



Calcite twinning fabrics along the Middle America trench, Costa Rica and the Motagua sinistral fault, Honduras and Jamaica: Tectonic implications for the Caribbean plate

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ABSTRACT

The Cretaceous oceanic crust of the Caribbean plate has a long and complex tectonic history as an indenter plate bounded by transcurrent faults (N and S) and subduction margins (W [east slab dip] and E [west slab dip]) with no strain data. Miocene forearc sediments and accreted ophiolites are exposed along the central Pacific coast of Costa Rica and preserve a variety of folding and faulting styles. These clastic sediments, deposited in the forearc as the Middle America trench evolved, contain calcite cements and are cross cut by calcite veins. Analysis of the mechanical twins in these two calcite groups (8 samples, $n = 267$ twins) at Punta Dominical and the Nicoya Peninsula ophiolite preserve a consistent sub-horizontal shortening strain that is oriented parallel to the current trench axis, as are most of the accretion-related fold axes. Differential stress magnitudes for the calcite twinning strain average ~ 450 bars, and there is little evidence of a twinning strain overprint (low NEVs). Obduction along the Middle America trench involves, in part, a component of trench-parallel horizontal shortening.

The Motagua fault originates in the Middle America trench and strikes east as the northern boundary of the Caribbean plate as a sinistral margin. The Roatan Islands are a series of islands composed of south-dipping rocks along the southern side of the Motagua fault. Recent, deformed clastic sediments are draped over gneisses, schists (^{40}Ar - ^{39}Ar biotite age of 14 Ma), conodont-free marbles and ophiolitic fragments of presumed Cretaceous age. Twinning studies ($n = 6$ samples, $n = 425$ twins) of these marbles preserve a N-S, horizontal shortening strain, normal to the sinistral plate boundary. Differential stress magnitudes for the calcite twinning strain average ~ 36 MPa. Only in a combined sample ($n = 189$ grains) is a strain overprint (high NEVs; $n = 47$) present, which records horizontal shortening strain at 132° , 5° . Jamaica is also along the eastern Motagua fault (Cayman trough) and twinning strain studies in Eocene limestones and younger calcite veins ($n = 4$ samples; $n = 136$ twins) preserve a horizontal shortening strain normal to the sinistral plate boundary.

Twinning strain results are compared to regional GPS, focal mechanism and SKS anisotropy results around the Caribbean plate, especially along the Middle America trench on the western margin of Costa Rica with some new insights into subduction dynamics.

1. Introduction

The Caribbean plate consists of Cretaceous oceanic lithosphere and has a long and complex tectonic history as an indenter plate bounded by the North and South American continental plates (north and south, respectively), the oceanic Cocos (W, east-dipping subduction) and Atlantic (E, west-dipping subduction) plates (Malfait and Dinkelman, 1972; Stein et al., 1988; Dengo and Case, 1990; Pindell and Barrett,

1990; DeMets et al., 2001; DeMets, 2001; Ellis et al., 2018). This geometry and kinematic pattern is similar to the Cretaceous Scotia plate located off the southern margin of South America (Dalziel and Elliot, 1971; Dalziel, 1984; Bird, 2003). Numerical models of plates (56) and microplates (31) identify the oceanic Cocos plate as one of the fastest moving plates (70–83 mm/yr toward 12° in a no-net rotation reference frame) on Earth. It currently subducts beneath central America (Middle America trench; MAT) and the oceanic Caribbean plate which is moving

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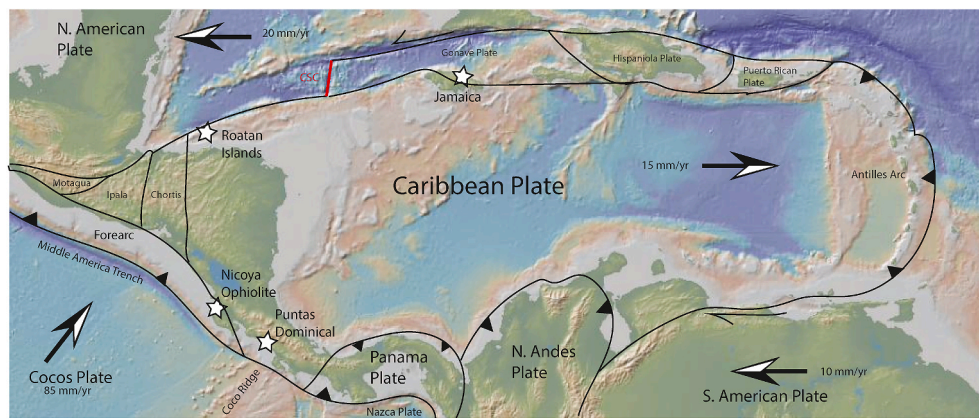


Fig. 1. Regional DEM image of the Caribbean plate with locations of field sites (stars) and tectonic boundaries (Malfait and Dinkelman, 1972; Mann et al., 2007; Argus et al., 2011; Benford et al., 2012a, b; Ellis et al., 2018).

at 18 mm/yr toward 74° (no-net rotation reference frame) with significant discordance between the orientations and rates of motions in all models (Fig. 1; Bird, 2003; Kreemer et al., 2006; Argus et al., 2011). GPS surveys of the Caribbean support the modelled results and also identify additional independently-moving microplates (Correa-Mora et al., 2009; LaFemina et al., 2009; Alvarado et al., 2011), and even microplates-within-microplates (Mann et al., 2002, 2007; Benford et al., 2015; Ellis et al., 2018, 2019). Missing in the understanding of these complex plate dynamics (see Fisher, 1996) is any finite strain data, which we have gathered along the Costa Rica subduction margin and the northern sinistral margin of the Caribbean plate (Fig. 1).

Obduction, or thrusting of oceanic lithosphere onto continental lithosphere, is an important aspect of subduction in many regions (Wada and Wang, 2009; Saffer and Tobin, 2011). The mechanics of this process are poorly understood largely because the rocks contain poor strain markers (see Ring and Brandon, 1999). Ophiolite successions are hydrothermally altered and dismembered, and do not contain the appropriate minerals (e.g., quartz, calcite) to record deformation associated with obduction. Similarly, the sedimentary record along subduction margins is dominated by immature, deep marine forearc clastic and volcanoclastic sediments (Fisher, 1996; Fisher et al., 2004) that do not contain strain-recording mineral assemblages. Along the Middle America trench in Costa Rica we have collected a suite of Jurassic ophiolite-hosted calcite veins and Miocene forearc clastic sediments with calcite cement and veins that record the strain of the obduction process and deformation in the forearc. We have also collected Cretaceous marbles (Roatan Islands, Honduras; deformed at 14 Ma) and calcite veins and limestone (<Eocene, Jamaica) along the northern Caribbean plate boundary to better constrain the regional stress-strain field. Calcite twinning studies are best constrained when vein or fault gouge calcite is also dated (U–Pb; Nuriel et al., 2017, 2019) and this study, of twinning strains along active plate boundaries, can be compared to results for small-offset faults in a variety of tectonic settings (Craddock et al., 2019).

2. Geologic background

2.1. Jamaica

The most comprehensive description of Jamaican geology is found in Lewis and Draper (1990) and Benford et al. (2015). The island's geology includes upper Cretaceous shale, conglomerate and volcanoclastic rocks unconformably overlain by the middle Eocene Yellow Limestone Grp., the upper Eocene-middle Miocene White Limestone Grp., then upper Miocene carbonates and Quaternary deposits. The island structure includes gentle SW-vergent folds bounded by high-angle faults that strike NW–SE with hanging wall motion to the SW (Lewis and Draper, 1990).

The role of Jamaica in the tectonic evolution of the northeast Caribbean is reviewed in Lewis and Draper (1990) but recent geophysical and GPS studies define Jamaica as part of the Gonave microplate (Fig. 1; DeMets and Wiggins-Grandison, 2007; Benford et al., 2012a, b) which, with further GPS analysis, has many evolving sub-microplates (Mann et al., 2007; Benford et al., 2015) and is bounded by a vertical fabric along sinistral faults defined by SKS wave splitting (Benford et al., 2012b).

2.2. Roatan Islands, Honduras

The Polochic and Motagua sinistral faults pass east from mainland Honduras forming the northern boundary of the Caribbean plate (Fig. 1) which separates the Bartlett (Cayman) trough north of the Roatan (Bonacca Ridge) archipelago. The local geology includes south-dipping gneisses, schists, and marbles of presumed Cretaceous age with top-to-the-north thrust kinematics overlain by reefal carbonates, alluvium and thin veneers of basalt (Powers, 1918; McBirney and Bass, 1967; Pindell and Barrett, 1990). The Motagua–Cayman plate boundary is seismically active and focal mechanism solutions indicate sinistral motion (Kikuchi and Kanamori, 1991; Ellis et al., 2018, 2019) and the plate boundary terminates to the east into the N–S striking Cayman spreading center.

2.3. Costa Rica

Galli-Olivier (1979) initially described Costa Rica geology in terms of zones parallel to the MAT where the Cocos plate dips east under central America, the forearc, including the Cretaceous–Eocene Nicoya–Osa ophiolite and Eocene–Pliocene sediments, the volcanic arc and the northeastern back-arc (Baumgartner and Denyer, 2006; Denyer et al., 2006). Seismicity cross sections indicate the Cocos plate slab dip shallows to the southeast where the Cocos ridge interacts with central American crust (Protti et al., 2001). Focal mechanism solutions indicate compartmentalized structural settings, all parallel to the MAT, with thrust fault solutions related to subduction (NE dipping faults; DeShon et al., 2003; Brown et al., 2005), thrust fault solutions in the SW-vergent Fila Costena thrust belt (NE-dipping faults; Fisher et al., 2004), then dextral solutions parallel to the volcanic arc along the Chicilagua fault (Alvarado et al., 2011). GPS velocity studies continue to sub-divide the Chortis block (central America) into additional microplates with complex local motions related to curvature of the MAT (Newman et al., 2002; Ellis et al., 2018, 2019). Second order vertical deformations are also observed as a function of down-going slab morphologies (Sak et al., 2004). Our strain samples are from the obducted ophiolitic sequence in the forearc, and from clastic sediments on the northwest end of the Fila Costena thrust belt, both rare examples of exposed forearc materials (Lallemand et al., 1992; Ranero and von Huene, 2000; Vannucchi et al.,



Fig. 2. Regional DEM of the Cayman Trough, separating Cuba from Jamaica (A). Field photos of folded Eocene-Miocene turbidites from the north coast of Jamaica (B) with crosscutting and sheared veins (C).

