Tectonic and geochemical investigation of basalts and associated deep sea sediments in the southern Península de Nicoya, Costa Rica

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INTRODUCTION

Basalts of the Península de Nicoya represent the ocean crust platform upon which the Central American magmatic arc is being constructed due to subduction at the Middle America Trench. (Gardner, this volume: Fig. 1) The southern peninsula basement outcrops are dominated by massive and pillow basalts with lesser amounts of associated deep sea sediments, conglomeratic broken formations, and monolithic basalt breccias. There is much debate concerning these basement rocks, in relation to both the isolated peninsula in question and to the greater Caribbean region. One area of contention comes out of the discrepancy between the models of Di Marco and others (1995) and Sinton (1996). Sinton (1996) uses geochemistry and geochronology to argue that the entire Península de Nicoya is underlain by thick, basaltic ocean crust of the Caribbean-Columbian Cretaceous Igneous Province (CCCIP) (Kerr *et al.*, 1997). The theory of a large igneous province (LIP) as a model for the anomalously thick (8km to >20km) oceanic crust of the Caribbean is widely supported in Costa Rican geology (see Donnelly, 1994 for a review). The LIP model implies that a more geochemically enriched source, possibly influenced by a hot spot plume head, thickens large areas of ocean floor (CCCIP = 6×10^5 km^2) in a matter of a few million years (CCCIP = 88-90 Ma) (Kerr *et al.*, 1997). In opposition to Sinton (1996), Di Marco and others (1995) used paleomagnetism and post-basalt stratigraphy to distinguish two terranes in the Nicoya region: the autochthonous Chorotega Terrane (CT), representing the Caribbean plate on the east half of the peninsula, and the allochthonous Nicoya Terrane (NT), which was accreted to create the western peninsula (Fig. 1). A third, slightly older model developed by Kuijpers (1980) suggests that the entire peninsula was involved in accretionary burial and nappe structure formation during its accretion onto the Caribbean plate.

OBJECTIVES, SAMPLING, AND METHODS

The goal of this investigation is to utilize geochemistry, geochronology, and micropaleontology to constrain the formation and evolution of the southern section of the peninsula, a multi-faceted project which is outlined below:

1. One of the main discrepancies in the debate is the fact that Sinton (1996) sampled only the northern section of the Península de Nicoya, well within Di Marco and other's (1995) NT. This study attempts to characterize the southern CT geochemically and compare these data to both Sinton's (1996) NT data set and to four NT samples collected during this investigation. Fourteen massive and pillowed basalt samples (10 CT, 4 NT) were gathered along coastal and road outcrops (Fig. 1). X-ray fluorescence (XRF) was conducted at the University of Massachusetts to obtain major and trace element geochemistry for all fourteen samples. In addition, six samples underwent instrumental neutron activation analysis (INAA) at Oregon State University for supplemental trace element data.
2. X-ray diffraction (XRD) was employed for eight samples, including two monolithic basalt breccias, in order to examine cryptocrystalline mineral phases for signals of alteration and/or subduction-related metamorphism.
3. One of the strongest arguments in support of the CCCIP is the contemporaneous igneous activity found across the Caribbean at 88-90 Ma (Sinton 1996). In order to investigate the possible link of the CT to the CCCIP, three of the freshest samples from the CT will be dated via whole rock ^{40}Ar - ^{39}Ar at the Massachusetts Institute of Technology. In addition, three inter-pillow radiolaria chert samples were collected for microfossil dating to help constrain the timing of volcanism.

