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Notes

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## *Gravity and geodesy of Concepción Volcano, Nicaragua*

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### ABSTRACT

Concepción is currently the most active composite volcano in Nicaragua. Ash explosions of small to moderate size (volcano explosivity index 1–2) have occurred on a regular basis. Gravity data collected on and around the volcano between 2007 and 2010 confirm that a younger cone is built atop an older truncated edifice of denser material, predominantly lavas. The bulk density of the volcanic cone is  $1764 \text{ kg m}^{-3}$  (with an uncertainty of at least  $\pm 111 \text{ kg m}^{-3}$ ), derived from gravity data. This estimated bulk density is significantly lower than densities (e.g.,  $2500 \text{ kg m}^{-3}$ ) used in previous models of gravitational spreading of this volcano and suggests that the gravitational load of the edifice may be much lower than previously thought. The gravity data also revealed the existence of a possible northwest-southeast-oriented normal fault (parallel to the subduction zone). Episodic geodetic data gathered with dual-frequency global positioning system (GPS) instruments at five sites located around the volcano's base show no significant change in baseline length during 8 yr and 2 yr of observations along separate baselines. Structures deformed after the Tierra Blanca Plinian eruption ca. 19 ka, which significantly altered the form and bulk density of the volcano, may be due to the spreading of the volcano, but may also be related to volcano loading, magmatic intrusions and their subsequent evolution, and other volcano-tectonic processes, or a combination of any of these factors. A joint interpretation of our gravity and geodetic GPS data of Concepción suggests that this volcano is not spreading in a continuous fashion; if it is episodically spreading, it is driven by magma intrusion rather than gravity. These results have important implications for

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**volcanic hazards associated with Concepción Volcano. Although during the last 15 yr tephra fallout and volcanic debris flows (lahars) have been the pervasive hazards at this volcano, earthquakes from an eventual slip of the fault on the east-northeast side of the volcano (delineated from our gravity measurements) should be considered as another important hazard, which may severely damage the infrastructures in the island, and conceivably trigger a volcano flank collapse.**

## INTRODUCTION

Volcanoes evolve depending on the nature of eruptions and eruptive products through time, the gravitational load of the volcano, and its interaction with the crust (Borgia, 1994; Borgia *et al.*, 2000; Merle and Borgia, 1996; van Wyk de Vries and Borgia, 1996; van Wyk de Vries and Matela, 1998). As the edifice of a volcano grows, the load of this edifice on the crust may cause the volcano to spread radially, and the resulting deformation affects hazards (e.g., potential for flank collapse and the location of potential flank eruptive vents). In this paper, we use gravity and global positioning system (GPS) measurements collected at Concepción Volcano, Nicaragua to improve knowledge of its structure, and to investigate the possibility that the volcano is laterally spreading under its own load. Concepción, along with Maderas volcano, forms Ometepe Island in Lake Nicaragua (Fig. 1). This small composite volcano is built upon sedimentary rocks and unconsolidated sediments in the lake, and it has been frequently cited as an example of a spreading volcano (Merle and Borgia, 1996; Borgia *et al.*, 2000; Borgia and van Wyk de Vries, 2003; Delcamp *et al.*, 2008). This potential spreading clearly has important implications for the ways in which volcanic hazards are assessed in populated areas on the island and possibly for all those living on the shores of Lake Nicaragua.

Bulk density is a crucial parameter contributing to the potential for a volcano edifice to spread (Merle and Borgia, 1996; Borgia *et al.*, 2000). Essentially, the higher the density of the volcano edifice, the more likely this load, added to the crust in a relatively short time, will cause isostatic adjustments. Isostatic adjustment, in turn, may enhance instability of slopes of the volcano or the response of the edifice to subsequent intrusions (Borgia, 1994; Borgia and van Wyk de Vries, 2003). Gravity surveys are widely used to study the structure of volcanoes (Yokoyama, 1963; Budetta *et al.*, 1983; Rymer and Brown, 1986; Brown *et al.*, 1987; Connor and Williams, 1990; Rout *et al.*, 1993; Camacho *et al.*, 1997; Affleck *et al.*, 2001). In particular, gravity data provide direct information about volcano density (Finn and Williams, 1982; Brown *et al.*, 1991; Deplus *et al.*, 1995; Schulz *et al.*, 2005; Cassidy *et al.*, 2007), which is of fundamental importance for determining the potential for a volcano edifice to spread laterally under its own load (Merle and Borgia, 1996; Borgia *et al.*, 2000; Jordan *et al.*, 2009). Similarly, GPS is one of the main tools for the study of volcano deformation (Dixon, 1991; Murray *et al.*, 2000; Blewitt, 2007; Dzurisin, 2007), and it offers the most direct evidence of whether a volcano is spreading and at what rate. Therefore, we undertook gravity investigations at Concep-

ción with the goal of investigating the structure and bulk density of the volcano, and GPS investigations in order to investigate the deformation (specifically, the change in baseline length between geodetic GPS stations) over time.

In the following, we describe the geologic and tectonic setting of Concepción Volcano with special reference to volcano spreading models. Then, we describe our new gravity map of Concepción Volcano and the way in which these data were used to estimate bulk density of the edifice and to refine our understanding of the major structural features of the volcano. GPS results from campaigns in 2001–2010 are presented, and these position data were analyzed on long-term (yearly) and short-term (daily) time scales. If permanent deformation associated with gravitational spreading is occurring at a high rate, then lengthening of the baselines between GPS stations positioned around the volcano should be observed on a long time scale. Instead, deformation is observed on short time scales (daily), and is associated with episodes of volcanic unrest, and is recoverable (resulting in elongation and shortening of baselines repeatedly).

## TECTONIC AND GEOLOGICAL SETTING

Concepción Volcano is a 1600-m-high composite volcano (Figs. 1 and 2). Concepción is part of the Central American volcanic arc, which results from subduction of the Cocos plate beneath the Caribbean plate. The volcanic arc is located within the Nicaraguan Depression, an Oligocene–Pliocene half-graben that extends 500 km in length from northern Costa Rica to the Gulf of Fonseca and has a width ranging from 40 km (northwest) to 70 km (southeast) (McBirney and Williams, 1965; Weinberg, 1992; Funk *et al.*, 2009). Although there have been several different theories as to the tectonic significance, geomorphology, and history of the Nicaraguan Depression, we are here primarily interested in the stratigraphy of the Nicaragua Depression and the current tectonics of the margin at the latitude of Concepción Volcano.

