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Intra-arc extension in Central America: Links between plate motions, tectonics, volcanism, and geochemistry

J. Phipps Morgan [a,*], C.R. Ranero [b], P. Vannucchi [c]

[a] Institute for the Study of the Continents, Cornell University, Ithaca, NY, 14853 USA
[b] ICREA at Institute of Marine Sciences, CMIMA (CSIC), Barcelona, Spain
[c] Dipartimento di Scienze della Terra, Università di Firenze, Via La Pira, 4, 50121, Firenze, Italy

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ABSTRACT

This study revisits the kinematics and tectonics of Central America subduction, synthesizing observations of marine bathymetry, high-resolution land topography, current plate motions, and the recent seismotectonic and magmatic history in this region. The inferred tectonic history implies that the Guatemala–El Salvador and Nicaraguan segments of this volcanic arc have been a region of significant arc tectonic extension; extension arising from the interplay between subduction roll-back of the Cocos Plate and the ~ 10–15mm/yr slower westward drift of the Caribbean plate relative to the North American Plate. The ages of belts of magmatic rocks paralleling both sides of the current Nicaraguan arc are consistent with long-term arc-normal extension in Nicaragua at the rate of ~ 5–10mm/yr, in agreement with rates predicted by plate kinematics. Significant arc-normal extension can 'hide' a very large intrusive arc-magma flux; we suggest that Nicaragua is, in fact, the most magmatically robust section of the Central American arc, and that the volume of intrusive volcanism here has been previously greatly underestimated. Yet, this flux is hidden by the persistent extension and sediment infill of the rifting basin in which the current arc sits. Observed geochemical differences between the Nicaraguan arc and its neighbors which suggest that Nicaragua has a higher rate of arc-magmatism are consistent with this interpretation. Smaller-amplitude, but similar systematic geochemical correlations between arc-chemistry and arc-extension in Guatemala show the same pattern as the even larger variations between the Nicaragua arc and its neighbors.

1. Introduction

The Central American Arc contains one of the most dramatic along-arc geochemistry variations in the world, with the Nicaraguan segments of the arc being type-examples of a 'flux-melting' arc signal (in Ba/La, $^{10}Be/^{9}Be$, U, etc.), while neighboring Costa Rica and El Salvador-Guatemalan segments have a smaller flux-melting signal. This evidence has been recently reviewed and summarized by Carr et al. (2003), who note several opposing trends (anti-correlations) between geochemical and geological observations of the arc: 1) high flux-melting geochemical signals in Nicaragua correlate with apparent geochemical fingerprints of high degrees of partial melting (e.g. low La/Yb) (Carr et al., 1990; Carr et al., 2003), yet arc crust in Nicaragua is thinner than at neighboring arc segments (the opposite of what would be anticipated if Nicaragua has experienced larger magma input through time), and 2) the sizes of Nicaraguan volcanic edifices are smaller than their more 'magma-starved' neighbors(Carr et al., 1990; Carr et al., 2003). We suggest that these anti-correlations can be consistently interpreted if arc-perpendicular extension is faster beneath Nicaragua than beneath Guatemala and northern Costa Rica, and even absent in the region affected by the subduction of the Cocos Ridge. We will first document the plate tectonic, structural, and geochronologic evidence for long-term intra-arc extension across the Nicaraguan Arc. Then we will examine the consequences of long-term arc-normal extension for estimates of Nicaraguan volcanic production rates through time. Finally we review how this mechanism can reconcile geochemical and geophysical correlations along the Central American Arc.

2. Plate kinematic framework

The large-scale plate motions in this region (Figs. 1 and 2) have been recently reassessed by DeMets et al. (2000) and DeMets (2001) in light of new GPS observations (DeMets et al., 2000; La Femina et al., 2002). Estimated plate motions with respect to the hotspot reference frame are shown in Fig. 2. The North American Plate is currently moving westward with respect to the Caribbean plate at an average longterm rate of ~ 21mm/yr (DeMets, 2001), somewhat constrained on a ~ 5Ma-time scale by the (poorly defined) marine magnetic anomalies along the very slow-spreading Cayman Trough (Leroy et al.,

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* Corresponding author.
E-mail address: jp369@cornell.edu (J. Phipps Morgan).

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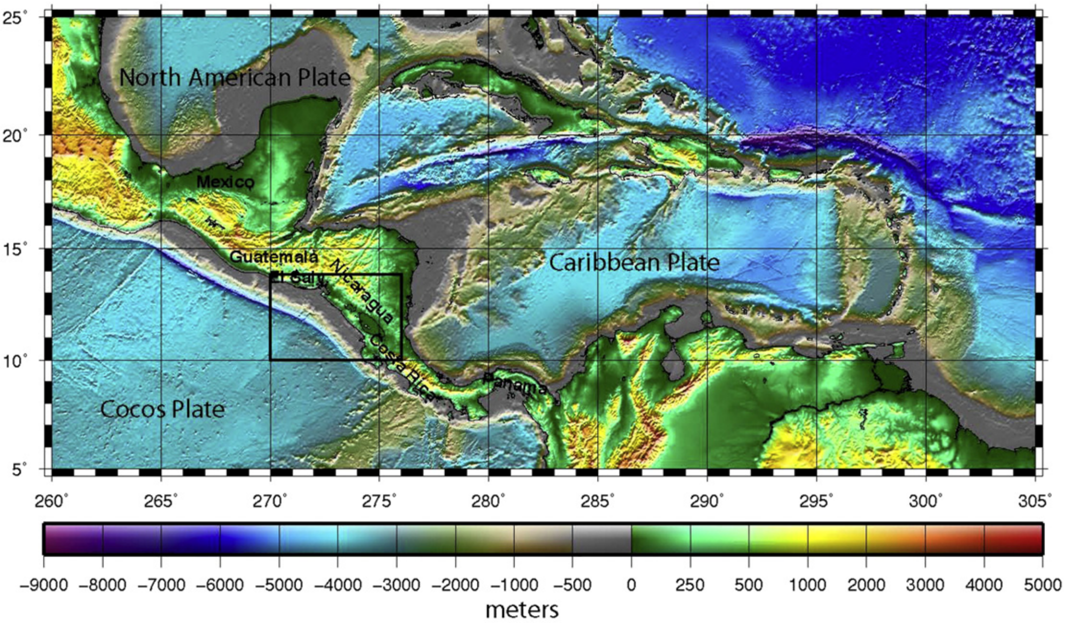