2001; Fisher et al., 2004) versus other trench settings where “out-of-sequence” (thrust motion up and out of the trench) remains submarine (Barbados trench, Westbrook et al., 1988; Nankai trench, Park et al., 2000; Saffer and Tobin, 2011).

3. Methods

3.1. Calcite twinning

The calcite strain-gage technique (CSGT) of Groshong (1972) allows investigation of intraplate stresses as constrained by intracrystalline twinning of rock-forming calcite grains. Although the result is a strain tensor, a similar orientation of the stress tensor is calculated in the case of coaxial deformation (Turner, 1953, 1962). The CSGT has been used to

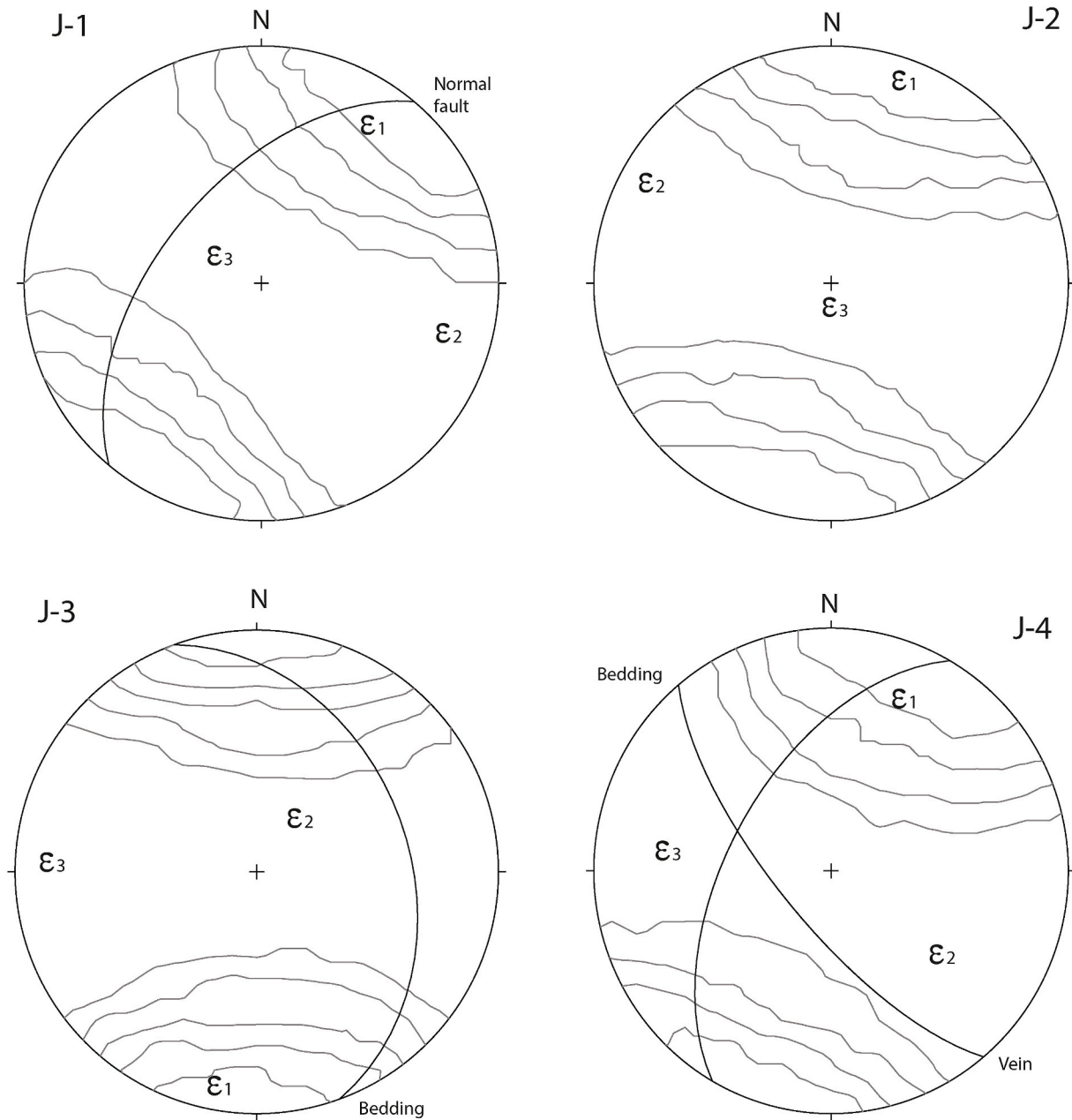


Fig. 3. Lower hemisphere stereoplots of calcite strain data for Jamaica (Table 1; E_1 = maximum shortening axis, E_2 = intermediate strain axis, E_3 = extension axis; Turner (1953) compression axes are contoured.

constrain three dimensional stress and strain tensor directions in veins (Kilsdonk and Wiltschko, 1988; Paulsen et al., 2014), limestones (Spang and Groshong, 1981; Groshong, 1975, 1976; Wiltschko et al., 1985; Craddock and van der Pluijm, 1989; Mosar, 1989; Ferrill, 1991; Craddock et al., 2000; Craddock et al., 2007a; Amrouch et al., 2010; Craddock et al., 2012), marble (Craddock et al., 2017), amygdaloidal basalts (Craddock and Pearson, 1994; Craddock et al., 1997, 2004) and calcite ocelli in lamprophyres (Craddock et al., 2007b).

Under temperatures of ca. 200 °C intracrystalline deformation of calcite results in the formation of e-twins. The formation of calcite e-twins requires a shear stress exceeding ca. 10 MPa (Wenk et al., 1987; Burkhard, 1993; Lacombe and Laurent, 1996; Ferrill, 1998). Calcite offers three glide systems for e-twinning. From U-stage measurements of width, frequency and orientation of twins, and the crystallographic orientation of the host crystals, a strain tensor can be calculated using a least-squares technique (Groshong, 1972). In order to remove “noise”

from the dataset, a refinement of the calculated strain tensor can be achieved by stripping 20% of the twins with the highest deviations (Groshong et al., 1984). This procedure has been used if the number of measured grains were large ($n > 20$). In cases where the data appear to be inhomogeneous, the separation of incompatible twins (“NEV” = negative expected values) from compatible twins (“POS” = positive expected values) of the initial dataset allows separate calculation of two or more least-squares deviatoric strain tensors. Thus, the CSGT can be used to obtain information on superimposed deformations (Groshong, 1972, 1974) and differential stress magnitudes (Rowe and Rutter, 1990).

The validity of this stripping procedure was demonstrated in experimental tests where the reliability depends on the overall complexity of deformation and the number of grains with twins (Groshong, 1974; Teufel, 1980). The stripping procedure was used in cases of high proportions of NEVs and a large number of measured grains. An experimental re-evaluation of the CSGT has shown that

Table 1
Calcite twinning strain results.

Sample	Location	Rock Type	Bedding	Vein	Grains (n =)	ε1	ε2	ε3	ε1(%)	NEV (%)	Δσ (bars)	Fabric (Bedding)	Fabric (Vein)
Jamaica													
J-1	Greencastle Estate	Vein in Limestone	Horizontal	N40° E, 55° N	21	35°, 14°	118°, 33°	322°, 68°	−8.3	4	302	LPS	VNS
J-2	Greencastle Estate	Shaly Limestone	Horizontal		38	28°, 3°	317°, 2°	178°, 82°	−2.3	11	262	LPS	
J-3	Robin's Bay	Vein in Turbidite	240°, 37° N	Horizontal	41	182°, 8°	42°, 63°	273°, 9°	−7.6	12	392	LNS	VPS
J-4	Robin's Bay	Vein in Turbidite	320°, 72° S	30°, 55° W	36	26°, 18°	121°, 38°	172°, 67°	−8.2	5	382	LNS	VPS
					n = 136							Avg. = -334	
Roatan, Honduras													
R-1	Western Roatan	Marble	Horizontal		34	16°, 6°	93°, 8°	185°, 88°	−8.1	7	373	LPS	
R-2	Western Roatan	Marble	Horizontal		34	355°, 12°	262°, 21°	157°, 72°	−4.9	32	355	LPS	
R-3	Central Roatan	Marble	Horizontal		27	32°, 6°	111°, 9°	277°, 82°	−3.7	17	312	LPS	
R-4	Eastern Roatan	Marble	Horizontal		28	1°, 7°	94°, 8°	271°, 87°	−3.9	22	345	LPS	
R-5	Eastern Roatan	Marble	99°, 6° S		31	6°, 7°	281°, 3°	184°, 83°	−5.7	33	380	LPS	
R-6	Isla de Guanja	Serpentinite	Horizontal	30°, 90°	35	353°, 7°	86°, 8°	268°, 84°	−6.1	21	377	LPS	VNS
PEV	Combined	Marble	Horizontal		189	181°, 2°	272°, 3°	88°, 87°	−5.9	0	368	LPS	
NEV	Combined	Marble	Horizontal		47	132°, 5°	225°, 6°	45°, 86°	−9.1	100	364	LPS	
					n = 425							Avg. = -359	
Costa Rica													
CR-1	Puntas Dominical	Sandstone, calcite cement	325°, 33° N		28	135°, 4°	38°, 22°	219°, 84°	−4.5	30	770	LPS	
CR-2	Puntas Dominical	Sandstone, calcite cement	321°, 35° N		33	141°, 8°	47°, 14°	227°, 81°	−9.2	20	350	LPS	
CR-3	Puntas Dominical	Vein in sandstone	341°, 42° N	58°, 90°	29	329°, 14°	236°, 14°	58°, 84°	−3.2	15	360	LPS	VNS
CR-4	Puntas Dominical	Vein in sandstone	341°, 42° N	63°, 90°	35	137°, 8°	241°, 9°	63°, 81°	−4.1	9	176	LPS	VNS
CR-5	Puntas Dominical	Sandstone, calcite cement	346°, 40° N		41	337°, 11°	26°, 33°	166°, 62°	−8.5	0	510	LPS	
CR-6	Puntas Dominical	Vein in sandstone	332°, 18° N	98°, 90°	27	309°, 7°	6°, 17°	101°, 90°	−3.6	5	500	LPS	VNS
CR-7	Nicoya Peninsula	Vein in ophiolite	330°, 18° S	3°, 90°	38	344°, 8°	265°, 7°	85°, 85°	−3.7	12	520	LPS	VNS
CR-8	Nicoya Peninsula	Vein in ophiolite	312°, 10° S	36°, 90°	36	328°, 8°	71°, 68°	263°, 12°	−6.1	5	432	LPS	VNS
					n = 267							Avg. = −452	
					(n = 828)								