The Nicaraguan Depression is flanked to the northeast by a late Oligocene to middle Miocene volcanic arc (El Coyol Group volcanics; Ehrenborg, 1996) and the Nicaraguan highlands, composed of pre-Mesozoic crust (Sundblad *et al.*, 1991). The volcanic arc migrated to the Nicaragua Depression during the middle Miocene (e.g., Ehrenborg, 1996; Plank *et al.*, 2002; Carr *et al.*, 2007; Saginor *et al.*, 2011) and resides there today. The depression is a half-graben with down-to-the-northeast displacement along margin-parallel (i.e., northwest-trending) normal faults along the southwestern margin. On the western edge of Lake Nicaragua, the boundary is composed of Late Cretaceous to Miocene

sedimentary and volcanoclastic rocks of the Sandino Basin that were folded and uplifted, and then faulted (Weyl, 1980; Weinberg, 1992; Ranero et al., 2000; Funk et al., 2009). The Pliocene El Salto Formation unconformably overlies the top of the Sandino Basin sequence (i.e., the middle Miocene El Fraile Formation, which is interbedded with the Tamarindo Group volcanics). The upper section of the El Salto Formation is interbedded with the Pleistocene Las Sierras Group volcanics, which represent the initiation of the “modern” volcanic arc (Weyl, 1980).

The stratigraphic thicknesses of the Late Cretaceous to Pliocene stratigraphy are best estimated from well logs from offshore and onshore wells (Ranero et al., 2000). The thicknesses of these formations are dramatically thinner than reported by Weyl (1980, and references therein) based on mapping studies. For example, the Sandino Basin sequence is reported as 10 km in thickness by Weyl (1980); however, the maximum thickness as measured

in wells is 4.2 km (Ranero et al., 2000). The Pliocene El Salto Formation is thicker (>700 m) in offshore wells (Argonaut-1 and Corvina-1 wells; Ranero et al., 2000) than has been mapped onshore (100 m thickness; Weyl, 1980). The Las Sierras Group has been mapped at a thickness of 680 m (Weyl, 1980). Unfortunately, the thicknesses of Quaternary alluvium and lacustrine sediments in Lake Nicaragua are not known. Various researchers have estimated or assumed the thicknesses of these deposits, with estimates ranging from ~100 m to >1000 m (Swain, 1966; Elming and Rasmussen, 1997; Borgia and van Wyk de Vries, 2003). The only direct measurement of Quaternary deposits in the Nicaragua Depression is from the M16 exploratory drill hole at the Momotombo geothermal field, ~140 km northwest of Concepción Volcano, which suggests 150 m of Quaternary sediment and ignimbrite that unconformably overlie Tertiary ignimbrites (van Wyk de Vries, 1993). We know of no wells in the Nicaragua

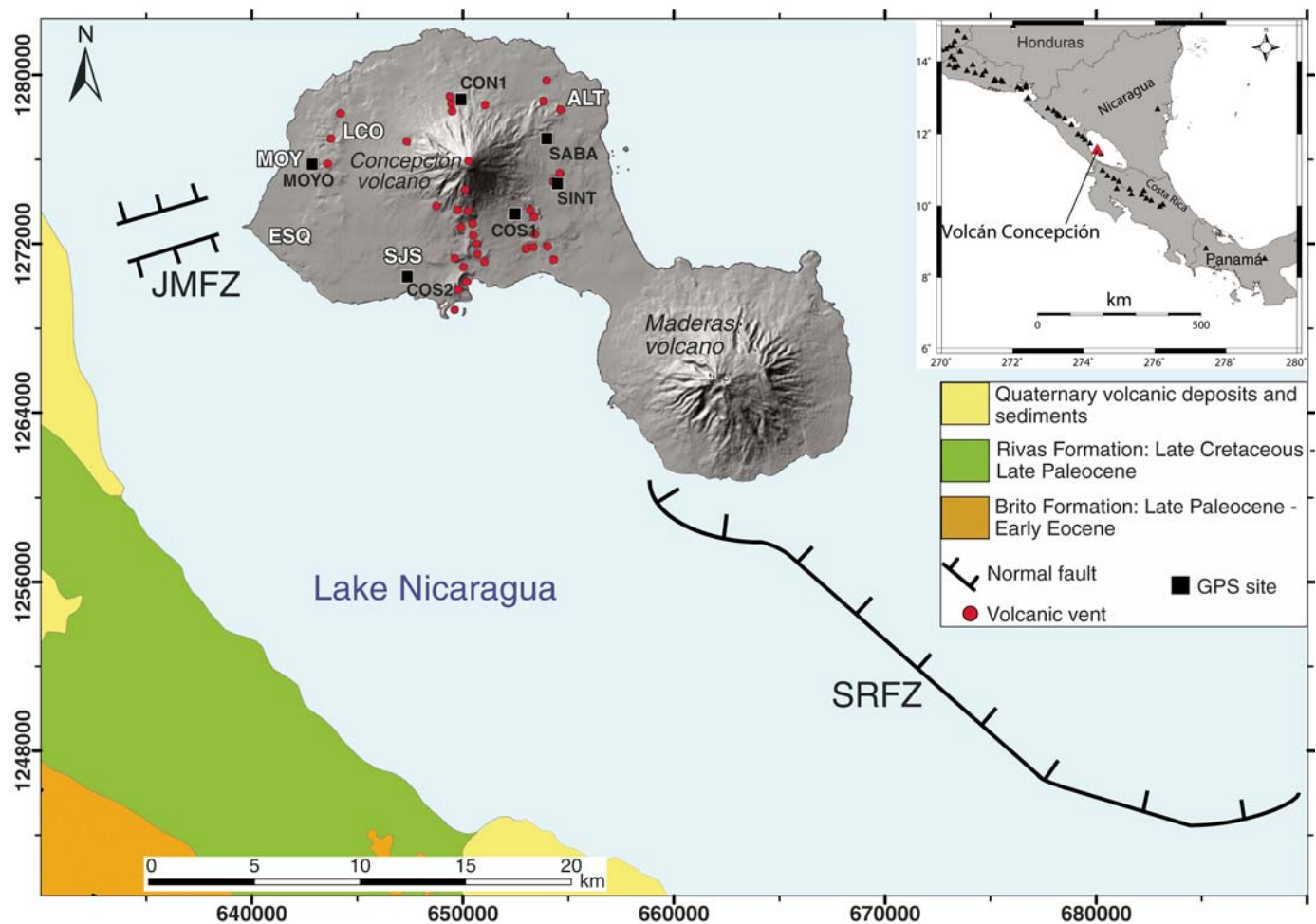


Figure 1. Location of Ometepe Island on the western side of Lake Nicaragua. Concepción Volcano forms the northwest part of the island. Names of major towns have been abbreviated as follows: LCO—La Concepción, MOY—Moyogalpa, ESQ—Esquipulas, SJS—San José del Sur, ALT—Altagracia. Black squares depict the location of global positioning system (GPS) monuments with their respective four-character code. Red circles represent volcanic vents. Faults within the lake (SRFZ—San Ramon fault zone, JMFZ—Jesús María fault zone) are from Funk et al. (2009). Inset: Location map of Concepción Volcano within Lake Nicaragua in Central America. Black triangles show the location of major Quaternary volcanoes along the Central America volcanic front. Projection: Transverse Mercator, UTM Zone 16N, Datum: WGS-1984.

