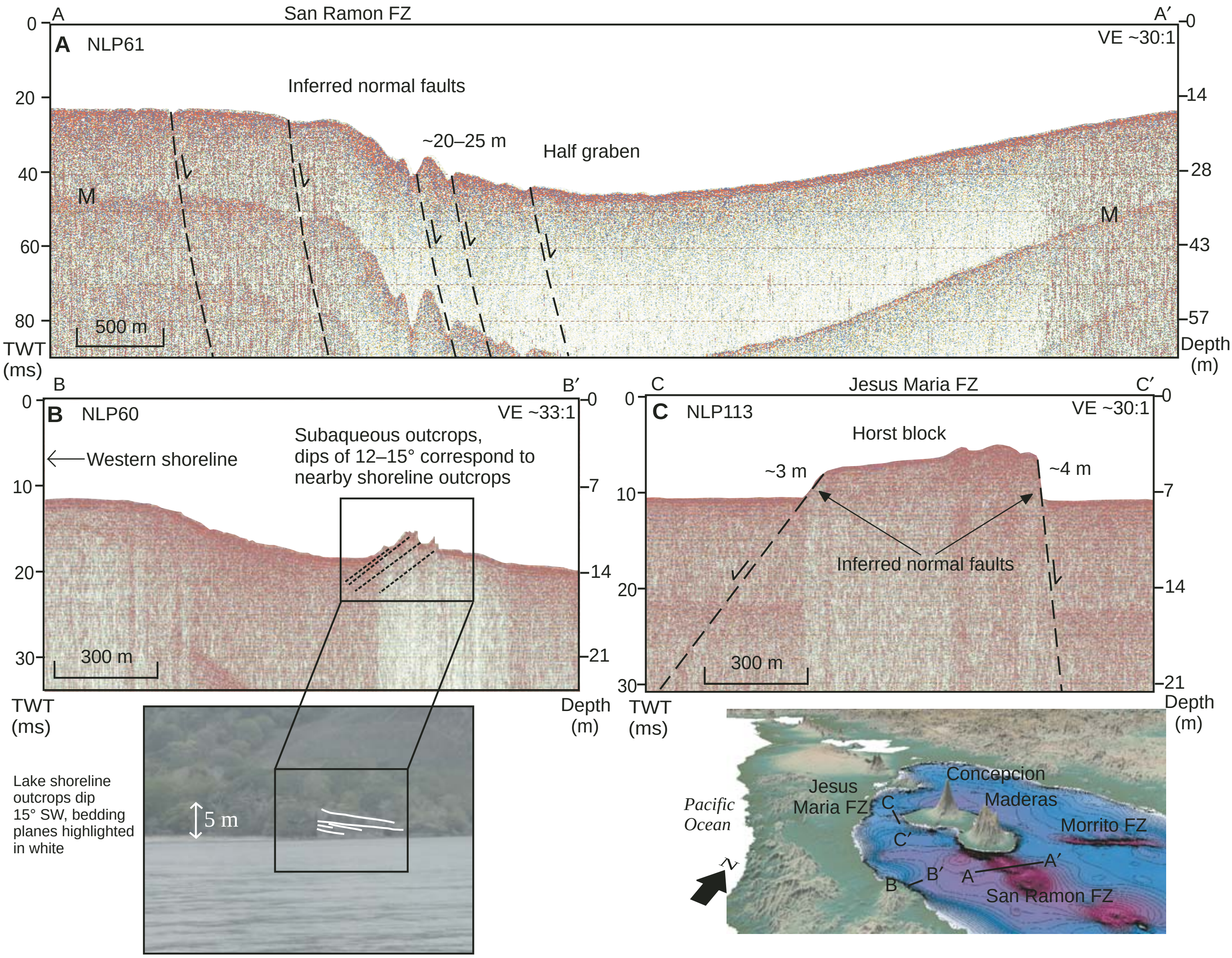

Figure 19. (A) 3.5 kHz subbottom profiler line NLP61 crossing San Ramon fault zone (FZ) in Lake Nicaragua. This area forms the deepest part of the lake, ~40 m in depth near the southern coast of Maderas volcano. The fault forms a linear trend approximately N45°W and controls an asymmetrical depocenter to the southwest. (B) This line near the western shore of the lake exhibits rock subcrops that are most likely part of the adjacent, onshore Rivas Formation. Based on the profile and outcrops seen near the shoreline during the survey, the bedding planes of the Rivas Formation dip 12°–15° to the west-southwest. (C) The second major fault zone in Lake Nicaragua, the Jesus Maria fault zone, trends approximately east-west and is associated with an anomalously uplifted, elongate ridge on the lake floor. Both sides of this linear feature appear to be fault bounded, show 3–4 m of vertical offset, and appear to be uplifted near the center of a more broad bathymetric high between Concepcion volcano and the western shoreline of the lake. VE—vertical exaggeration.

duction zones result in backarc extension, and Chilean-type subduction zones result in backarc shortening (Uyeda and Kanamori, 1979). Slab dip along the El Salvador segment of the Middle America Trench subduction zone (~250 km) is intermediate between Mariana-type (typically over 51°) and Chilean-type (typically less than 31°) subduction zones, and this may explain why the Median Trough in El Salvador is not as well-developed structurally and geomorphically as back-arcs in other Marianas-type subduction zones (Lallemand et al., 2005) (Fig. 5).