Key: E1 = maximum shortening axis; E2 = intermediate axis; E3 = extension axis. LPS = layer-parallel shortening; LNS = layer-normal shortening; VPS = vein-parallel shortening; VNS = vein-normal shortening; $\Delta\sigma = -51 + \log 171(\text{\#twins/mm})$.

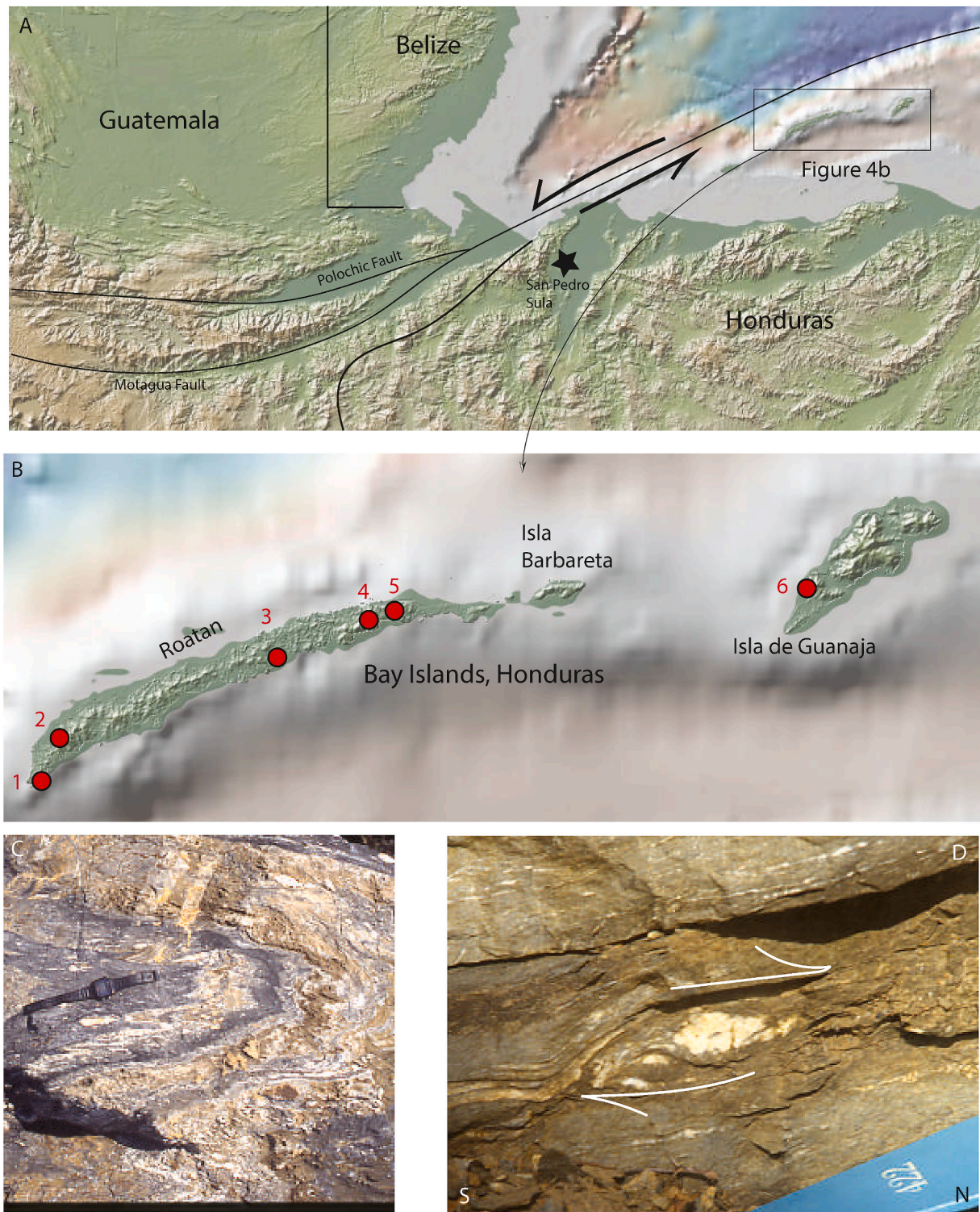


Fig. 4. Regional DEM basemap (A) showing the Motagua fault extending east into the Caribbean Sea along the northern side of the Roatan Islands (B) with folded marbles (C) and top to the north kinematic indicators (D, key for scale).

measurements of about 50 grains on one thin-section or 25 grains on two mutually perpendicular thin-sections yield the best results (Groshong et al., 1984; Evans and Groshong, 1994; Ferrill et al., 2004). The chance to extract the records of more than two deformations from one dataset is limited when dealing with natural rocks (Burkhard, 1993). Individual analyses of veins, matrix, nodules, etc. allows the acquisition of several strain tensors without applying statistical data stripping. The complexity of rotational strains in fault zones has limited the application of this

method to the efforts of Gray et al. (2005). Application of the CSGT requires the following assumptions to be valid: (1) low temperatures (dominance of Type I and Type II twins), (2) random c-axis orientations of calcite, (3) homogenous strain, (4) coaxial deformation, (5) volume constancy, (6) low porosity materials and (7) low strain (<15%). If these conditions are not fully met, the underlying dataset of the calculated strain tensor could be biased, modified or random. Strain tensors were calculated from calcite e-twin datasets using the software package of

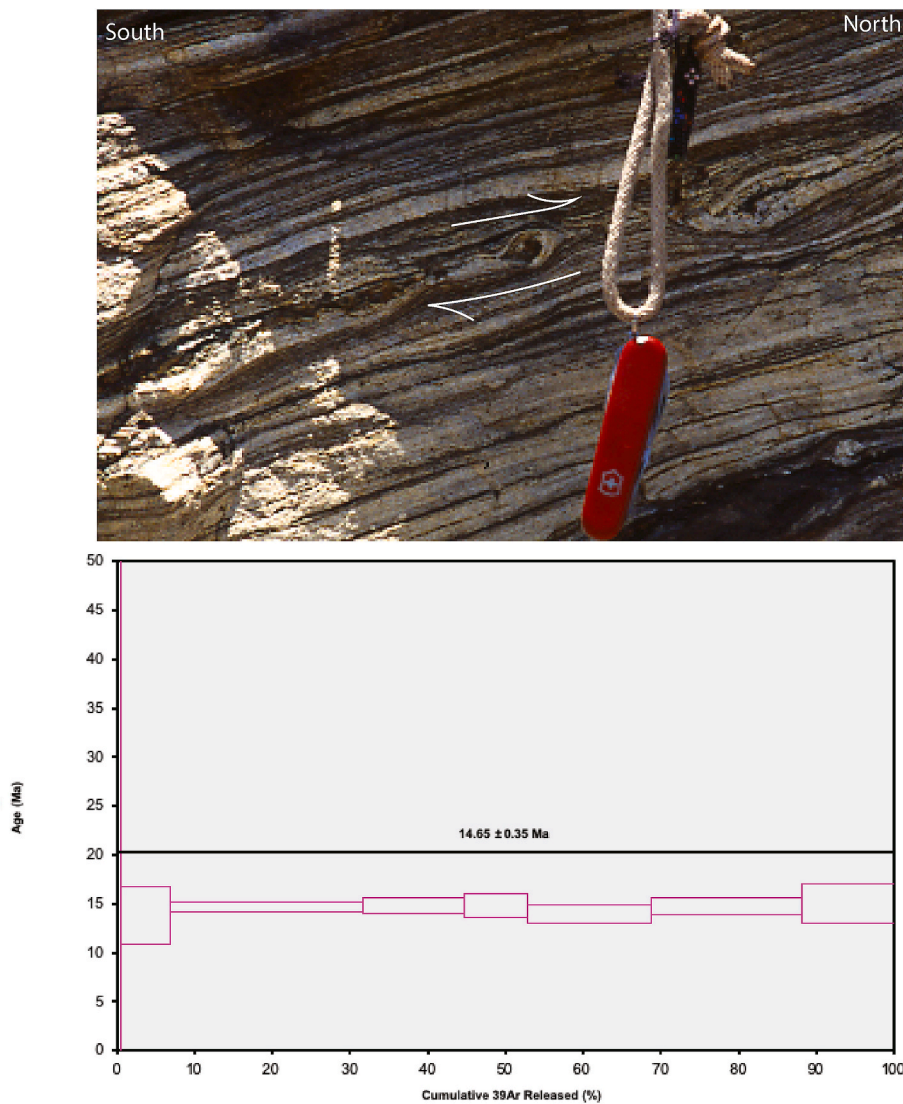


Fig. 5. Field photos of sheared gneiss, western Roatan Islands (Site 2, Fig. 4), with top-to-the-north kinematics. Biotite Ar-Ar age plateau (14.65 Ma; Table 2) is from biotite from this gneiss.