Depression that have reported well logs. Recent seismic-reflection data collected in Lake Nicaragua indicate >20 m of sediment (Funk *et al.*, 2009) but could not confirm total thickness of the sediments due to rapid attenuation of seismic waves.

The neotectonics of the Central American margin have been the focus of recent studies to investigate the kinematics of deformation of the forearc and volcanic arc. Geodetic studies indicate that the forearc is migrating from central Costa Rica to Guatemala at rates of 8–17 mm yr<sup>-1</sup> (Norabuena *et al.*, 2004; Correa-Mora *et al.*, 2009; La Femina *et al.*, 2009; Alvarado *et al.*, 2011). Although it is debated how this forearc motion is accommodated in Nicaragua, it is clear that there are three active structural trends: (1) northwest-trending, right-lateral strike-slip and normal faults; (2) northeast-trending, left-lateral strike-slip

and normal faults; and (3) north-trending normal faults and volcanic alignments.

Recent seismic-reflection data collected in Lake Nicaragua imaged three faults that vertically displace the lake bottom: the San Ramon, Jesús María, and Morrito fault zones (Funk *et al.*, 2009). The San Ramon fault zone is a northwest-trending, down-to-the northeast, dip-slip normal fault that is located at the southwestern end of Maderas Volcano and extends 25 km to the southeast (Funk *et al.*, 2009). The Jesús María fault zone (Fig. 1) is a northeast-trending, irregularly surfaced topographic high with ~4–7 m vertical scarps (Funk *et al.*, 2009). This structure is located directly southwest and aligned with an extended peninsula of Concepción Volcano, and a broader topographic high between Ometepe Island and the western edge of Lake Nicaragua

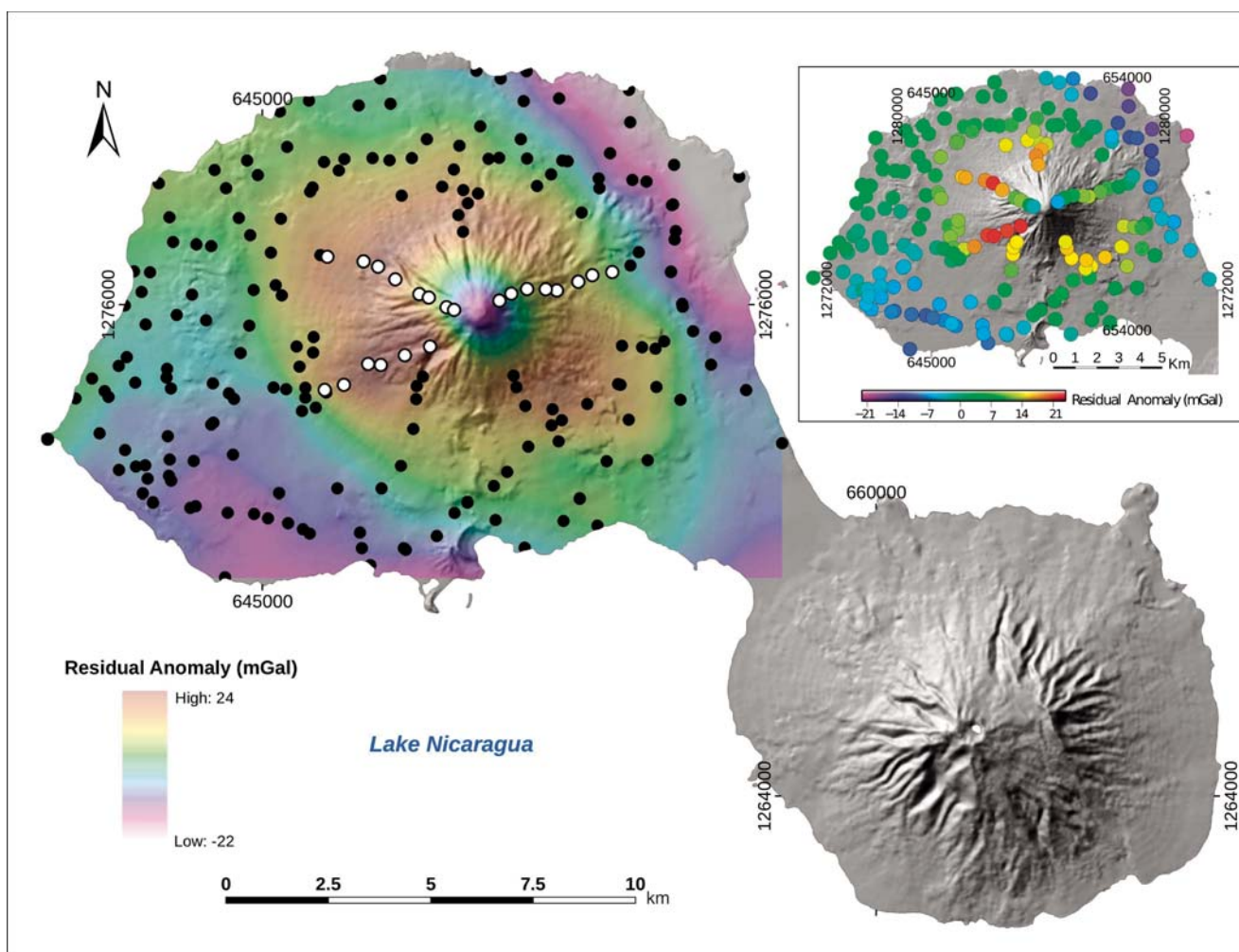


Figure 2. Residual gravity anomaly interpolated using the cubic spline algorithm draped on top a shaded relief map of Ometepe Island. The residual gravity anomaly was computed by subtracting a regional trend from the complete Bouguer anomaly calculated using a density of  $1764 \pm 111 \text{ kg m}^{-3}$ ; see text for details. Black circles represent gravity observation points. White circles represent gravity observation points used to compute the bulk average density of the volcano by means of the one-dimensional Nettleton (Nettleton, 1939) and Parasnis (Parasnis, 1997) methods. Inset: Point color map of residual gravity anomaly on Concepción Volcano. The residual gravity anomaly map reveals concealed geologic structures of the volcano, and possible faults on the northeastern and southwestern sides. Projection: Transverse Mercator, UTM Zone 16N, Datum: WGS-1984.

(Funk et al., 2009). The Morrito fault zone is a 20-km-long, 5-km-wide, northeast-trending depression with 5–7 m scarps located northeast of Ometepe Island (Funk et al., 2009).

In addition to these fault zones, a magnetic anomaly along the southeastern shore of Lake Nicaragua has been interpreted qualitatively as the Lake Nicaragua fault zone (Funk et al., 2009), a northeast-dipping depression-bounding normal fault. Funk et al. (2009) proposed that these faults have been reactivated as dextral oblique-slip faults in the current kinematic regime to accommodate forearc motion; however, no historical seismicity is known to be associated with these fault systems. Instead, there have been two recent earthquakes located on northeast-trending, left-lateral, strike-slip faults northwest and southeast of Ometepe Island: the 1987 Mw 6.1 Lake Nicaragua and 2005 Mw 6.3 Ometepe earthquakes, respectively.