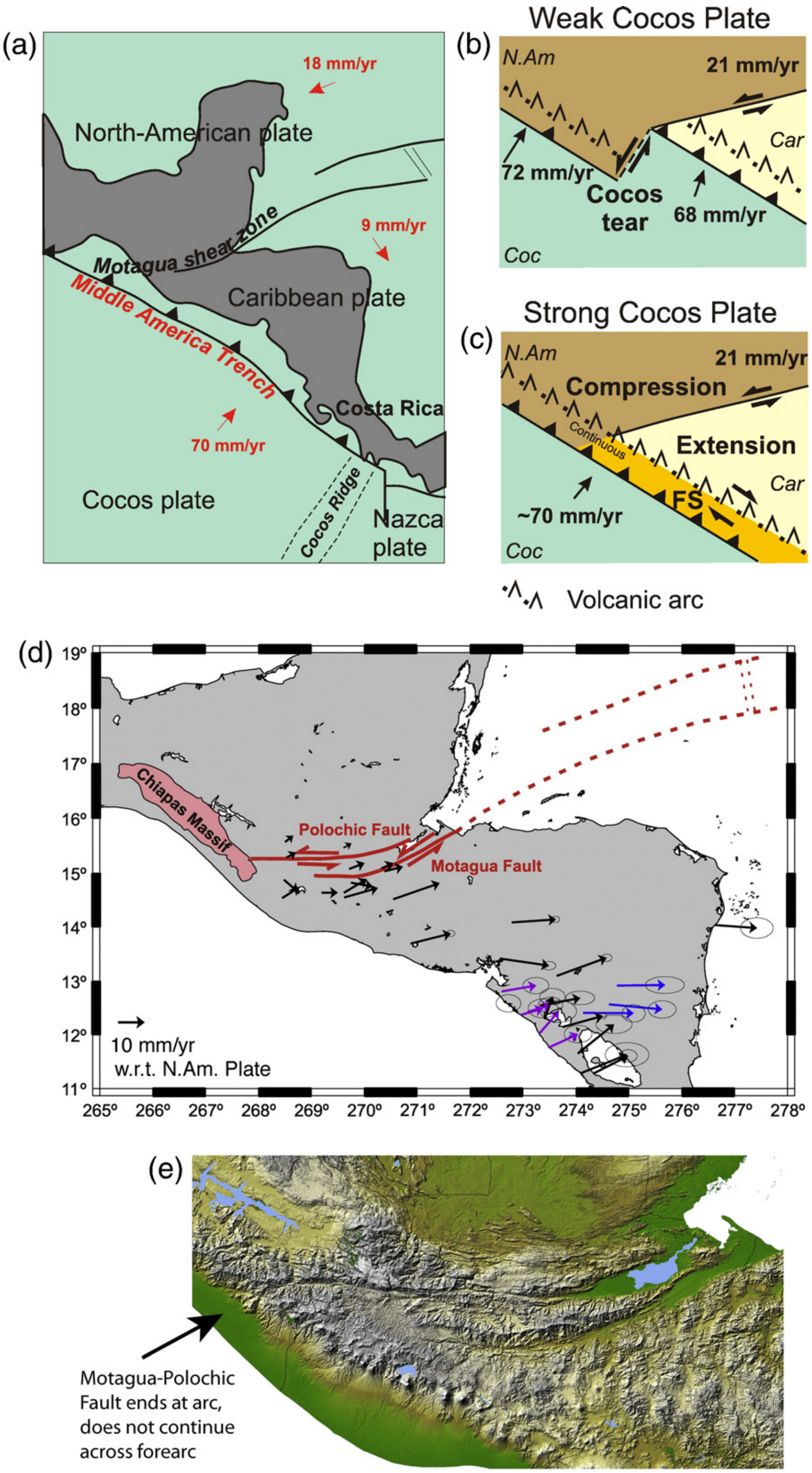
Fig. 1. (a) Regional Map of Central America and the Caribbean Plate. Across Central America, the Caribbean–North American Plate boundary follows the Motagua–Polochic fault system up to the axis of the arc; it does not have a structural continuation across the forearc (see blow-up of the topography in this region in Fig. 2e and further discussion of this point in Fig. 2d–e.). Deformation within Central America is strongly correlated with changes in the motion of the overriding plate relative to the subducting Cocos Plate. North of the Cocos–Caribbean–North American Triple Junction (located above the 'G' in Guatemala, see also Fig. 2a) the 'extra' westward component of North American plate motion relative to Caribbean plate motion correlates with compressive arc tectonics in Chiapas, Mexico. South of the Triple Junction, the extra 'eastward' component of Caribbean plate motion relative to North American correlates with extensional and shear tectonics within the arc (In Guatemala, extension occurs in separate rift structures located behind the arc). The location of Fig. 3 is shown by the black box.