Evans and Groshong (1994). Fabric interpretations are based on the orientation of the shortening axis (ϵ_1), which usually plots near the contoured maxima of the Turner (1953) axes, and if ϵ_1 is $\sim 20^\circ$ from the sample bedding, layer-parallel shortening (LPS) is valid. Layer-normal shortening (LNS) is the fabric where ϵ_1 is at a high angle ($>45^\circ$) to bedding.

3.2. Geochronology

We report one Ar-Ar age from biotite in a gneiss from Roatan Island, Honduras, analyzed at the University of Wisconsin. $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating experiments using a defocused CO_2 laser beam were performed at the University of Wisconsin Rare Gas Geochronology Laboratory, following procedures described in Smith et al. (2006). A few milligrams of biotite single crystals, each optically clear and fresh, were hand-picked and then irradiated in the CLICIT facility (cadmium-shielded) of the Oregon State University nuclear reactor for 40 h. The conversion efficiency of ^{39}K to ^{39}Ar was monitored using sanidine from the 28.34 Ma Taylor Creek Rhyolite (Renne et al., 1998). Final data reduction was via ArArCalc (Koppers, 2002). The uncertainties of all reported ages are at the 2σ level. Attempts at U-Pb dating of vein and fault gouge calcite failed (Nuriel et al., 2017, 2019) due to low U-levels.

3.3. Geophysical data

We compile existing geophysical products (focal mechanisms and GPS data) to assess modern stress regimes across the Caribbean. Focal mechanism data were downloaded for all data in the Global CMT catalog (Dziewonski et al., 1981; Ekström et al., 2012) and were plotted with calcite strain data (Figs. 3, 6, 8–11). Geodetically determined strain data from Kreemer et al. (2014) were downloaded and plotted to show the modern stress regime across the Caribbean plate. Strain style (compressional, strike-slip, or extensional) was determined using the equation:

$$\sqrt{(\dot{\epsilon}_1 + \dot{\epsilon}_2)/\max(|\dot{\epsilon}_1| + |\dot{\epsilon}_2|)}$$

Where $\sqrt{\dot{\epsilon}_1}$ and $\sqrt{\dot{\epsilon}_2}$ are the largest and smallest geodetically-derived strain eigenvalues, respectively (Kreemer et al., 2014).

Receiver functions are a common seismic analysis technique that uses the difference in arrival times between initial P waves and P-to-s conversions formed at velocity contrasts to determine the depth of these contrasts. In our plots, positives (red) represent increases in velocity with depth while negatives (blues) represent decreases in velocity. The amplitude of the signal provides insight into the magnitude and sharpness of the contrast with higher amplitudes associated with higher

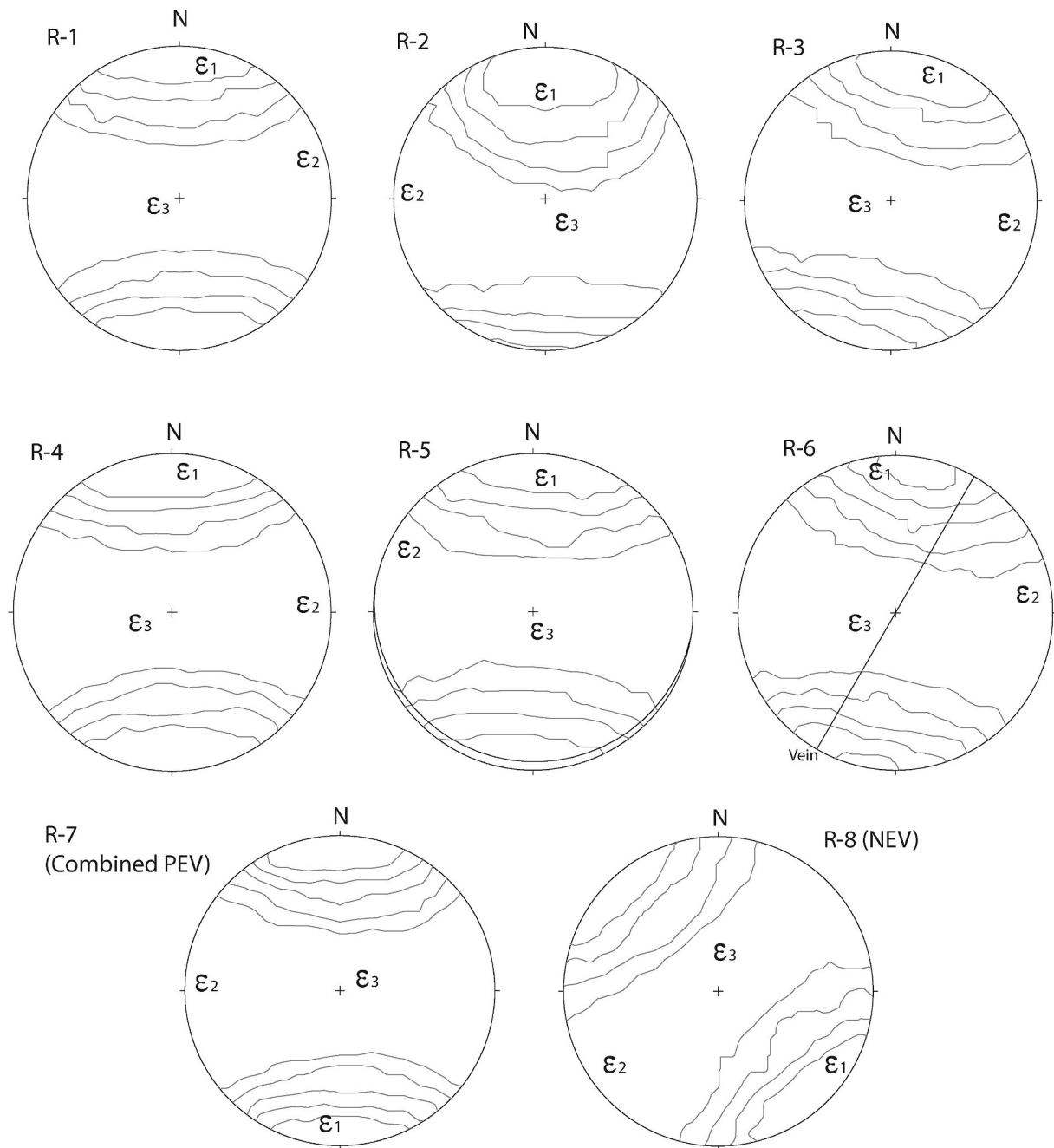


Fig. 6. Lower hemisphere stereoplots of calcite strain data for Roatan, Honduras (Table 1; E_1 = maximum shortening axis, E_2 = intermediate strain axis, E_3 = extension axis; Turner, 1953 compression axes are contoured).

magnitudes/sharper contrasts. Receiver functions were calculated using publicly available seismic data from Costa Rica. Earthquake signals used for calculation of the receiver functions were downloaded from the Incorporated Research Institute of Seismology's Data Management Center (IRIS DMC). All teleseismic earthquakes recorded between 1990 and 2018 greater than magnitude 5.8 were downloaded. A total of 18,464 events between 30° and 90° away from each station were used in the receiver function analysis. These events were recorded on 127 seismic stations in Costa Rica and southern Nicaragua. Receiver functions were calculated using an iterative time-domain deconvolution technique (Ligorria and Ammon, 1999). Receiver functions with high variance ($<80\%$ reduction) or extreme amplitudes (less than -0.5 or greater than 1) were discarded. Receiver functions were migrated to depth using the Common Conversion Point (CCP) technique (Dueker and

Sheehan, 1998). This was accomplished using a modified version of the code presented in Haddon and Porter (2018) and the seismic velocity model presented in DeShon and Schwartz (2004). In the CCP plots, a bin size of 14 km with an overlap of 1.25 bins was used. Earthquake locations in the plot were taken from Deshon et al., (2006).

Shear wave splitting (SKS waveforms) occurs when an upgoing polarized shear wave encounters an anisotropic medium. While traveling through the polarized medium, the initial wave separates into two orthogonal polarized waves. The shear wave polarized parallel to fast anisotropic axis will travel fastest and arrive first at a seismic station with the second polarized wave arriving later. Analyzing the particle motion and difference in arrival times between the two waves gives insight into the orientation of the anisotropic fabric in the medium. SKS splitting measurements are used to determine anisotropic fabrics due to