## CONCEPCIÓN VOLCANO

The volcano is predominantly composed of clinopyroxene-plagioclase-bearing andesite rocks found low and high on the slopes exposed in gorges. Basalts also occur and are found mostly on lateral vents and in some summit eruptions. A dacite pumice deposit is found at the north base of the volcano (McBirney and Williams, 1965; van Wyk de Vries, 1993; Borgia and van Wyk de Vries, 2003). Lahars, pyroclastic units, and lava flows are all common products of Concepción (McBirney and Williams, 1965; van Wyk de Vries, 1993; Borgia and van Wyk de Vries, 2003). Van Wyk de Vries (1993) and Borgia and van Wyk de Vries (2003) provided a detailed magmatic evolution of the volcanic system. Stratigraphically older magmas erupted from Concepción are termed the Quebrada Grande stage and are low-alumina (~16 wt%  $\text{Al}_2\text{O}_3$ ) and high-magnesium (~8 wt% Mg) basalts. Following the Quebrada Grande stage, magmas evolved to a more silica- and alumina-rich composition, culminating in the dacite amphibole-bearing Tierra Blanca tephra deposits (~63–66 wt%  $\text{SiO}_2$ ) (van Wyk de Vries, 1993; Borgia and van Wyk de Vries, 2003). The Tierra Blanca tephra is widespread throughout the region and is found in cores collected offshore, in the Pacific Ocean. The Tierra Blanca tephra is dated at ca. 19 ka (Kutterolf et al., 2008) and marks the most explosive (Plinian-style) activity known to have occurred at Concepción. Following the Tierra Blanca eruption, most tephra and lava compositions have been 50–55 wt%  $\text{SiO}_2$ , although the top sections of the tephra erupted in 1957 had 62 wt%  $\text{SiO}_2$  (Borgia and van Wyk de Vries, 2003), and eruptions from lateral vents generally have less silicic compositions than central vent eruptions (Fig. 1) (van Wyk de Vries, 1993).

A geodynamic model of Concepción proposed by Borgia and van Wyk de Vries (2003) suggests that spreading of the volcano edifice began after the Tierra Blanca eruption, during the El Mogote phase, when the volume of newly erupted products became sufficient for the load of the edifice to initiate spreading on the underlying ductile lake sediments. In their model, this spreading involves a thicker portion of the sedimentary section,

and even the magma chamber, over time. As the increased load of the volcano edifice drives spreading, deformation with spreading should be continuous (Borgia et al., 2000), but may be episodic if the Maxwell relaxation time is small compared to the characteristic spreading time (Borgia and van Wyk de Vries, 2003). Characteristic spreading time,  $T$ , is given by Borgia et al. (2000) as:

$$T = \frac{3\mu L^2}{\rho g H_v H_d^2}, \quad (1)$$

where  $\mu$  is the viscosity of the deforming ductile layer of thickness  $H_d$  beneath the volcano of radius  $L$ , bulk density  $\rho$ , and height  $H_v$ , and  $g$  is gravitational acceleration. Thus, a low bulk density and thin ductile layer will result in longer characteristic spreading time than a high bulk density and thick ductile layer, for a volcano of a given geometry. Although the viscosity of the ductile substratum layer can vary by several orders of magnitude, at Concepción it is assumed to be low because it is composed of soft clayey sediments (van Wyk de Vries, 1993; Borgia and van Wyk de Vries, 2003). Van Wyk de Vries and Matela (1998) proposed a viscosity in the range of  $10^{15-18}$  Pa·s.

North-south-trending fissures and aligned eruptive vents on the volcano edifice may be a manifestation of overall east-west extension associated with spreading (Borgia and van Wyk de Vries, 2003), although north-south-trending fissures and vent alignments are ubiquitous on volcanoes in this part of the arc and are generally attributed to extension within the dextral shear zone that defines Central America forearc motion relative to the Caribbean, without requiring volcano spreading.

The most recent comparatively large-volume effusive eruption of Concepción was in 1957 (volcanic explosivity index [VEI] 2), and a minor effusive eruption took place in 1986 (VEI 1) (McBirney and Williams, 1965; Siebert et al., 2011). Ash explosions from small to moderate size occur frequently, characterized by VEI of 1 and 2 (Siebert et al., 2011). This activity is sufficient to maintain a summit pyroclastic cone, degradation of which results in seasonal lahars that reach populated and agricultural areas at the base of the volcano.

## GRAVITY

### Data and Processing

In total, 206 gravity readings were collected on and around Concepción Volcano during four different campaigns between 2007 and 2010, covering an area of ~18 km × 12 km on Ometepe Island (Fig. 2). The 2007 gravity campaign was carried out with a G-58 LaCoste and Romberg instrument. The 2008–2010 campaigns were conducted with a Burris gravity meter (B-38). During all surveys the observation points were positioned with a differential GPS instrument to achieve absolute vertical accuracies of at least 10 cm. The observed data were reduced using the standard procedure described by LaFehr (1991) and Nowell (1999), by applying corrections for: solid earth tide, instrument drift,

geographical latitude, free-air, Bouguer slab (simple Bouguer correction or Bullard A correction), spherical cap (Bullard B correction), and terrain (complete Bouguer, or Bullard C correction).

Terrain corrections were computed in three steps using a 20 m digital elevation model (DEM), provided by the Instituto Nicaragüense de Estudios Territoriales (INETER). These three steps are based on the distance from the gravity observation point to points on the DEM grid. The inner-zone correction accounts for topographic variation within Hammer's zone C, 53.3 m, and was computed using the quarter-wedge method described by Nowell (1999), an improved version of the power-law approximation method of Campbell (1980). The intermediate-zone correction was performed for DEM grid points that fall between Hammer's zone D, >53.3 m, and the outer radius of Hammer's zone K, 9903 m. This terrain correction was done using the simplified gravity attraction of a prism approximated as an annular ring, described by Kane (1962). The far-field terrain correction was performed for distances >9903 m and up to the extent of the input DEM, including all of the area of Ometepe Island. This far-field correction was carried out by means of the vertical line mass approximation described by Blais and Ferland (1984), which is the approximation of the gravity attraction due to a prism in the far-field. The lack of precise bathymetry data from Lake Nicaragua prevented implementation of a correction for the gravitational attraction from the water lake layer, but this effect must be small compared to the island terrain correction as lake depth is shallow, around 20 m in maximum depth in the region around Ometepe Island, and 43 m at its maximum reported depth in the central part of the lake (Swain, 1966). The maximum terrain correction obtained using this method was 5.27 mGal, for a station located on the highest point along the ridge on the southwest flank of the volcano and located very near the San José del Sur gully (Fig. 1). Only points located on the slopes of the volcano have terrain corrections >1 mGal.