The forearc sliver boundary in El Salvador, the right-lateral El Salvador fault zone, exhibits a much more developed and geomorphically prominent strike-slip character than arc-parallel faults in Nicaragua, especially along its San Vicente and Berlin segments (Fig. 8A). Arc-parallel faults in El Salvador and Nicaragua align well with small circles of rotation predicted by Turner et al. (2007) from GPS velocity measurements (Figs. 4 and 22). Outside this predicted right-lateral shear zone along the Central America forearc sliver, faults that misalign with small circles of rotation are expected to be more diffuse and less well defined, and not organized into single through-going fault zones. In this interpretation, the Santa Ana and San Miguel segments do not align with small circles and therefore show less well-defined faults (Fig. 22).

Additional tectonic controls on regional faulting and deformation may also include the large-scale east-west rifting of the northwestern Caribbean plate (Guzman-Speziale, 2001; Morgan et al., 2008), which may superimpose structural effects produced by the transport of

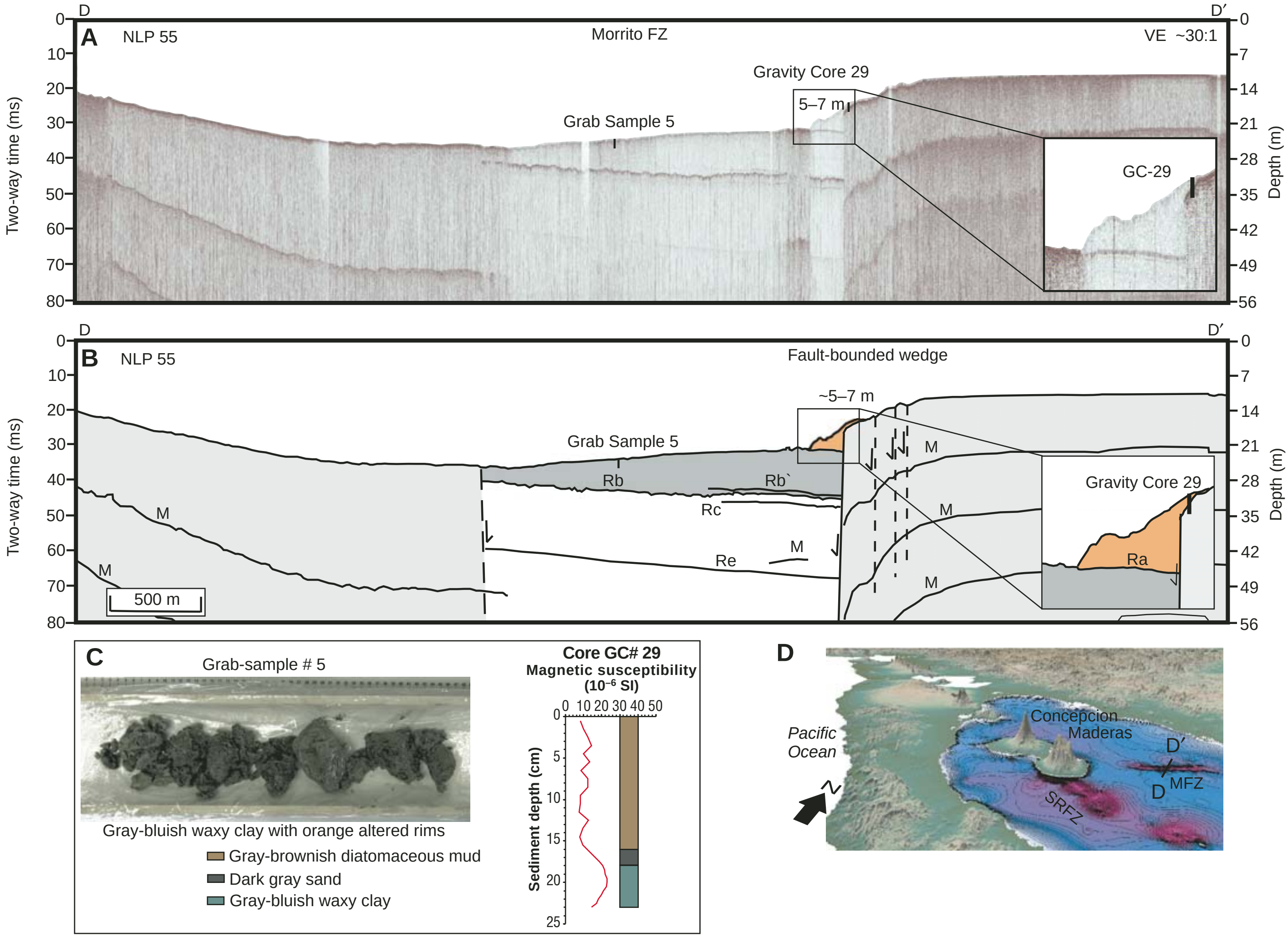

Figure 20. (A) Uninterpreted 3.5 kHz subbottom profiler line NLP55 crossing the Morrito fault zone of Lake Nicaragua. This linear depression trends approximately N75°E, exhibits 12–15 m of vertical offset, is not traceable westward to Maderas volcano, and shallows significantly to the east. VE—vertical exaggeration. (B) Interpreted 3.5 kHz subbottom profiler line NLP55. The southern margin of this fault zone appears to be covered by a clastic wedge that provides evidence for the age of active faulting; reflectors Ra–Re are the only subsurface layers imaged beneath the lake. (C) Several cores and grab samples were also taken across this profile. These cores show gray-blue waxy clay just below the surface of the upthrown block, through the clastic wedge, dated at 11,271–11,403 cal ^{14}C yr B.P. The same clay found in grab sample #5 constrains the age of fault activity and shows an