2000), poorly constrained by global plate motion inversions where earthquake slip vectors between the subducting Cocos plate and forearc provided most of the constraints on the motion of the Caribbean plate (e.g. NUVEL1a (DeMets et al., 1994)), and best constrained by regional GPS measurements on a decadal time-scale (DeMets, 2001). The North American plate is moving in a westward direction with respect to the hotspot frame (see Fig. 2a) determined from a best-fit solution for global hotspot tracks to an assumed fixed hotspot frame under the assumption of NUVEL-1a relative plate motions (Morgan and Phipps Morgan, 2007). This westward drift is most likely driven by the westward retreat of the subducting and subducted portions of Cocos–Farallon plate. The Caribbean plate is moving ESE with respect to the hotspot frame in the DeMets (2001) solution (see Fig. 2a), and SW with respect to the hotspot frame in the NUVEL-1a model. The DeMets (2001) GPS-based solution is likely to be more accurate than the NUVEL-1a earthquake slip-vector-based solution since slip-vector- based constraints are inaccurate when there is relative motion between the forearc and Caribbean plate — as there is (see Fig. 2d). In any case, the NUVEL-1a solution also has the Caribbean plate lagging the westward drift of the North American plate. We think the Caribbean plate cannot as easily drift westward because of the pinning effect of the Antilles subduction zone along its eastern margin. The Cocos plate is currently moving NNE in the hotspot reference frame (see Fig. 2a). The choice of hotspot reference frame does slightly affect these conclusions; two recent absolute motion models of Gripp and Gordon (1990, 2002) have all plates moving westward about 1cm/yr faster than our preferred values, while the Gripp and Gordon models least influenced by uncertainties related to the interpretation of a systematic too-young age-bias for the past ~ 3Ma of volcanism along the Hawaiian Island chain more closely matches our preferred absolute plate motion frame (R. Gordon, personal communication, 2007).

If the Cocos–Caribbean–North American Triple Junction were an ideal 'stable triple junction' in the sense of McKenzie and Morgan (1969), then the Cocos Plate would tear at the triple junction, and a new Cocos-NAm transform would be growing as sketched in Fig. 2b. (Note this inference holds for both the NUVEL-1a and DeMets (2001) solutions for the motion of the Caribbean Plate.) Obviously, this is not

Fig. 2. (a) Tectonic map of Central America. Major Plate boundaries are marked, as is the location of the Cocos aseismic ridge. Arrows show absolute plate motions (Morgan and Phipps Morgan, 2007) of the Cocos, North American, and Caribbean Plates in mm/yr. See text for further discussion. (b) Predicted 'ideal' McKenzie and Morgan (1969) geometry for a stable Cocos–Caribbean–North American Triple Junction (TJ) if it behaved according to the kinematic rules proposed by McKenzie and Morgan (1969), in which case the Cocos Plate should tear at the TJ, and a stable rigid plate TJ should have a fault–fault–trench configuration. This behaviour is not seen, the actual fault–trench–trench TJ geometry is sketched in panel (c). (c) Observed plate tectonic geometry near the Co–Car–NAm TJ. The Cocos Plate does not tear. Instead, differential NAm–Car plate motion is accommodated by arc compression N. of the Car–NAm transform fault (the Motagua–Polochic shear zone), and by shear and extension south of the Car–NAm transform boundary. The forearc remains continuous across the location of the TJ, which implies that the Central American forearc arc-normal motions are coupled to the roll-back of the Cocos Plate (e.g. are more North American than Caribbean motion); while the relative lack of arc-perpendicular extensional structures within the Central American Forearc implies that it has at most a small SE-ward motion with respect to the forearc N. of the triple junction, so that its entire motion can be viewed as mostly 'North American'. This implies that Guatemala, El Salvador, and Nicaragua should be regions of arc-normal extension between the NAm-like forearc and the Caribbean backarc. See text for further discussion. (d) Location of the Chiapas Massif batholith that is uncut by the Polochic Fault (Guzman-Speziale and Meneses-Rocha, 2000). Also shown are recent GPS velocity measurements with respect to the North American plate, using the Car–NAm solution of DeMets (2001). Vectors without uncertainty ellipses are from Lyon-Caen et al. (2007), who estimate their uncertainties to be about ±2 mm/yr. Velocity vectors with uncertainties are from Turner et al. (2007). The three blue vectors are those used for the GPS estimate of the Caribbean plate motion east of the Nicaraguan arc in Fig. 3. The 5 purple vectors are those used for the GPS estimate of the Nicaraguan forearc motion west of the Nicaraguan arc in Fig. 3. (e) Blowup of the topography near the Cocos–Caribbean–North American Triple Junction. (Figure courtesy NASA/JPL-Caltech). Note that the North American–Caribbean transform boundary does not continue as a structural feature within the forearc. See text for further discussion.

happening — it seems that the oceanic Cocos Plate is mechanically stronger than its continental neighbors. Since the subducting Cocos Plate does not tear, the necessary interplate triple junction-related deformation must be accommodated within the North American and Caribbean Plates as sketched in Fig. 2c. If the Cocos Plate does not tear, then its slab roll-back will be continuous along the Middle American Trench. Continuous slab rollback means that the forearc motions must also be continuous across the triple junction. To first order this is observed. The long-term geologic evidence for this (Guzman-Speziale and Meneses-Rocha, 2000) is that the Polochic fault — the westward portion of the Motagua–Polochic plate boundary — has not sheared and offset the Chiapas batholith outcropping in this portion of the forearc (see Fig. 2d). Further neotectonic evidence supporting this is that the surface expression of the Motagua–Polochic Fault stops at the arc without a clear topographic expression across the forearc (see Fig. 2e). The sole published GPS velocity measurement for the



Guatemalan forearc (Lyon-Caen et al., 2007) also indicates that the Guatemalan forearc is moving at roughly the same velocity as its adjacent NAm forearc (see Fig. 2d). More and longer-duration GPS measurements for the Guatemalan forearc would be very helpful to ground-truth this key observation, as would measurements in the Chiapas Massif to determine if this portion of the NAm forearc is also slowly moving eastward with respect to NAm at the ~ 5mm/yr rate observed for the Guatemalan forearc by Lyon-Caen et al. (2007).

If the triple-junction-related deformation needed for the Cocos Plate not to tear is accommodated by deformation within both the Caribbean and North American Plates (Fig. 2c), then, away from the plate boundary, the Caribbean Plate would lag the westward slab rollback along this section of the arc, while the North American Plate would move westward faster than the local rate of slab-rollback. These plate kinematics will have two main consequences for along-arc tectonics.