PETROGRAPHY AND MINERAL CHEMISTRY

Southern Península de Nicoya basalts are aphyric with the following mineral assemblage and modal percentages: plagioclase (dominantly An_{50-70}), 40-55%; augite, 30%; Ti-magnetite and illmentite, 10-15%; altered mesostasis, cryptocrystalline alteration minerals, and calcite veining; 5-15%. Augite crystals display varying degrees of Fe rimming. One sample from the NT has highly altered plagioclase in which An_{70-73} has been converted to An_{23}-

mean direction was calculated to be 320°, 15°(k=8.1, alpha-95=18°, n=10). The kappa of 8.1 for the deplunged vectors shows a considerable reduction of dispersion over the standard stratigraphic frame. The stratigraphic inclination from Playa Cabuya was used to calculate a paleolatitude from the equation:

$$\text{Tan I} = 2 \text{ Tan } \lambda$$

where *I* equals the inclination and λ equals the paleolatitude. Playa Cabuya (Paleocene) samples yielded a 7.6 ° (± 8°) N paleolatitude and Miocene cores at Punta Barrigona yield 18 ° (± 4°) N paleolatitude (Figure 3). The Playa Cabuya paleolatitude indicates that the Nicoya Terrane was at its present latitude relative to the Chorotega Terrane by the Paleocene and probably in place. With no stability tests and only 6 beds measured, the Miocene samples may not be a reliable tectonic indicator. The somewhat high paleolatitude of the Miocene samples may be due to incomplete averaging of secular variation over time; however, the paleolatitude is in rough agreement with the Paleocene value.

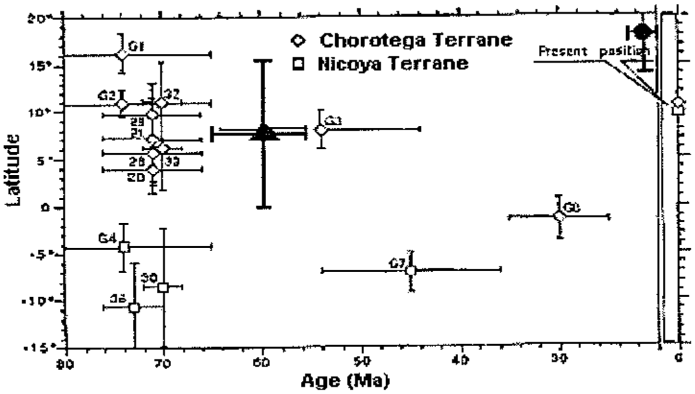


Figure 3. Compilation of paleolatitudes for Chorotega and Nicoya Terranes. Solid triangle is paleolatitude for Cabuya data. Solid hexagon is paleolatitude for Punta Barrigona data. There are no stability tests for the Punta Barrigona data and secular variation may not have been averaged out; thus, Miocene paleolatitude is not well constrained. Diagram from DiMarco et al. (1995) (Figure 22).

Conclusions

The purpose of this project is to provide data on the accretion age/timing of the Nicoya Terrane. The samples from Punta Barrigona (Miocene) yielded equivocal data possibly due to the lack of stability tests and sufficient averaging of secular variation. Data from Playa Cabuya, after a two-stage tectonic correction, pass both fold and reversal tests, insuring the presence of a primary remanence. The paleolatitude calculated for Paleocene cores give a value of 7.6° (± 8°). This value is essentially the same as today's latitude indicating that the Nicoya Terrane was in place relative to the Chorotega Terrane during the Paleocene.

Acknowledgments

Thanks to the Costa Rica Keck Group and Dr. Bruce Panuska for their help and support.

References Cited

Butler, Robert F., 1992, Paleomagnetism: Magnetic Domains to Geologic Terranes. Boston: Blackwell Scientific Publications, 319 p.

DiMarco, G., Baumgartner, P.O., and Channell, J.E.T., 1995, Late Cretaceous-early Tertiary paleomagnetic data and a revised tectonostratigraphic subdivision of Costa Rica and western Panama: in Mann, P., ed., Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America, Boulder, CO, Geological Society of America Special Paper 295, p. 1-27.

Gose, W.A., 1983, Late Cretaceous-Early Tertiary tectonic history of Southern Central America: Journal of Geophysical Research, v. 88, p. 10585-10592.

Watson, G. S., A test for randomness of direction: Monthly Notices Geophys. J. Roy. Astron. Soc., v. 7, 160-161, 1956.