average vertical slip rate of 73 cm per 1000 yr (Wulf et al., 2007). This same clay is found in a grab sample near the center of the Morrito fault zone trough, suggesting 12–15 m of vertical displacement throughout the Holocene. (D) Oblique view of Lake Nicaragua showing cross-section location. MFZ—Morrito fault zone, SRFZ—San Ramon fault zone.

the Central American forearc sliver (Fig. 22). Moreover, La Femina et al. (2002) have proposed that the Miocene and younger Cocos collision in Costa Rica may provide another tectonic mechanism to explain the oblique motion of the Central American forearc in Costa Rica to Nicaragua. While the Cocos collision appears to control the complex changes in GPS vectors in the area of the Costa Rica–Nicaragua border, we find it hard to imagine how the localized collisional effect of the Cocos ridge might deform areas as far north as El Salvador, a distance of 700 km from the centerline of the Cocos Ridge.

Faults in the Gulf of Fonseca

The San Miguel segment of the right-lateral El Salvador fault zone adjacent to the Gulf of Fonseca is interpreted here as a major transition zone in trend of the Central America forearc sliver. Figure 9B shows the interpretation of this boundary as a broad strike-slip zone that forms a pull-apart basin in the Gulf of Fonseca and reconnects with arc-parallel faults in the Nicaraguan depression. Well-defined, arc-parallel faults in the Gulf of Fonseca, shown on the seismic lines NS102 and NS100 (Figs. 11 and 12), are interpreted as the main normal boundary faults of the Nicaraguan depression based on their prominent expression on seismic lines. We infer that these arc-parallel faults are deeply rooted, steeply dipping faults that accommodate extension of the northern Nicaraguan depression (Figs. 9B and 22A). The youngest Pliocene–Pleistocene sedimentary units show that the majority of these inferred normal faults are presently inactive, although some uplifted or inverted strata along these faults indicate active transpressional faulting (Figs. 11 and 23A).