The first consequence is that the region of the North American Plate north of Motagua–Polochic shear zone should be characterized by compressive structures near the triple junction (TJ), as seen (Fig. 1 and Guzman-Speziale and Meneses-Rocha, 2000). A related argument can be made for the southern Caribbean–Cocos–Nazca TJ in Costa Rica/Panama, but in southern Costa Rica the subduction of the Cocos Ridge is also having a major effect on the deformation of the Caribbean plate (LaFemina et al., 2005). This compression being caused by the differential motion between plates which leads to arc-normal compression in the segments next to the TJ of the faster moving overriding plates — as is seen in Chiapas, Mexico (and southern Costa Rica/Panama) (Fig. 1).

Although unrelated to plate kinematics per se, it is curious that both of the regions where arc-parallel thrust-structures form in the overriding plate are also areas of current shallow-angle subduction, with young lithosphere subducting under southern Mexico, and the thick-crust Cocos Ridge subducting under southern Costa Rica.

The second consequence is that segments of the arc in the Caribbean Plate should be under arc-normal extension, if slab-rollback rates are similar to those beneath Mexico, As seen in Fig. 3, due to the changing azimuth of the subduction plate boundary, arc- normal extension will be larger in Nicaragua than in El Salvador, while along-arc shear will be slower in Nicaragua than in El Salvador. Guatemala appears to be somewhat more complex in that, while shear occurs along the arc, fore-arc-Caribbean Plate extension appears to be accommodated in rift zones (Burkart and Self, 1985; Guzman-Speziale, 2001; Lyon-Caen et al., 2007) located near the terminus of the strike-slip fault-boundary between the Caribbean and North American Plates (Fig. 1) — in Guatemala, the strike-slip and extensional deformation belts between the forearc and the stable Caribbean plate have formed as two distinct deformation structures.

The existence of arc-normal extension in the Middle American Arc should not be surprising. Evidence for extension behind the arc is a long-accepted fact in Guatemala (Burkart and Self, 1985; Guzman-Speziale,2001; Lyon-Caen et al., 2007), where it is usually attributed to be a byproduct of the interaction of the Caribbean–North American plate boundary with the Middle American Arc. Coupled shear and extensional arc deformation have been well-documented in the tectonically analogous Taupo segment of the New Zealand subduction zone (Webb and Anderson, 1998; Acocella et al., 2003). Arc-normal extension is also well known to have been associated with rifting and ultimate splitting of the oceanic Marianas Arc to create the modern Marianas back-arc spreading center at ~ 6Ma (Taylor and Karner, 1983), even earlier splitting of the proto-Marianas arc at ~ 30Ma to create the relict Kyushu–Palau Ridge (Taylor and Karner, 1983), and similar splitting of the Lau–Tonga Arc at ~ 6Ma to create the relict Lau Ridge (Weissel, 1977). However, because of the overwhelming seismic, tectonic, and geodetic evidence of extensive arc-parallel shear in Nicaragua (cf. La Femina et al., 2002) and El Salvador (cf. Corti et al., 2005), multiple lines of geologic evidence for Nicaraguan arc-normal extension have usually been minimized or overlooked. Therefore we will focus on this evidence before returning to the implications of this process for the entire Middle American Arc.

The morphology of the Nicaraguan Arc certainly hints at active present-day extension; the active Nicaraguan arc segment lies within a large basin – the Nicaraguan graben – containing Lake Nicaragua and Lake Managua (Fig. 3). The ages of past arc volcanism dated around the Nicaraguan graben also hint at large amounts of extension. For example, there are 'lineaments' of 14–18Ma volcanism on either side of the graben (Fig. 3), separated by over 100km of intervening basin (Plank et al., 2002). If extension were steady-state, this amount of separation would be produced by extension at a rate of 100km/18Ma ≈ 6mm/yr. Paleo-fault patterns also hint that persistent extension has occurred in this region. Abundant basin-parallel fault-like features are seen north of the Nicaraguan graben (Fig. 3), which could certainly have been generated by normal faulting during basin extension. What is missing in Nicaragua (in contrast to the Taupo belt in NZ) is seismic evidence of active normal faulting; instead recent seismicity is dominated by bookshelf-fault shear across the arc (La Femina et al., 2002). Since even Nicaragua requires more arc-parallel shear than arc-normal extension to decouple (slab-pull-induced) forearc retreat from the motion of the Caribbean plate, it should not surprise that strike-slip faulting dominates the shallow tectonic deformation. If Mexico east of the forearc Chiapas Massif had no arc-normal shortening, then ~ 15mm/yr (DeMets, 2001) of arc-normal extension would be required in Nicaragua for the Cocos-Plate to both roll back at the speed of the overriding North American plate and still not tear at the Cocos–NAm–Car triple junction. However, if the Cocos Plate can roll back more slowly because Nam–Cocos shortening accommodates ~ 1/3 (~ 5mm/yr) of the deformation needed for the Cocos Plate not to tear at the Cocos–NAm–Car triple junction, then the required amount of Nicaraguan arc-normal extension would be ~ 10mm/yr. The offset between 14–18Ma volcanic belts in Nicaragua (see Fig. 3) implies that average arc-normal extension rate was ~ 6mm/yr during the past 15Ma. GPS observations in the Nicaraguan forearc (Turner et al., 2007) suggest that the forearc is rotating slightly NE-ward with respect to the NAm plate (Fig. 3), so that the current rate of arc-normal extension across the Nicaraguan volcanic belt is only ~ 3mm/yr (see Figs. 2d and 3). This would occur if the Guatemalan–Nicaraguan forearc sliver and underlying Cocos Plate are bending but not breaking with respect to the North American forearc at the triple junction — i.e. both the forearc and its underlying subducting Cocos Plate are continuously and progressively deforming as one moves southeastward along the arc so that they retreat westward more slowly than the NAm forearc. It is quite possible that the rate of arc-normal extension in Nicaragua has lessened since the Cocos Ridge recently began to subduct beneath Costa Rica. More accurate GPS observations are needed to accurately differentiate between ~ 3mm/yr vs. ~ 6mm/yr rates of present-day arc-normal extension. While 3–10mm/yr extension would be very slow for an oceanic spreading center, in the next section we will see that this magnitude of extension would have a major impact on estimates for arc-volcanism in Nicaragua.