Ab_{31-35}-Or_{42-46}, indicating some element mobility.

XRD analyses searched for eight specific subduction-related minerals: lawsonite, aragonite, glaucophane, jadeite, pumpellyite, prehnite, actinolite, and epidote. No such metamorphic phases were detected; the majority of XRD peaks were explained by feldspar and pyroxene. On the other hand, veins of the zeolite clinoptilolite were encountered with both SEM and XRD analysis; clinoptilolite is interpreted to be an alteration phase. Incompatible trace element plots show scatter for Sr, Rb, and Ba. Together, this evidence suggests typical hydrothermal alteration.

GEOCHEMICAL CHARACTERIZATION AND COMPARISON

Coherent trends of major and trace elements imply that the rocks from this study were derived from a similar parental source and variation between samples can be explained through fundamental magmatic processes. In addition, similarity to Sinton's (1996) data from the northern peninsula demonstrate a high probability that a common parental magma is responsible for producing the basement rocks of the entire Península de Nicoya.

Basalts of this study are tholeiitic with 4 to 9 wt % MgO, represented by a total alkalis-silica (TAS) chart (Fig. 2) and an AFM diagram (Fig. 3). Bi-variate diagrams versus MgO indicate that this basalt sequence has simultaneously undergone fractionation of clinopyroxene and plagioclase, with late-stage opaque phases. Figure 4a displays a decrease in the ratio CaO/Al_2O_3 with magma evolution (decreasing MgO) because clinopyroxene fractionation forces the removal of CaO relative to Al_2O_3. Figure 4b shows the synchronous crystallization of clinopyroxene and plagioclase as the incompatible phase TiO_2 increases sharply with decreasing MgO. Yet, at 4 wt % MgO, an inflection in the data indicates late-stage fractionation of Ti-oxides. Steep negative slopes on plots of other incompatible elements (Y, Nb, Ce, and P) versus increasing MgO indicate concurrent clinopyroxene and plagioclase fractionation; steep positive slopes for compatible elements, especially Ni, give evidence for the fractionation of olivine, despite its absence in the rocks of this study.

Bi-variate plots using the highly incompatible elements Ce, Zr, and Y versus Nb display reliable linear trends that pass through the origin, showing that these elements retain a constant ratio through magma evolution (Ce versus Nb is shown as an example in Fig. 5). Because of this coherency and because these elements are readily released to the liquid upon initial melting, the patterns suggest a common source for the basement rocks of Sinton (1996) and those of this investigation. Similarly, when ratios of incompatible elements are plotted against Nb (eg. Zr/Y, Ce/Y, Zr/Nb, and Nb/Y), nearly horizontal trends indicate that common source ratios are retained through fractionation for all samples, thus substantiating the relationship of the CT and NT basalts.

TECTONIC DISCRIMINATION

Standard basalt tectonic discrimination diagrams pose several problems, including utilization of mobile elements and ambiguity in defining tectonic setting due to overlapping fields. Using these triangular plots, rocks from this study could have formed in mid-ocean ridge (MORB), island arc (IARC), or ocean island (OIB) settings. This investigation chooses to rely upon trace element spider diagrams in order to assess the tectonic setting of the southern peninsula. Figure 6 is a multi-variable spider diagram showing relatively flat patterns for rocks of this study, normalized to primordial mantle; Sinton's (1996) data show comparable trends. Península de Nicoya basalts show enrichment relative to normal MORB (N-MORB) for the most incompatible elements, but neither does the pattern resemble that for OIB.

Chondrite normalized rare earth elements (REE) for this study are plotted in Figure 7. Because N-MORB REE patterns are characteristically light REE (LREE) depleted, the flat pattern of these six samples suggests that volcanism in the study area was affected by some enrichment process, possibly hot spot activity (Sinton 1996).