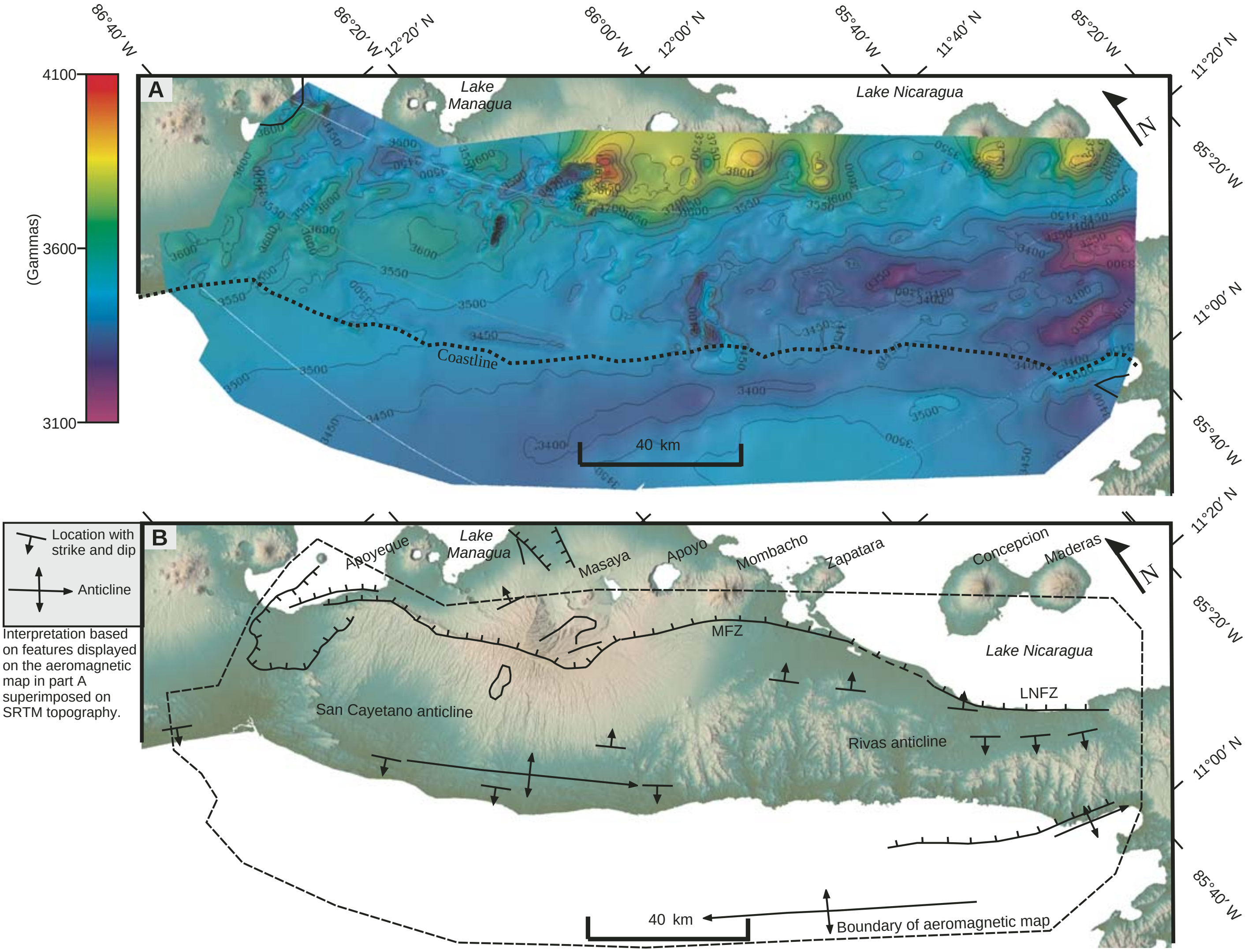

Figure 21. (A) An aeromagnetic data set (contour interval 50 gammas) acquired in 1969 by Superior Oil Associates covering the Pacific coast and the western regions of Lake Managua and Nicaragua. (B) Aeromagnetic interpretation is critical in correlating known offshore faults and folds with the onshore geology and helps constrain the location of the poorly known southwestern boundary fault of the Nicaraguan depression, the Morrito fault zone (MFZ) and the Lake Nicaragua fault zone (LNFZ). Faults and folds are based on the interpretation of aeromagnetic data from the Lake Nicaragua and Managua surveys and previously published geologic maps.

The structural cross section in Figure 23A shows that Oligocene–Miocene sedimentary sections pinch out against a main bathymetric high, indicating the onset of uplift and subsequent erosion of the Central America volcanic front and contemporaneous deposition into the Sandino forearc basin (Stephens et al., 2007). The onlapping of Oligocene–Miocene sediment occurs to the west and east of the main volcanic uplift and shows that both syndepositional filling of the Nicaraguan depression and the Sandino forearc basin uplift of the volcanic front occurred during Oligocene and Miocene time in this region (Fig. 23A). It is possible that this early uplift event was related to the seaward change in the axis of volcanism during the period of 14–18 Ma (Ehrenborg, 1996; Balzer, 1999; Plank et al., 2002) (Fig. 3). It is unclear if this Miocene seaward jump represents the entire Central America volcanic front or whether this was a localized pulse of volcanism in the forearc area, since it does not fit the overall northeast to southwest younging trend (Fig. 5B).

Older Tertiary volcanic rocks are folded and uplifted between Cosiguina volcano and San Cristobal volcano (Figs. 5 and 9A). This belt of older rocks is interpreted in Figures 9B and 22 as a restraining bend structure formed as the result of transport of the Central American forearc sliver to the northwest. In a right-lateral strike-slip setting, this left-stepping fault geometry would produce the Congo restraining bend between offset segments of the Central America volcanic front (Fig. 22). From SRTM topography, the restraining bend appears to be bounded by well-defined faults to the north and south of elevated and tilted area of Cenozoic rocks (Fig. 9A).

Lake Managua and Marabios Cordilleran Segment

The Central America volcanic front segment from the Gulf of Fonseca to Lake Managua appears to occur along a single, arc-parallel,