A residual gravity anomaly was computed by subtracting the complete Bouguer anomaly (the anomaly obtained after the application of the terrain correction) from an assumed regional trend, estimated by fitting a plane to the complete Bouguer anomaly map using the generalized least-squared method (Fig. 2).

### Estimate of the Bulk Density of Concepción Volcano

A primary goal of collection of gravity data on Ometepe Island was to estimate the bulk density of Concepción Volcano. Initially, the bulk density of the volcano edifice was estimated using the Nettleton (Nettleton, 1939) and Parasnis (Parasnis, 1997) methods, using gravity stations along two profiles that cross the volcano edifice. These methods are based on the observation that complete Bouguer gravity anomalies should be minimally correlated with topography in geologically homogeneous terrains. Ometepe Island is constructed predominantly of tephra and lavas in an area where lake sediments are dominated by volcanoclastic material (Swain, 1966), so this assumption is reasonable. The Nettleton and Parasnis methods yield a bulk average

density of the volcano of  $1439 \pm 67 \text{ kg m}^{-3}$  and  $1539 \pm 89 \text{ kg m}^{-3}$  on each profile. However, the resulting Bouguer anomaly maps are positively correlated with topography, indicating that these densities are lower than the actual bulk density of the terrain.

To improve the density estimate, we extended the Nettleton's method from a one-dimensional (1-D) to a two-dimensional (2-D) grid by encompassing the entire volcano edifice (including many more observed points) and computing the correlation between the topography and Bouguer gravity anomaly for a series of bulk densities. The most likely bulk density of the volcano minimizes this correlation. The density thus obtained was  $1764 \text{ kg m}^{-3}$ . We do not know the uncertainty in the model due to the real density heterogeneities below the targeted area (i.e., the volcano edifice), but from the analysis of regression, we estimate uncertainty to be  $\pm 111 \text{ kg m}^{-3}$ . Thus, we deem the latter value as the uncertainty's lower bounds for the bulk average density estimation. This bulk density is significantly less than values used in previous volcano spreading models (Borgia and van Wyk de Vries, 2003), but it is consistent with the density of other volcanoes dominated by the accumulation of pyroclasts (Minakami, 1941; Brown *et al.*, 1991; Affleck *et al.*, 2001; Cassidy *et al.*, 2007). Using a bulk density of  $2500 \text{ kg m}^{-3}$  (Borgia and van Wyk de Vries, 2003), the Bouguer anomaly map is negatively correlated with topography, indicating that  $2500 \text{ kg m}^{-3}$  is an overestimate of the density (see maps in GSA Data Repository<sup>1</sup>).

### Gravity Anomalies

The distribution of gravity anomalies clearly reveals additional structure within the edifice of Concepción Volcano and on Ometepe Island (Fig. 2). First, the gravity map of the volcano is dominated by a gravity low in the upper edifice of the volcano and comparatively high gravity values low on the edifice. The transition between the high and low values correlates with a slight break in slope visible on the flanks of the volcano produced by the Tierra Blanca explosive phase, and the subsequent addition of pyroclastic material. The low gravity values found on the upper slopes of the volcano are interpreted to reflect the low-density pyroclastic cone that forms the summit area of the volcano. In contrast, the lower slopes of the volcano have a slightly higher density, resulting in a positive gravity anomaly.

Sharp gradients in the residual gravity anomaly map (Fig. 2) delineate faults that are partially and/or completely buried by young volcanic products. The low-residual-gravity anomaly,  $< -7 \text{ mGal}$  trending  $N40^\circ W$  (parallel to the subduction zone in Nicaragua) on the northeast side of Concepción (Fig. 2), may represent a fault, possibly an extension of the mapped faults on Maderas Volcano with about the same strike, and it matches the fault partially mapped north-northeast of Concepción by van

<sup>1</sup>GSA Data Repository Item 2013350, Figures DR1–DR12: Bouguer anomaly maps, temporal changes, and temporal variations, is available at [www.geosociety.org/pubs/ft2013.htm](http://www.geosociety.org/pubs/ft2013.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

Wyk de Vries (1993). If this anomaly is indeed associated with a normal fault, its hanging-wall block should be down-to-the-northeast. The other low-residual-gravity anomaly southwest of *Concepción Volcano* is more complex in geometry (Fig. 2) and may be related to possible structural discontinuities of volcanic products within mudstones, which may also be associated with an extension of the San Ramon and Jesús María fault zones (Funk et al., 2009).

## GEODETIC GPS TIME SERIES

### Data and Processing

To assess the current deformation of *Concepción Volcano's* edifice, dual-frequency GPS data were collected at six different points on the volcano between 2001 and 2010. The first two sites (CON1 and COS1; Fig. 1) were installed during a campaign in late 2001. Three more sites (COS2, MOYO, and SABA) were installed during the 2008 campaign (Fig. 1). A water well was constructed in late 2009 a few meters from the COS1 site. Because of the potential for displacements associated with water pumping from the new well, in April 2010, a new GPS site (SINT, ~2.5 km northeast of COS1; Fig. 1) was installed to replace COS1. A week of data was collected simultaneously between the two sites to perform a tie and construct a common time series between COS1 and SINT. In the rest of the paper, we will refer to the combined time series as SINZ.

Data were collected in episodic GPS (EGPS) campaign mode in 2001, 2005, 2007, and nearly on an annual basis since 2008. Unfortunately, the two receivers used during the 2007 campaign had problems with firmware and provided results that are not reliable and with a large formal error in the measured position, a problem noted also for other sites where the instruments were utilized (H. Turner, 2007, personal commun.). For completeness, we present these data in the graph, but they were not used in the analysis. During all campaigns, the geodetic markers were observed by mounting the antenna on fixed-height spike mounts to reduce uncertainties in vertical displacement. All the observations lasted at least 2 full UTC days to diminish the noise in the measured positions (in particular, for effects due to troposphere, tide, and signal multipath). The success rate in collecting the full day was significant, and we made an effort to analyze only files with at least 20 h of continuous data collection. Every other epoch that for various reasons (e.g., power supply failure) had fewer data was discarded.

All GPS data were processed to produce nonfiducial daily solutions with the Jet Propulsion Laboratory (JPL)'s software GIPSY-OASIS 6.1.2 using the standard precise point-positioning (PPP) analysis strategy described by Zumberge et al. (1997) with nonfiducial orbits, clocks, and Earth orientation parameters provided by JPL ([ftp://sideshow.jpl.nasa.gov/pub/JPL\\_GPS\\_Products/Final/](ftp://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/Final/)). To improve the PPP of each daily solution, we resolved phase ambiguity using the single-receiver phase ambiguity resolution algorithm of Bertiger et al. (2010), implemented

in the GIPSY-OASIS 6.1.2. The fiducial-free daily solutions were transformed into the International Terrestrial Reference Frame 2008 (ITRF08; Altamimi et al., 2011) through a seven-parameter transformation using parameters provided by JPL. The final product of the analysis consists of time series of the three components (E-W, N-S, and up-down) of the daily position for each site with respect to the ITRF08 reference frame.