From this study, ratios of chondrite-normalized La to Ce for fresh basalts in both the CT and the NT are 0.833 to 1.500. This enrichment of La relative to Ce, both highly incompatible, indicates a less depleted mantle source (E-MORB) than N-MORB, which has $(La/Ce)_N$ significantly less than 1.0 (Kaula, 1981). In sum, interpretation of the Península de Nicoya as an LIP, with likely plume influence, is reasonable.

CONCLUSIONS

Geochemical comparison of NT and CT basalts does not support the separation of the Península de Nicoya basement rocks into two terranes of differing origins, as proposed by Di Marco and others (1995) Instead, this study finds a set of basalts that can be related, through fractional crystallization, to a similar parental magma source. Sinton (1996) has already tied the NT to the CCCIP with geochronology, supporting the idea that the entire peninsula was created during the same event. Therefore, this debate is restricted to the following two models: 1) both the CT and the NT formed from the same event at the same location; or 2) the CT and the NT formed from the same source, spatially separated, and then were tectonically juxtaposed via movement of the allochthonous NT. The latter model would account for the fossil and sediment differences documented by Di Marco and others (1995), which suggest a more open ocean environment for the NT than the CT following basalt formation. To further constrain the evolution of this region, ^{40}Ar-^{39}Ar whole rock geochronology and inter-pillow radiolaria chert dating will test the hypothesis that the CT is indeed contemporaneous with the CCCIP. Finally, the theory of Kuijpers (1980) is not supported by the SEM and XRD analyses of this investigation. Thus, a lower plate origin for the NT is not substantiated.

Regardless of which of the above theories is more probable, the geochemical studies of this and previous investigations point to an E-MORB style of volcanism for the entire Península de Nicoya basement. The influence of an enriched plume head during the CCCIP formation appears to be a probable mechanism to explain the volcanic history of this region.

ACKNOWLEDGEMENTS

I would like to thank the KECK Undergraduate Research Consortium and the Costa Rica 1998 project leaders, Thomas Gardner, Edward Buetner, Dorothy Meritts, and Marino Protti for giving me this amazing opportunity to explore and learn. Many thanks to my fellow Costa Rica KECK participants.

REFERENCES

Di Marco G., Baumgartner, P.O., and Channell, J.E.T., 1995, Late Cretaceous-early Tertiary paleomagnetic data and a revised tectonostratigraphic subdivision of Costa Rican and western Panama: Geological Society of America Special Paper 295, p. 1-27.

Donnelly, T.W., 1994, The Caribbean Cretaceous basalt association: A vast igneous province that includes the Nicoya Complex of Costa Rica: Profil, (University of Stuttgart) 7, p. 17-45.

Kaula, W.M., ed., 1981, Basaltic Volcanism on the Terrestrial Planets: New York, Pergamon Press, 1286 p.

Kerr, A.C.,Tarney J., Marriner G.F., Nivia A., Saunders A.D., 1997, The Caribbean-Colombian Cretaceous Igneous Province: The internal anatomy of an oceanic plateau, *in* Mahoney, J. and Coffin, M.F., eds., Geophysical Monograph 100: Large Igneous Provinces, Washington, DC, American Geophysical Union, p. 123-144.

Kuijpers, E. P., 1980, The geologic history of the Nicoya Ophiolite Complex, Costa Rica, and its geologic significance: Tectonophysics, v. 68, p.233-255.

McDonough, W.F. and Sun, S.-s.,1995, The composition of the Earth: Chemical Geology, v. 120, p. 223-253.

McDonough, W.F., Sun S., Ringwood A.E., Jagoutz E., and Hoffmann A.W., 1991, K, Rb, and Cs in the Earth and Moon and the evolution of the Earth's mantle: Geochimica et Cosmochimica Acta, Ross Taylor Symposium volume.

Sinton, C.W., 1996, A tale of two large igneous provinces: Geochronological and geochemical studies of the North Atlantic Volcanic Province and the Caribbean Oceanic Plateau: unpublished PhD thesis, Oregon State University, 179 p.

Sun, S.S., 1980, Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands, and island arcs. Phil. Trans. R. Soc., A297, 409-445.