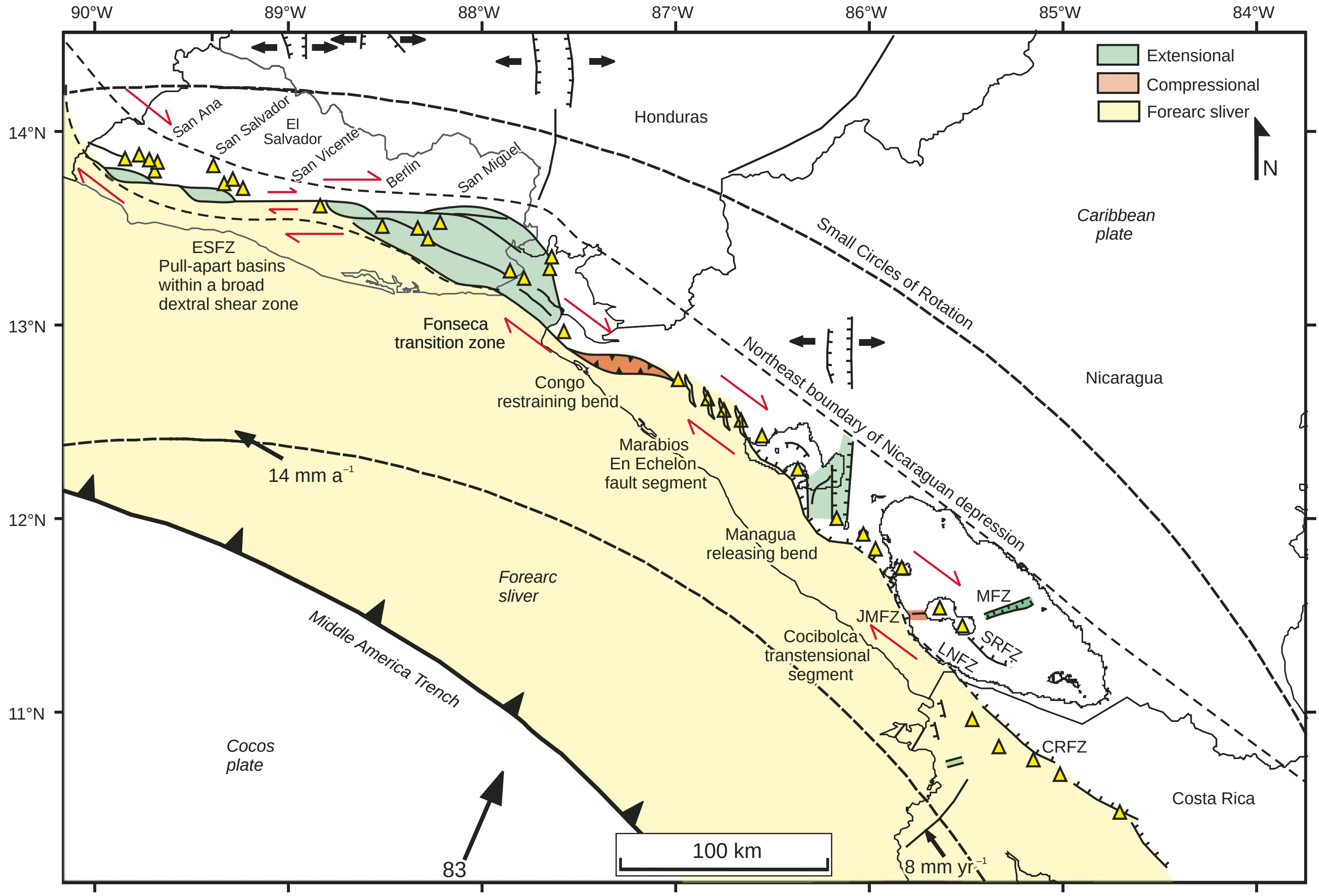

Figure 22. Regional tectonic map of Central America emphasizing key structures described in this paper. The El Salvador fault zone (ESFZ) is characterized by a broad right-lateral shear zone accommodating transtensional motion that results in multiple pull-apart basins. A major transition zone occurs in the Gulf of Fonseca, where strike-slip fault zones along the Central American forearc sliver change strike from dominantly east-west strikes in El Salvador to northwesterly strikes in Nicaragua. A proposed restraining bend connects faults mapped in the Gulf of Fonseca with fault scarps deforming Cosiguina volcano and faults of the Central America volcanic front north of Lake Managua. Diffuse and poorly exposed faults parallel to the Central America volcanic front in northern Nicaraguan segment are inferred to represent a young fault boundary in which right-lateral shear is accommodated over a broad zone. This model proposes a young en echelon pattern of strike-slip and secondary faults based on secondary extensional features and fissure eruptions along the Marabios segment of the Central America volcanic front. Lake Managua and the Managua graben are interpreted to occur at a major releasing bend in the trend of the Nicaraguan depression and are marked by the curving surface trace of the Mateare fault interpreted from aeromagnetic data. Subsequent right-lateral strike-slip motion related to translation of the Central America forearc sliver may occur along these reactivated normal faults. The Lake Nicaragua segment of the Central America volcanic front is bounded by a normal fault (LNFZ—Lake Nicaragua fault zone) offsetting the Rivas anticline, the southeastward continuation of this normal fault into Costa Rica (CNFZ—Costa Rica fault zone), and a synthetic normal fault (SRFZ—San Ramon fault zone) that we discovered in our survey of Lake Nicaragua. Transverse faults (MFZ—Morrito fault zone, JMFZ—Jesus Maria fault zone) strike approximately east-west across the Central America volcanic front. North-south–trending rift zones are abundant in El Salvador but less common in Nicaragua and may also be controlled by regional east-west extension affecting the northwestern corner of the Caribbean plate.

right-lateral strike-slip fault zone, based on focal mechanisms and earthquake epicenters (Figs. 1, 2, and 13B). The axis of the Central America volcanic front in Lake Managua remains parallel to the southwestern boundary of the Nicaraguan depression, as also observed in the Gulf of Fonseca (Fig. 23B). Following a Miocene–Pliocene extensional phase, which created this part of the Nicaraguan depression, northwestward transport of the Central American forearc sliver reactivated the basin-forming normal faults as right-lateral strike-slip faults. Complex zones of faults and fissure eruptions of the Central America volcanic front suggest that right-lateral shearing may have been accommodated by a series of en echelon faults and folds rather than a single strike-slip fault zone as seen in El Salvador (Fig. 22). Studies by Cailleau et al. (2007) provide further evidence for this type of diffuse fault pattern formed by fault rupture along planes between main volcanic centers produced