The horizontal components of the daily solutions of our GPS sites at *Concepción* were detrended using the data from the continuously operating reference station MANA, located in Managua, Nicaragua (~95 km away from our network). We deem that this approach will enhance the volcanic signal by removing tectonic effects. The MANA site is about the same distance from the subduction trench as our network and is within the same tectonic block (DeMets, 2001). The long-term velocity of the MANA site was computed by applying the same PPP analysis previously described for EGPS sites to daily observations from the continuous site. To avoid co- and postseismic effects related to the October 2004 earthquake in the Nicaraguan part of the subduction zone, only data after December 2006 were analyzed. Long-term velocities of MANA in the north and east directions with respect to ITRF08 were computed by linear fitting of the latitude and longitude time series, respectively ( $9.5 \pm 0.4$  mm yr<sup>-1</sup> for the north direction, and  $7.8 \pm 0.7$  mm yr<sup>-1</sup> for the east direction; velocity uncertainties were computed using the Hackl et al. [2011] algorithm). We used these velocities to detrend the *Concepción's* network time series (see the GSA Data Repository for the resulting time series [see footnote 1]).

To better understand the deformation of *Concepción Volcano* and to increase the signal to noise ratio, we mainly analyzed the change in length of two baselines across the volcanic edifice. The first baseline runs in a northwest-southeast direction on the northeastern side of the volcanic edifice and connects the two oldest sites CON1-SINZ (Figs. 1 and 3). The mean length of the baseline is 5915.765 m, and it has a time span of observations of 8.625 yr. The time series for the CON1-SINZ baseline length is presented in Figure 3. The second baseline runs across the volcano along an east-west direction and connects the sites MOYO and SABA (Figs. 1 and 4). The mean baseline length is 11,146.439 m, and it covers 1.882 yr; this time series is plotted in Figure 4. Both baselines cover times with unusual seismic activity near *Concepción Volcano* reported by INETER (INETER, 2002a, 2002b, 2002c, 2002d, 2002e, 2003, 2005a, 2005b, 2008) and documented in the scientific literature (French et al., 2010) (periods indicated by light-gray vertical bar in Figs. 3–4; see the GSA Data Repository [see footnote 1]). They also cover times of volcanic activity consisting of the emission of volcanic ash through small to moderate explosions (VEI 2) (dark-gray vertical bar in Figs. 3–4; see GSA Data Repository). In particular, the MOYO-SABA baseline time series begins in mid-August 2008 (Fig. 4), 19 d after June 30, when a seismic event was recorded at the *Concepción* seismic station and the Civil Defense reported two ash explosions from *Concepción Volcano* (INETER, 2008).



## GPS Results

Overall, the two baselines do not suggest long-term permanent deformation, at least within the detection limits of our data, described here. The maximum amplitude of baseline length change,  $\sim 40$  mm, is observed in the CON1-SINZ baseline between 2001 and 2005 (Fig. 3, upper diagram). In principle, this could be compatible with episodic spreading of the volcanic edifice, but it is very difficult to attribute it to a particular phenomenon (or phenomena) due to the large temporal gap and the intense seismic activity between the two GPS observation campaigns. In

addition to the large Mw 6.8 9 October 2004 subduction earthquake, which should not have affected our network, INETER (INETER, 2002a, 2002b, 2002c, 2002d, 2002e, 2003) documented seismic activity at Concepción between June and October 2002, and April and June through August 2003, consisting of low-frequency volcanic tremors and low-magnitude earthquakes (i.e.,  $ML \leq 2.7$ ; INETER, 2002a, 2003). Furthermore, during the campaigns with a longer period of observation (CON1-SINT 2005 and 2010, Fig. 3), the data contain large scatter, covering a range of deformation as large as the 2001–2005 signal (Fig. 3). During the 2005–2010 period, within the scattering