Figure 1: Sketch map of the Peninsula de Nicoya (see Gardner, this volume, figures 1 and 2, for general tectonic setting).

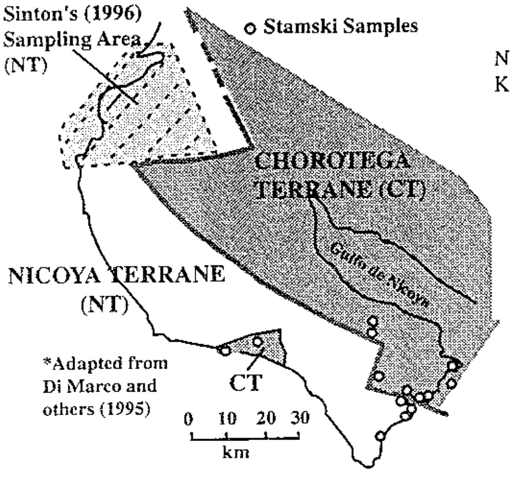
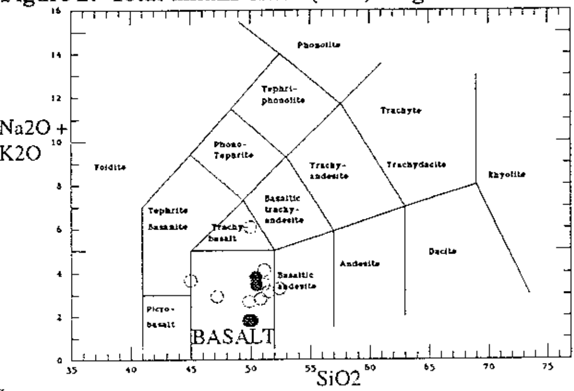


Figure 2: Total alkalis-silica (TAS) diagram for this study.



LEGEND FOR ALL DIAGRAMS:
○ CHOROTEGA TERRANE (CT)
● NICOYA TERRANE (NT)
△ NT DATA OF SINTON (1996)

Figure 3: AFM diagram for this study showing tholeiitic compositions.

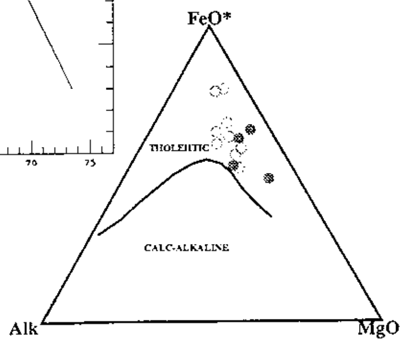
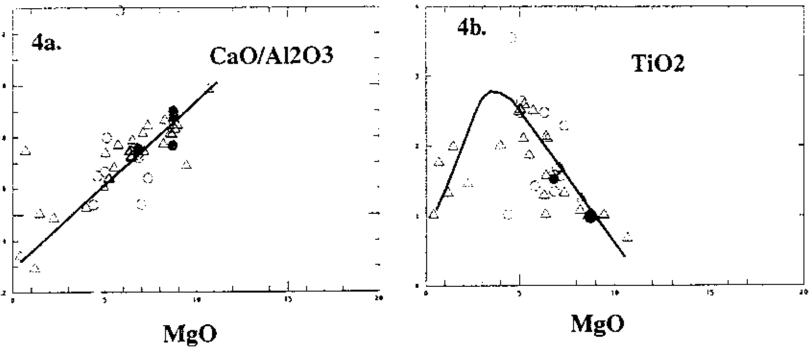


Figure 4: Bi-variate plots of CaO/Al2O3 and TiO2 versus increasing MgO. 4a shows fractionation of clinopyroxene. 4b exhibits concurrent plagioclase and clinopyroxene crystallization with magma evolution. Inflection at 4 wt% MgO indicates fractionation of late-stage Ti-oxides. Coherent trends for data from this study and from Sinton (1996) suggest a similar magmatic source.