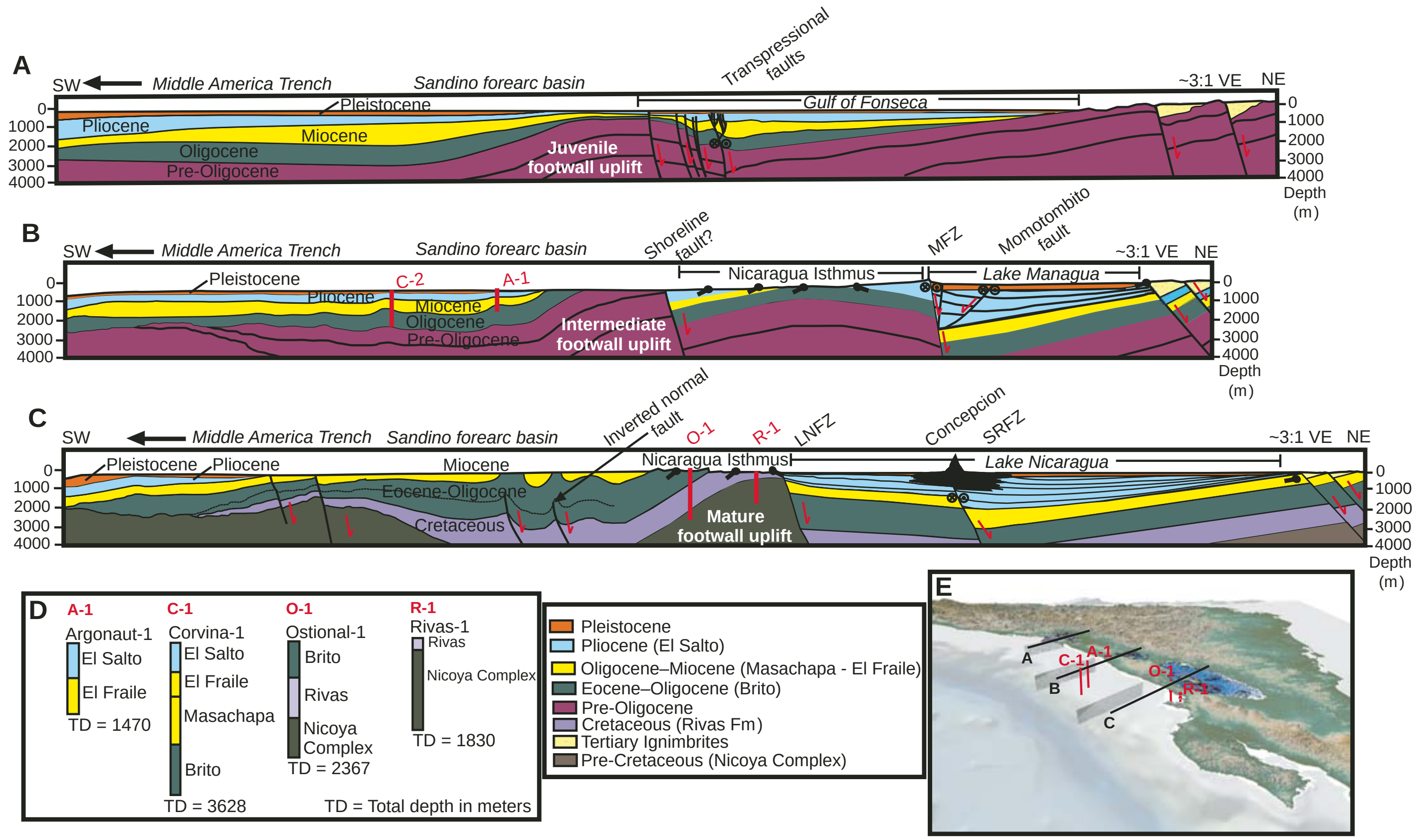

Figure 23. (A) The Gulf of Fonseca segment exhibits a half-graben structure with northeastward-dipping normal faults bounding the Nicaraguan depression. There is no offshore folding trenchward of the Central America volcanic front along this segment. Offshore seismic data and wells interpreted from Ranero et al. (2000) and Stephens et al. (2007) and volcanic dating (Ehrenborg, 1996; Balzer, 1999; Plank et al., 2002) indicate an uplift event occurred prior to the Oligocene–Miocene; however, the least amount of erosion and youngest rocks exposed suggest it is in juvenile stage of footwall uplift. VE—vertical exaggeration. (B) The Lake Managua segment exhibits a half-graben structure bound to the southwest by northeasterly dipping normal faults. The Mateare fault bounds the Nicaragua depression as a deeply rooted, steeply dipping normal fault; the antithetic Momotombito normal fault to the northeast is inferred to dip to the southwest. These faults may represent weak zones of the Central America volcanic front that have been preferentially reactivated during the current transtensional strike-slip phase of deformation (Weinberg, 1992). MFZ—Morrito fault zone. (C) The Lake Nicaragua segment shows localized folding and thrust faulting in the offshore region and two main normal faults bounding the Nicaraguan depression. The Rivas anticline underlies much of the narrow Nicaraguan Isthmus area and may represent a normal footwall block bounding the southwestern edge of the highly asymmetrical Nicaraguan depression. The San Ramon fault zone (SRFZ) is interpreted as a synthetic normal fault to the main bounding normal fault of the depression (Lake Nicaragua fault zone [LNFZ]) that produces the overall basin asymmetry. (D) Core data modified from Ranero et al. (2000) were used to construct cross-sections B and C. (E) Oblique view of the Cocos-Caribbean subduction zone showing locations of the cross sections and wells.

by the transfer of stresses between mechanically weak volcanic centers and mechanically strong areas between centers.