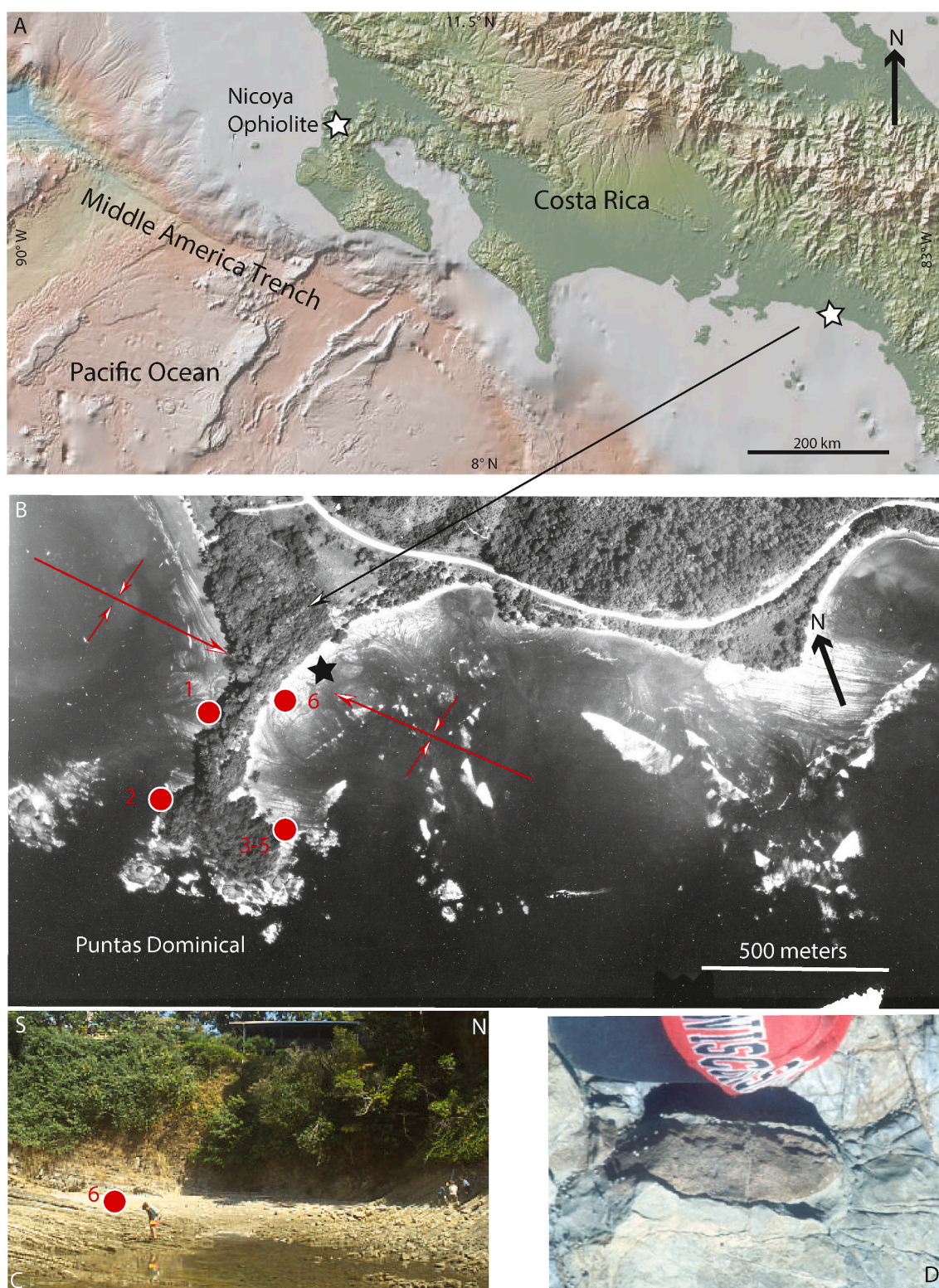


Fig. 7. Tectonic setting of Costa Rica and the Middle America trench (A) with field locations, especially Puntas Dominical (B) with sample sites, folding style (C) and whale vertebra (D).

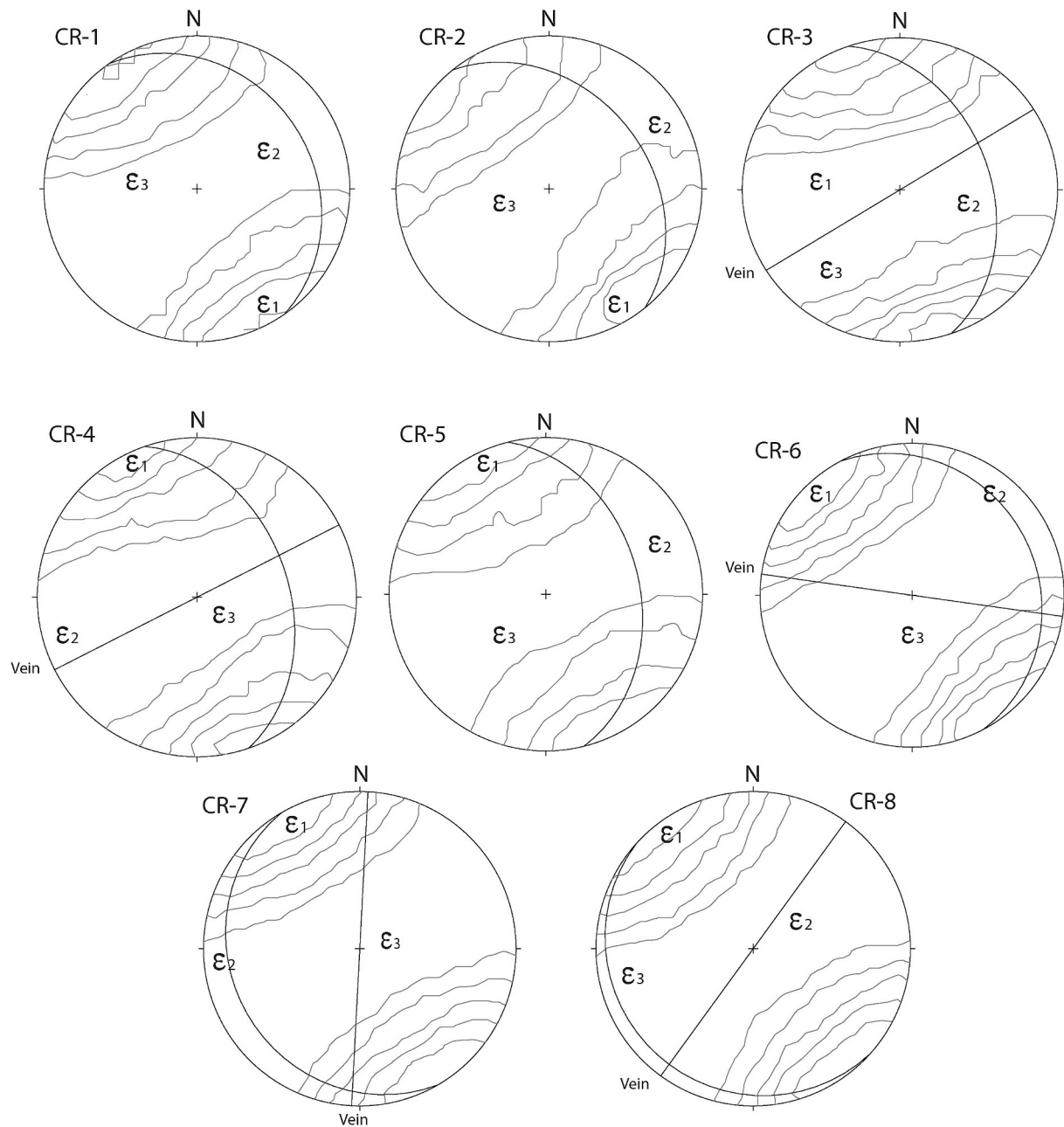


Fig. 8. Lower hemisphere stereoplots of calcite strain data from the west coast of Costa Rica (Table 1; E_1 = maximum shortening axis, E_2 = intermediate strain axis, E_3 = extension axis; Turner, 1953 compression axes are contoured).

olivine alignment within the mantle. These fabrics form due to shearing of the mantle during flow and the orientation of the fast direction is commonly interpreted as indicative of the mantle flow direction at the base of the mantle (Zandt and Humphreys, 2008) and attempts have been made to correlate stress-strain fields along faults with absolute plate motion GPS velocities; often all three are sub-horizontal and parallel (Craddock et al., 2019).

4. Results

4.1. Cayman Trough, Jamaica

We collected 4 oriented carbonate samples along the north coast of Jamaica, 2 veins from the Eocene Richmond Fm. turbidites, calcite fault gouge from a normal fault crosscutting the middle Eocene Font Hill Fm. (Craddock et al., 2020, Sample J-1), and limestone from the Font Hill

Fm. (Fig. 2). Twinning strains all record horizontal shortening normal to the Caribbean plate margin to the north (Fig. 3, Table 1) with no strain overprint and an average differential stress of -334 bars. Fabric interpretations are a combination of LPS and LNS, relative to bedding, and VNS and VPS relative to vein orientations. Uranium concentrations in vein calcite were too low to obtain a U–Pb age.

4.2. Motagua fault, Roatan, Honduras

We collected oriented marble samples around Roatan, one vein sample hosted in serpentinite from Isla de Guanaja (Fig. 4), and one gneiss sample from western Roatan for radiometric dating (Fig. 5). Conodonts were not found in any of the marbles. Top-to-the north kinematic indicators were observed in schists (Fig. 4d) and gneisses (Fig. 5a). Biotites from the gneiss yielded a ^{40}Ar – ^{39}Ar of 14.65 ± 0.35 (Fig. 5b, Appendix 1), presumably the age of metamorphism. All the calcite