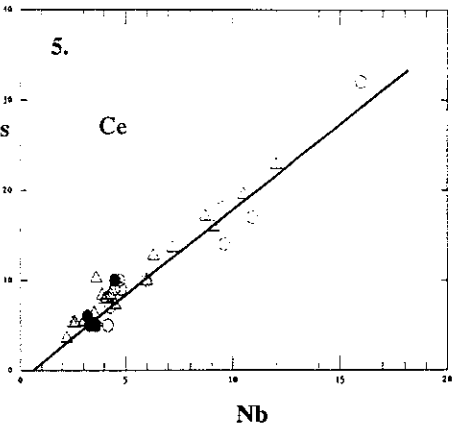


Figure 5: Bi-variate plot of highly incompatible elements shows retention of source ratio through fractionation. No distinctions between the CT and NT can be inferred.

Figure 6: Multi-element diagram normalized to primordial mantle of McDonough *et al.* (1991). Flat overlapping patterns generated from rocks of this study combined with data from Sinton (1996) show E-MORB affinities for both data sets.

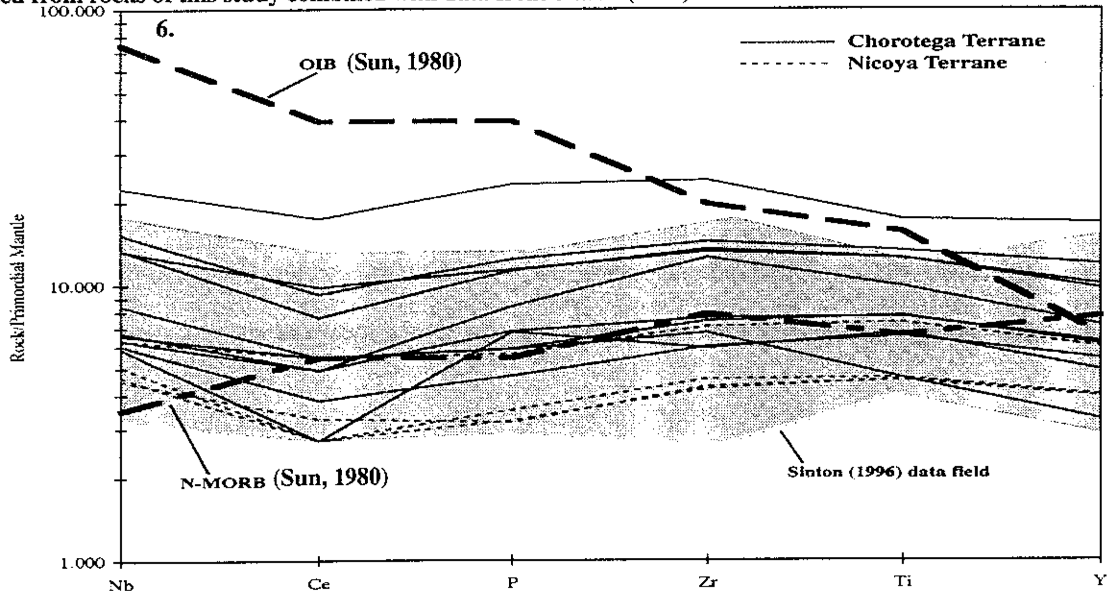
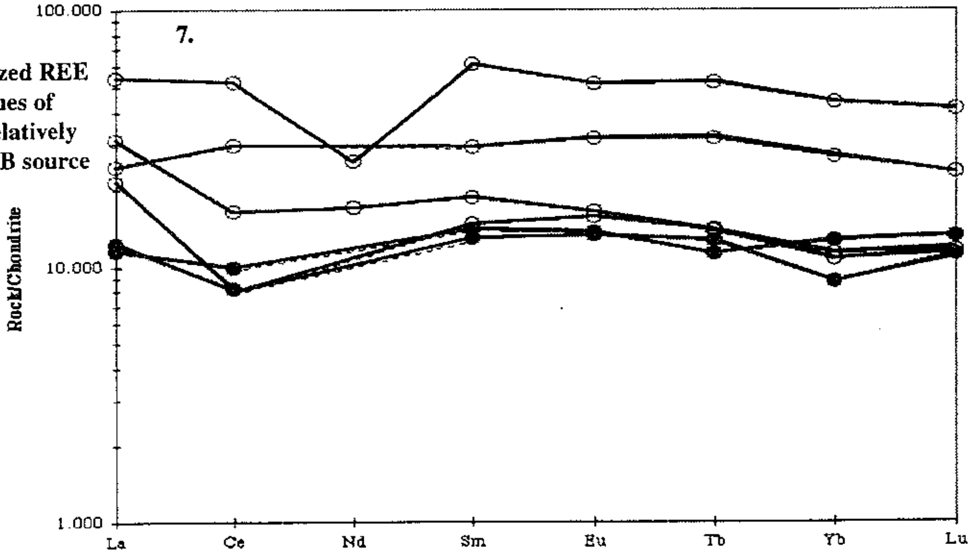