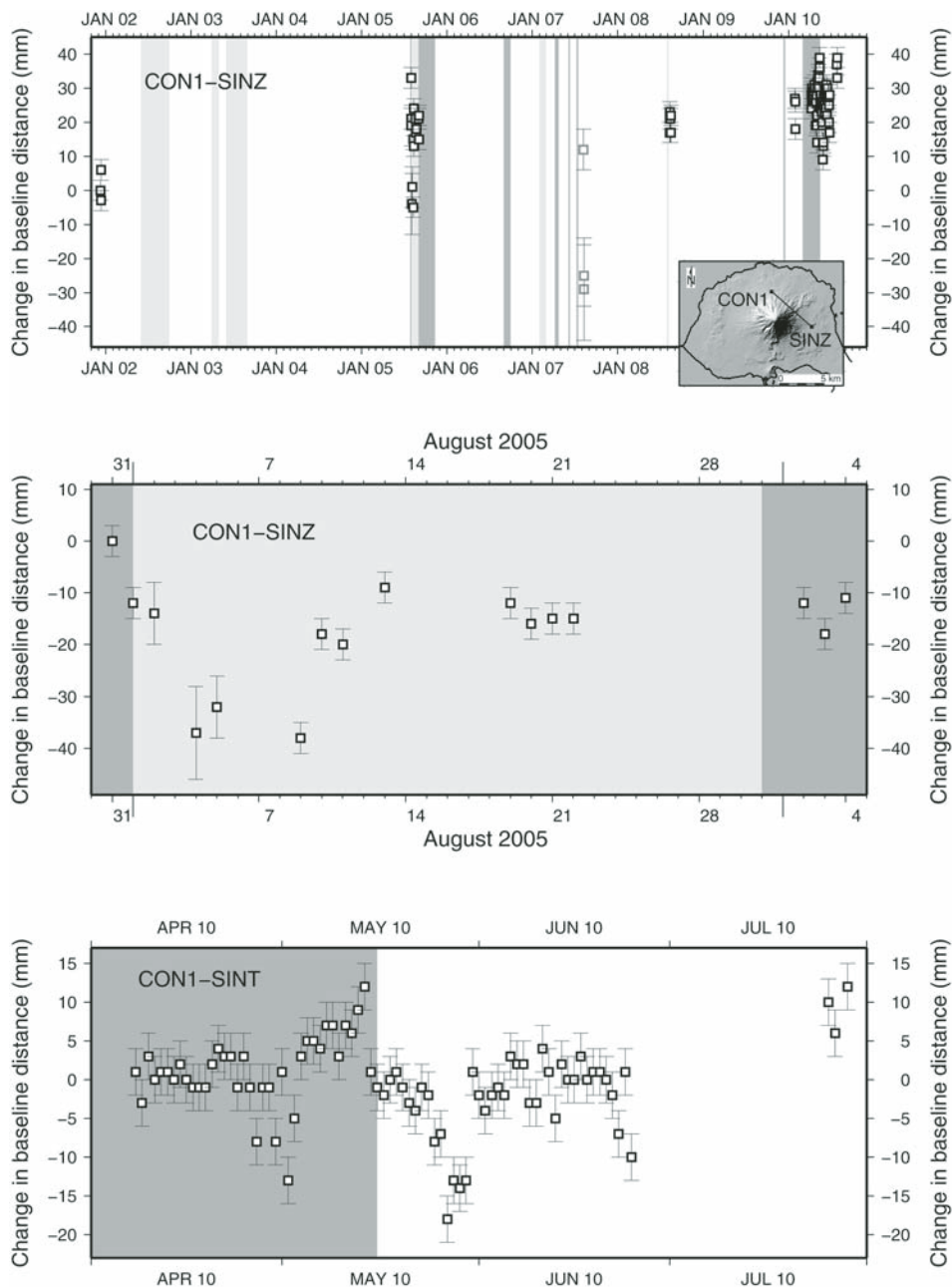


Figure 3. CON1-SINZ and CON1-SINT baseline changes running northwest-southeast across the volcano. In April 2010, the global positioning system (GPS) site COS1 (see Fig. 1) was tied to the new site SINT because a water well pump was built a few meters from COS1 in early 2010. All data originally measured at COS1 but tied to SINT, before April 2010, are referred to as SINZ. Note that no changes in this baseline length are associated with the tie between the two sites. Light-gray vertical bars indicate periods of unusual seismic activity on Concepción Volcano and/or near Ometepe Island, while dark-gray vertical bars represent periods of volcanic activity characterized by ash and gas explosions. Upper diagram: full time series that includes data from all campaigns. Data from the 2007 campaign, gray squares, have been excluded from our analysis due to receivers' firmware problems at that time. Inset shows the location of CON1 and SINT sites. Middle diagram: detail of the 2005 baseline. Lower diagram: detail of the 2010 baseline.

of the data, the average length of the two baselines does not apparently change.

Although affected by large short-term variation with an amplitude of  $\sim 35$  mm between July and September 2005, the average baseline length between CON1 and SINZ did not change (Fig. 3). During this period, the volcano renewed ash and gas explosions, on 28 July 2005, without unusual seismic activity (INETER, 2005b), and the eruptive activity continued for the next 2 mo. Six days later, on 3 August, seismic activity associated with local faulting in Lake Nicaragua started with a seismic swarm that lasted  $\sim 3$  wk (INETER, 2005a) (the main shock was Mw 6.3 located on a northeast-trending fault located  $\sim 6$  km south of Maderas volcano; French et al., 2010). A similar situation was observed during the 2010 campaign, when the volcano was erupting ash and emitting gas from March through May of that year (INETER, 2010). It is interesting to note that the only observations made during quiet periods (2001 and 2009) seem to have a narrower distribution of the observed baseline length (note that these observations also correspond to short observations of only 2 full UTC days).

A closer look at the data during the 2010 campaign (Fig. 3, bottom diagram) indicates that the scattering of the data is not likely related to purely stochastic processes, but instead reveals a very high temporal correlation. The data show periods of high-frequency inflation- and deflation-like elastic deformation ( $\sim 30$  mm in amplitude) in May 2010. A number of possible processes can cause this type of deformation, including volcanic or hydrothermal activity, shrink and swell of the material below the GPS sites, and accumulation of volcanic ash on the antenna. We note that the volcano was erupting ash and gas during March through May in 2010, and so suggest that this deformation signal is directly related to volcanic activity. This nonpermanent deformation is significantly larger than the maximum deformation observed during the full study period and can lead to large changes in baseline length in the span of a few days.

The time series of baseline change between MOYO and SABA stations (Fig. 4) forms almost an east-west-oriented baseline across the volcano (Fig. 1; inset in Fig. 4). This time series

begins in mid-August 2008, 19 d after the seismic event recorded on Concepción's seismic station on 30 July, and the Civil Defense reported two ash explosions from Concepción Volcano the same day (INETER, 2008). The scatter of the data seems to be less in periods with no volcanic activity. This baseline shows amplitude of almost 15 mm, which is about a half of the amplitude of the change observed in the CON1-SINZ baseline. The MOYO station is about twice as far from the volcano than the other stations involved (Figs. 1 and 4), leading to a baseline length two times longer than the CON1-SINZ, or CON1-SINT, baseline. Because we do not have baselines among other station pairs, we cannot investigate whether the amplitudes of the variations in baselines are also related to the distance from the volcano, or if it is simply a casual relationship. We did not compute baselines among other GPS station pairs because the overlapping observation times were too short.

The changes with regard to the first measurement in all components for each of the five GPS sites around Concepción Volcano are shown in the figures in the GSA Data Repository (see footnote 1). The CON1 site shows the largest scatter during August 2005 and March–July campaigns in 2010, which were periods of comparatively intense seismic activity and volcanic ash eruption, and it is the same pattern shown by the change in baseline from CON1 to SINT described previously.

## DISCUSSION AND CONCLUSIONS

New gravity data collected at Concepción Volcano allow us to estimate the bulk density of the volcanic edifice to be  $1764 \pm 111$  kg m $^{-3}$ . This value is significantly lower than densities of 2500–2700 kg m $^{-3}$  previously assumed in spreading models for this volcano (van Wyk de Vries and Borgia, 1996; van Wyk de Vries and Matela, 1998; Borgia et al., 2000; Borgia and van Wyk de Vries, 2003). A higher density favors gravitational spreading because the volcano will represent a bigger load resting upon weak lake sediments. Conversely, a lower density means less potential energy is available to deform and to induce flow of the substratum, and produce induced gravitational spreading of the volcanic

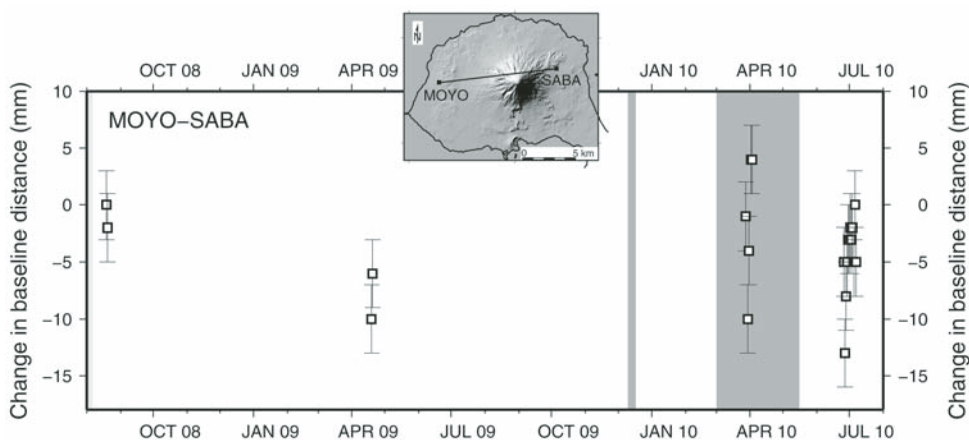


Figure 4. MOYO-SABA baseline change running west-northeast across the volcano. Light-gray vertical bars indicate periods of unusual seismic activity on Concepción Volcano and/or near Ometepe Island, while dark-gray vertical bars represent periods of volcanic activity characterized by ash and gas explosions. Inset shows the locations of MOYO and SABA sites.

edifice. Geodetic GPS data do not show evidence of continuous spreading of the volcano during our longest campaigns, 2005 and 2010. Nonetheless, because the density of a volcano is not the only factor controlling spreading (proper stress field condition, thickness and viscosity of the underlying substratum, magmatic intrusions, etc., also play an important role; see, e.g., van Wyk de Vries and Matela, 1998), we do not rule out the occurrence of volcano spreading at Concepción as an episodic or transient event possibly driven by magma intrusion, as already suggested by Borgia and van Wyk de Vries (2003), or by the interplay with other factors such as regional and/or local seismicity.