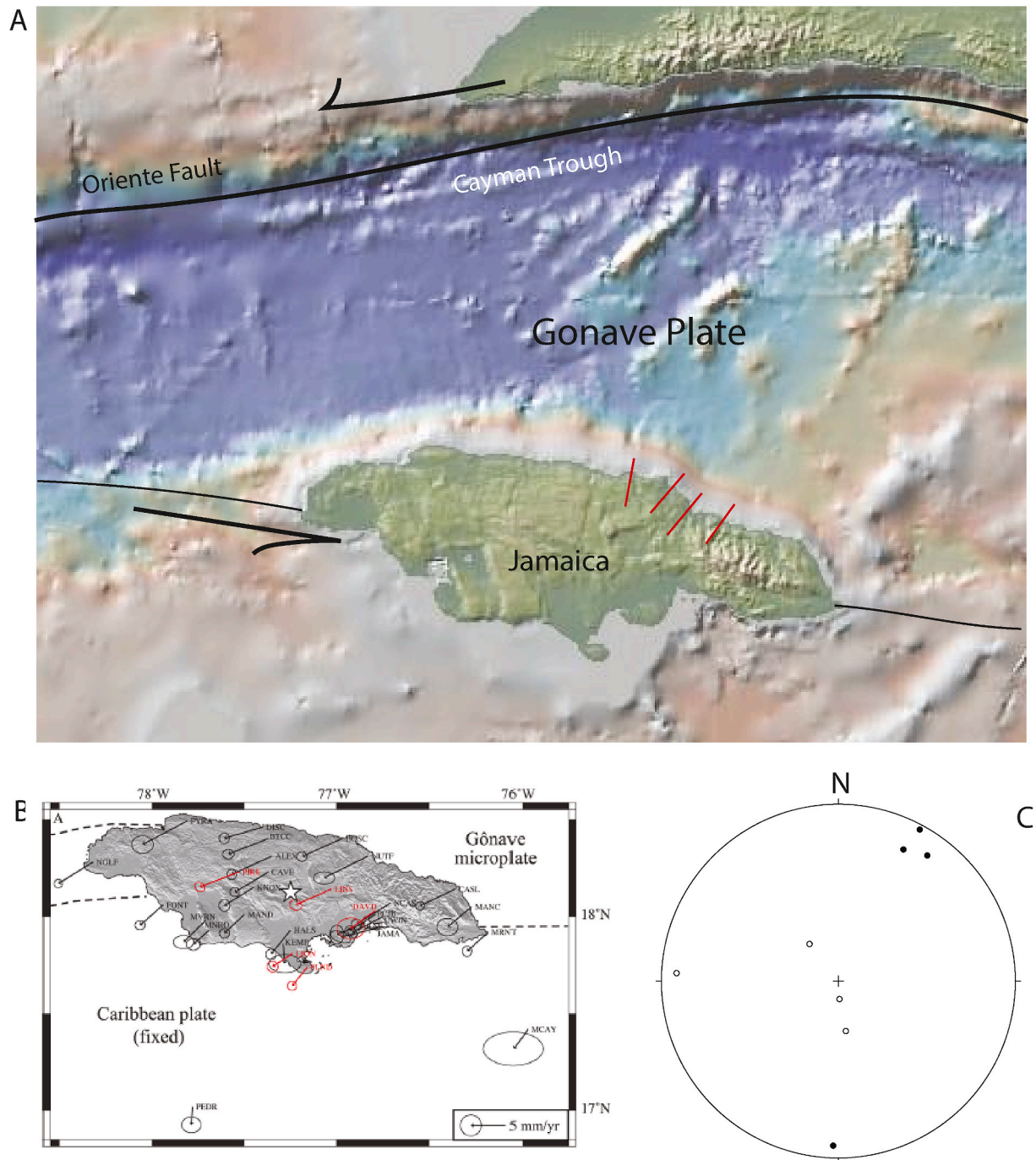


Fig. 9. DEM base of Jamaica with tectonic boundaries and focal mechanism solutions and plots of calcite shortening axes (A). GPS velocity field from Benford et al. (2012a, b, B). Lower hemisphere plot of calcite strain data (circles - shortening axes, open circles - extension axes).

twinning analyses preserve a horizontal shortening strain that is parallel to local bedding (LPS) and oriented $\sim$ N-S, or normal to the plate boundary along the north side of the Caribbean plate (Fig. 6, Table 1). We measured 425 twins, of which 47 were NEVs (24%) and removed by routine data cleaning; forty seven twin measurements does allow for analyzing a secondary twinning strain overprint and this result is a horizontal shortening strain oriented at $132^\circ \pm 5^\circ$, approximately parallel to the plate boundary (Fig. 6; Table 1). The average differential stress associated with twinning was -359 bars. No titanite was observed in the marbles so we were unable obtain a U-Pb age.

4.3. Pacific margin, Costa Rica

Oriented carbonate samples were collected from the Miocene Terraba Fm. forearc sediments at Punta Dominical ($9^\circ 13' 16.60''$ N, $83^\circ 50' 40.46''$ W; see Phillips, 1983) and from the Cretaceous-Eocene Nicoya ophiolite to the northwest (Fig. 7). The Terraba Fm. includes sandy units with calcite cements and crosscutting calcite veins ($n = 6$) within a setting of shallowly plunging pericline folds that trend parallel to the coast (Fig. 7c; see Fisher et al., 2004) and include whale fossils (Fig. 7d). Two calcite veins were collected from the Nicoya ophiolite (Bourgeois et al., 1984; Berrange' and Thorpe, 1988; Baumgartner and Denyer, 2006). Calcite twinning strain results are remarkably uniform,

Table 2
Ar-Ar age, Roatan gneiss.

Summary of ⁴⁰ Ar/ ³⁹ Ar incremental heating experiment of biotite from Roatan Gneiss											
Sample	Experiment	Material	K/Ca Total	Weighted Mean Analysis			N	Isochron Analysis			
				MSWD	Age (Ma) ± 2 σ			⁴⁰ Ar/ ³⁶ Ar _i ± 2 σ	MSWD	Age (Ma) ± 2 σ	
Roatan	UW65D19b	Biotite	15.546	0.42	14.65 ± 0.35		8 of 8	295.0 ± 8.5	0.49	14.74 ± 1.69	
COMPLETE ⁴⁰ Ar/ ³⁹ Ar INCREMENTAL HEATING RESULTS											
Sample ID	File #	Laser Power (%)	⁴⁰ Ar/ ³⁹ Ar ± 1σ	³⁷ Ar/ ³⁹ Ar ± 1σ	³⁶ Ar/ ³⁹ Ar ± 1σ	F ^a ± 1σ		⁴⁰ Ar* (%)	³⁹ Ar mol x 10 ¹⁶	K/Ca	Apparent Age ± 2σ Ma ^b
Roatan											
Single crystal incremental heating			Biotite			J = 0.016141 ± 0.3% (1σ) ^c					μ = 1.0032 ± 0.02% (1σ) ^d
BE2249	# 1.5		5.2526 ± 0.0777	0.0393	±0.0141	### ##	## ± 0.6893	10.33	0.47	10.933	15.73 ± 39.79
BE2250	# 1.8		4.2968 ± 0.0081	0.0170	±0.0013	### ##	## ± 0.0508	11.06	6.31	25.221	13.79 ± 2.93
BE2252	# 2.2		2.5912 ± 0.0033	0.0129	±0.0005	### ##	## ± 0.0090	19.57	24.87	33.442	14.71 ± 0.52
BE2253	# 2.5		2.1666 ± 0.0024	0.0243	±0.0006	### ##	## ± 0.0139	23.67	13.11	17.676	14.87 ± 0.80
BE2255	# 3.2		3.1354 ± 0.0062	0.1274	±0.0029	### ##	## ± 0.0201	16.31	8.14	3.376	14.83 ± 1.16
BE2256	# 4.0		2.4156 ± 0.0026	0.0833	±0.0018	### ##	## ± 0.0169	19.92	15.88	5.160	13.96 ± 0.98
BE2258	# 5.5		2.0370 ± 0.0041	0.0534	±0.0014	### ##	## ± 0.0150	24.88	19.43	8.056	14.70 ± 0.87
BE2259	# 20.0		3.4977 ± 0.0055	0.0832	±0.0018	### ##	## ± 0.0343	14.81	11.79	5.169	15.02 ± 1.98
Weighted Mean from 8 of 8 steps:						MSWD	0.42			Weighted Mean age:	14.65 ± 0.35
Inverse Isochron from 8 of 8 Steps:				⁴⁰ Ar/ ³⁶ Ar ± 2σ:	295.0	###	MSWD	0.49		Isochron age:	14.74 ± 1.69

All ages calculated using the decay constants of Steiger and Jäger ($\lambda_{40K} = 5.543 \times 10^{-10} \text{ yr}^{-1}$).

J-value calculated relative to 28.02 Ma for the Fish Canyon sanidine.

Age in **bold** is preferred

indicates increments that have been included in weighted mean and isochron calculations.

^a F is the ratio of radiogenic ⁴⁰Ar to K-derived ³⁹Ar.

^b All ages calculated using the decay constants of Steiger and Jäger ($\lambda_{40K} = 5.543 \times 10^{-10} \text{ yr}^{-1}$) and corrected for ³⁷Ar and ³⁹Ar decay, half lives of 35.2 days and 269 years, respectively.

^c J-value calculated relative to 28.34 Ma for the Taylor Creek rhyolite sanidine.

^d μ: mass discrimination per atomic mass unit.

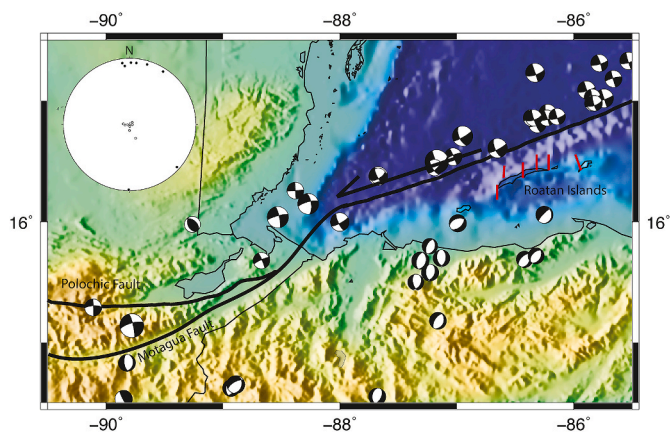


Fig. 10. Regional DEM base of the western Caribbean basin with the Polochic-Motagua-Cayman plate boundary, shortening axes for calcite strain data from Roatan (red lines), a lower hemisphere plot of the strain data (circles = shortening axes, open circle = extension axes) and focal mechanism solutions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

preserving horizontal shortening parallel to the Middle American Trench with no twinning strain overprint (low NEVs; Fig. 8, Table 1). The strain fabric is layer-parallel shortening for all results; the five veins preserved shortening normal to the various vein orientations and the tectonic stress responsible for twinning the calcite is -452 bars. Uranium levels in vein calcite were too low to obtain a U-Pb age.