3. Nicaraguan extension is being filled by intrusive volcanism?

If 100km of extension has occurred across the arc during the past ~ 15Ma as implied by the separation of the two sections of the split fossil arc, this would imply that original crustal thickness would be thinned by a factor of 3.3, so that assuming a ~ 30–40km thick pre-extension arc crust would imply a present-day crustal thickness of ~ 10km, instead of the ~ 30–35km that is observed. Limited seismic data (Walther et al., 2000) and gravity modeling (Elming and Rasmussen, 1997; Walther et al., 2000) across the Nicaraguan arc suggest a relatively constant crustal thickness of ~ 30km. Preliminary analysis of the more recent TUCAN seismic experiment does suggest some thinning — about ~ 10km of thinning from a regional crustal

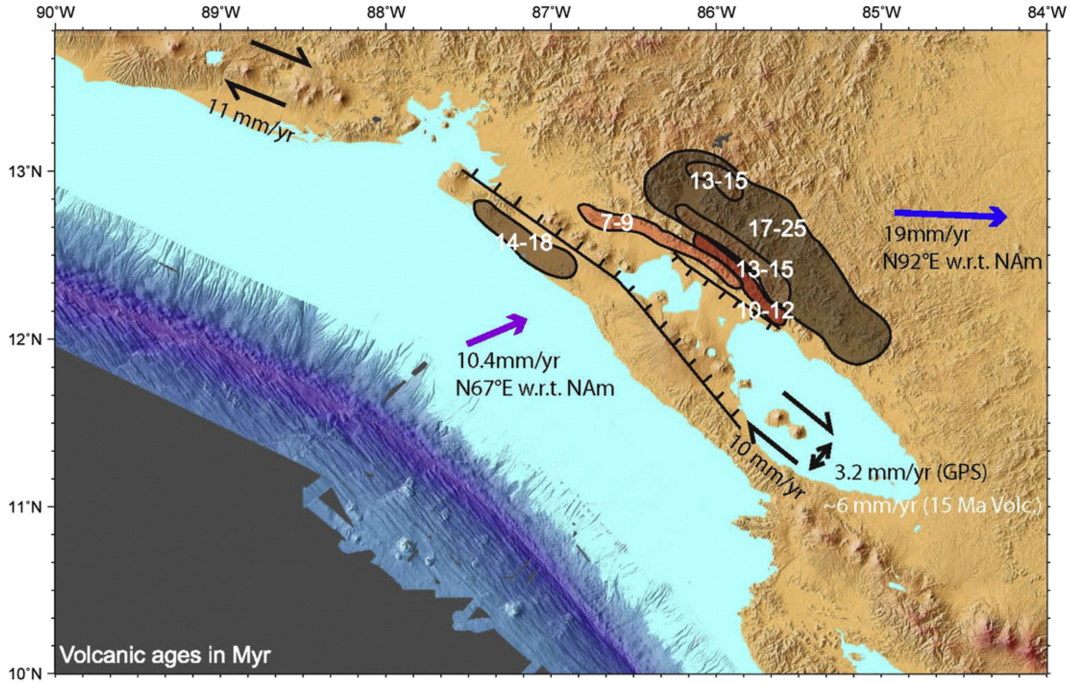


Fig. 3. Blow-up of the tectonic structures and lava-ages within the Nicaraguan section of the Middle American arc. Note the arc-parallel tectonic structures bounding the Nicaraguan graben, and the symmetric older arc-lava ages on both sides of the active arc. Strike-slip bookshelf faulting in the graben (La Femina et al., 2002) possibly coexists with persistent arc-normal extension. Arrows show rates of North American–Caribbean Plate motion (Demets, 2001 and this study) projected to arc-parallel shear and arc-normal extension in Nicaragua and El Salvador. Solely due to the change in strike of the arc, Nicaragua has a larger component of predicted extension that does El Salvador. If the Cocos Plate does not tear at the Cocos–Caribbean–North American TJ, then arc-perpendicular motion of the Central American forearc will be coupled to the roll-back of the Cocos Plate, in which case the forearc would be expected to retreat westward somewhat slower than the westward motion of the North American Plate (Fig. 2b). If the Cocos Plate smoothly deforms 'towards' a Caribbean rate of rollback, then there would be a gradual southwards reduction in rollback. In this case, arc-normal extension would be reduced — we think the reduction is from the ~15 mm/yr predicted for a rigid North American forearc moving at NUVEL1a velocity with respect to the Caribbean Plate to the ~6 mm/yr inferred from the ~100 km arc-normal separation between the 14–18 Ma sections of the paleo-arc. Note that the two volcanic belts on either side of the graben would also have undergone ~100 km of arc-parallel shear, with the seaward 14–18 Ma volcanic center having remained relatively stable with respect to the North American Plate, while the interior volcanic complexes translated towards the East as they remained relatively fixed with respect to the Caribbean plate. The purple and blue GPS vectors that suggest a modern arc-normal extension rate of ~3 mm/yr are based on the average velocities of the purple and blue velocity vectors shown in Fig. 2d (Turner et al., 2007). They show Nicaraguan forearc (purple arrow) and backarc=Caribbean (blue arrow) velocities with respect to the North American Plate.

thickness of 35km (Elming and Rasmussen, 1997;Auger et al., 2007). Electromagnetic measurements also suggest slightly thinner crust beneath the basin, with as much as ~ 5–10km of sedimentary basin infill from the eroded margins. Even assuming that both the TUCAN estimate of crustal thinning and sediment infill have occurred, however, would still require that at least a magma volume equivalent to a 10km thickness of new Nicaraguan arc crust has been intruded during the 100km extension of this basin over the past ~ 15Ma.