The gravity data also provide new information about the structure of the volcano, revealing two distinct lithologies within the edifice, which we infer represent the change to dominantly low-energy pyroclastic activity during the rapid reconstruction phase following the Tierra Blanca eruption, which corresponds to the second building phase of the volcano according to Borgia and van Wyk de Vries (2003). Instead of a spreading-related thrust anticline, as pointed out by Delcamp *et al.* (2008), we infer that the linear residual gravity anomaly trending N40°W (Fig. 2) on the northeastern side of the volcano is associated with a regional normal fault with its downthrown block on the northeast, partially buried by volcanic products, and the northernmost end of which was mapped by van Wyk de Vries (1993). If this is the case, this fault is associated with the 135°-striking dextral transtensional fault zone below Maderas Volcano described by Mathieu *et al.* (2011).

This fault must be taken into account in the seismic hazard assessments of Ometepe Island. This fault may also have a component of right-lateral strike-slip displacement produced by the accommodation of the oblique convergence at the subduction zone in Nicaragua, similar to those found and described by Funk *et al.* (2009), and possibly is a manifestation of tectonic escape, a product of the collision of the Cocos Ridge in central Costa Rica (La Femina *et al.*, 2009). Further research on both volcanoes may help differentiate between these models and better delineate the fault zone.

The low-gravity anomalies found in the southwestern side of our study area (Fig. 2) have a more complicated geometry that cannot be clearly discerned by our gravity survey due to our relatively low-resolution sampling coverage in that area. However, surface faulting and structural discontinuities mapped within this area by van Wyk de Vries (1993) and Borgia and van Wyk de Vries (2003) are to a great extent correlated with the gravity anomalies. There is the possibility that these anomalies may be an extension of the San Ramon fault zone and/or Jesús María fault zone (Fig. 1; Funk *et al.*, 2009). Both gravity data (this study) and geologic mapping (previous studies) show that the southwestern side of Concepción Volcano (Moyogalpa, Esquipulas, and Los Angeles; Figs. 1 and 2) is the locality of small-scale complex structural features (e.g., local/regional faulting). More detailed geophysical study is required to elucidate the nature of these features and thus estimate the hazard they represent to the people living in the island.

The deformation (tilting and faulting) of the deposits from the Tierra Blanca destructive phase, and younger deposits inclusive, mapped by van Wyk de Vries (1993) and Borgia and van Wyk de

Vries (2003), opens the possibility that volcano spreading was at work at some time since that eruption, although this does not tell us what driving mechanisms were in operation. In a recent study based on experimental modeling, Galland (2012) demonstrated that the complex pattern of surface deformation and its evolution in volcanic areas are strongly related to the shape of the intrusion and its subsequent evolution. Concepción Volcano lies next to a shear zone (the boundary of the Central American forearc sliver with the relatively stable Caribbean plate; DeMets, 2001; Turner *et al.*, 2007; La Femina *et al.*, 2009), and other fault zones within Lake Nicaragua (Funk *et al.*, 2009). In addition, the gravity map, the relationships between intrusions and surface deformation reproduced by Galland (2012), and the volcanic activity from Concepción (indicating the presence of magma bodies below the volcano) all indicate the possibility that the deformation of the recent and older deposits from Concepción may not necessarily be related to spreading of the volcano, but rather to a complex interplay of volcano-tectonic processes and features.

When the network was observed more regularly, as in 2005 and 2010, the volcanic edifice underwent significant high-frequency recoverable deformation that led to changes of the baselines up to 3 cm within a few days. This nonpermanent, high-frequency signal poses a significant problem in the evaluation of the long-term deformation of the volcano using episodic observations, as misleading interpretations may result from samples collected for a short time and at large intervals. In our case, the amplitude of the high-frequency signal is comparable, if not larger than, the largest deformation measured, indicating that the trend observed between 2001 and 2005 may be the result of low resolution of signal sampling. It is clear that a full understanding of the deformation of the volcanic edifice will be achieved only by deploying permanent or semipermanent observation stations.

Borgia and van Wyk de Vries (2003) carried out two GPS campaigns with dual-frequency instruments, the first one in November 1994 and the second in May 1997. Their network consisted of 20 stations spaced between 2 and 5 km apart, located around the volcano's base and halfway up the cone. A central station was used to measure the displacements of all other points. For baselines shorter than 10 km, they used a "rapid static technique," rather than a "static technique," which is the technique that yields the highest accuracy (Dzurisin, 2007) and is the one we used in our study. In general, the rapid static technique produces data uncertainty on the order of three times the error of static methods (Dzurisin, 2007), or ~1.5–2 cm on Ometepe Island. Nevertheless, Borgia and van Wyk de Vries (2003) interpreted their results, especially the pattern of deformation, to be consistent with radial spreading of the volcano. However, this interpretation is complicated by several factors, including the data collection methods used, the possibility of base station motion during their survey, and the nature of the high-frequency movement we identify in our data sets. The 2001–2010 time series of baseline length indicate possible permanent change in baseline length over this total period of <40 mm, or ~4 mm per year, a value similar to or less than short-term recoverable (nonpermanent) changes in

baseline length. For example, short-term recoverable deformation of 30 mm is observed in the time series in May 2010 (Fig. 3).

Based on the characteristic behavior shown by Concepción Volcano and described herein, we believe that Concepción is predominantly an open-vent volcano with a shallow magmatic reservoir, and its upper conduit is eventually overpressurized, leading to small to moderate (VEI 1–2) ash and gas explosions. This is reflected in the relatively small-amplitude variations in the GPS baselines and the short-term recoverable deformation.

In conclusion, based on our observations, we consider that Concepción Volcano is composed of two distinct lithologies, has a bulk density of  $1764 \pm 111 \text{ kg m}^{-3}$ , and is not currently undergoing continuous gravitational spreading. Instead, spreading is perhaps taking place in an episodic fashion and is nonpermanent, driven by factors other than gravitational loading (e.g., magmatic intrusion).

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