We do not interpret these diffuse fault patterns to represent bookshelf faulting (Fig. 7C), mainly because of the absence of regular and parallel, left-lateral strike-slip faults in Lakes Managua or Nicaragua. Young faults in the lakes instead appear to be localized parallel to the Central America volcanic front and do not extend significant distances beyond the Central America volcanic front, as predicted by the bookshelf model (La Femina et al., 2002). The absence of a single, through-going fault along the Central America volcanic front in both lakes also is not supportive of the pull-apart model with rupture along the thermally weakened crust of the Central America volcanic front.

Our three structural cross sections suggest that the offshore strata have been deformed by tight folding and thrust faulting near the Pacific coastline (Fig. 23B). We infer that these localized zones of steep dips and localized folding are the result of footwall uplift (i.e., out-of-syncline shortening adjacent to the uplifted normal footwall uplift). Therefore, this localized footwall-related shortening accompanying the formation of the adjacent Nicaraguan depression began in the Miocene (Fig. 23B).

Georeferencing of the aeromagnetic data set near Lake Managua suggests that the Mateare fault aligns well with its topographic scarp along the western edge of Managua (Fig. 21). This prominent scarp was previously thought to represent a fault-line scarp eroded back to the southwest (La Femina et al., 2002). The recognition of this fault location has implications for geologic hazard assessments around Managua, since its prominent topographic relief in a high-rainfall setting suggests this fault has remained active into the late Holocene (Cowan et al., 2002). The Lake Managua study mapped the bathymetric expression of a synthetic normal fault running parallel to the Mateare fault in western Lake Managua (Figs. 13C and 23B). The arcuate Momotombito fault zone shown in Figure 13C in the center of the lake is interpreted here to represent an antithetic normal fault to the main bounding-normal fault, the Mateare fault (Figs. 13C and 23B). Both of these fault zones represent the possible reactivation of older faults along which strike-slip motion has superimposed the once dominant dip-slip movement. This area of Lake Managua, along with correlated onland faults, is interpreted as east-west extension from the Mateare fault through the Nejapa-Miraflores volcanic alignment to the Airport graben, terminating at the Cofradía fault (Fig. 22). The Cofradía fault appears in the Lake Managua data as a series of en echelon faults offsetting several drainage networks (Fig. 13C). This is evidence for a relatively young fault zone with mainly dip-slip movement, but also with an apparent left-lateral motion, consistent with a recent transtensional regime. Although many other faults were recognized in the lake, few could be correlated between adjacent lines (Figs. 13, 15, and 16).

The tectonic mechanism for opening of the Nicaraguan depression in the Lake Managua area may be similar to the El Salvador segment, where east-west rifting of the Caribbean plate may play an important role (Fig. 22). One possibly rifted area occurs north of Lake Managua and is collinear with the eastern part of the Lake Managua depression (Fig. 22). The angle of oblique convergence in Nicaragua (15°) is much more oblique than in El Salvador (2°–3°), and it should create a greater degree of shearing along the volcanic front in Nicaragua. On the other hand, the influence of north-south rifts dissipates in Nicaragua from areas to the north in El Salvador (Agostini et al., 2006).

Faults Bounding the Nicaraguan Depression Near Lake Nicaragua and in Costa Rica

Aeromagnetic data show that the Mateare fault does not continue as a straight and continuous subsurface fault into the Lake Nicaragua area (Fig. 21). The magnetic high produced by the Quaternary stratovolcanoes masks the most eastward coverage of the aeromagnetic data and limits its usefulness for fault interpretation in that area (Fig. 21). Seaward-dipping outcrops (15°–25°) of the Cretaceous Rivas Formation (Figs. 5 and 18) can be interpreted as either the limb of a large anticline produced by a regional folding event (Weinberg, 1992; Borgia and van Wyk de Vries, 2003) (Fig. 6B), or, as we propose, the uplifted and back-tilted footwall of a large normal fault inferred along the southern coast of Lake Nicaragua (Fig. 23C). Our proposed footwall model suggests that only one extensional deformational event of Oligocene and early Miocene age was responsible for uplift and folding in the Nicaraguan Isthmus and simultaneous folding/faulting in the offshore Sandino basin formed by a mechanism of out-of-syncline thrusting. For this reason, we are doubtful whether the Miocene convergent phase of Weinberg (1992) is necessary to explain the regional tectonic history of the area. A simpler explanation is that there was no rapid change between Miocene compression and Pliocene extension, as proposed by Weinberg (1992), and instead there was simply a more protracted Miocene-Pliocene extensional phase that produced folding in the footwall block of the largest normal faults.

This protracted extensional episode would also have formed the normal synthetic faults proposed within both lakes (Fig. 23C). The age of footwall uplift related to opening of the Nicaraguan depression is constrained by lateral thickening-thinning of late Oligocene–early Miocene and Pliocene strata (Stephens et al., 2007) (Fig. 23C). The depth to basement in the Nicaraguan depression is not known due to the lack of seismic penetration during the NicLakes survey. The sedimentary fill of the Nicaraguan depression has been proposed to include the Oligocene–Miocene Masachapa Formation based on a single, poorly documented geothermal well (M. Traña, 2006, personal commun.).

Prerift stages of deformation are shown by units with constant thickness, including the Eocene–Oligocene Brito Formation and Cretaceous Rivas Formation (Fig. 23C). Synrift deposits show lateral thinning to the northeast and southwestern boarders of the depression and include the Oligocene–Miocene Masachapa and El Fraile Formations and the Pliocene El Salto Formation. Postrift deposits lie unconformably above the prerift deposits and include Pleistocene to present sediments (Fig. 23C).