The implied fluxes of intrusive volcanism are much larger than estimated rates of extrusive volcanism based on the sizes of volcanic edifices. For example, if the arc-crustal thickness is ~ 30km, then extension at 6mm/yr would be balanced by new magmatic intrusions at a rate of 30km × 6km/Ma, or ~ 180km^3/km/Ma of intrusive volcanism. Even if only half the crustal extension is being compensated by new magma intrusions, while the rest is being accommodated by crustal thinning and sediment infill by erosive transport from the flanks of the central basin, one would still estimate roughly ~ 90km^3/km/Ma of intrusive volcanism within the Nicaraguan arc over the past ~ 15Ma of volcanic activity.

The rates inferred for Nicaraguan magmatic input including extension, although large in comparison to estimated rates of extrusive volcanism, are actually not large in comparison with the long-term magmatic production rates inferred for other arcs. The long-term magmatic production rate for the Aleutian Arc has been inferred to be ~ 80km^3/km/Ma (Holbrook et al., 1999) to 110–205km^3/km/Ma (Jicha et al., 2006). Clift and Vannucchi (2004) estimated a Central American rate of ~ 110km^3/km/Ma, and an average global rate of ~ 90km^3/km/Ma, both of which are very close to the rates inferred with the inclusion of arc-extension.

4. Implications of arc-extension for arc-magma fluxes

In Central America, prior overlook of arc-normal extension is likely to have led to significant underestimates of the volume of arc magmatism. The volumes of recent extrusive volcanism along the arc have been recently compiled by Carr et al. (2003), who determine the extrusive (volcano-forming) magmatism within approximately the past 100ka (see Carr et al., 2003, for discussion of the uncertainties in these measurements. Carr et al. (2007) revised their estimate of extrusive arc-volcanism downwards for neighboring Costa Rica, but kept the 2003 estimate of extrusive volcanic flux for Nicaragua.) Here we have recast their production rates into rates in cubic-km/km-arc-length/Ma, by dividing the volcanic growth rates by the along-strike length of each volcanic complex as defined by the mid-points between volcanic centers, and by multiplying by 10 to convert into rates per Ma. The resulting extrusive volcanic production rates are highly variable along-strike, reaching maximum values of 76km^3/km/Ma around Atitlan in Guatemala, and minima of 1.1–8.4km^3/km/Ma around Conchagua–Conchaguita in Nicaragua (Fig. 4).

The analysis in the previous section predicted that rates of Nicaraguan arc-extension-associated magmatic intrusion should range from 1–2 times as large as the highest extrusive rates along the Middle American arc (observed at Atitlan), and, more significantly, should be 1–2 orders of magnitude larger than measured amounts of recent Nicaraguan extrusive volcanism (Carr et al., 2003, 2007). This inferred robust intrusive magmatism within the Central Nicaraguan basin should be linked to geochemical characteristics of Nicaraguan volcanism that are analyzed in the next section.

5. Arc-extension in Nicaragua is consistent with geochemistry

The above new estimate of intrusive Nicaraguan extension-related arc magmatism is consistent with the geochemical characteristics of the Nicaraguan arc-volcanism. The geochemistry of Nicaraguan arc lavas in Fig. 4b implies – at least in its simplest interpretation (Carr et al., 1990, 2003) – that the largest degrees of melting beneath the Middle American arc take place beneath Nicaragua. The inverse-ratio of moderately incompatible to more compatible rare earth elements Yb/La is a common geochemical tracer used to infer relative degrees of source melting. Middle American volcanism has always presented the apparent paradox (Carr et al., 1990, 2003) that, in Guatemala, low Yb/La signifying large degree of source melting correlates strongly with large rates of extrusive volcanism, while Nicaragua, the one section of the arc with even lower Yb/La than Guatemala (implying even larger degrees of source melting), has the lowest observed rates of extrusive volcanism along the arc. However, the crude estimates above for rates of Nicaraguan magmatic activity are consistent with the observed geochemical trends — Nicaragua in fact has the highest flux of arc-magmatism along the Middle American arc, and this is why it has the lowest Yb/La along the arc.