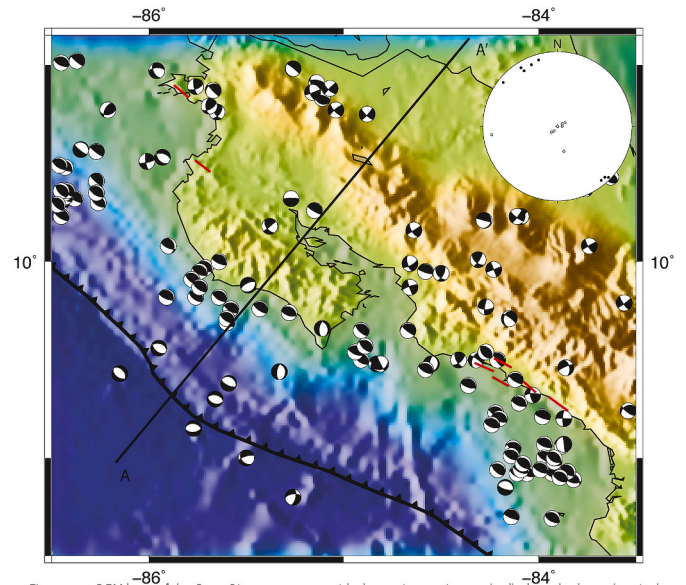


Fig. 11. a, DEM base of the Costa Rica west coast with shortening strain axes (red) plotted, a lower hemisphere stereoplot of shortening (circles) and extension (open circles) axes with belts of focal mechanism solutions (see Fig. 12). b, DEM base of the Costa Rican west coast with shortening strain axes (red) plotted, a lower hemisphere stereoplot of shortening (circles) and extension (open circles) axes with belts of focal mechanism solutions (see Fig. 11a, Appendix 1). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

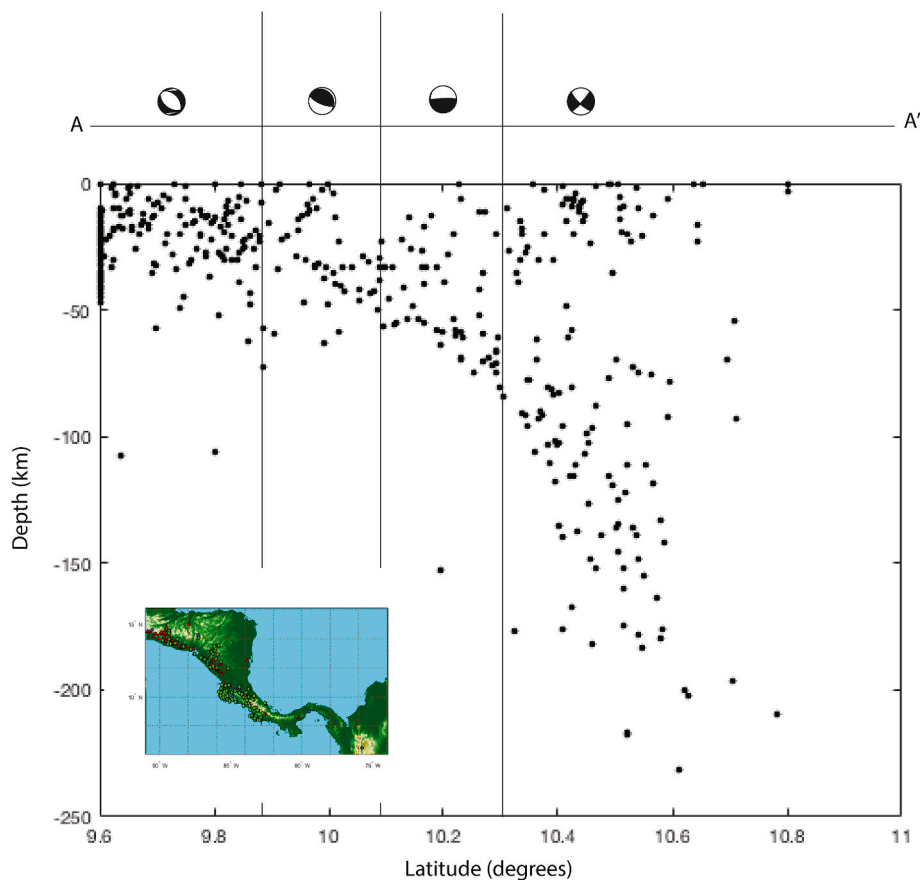


Fig. 12. Cross section (A-A', see Fig. 11) across the Middle America trench and Costa Rica based on seismic events recorded at stations in central America (inset). Seismic events are compartmentalized by their focal mechanism solutions, which are parallel belts (Fig. 11, Appendix 1).

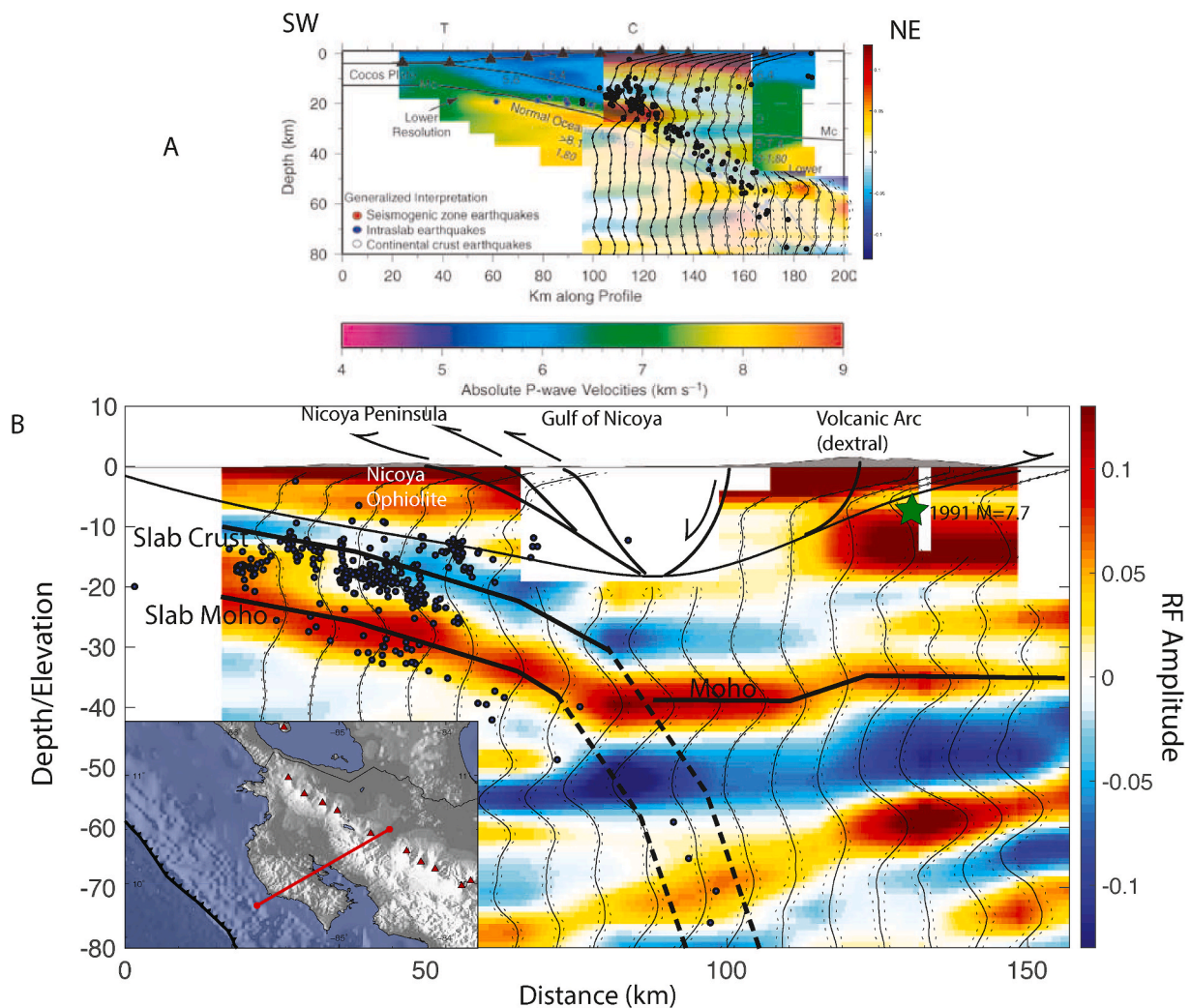


Fig. 13. A) Receiver function cross section overlain over absolute P-wave velocities and earthquakes from [Deshon et al. \(2006\)](#). B) Interpreted receiver function profile across the Nicoya Peninsula. Reds indicate increases in velocity with depth, blues represent decreases. Blue dots are earthquakes from [Deshon et al. \(2006\)](#). Inset shows cross section location for part B. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

5. Discussion

In this study we have used three field areas along the west (Costa Rica) and north (Roatan Island and Jamaica) of the Caribbean plate to document calcite twinning strain history of veins, cements and marbles, ideally acquiring U–Pb ages on the calcite where we measure the mechanical twins in calcite ([Nuriel et al., 2017, 2019](#)). Calcite veins in Jamaica and Costa Rica were U–Pb poor so no U–Pb age was possible. The marbles in the Roatan Islands were devoid of both conodonts or titanite (U–Pb age) so we know the deformation there is 14.65 Ma ([Fig. 5](#)) or younger. Our leap-of-faith is to lump these widely-separated field sites on the margins of the Caribbean plate as Neogene and compare these strain results with active deformation (GPS velocities, [Figs. 1 and 9](#); focal mechanism solutions, [Fig. 1 and Appendix 1](#); SKS fabrics, [Fig. 15](#)), an approach supported by the regional synthesis of [Pindell and Kennan \(2009\)](#).