CONCLUSIONS

(1) Remote-sensing data and previously published geologic and structural data from El Salvador support the interpretation of previous workers that the arc-parallel El Salvador fault zone is a major right-lateral strike-slip fault that accommodates large-scale, northwestward displacement of the Central America forearc sliver. Deviations in the right-lateral El Salvador fault zone produce several pull-apart and restraining bend segments with large volcanoes preferentially occupying pull-apart segments.

(2) Bathymetric and multichannel seismic-reflection data from the Gulf of Fonseca show the presence of active normal or oblique-slip faults bounding the northwestern, submarine extension of the Nicaraguan depression. A curve in the fault produces a major pull-apart segment underlying the Gulf of Fonseca.

(3) The bathymetry and distribution of active faults in Lakes Managua and Nicaragua indicate that the late Neogene basins underlying both lakes are asymmetrical half-grabens controlled by deeply rooted, steeply dipping normal faults that parallel the southwestern shores of both lakes (Figs. 23B and 23C).

(4) Active, asymmetrical subsidence of Lake Managua and its underlying sedimentary basin can be attributed to the northeastward-dipping Mateare fault, interpreted here as a steeply dipping normal fault, with at least one newly described antithetic (southwestward-dipping) normal fault present in the center of Lake Managua (Figs. 13C and 23B). The Mateare fault dips northeastward toward Lake Managua, back-tilts young volcanic sediments to the southwest (Fig. 14), and corresponds to a prominent subsurface basement lineament observed on the aeromagnetic map (Fig. 21). The Momotombito fault zone in the deeper central part of Lake Managua (23 m below lake level) is interpreted as an antithetic normal fault dipping to the southwest and intersecting the plane of the Mateare master fault at depth (Fig. 23B).

(5) Lake Nicaragua occupies a similar, asymmetrical half-graben, although its proposed master fault (the continuation of the Costa Rica fault zone shown in Fig. 18) is not well exposed at the southwestern lakeshore (Fig. 23C). The San Ramon fault, in the deeper, central part of Lake Nicaragua, is interpreted as a synthetic normal fault dipping to the northeast. The total sedimentary thickness of the Lake Nicaragua basin has not been drilled, nor is it known from seismic-reflection imaging.

(6) The elevated highlands of the Nicaraguan Isthmus separate Lakes Managua and Nicaragua from the Pacific Ocean. We interpret these highlands, which include the Rivas and San Cayetano anticlines, as the footwall block of the Mateare–Lake Nicaragua fault zone along the southern coasts of both lakes (Figs. 18 and 22). Uplift, erosion, and localized folding of the isthmus footwall block occurred coeval with downdropping of the blocks that formed the two lakes and their underlying basins.

(7) GPS data from previous workers show that active plate motions in the forearc areas of Nicaragua and Costa Rica are arc-parallel rather than arc-normal (Fig. 4). For this reason,

the normal faults described here that form the main sedimentary basins beneath both lakes are inferred to have an overprinting component of active, right-lateral strike-slip motion that accommodates northwestward displacement of the Central America forearc sliver (Fig. 22). Variations in GPS vectors indicate that the main zone of right-lateral strike-slip displacement passes close to the city of Managua, along the southwest shore of Lake Managua (Fig. 4). We propose that the main zone of strike-slip faulting in the Lake Nicaragua area parallels the lake normal fault and extends to the southeast along the Costa Rica fault zone.

(8) Three regional, serial structural cross sections constructed from all available seismic and geological data compiled for this study provide new constraints on the age of the Nicaraguan depression, its deformation accompanying northwestward forearc sliver transport, and structural variation of the Central America forearc sliver along 1000 km of its strike from Nicaragua to El Salvador (Fig. 23). Interpretation of the cross sections suggests that the Nicaraguan depression initially formed in the Lake Nicaragua area in late Oligocene–early Miocene time and propagated northward to the Gulf of Fonseca, where the rift is Miocene–Pliocene in age. Because the Lake Nicaragua segment of the depression is oldest, this area exhibits the most extensive footwall uplift and oldest rocks (Cretaceous) in the core of the footwall uplift (Fig. 23C). The Lake Managua segment represents an intermediate stage of footwall uplift, based on the onlapping Miocene–Pliocene sediments, and absence of older Cretaceous strata in the core of its footwall uplift (Fig. 23B). The Gulf of Fonseca segment represents a juvenile stage of uplift with the least amount of footwall uplift and erosion (Fig. 23A).

(9) The lack of transverse faults within the Nicaraguan lakes does not support the bookshelf model for the mode of fault deformation along the right-lateral forearc sliver boundary. The lack of a single, through-going fault along the trend of the Central America volcanic front in both lakes also does not support the pull-apart model along the Nicaraguan segment of the forearc sliver. However, the pull-apart model appears more relevant for the right-lateral El Salvador fault zone, as indicated by the right-stepping offsets of the Central America volcanic front (Fig. 23). The inferred right-lateral strike-slip fault parallel to the Central America volcanic front in Nicaragua appears to be controlled by a more complex deformation style that includes isolated segments of right-lateral shear, the Congo restraining bend, the Marabios en echelon fault zone, the Managua releasing bend, and the Cocibolca transtensional segment (Fig. 22).

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