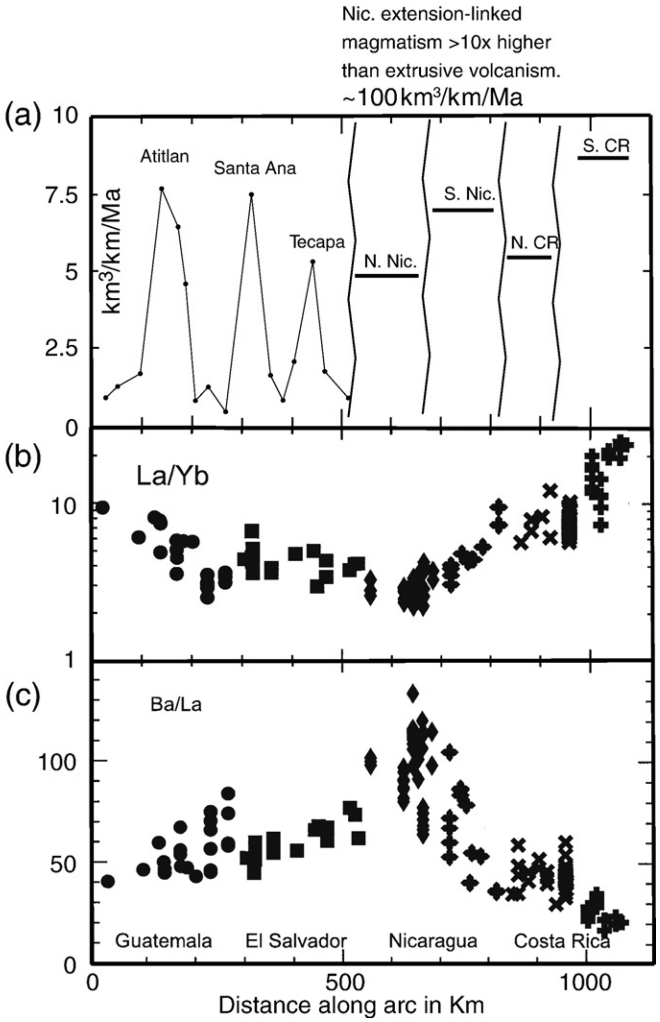


Fig. 4. (a) Recent rates of extrusive volcanism in km^3/km-along-arc/Ma along the Middle American Arc. After Carr et al. (2003) for rates in Guatemala and El Salvador and Carr et al. (2007) for rates in Nicaragua and Costa Rica. Our estimated extension-linked magmatic intrusion rate within the Nicaraguan basin is also shown; it is more than 10× higher than the highest rates of extrusional magmatism along the arc. (b) Yb/La — geochemical tracer for along-arc variations in the extent of sub-arc melting (panel from Carr et al., 2003). (c) Ba/La — geochemical tracer for the input-flux of slab-derived water into the arc melting region. (after Carr et al., 2003).

Middle American geochemical trends show other apparent correlations with variations in arc-normal extension. Within Guatemala, a strong local correlation has already been reported between the regions of greatest extension (Burkart and Self, 1985), regions of highest magma productivity, and the strongest geochemical 'slab-melting' Ba/La signal (Carr et al., 2003) (see Fig. 3c). The correlation noted locally in Guatemala also appears to hold over the entire arc — with Nicaragua having the largest magmatic arc productivity (after including intrusive activity), the largest rates of arc-normal extension, the strongest slab-water flux, and the strongest 'slab-melting' and 'source-degree-of-melting' signals (Fig. 3b–c). Thus it appears that in Central America the amount of upper-plate extension correlates with a strong slab-signal — and the presence of large arc-magma fluxes. We speculate that this may be both a cause and an effect of upper-plate extension. Perhaps magma intrusions and the volume infill associated with intrusive magmatism are an important means of weakening the upper plate above the arc, thus promoting arc-normal extension. In addition, upper plate extension would promote sub-arc melting (due to increased vertical upwelling and decompression melting directly below the arc) and, equally important, would facilitate rapid magma ascent and eruption without the magma having experienced intra-crustal residence that dilutes the slab-melting signal of their source. This second possibility is also consistent with the much higher dispersion (variations in composition between lavas from the same volcano) in geochemical signals seen in the volcanics erupting above the Guatemalan and Nicaraguan regions of arc-extension in comparison to neighboring sections of the arc (Carr et al., 2003) (Fig. 3). Possibly the increased 'dynamic range' of geochemical variation in these regions mostly reflects that many of these magmas can more easily reach the surface without much intermediate assimilation and fractionation? Or that they reflect more variable and higher overall degrees of melting in the source? To properly answer these and other questions, we will need to gain much better observational constraints on the extent of intrusive activity within the crust underlying the Nicaraguan graben.

6. Speculations on arc-evolution and continental growth

Are episodes of intra-arc extension and magmatic activity the main times when arc magmatism has contributed to continental growth? Current subduction erosion along the Guatemalan and Nicaraguan margins has been estimated to be currently occurring at ~ 14km^3/km/Ma (Vannucchi et al., 2004), with Costa Rica currently eroding by this process at ~ 100km^3/km/Ma (Vannucchi et al., 2003). These estimated rates are larger than observed extrusion rates, which would suggest that the arc is in a period of net mass removal. However, if intra-arc magmatism is included, then Nicaragua could be in a current state of net-crustal growth, while only Costa Rica would have experienced net crustal removal in the recent past.

Intra-arc-extension leading to arc-splitting is known to have created most of the major crustal structures preserved in recent Pacific back-arc basins (e.g. Lau and Marianas); perhaps these major features become the main arc-volcanic fragments that are eventually swept into colliding continents during the closure of ocean basins, consistent with the typical back-arc setting of most ophiolites. While still not well constrained for Nicaragua, we suggest that it will be important for the future study of Central America to better document how much crustal accretion has occurred within Nicaragua by magmatic intrusion processes; to determine whether these often-overlooked processes are playing a key role in the evolution of this arc.

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References

Acocella, V., Spinks, K., Cole, J., Nicol, A., 2003. Oblique back-arc rifting of Taupo Volcanic Zone, New Zealand. Tectonics 22, 1045. doi:10.1290/2002TC001447.

Auger, L., Abers, G., Syracuse, E., Fischer, K., Strauch, W., Protti, M., Gonzalez, V., 2007. Crustal thickness of the Central American Arc. Abstract in Proceedings for the Workshop to integrate subduction factory and seismogenic zone studies in Central America (SubFac-Seize), Heredia, Costa Rica.

Burkart, B., Self, S., 1985. Extension and rotation of crustal blocks in Northern Central-America and effect on the volcanic arc. Geology 13, 22–26.

Carr, M.J., Feigenson, M.D., Bennett, E.A., 1990. Incompatible elements and isotopic evidence for tectonic control of source mixing and melt extraction along the Central America Arc. Contrib. Min. Pet. 105, 369–380.

Carr, M.J., Feigenson, M.D., Patino, L.C., Walker, J.A., 2003. Volcanism and geochemistry in Central America: progress and problems. In: Eiler, J. (Ed.), Inside the Subduction Factory. Geophysical Monograph, vol. 138. The American Geophysical Union, pp. 153–179.