5.1. Jamaica

The strain results from Jamaica record a complex sample-by-sample fabric ([Table 1](#)) but a consistent horizontal shortening strain normal to the Caribbean plate boundary ([Fig. 9](#)). There is no twinning strain overprint with a differential stress of –339 bars, a high value, and

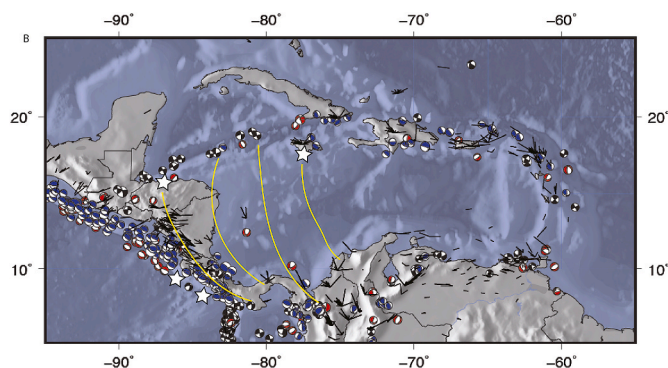


Fig. 14. Regional DEM image of the Caribbean plate with locations of field sites (stars) and interpretation of the shortening based on calcite twinning strains (red) projected across the Caribbean plate with earthquake focal mechanisms and shear wave splitting (SKS) orientations. Focal mechanisms are from the Global Centroid Tensor Catalog ([Dziewonski et al., 1981; Ekström et al., 2012](#)). Shear wave splitting measurements are downloaded from the IRIS-SES-DB ([IRIS-DMC, 2012; Trabant et al., 2012](#)). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

related to the active seismicity of the Gonave plate. The calcite shortening axes are $\sim$ parallel to the motion of the Gonave plate (DeMets, 2001; DeMets and Wiggins-Grandison, 2007; Benford et al., 2012b) but our sample sites do not allow an interpretation of the sub-plates in the Gonave plate (Mann et al., 2002, 2007; Benford et al., 2015; Ellis et al., 2018, 2019). Focal mechanisms within the Gonave plate also indicate plate-normal horizontal shortening but the fault motions are more complex to the north along the Cayman Trough (Orient fault). Plots of SKS fabrics for the Gonave plate are very heterogeneous but steep (Fig. 13; Benford et al., 2012a, b).

5.2. Roatan

Marbles are exposed along the Roatan archipelago interbedded with schists and gneisses that preserve top-to-the-north (thrust) kinematics (Fig. 4) and yielded a biotite ^{40}Ar - ^{39}Ar age of 14.65 Ma (Fig. 5; Table 2). Calcite twinning strains (differential stress = -359 bars) preserve a horizontal, plate-normal shortening fabric; there is a twinning strain overprint from the composite samples (Fig. 6, sample R-8) which is almost a plate margin-parallel horizontal shortening strain; the two shortening strains are consistent with the sinistral focal mechanism solutions to the north along the Motagua fault extension (Fig. 10). Focal mechanism solutions in mainland Honduras to the south are very different (Correa-Mora et al., 2009). There are no GPS arrays in the Roatan Islands, nor is there any SKS anisotropy fabric data (Fig. 15).

5.3. Costa Rica

Our twinning strain data, from veins and calcite cements, record a consistent trench-parallel horizontal shortening strain along ~ 250 km of coastal west Costa Rica in Miocene fore-arc sediments and the Nicoya ophiolite (Fig. 11). There is no strain overprint and the tectonic differential stresses are -452 bars. Tectonic compression and shortening *parallel* to the Middle American trench, which has the highest convergent plate velocity (85 mm/yr; Fig. 1), is not the expected result especially as our samples are from the Fila Castena fold-and-thrust belt where thrust displacement is *normal* to the trench (Fisher et al., 2004) which is *parallel* to the trench shortening direction. Housen and Kanamatsu (2003) report AMS fabrics from MAT core sediment which preserves a vertical Kmin (shortening) axis and a horizontal, trench-normal Kmax (extension) axis.

We have analyzed seismicity and focal mechanisms across the Costa Rican margin, first eliminating magmatic seismic events (Hagerty et al., 2000), and thereby defining slab dip (see Newman et al., 2002; Protti and Schwartz, 1994; DeShon et al., 2003; Brown et al., 2005) and four trench-parallel zones with unique focal mechanism patterns (Fig. 11a and b, 12 and Appendix 1). Shallow earthquakes on the southwest are related to subduction extension and normal faulting, to the northeast is a belt with thrust fault offsets, then another belt of normal fault offsets (see vertical uplifts and terraces in Sak et al., 2004), then a belt of dextral fault offsets parallel to the arc volcanoes (Alvarado et al., 2011). If we equate the seismic record (Modern; 1980–2020) with our calcite twinning strains (older?), there are a few sinistral focal mechanism solutions in proximity to our trench-parallel horizontal shortening axes where these compression and shortening axes align (Fig. 11a). Ellis et al. (2019) report similar trench-parallel GPS vectors, relative to the Caribbean plate along the Costa Rica-Nicaragua Pacific coast. Using the available focal mechanism record (1980–2020; $n = 18,464$ events) there is no apparent fault offset cyclicity (Appendix 1) where one fault type (panel) is active then faulting shifts to a different fault type (and panel).

5.4. Regional synthesis

Jamaica lies along the northern margin of the Caribbean plate and is now identified as the Gonave microplate (DeMets, 2001; DeMets and Wiggins-Grandison, 2007; Benford et al., 2012b) which has additional,

internal microplate subdivisions (Mann et al., 2002, 2007; Benford et al., 2015; Ellis et al., 2018, 2019). Our calcite shortening strains are sub-horizontal and parallel to the Gonave plate motion (NE) and normal to the sinistral motion along the Caribbean-North American plate boundary (Figs. 9, 14 and 15) where SKS fast directions are steep (Benford et al., 2012a, b). Sub-horizontal shortening axes normal to the strike-slip plate boundary is the expected result (Mount and Suppe, 1987; Zoback et al., 1980; Zoback and Zoback, 1989) but different than the twinning strain results along small-offset strike slip faults where the shortening strain axis is horizontal and parallel to the fault (Craddock et al. 2019). Our calcite strain results to the west, in the Roatan Islands (Figs. 10 and 14), along the same plate boundary setting as Jamaica, are similar although there are no SKS results (Fig. 15).

Central America is dominated by subduction of the Cocos plate (85 mm/yr) along the MAT where slab dip changes along strike northwest of the collision of the Cocos ridge. Formerly known as the Chortis block, central America is a complex agglomeration of microplates (Alvarado et al., 2011; Ellis et al., 2018, 2019) that have identified panels of focal mechanism solutions parallel to the MAT. This includes the role of the dextral Chicilagua fault system parallel to the trench but along strike of the andesitic volcanoes in the arc. We've created a cross section through the Costa Rican portion of the margin (Figs. 11–14) to include the FMS panels on the trench side and the evolving E-vergent thrust system on the Caribbean passive margin (Plafker and Ward, 1992; Protti and Schwartz, 1994; Suárez et al., 1995). Our calcite strain shortening axes are horizontal and *parallel* to the MAT, or *normal* to the plate convergence direction. There are a few strike-slip FMS in proximity to our sample sites (Fig. 11a) and Ellis et al. (2019) report trench-parallel GPS velocity vectors (relative to the Caribbean plate) north of Costa Rica. SKS anisotropy orientations are complex around the Caribbean plate (Fig. 14).

Our summary figure includes correlation of the horizontal shortening axes from our calcite strain studies (Figs. 9–11) across the Caribbean plate (red lines, Fig. 14) and a compilation of FMS and SKS results (Figs. 14 and 15, Appendix 1). The calcite strain results record horizontal shortening *normal* to the Caribbean plate motion at all three locations (Jamaica and Roatan, $\sim$ N–S shortening, easterly Caribbean plate motion; Costa Rica, SE–NW shortening, easterly Caribbean plate motion)

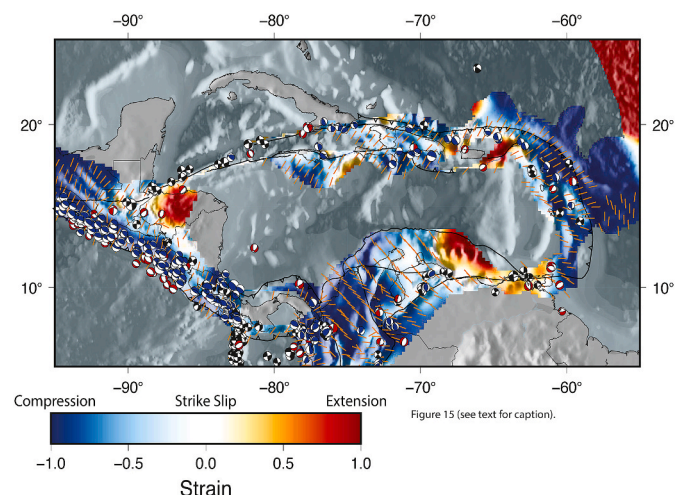


Fig. 15. Strain map of the Caribbean region based on geodetic data (Kreemer et al., 2014) and earthquake data from the Global Centroid Moment Tensor Catalog (Dziewonski et al., 1981; Ekström et al., 2012) for earthquakes less than 30 km depth. Colors represent strain type (blue, white, orange) from geodetic data. Orange lines are the direction of maximum shortening strain in compressive environments from geodetic data. Focal mechanism colors indicate the type of faulting, red = extension, blue = compression, black = strike slip. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and correlate nicely with the geodetic velocity fields for the Caribbean plate *except* along the MAT in Costa Rica where it seems strike-slip motions are more pervasive (Alvarado et al., 2011) if our SE-NW horizontal calcite shortening strains are parallel to local strike-slip faults (Craddock et al. 2019). There are no SKS shear wave splits in the Roatan area but a northeasterly result, parallel to the Gonave plate motion and our twinning strains, is present in Jamaica. Along the MAT in Costa Rica SKS fast directions are *parallel* to the trench and our shortening strain axes (SE-NW) yet normal to the subduction convergence direction (Figs. 14 and 15).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

(A) Map of Costa Rica focal mechanisms from the global CMT catalog. Colors Indicate primary stress. Blue = compressional, red = extensional, black = strike-slip. B) Timeline of events shown in A.

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