Carr, M.J., Saginor, I., Alvarado, G.E., Bolge, L.L., Lindsay, F.N., Milidakis, K., Turrin, B.D., Feigenson, M.D., Swisher III, C.C., 2007. Element fluxes from the volcanic front of Nicaragua and Costa Rica. Geochem. Geophys. Geosys. 8. doi:10.1029/2006GC001396.

Clift, P.D., Vannucchi, P., 2004. Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust. Rev. Geophys. 42 RG2001. doi:10.1029/2003RG000127.

Corti, G., Carminati, E., Mazzarini, F., Garcia, M.O., 2005. Active strike-slip faulting in El Salvador, Central America. Geology 33, 989–992.

DeMets, C., 2001. A new estimate for present-day Cocos–Caribbean plate motion: implication for slip along the Central American volcanic arc. GRL 28, 4043–4046.

DeMets, C., Gordon, R.G., Argus, D.F., Stein, S., 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. GRL 21, 2191–2194.

DeMets, C., Jansma, P.E., Mattioli, G.S., Dixon, T.H., Farina, F., Bilham, R., Calais, E., Mann, P., 2000. GPS geodetic constraints on Caribbean–North America plate motion. GRL 27, 437–440.

Elming, S.A., Rasmussen, T., 1997. Results of magnetotelluric and gravimetric measurements in western Nicaragua, Central America. GJI 128, 647–658.

Gripp, A.E., Gordon, R.G., 1990. Current plate motions relative to the hotspots incorporating the NUVEL-1 global plate motion model. GRL 17, 1109–1112.

Gripp, A.E., Gordon, R.G., 2002. Young tracks of hotspots and current plate velocities. GJI 150, 321–361.

Guzman-Speziale, M., 2001. Active seismic deformation in the grabens of northern Central America and its relationship to the relative motion of the North America–Caribbean plate boundary. Tectonophoys 337, 39–51.

Guzman-Speziale, M., Meneses-Rocha, J.J., 2000. The North-America–Caribbean plate boundary west of the Motagua–Polochic fault system: a fault jog in southeastern Mexico. J. S. Am. Earth Sci. 13, 459–468.

Holbrook, W.S., Lizarralde, D., McGeary, S., Bangs, N., Diebold, J., 1999. Structure and composition of the Aleutian island arc and implications for continental crustal growth. Geology 27, 31–34.

Jicha, B.J., Scholl, D.W., Singer, B.S., Yogodzinski, G.M., Kay, S.M., 2006. Revised age of Aleutian island arc formation implies high rate of magma production. Geology 34, 661–664.

La Femina, P.C., Dixon, T.H., Strauch, W., 2002. Bookshelf faulting in Nicaragua. Geology 30, 751–754.

LaFemina, P.C., Dixon, T.H., Schwatz, S., Protti, M., Gonzalez, V., 2005. Subduction of an aseismic ridge. Interseismic Deformation Above the Cocos Ridge, Costa Rica, EOS Trans. AGU, Abstract #T42A-07, AGU Fall Meeting.

Leroy, S., Mauffret, A., Patriat, P., Mercier de Lepinay, B., 2000. An alternative interpretation of the Cayman Trough evolution from a reindentification of magnetic anomalies. GJI 141, 539–557.

Lyon-Caen, H., Barrier, E., Lasserre, C., Franco, A., Arzu, I., Chiquin, L., Chiquin, M., Duquesnoy, T., Flores, O., Galacia, O., Luna, J., Molina, E., Porras, O., Requena, J., Robles, V., Romero, J., Wolf, R., 2007. Kinematics of the North American–Caribbean–Cocos plates in Central American from new GPS measurements across the Polochic–Motagua fault system. Geophys. Res. Lett. 34, L19309. doi:10.1029/2006GL027694.

McKenzie, D.P., Morgan, W.J., 1969. Evolution of triple junctions. Nature 224, 125–133.

Morgan, W.J., Phipps Morgan, J., 2007. Plate velocities in the hotspot reference frame, in Plates, Plumes, and Planetary Processes. In: Foulger, G.R., Jurdy, D. (Eds.), GSA Spec. Pub., vol. 430, pp. 65–78.

Plank, T., Balzer, V., Carr, M., 2002. Nicaraguan volcanoes record paleooceanographic changes accompanying closure of the Panama gateway. Geology 30, 1087–1090.

Taylor, B., Karner, G.D., 1983. On the evolution of marginal basins. Rev. Geophys. 21, 1721–1741.

Turner III., H.L., LaFemina, P., Saballos, A., Mattioli, G.S., Jansma, P.E., Dixon, T., 2007. Kinematics of the Nicaraguan forearc from GPS geodesy. Geophys. Res. Lett. 34, L02302. doi:10.1029/2006GL027586.

Vannucchi, P., Ranero, C.R., Galeotti, S., Straub, S.M., Scholl, D.W., McDougall-Ried, K., 2003. Rates of subduction erosion along the Costa Rica Pacific margin: implications for non-steady rates of crustal recycling at subduction zones. J. Geophys. Res. 108 (B11), 2511. doi:10.1029/2002JB002207.

Vannucchi, P., Galeotti, S., Clift, P., Ranero, C.R., von Huene, R., 2004. Long term subduction erosion along the Middle America trench offshore Guatemala. Geology 32/7, 617–620.

Walther, C.H.E., Flueh, E.R., Ranero, C.R., von Huene, R., Strauch, W., 2000. Crustal structure across the pacific margin of Nicaragua: evidence for ophiolitic basement and shallow mantle sliver. GJI 141, 759–777.

Webb, T.H., Anderson, H., 1998. Focal mechanism of large earthquakes in the North Island of New Zealand: slip partitioning at an oblique active margin. GJI 134, 40–86.

Weissel, J.K., 1977. Evolution of the Lau Basin by the growth of small plates, in Island Arcs, Deep Sea Trenches, and Back-Arc Basins. In: Talwani, M., Pitman, W.C. (Eds.), AGU Monograph, pp. 429–436.