Figure 7: Chondrite normalized REE diagram using chondrite values of McDonough *et al.* (1995). Relatively flat patterns suggest E-MORB source for this study (see legend on preceeding page).



Geodetic measurements of Holocene deformation in response to subducting seamounts, southern Península de Nicoya, Costa Rica.

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INTRODUCTION

Costa Rica is located on the southern end of the Central American arc system, which marks the beginning of the subduction of the Cocos plate and associated rough crust beneath the Caribbean plate (Gardner, this volume, Fig. 1). The Pacific margin of Costa Rica is affected by orthogonal convergence as the Cocos plate subducts beneath the Caribbean plate along the Middle American Trench (MAT) at the rate of 9.1 cm/yr (DeMets et al., 1990). Linear chains of seamounts oriented perpendicular to the margins, rising thousands of meters above the sea floor of the Cocos plate, are actively deforming the accretionary prism and forearc as they encounter the central Pacific segment of the subduction zone in Costa Rica (Gardner, this volume, Fig. 2). Furthermore, these seamount chains might be affecting the southern portion of the Península de Nicoya, which provides a unique opportunity to study this deformation because shorelines run both parallel and perpendicular to the direction of convergence. Uplift rates determined from ^{14}C dating of shells from Holocene terraces indicate the forearc is uplifting 1-5 mm/yr and tilting towards the arc at a rate of 0.01-0.02°/k.y. (Marshall and Anderson, 1995). Additionally, more than 1 m of uplift occurred along the Pacific coastline during the last major rupture of the Nicoya subduction zone in 1950, which resulted in a M7.7 earthquake located beneath the Península de Nicoya (Marshall and Anderson, 1995). Five years later the Instituto Geografico Nacional de Costa Rica installed numerous surveying monuments across the peninsula and completed a geometric leveling line tied to mean sea level. Because only two monuments were located during this 1998 project, one of which was vandalized, there is no accurate means to geodetically tie into the 1955 survey. Therefore, attempts to quantify the interseismic deformation during current or future earthquake cycles are difficult and relative at best.

The main focus of this project is to create a base-line survey that can be reoccupied at a later date. Through comparisons between this 1998 base-line survey and a future survey, the relative magnitude and direction of forearc deformation can be determined. A second focus of the project is to compare the accuracy of three survey techniques to see which is best suited for geodetic studies on the Península de Nicoya. The last objective is to create a forward model of the uplifted forearc and subsided forearc basin using a simple dislocation program to determine the geometry of the Nicoya subduction zone.

METHODS

Geometric Leveling. Geometric leveling is a first-order leveling method with the precision of ± 1mm. The technique uses two stadia rods, each with a strip of graduated invar steel designed to resist expansion and contraction from heat. In addition, a Wild Nak 2 precision optical level with a micrometer plate is attached to a surveyor's tripod. Two stadia rods are placed on either side of the level and a reading is taken from both rods. The readings are used to calculate changes in elevation from the first to the second stadia rod.

Trigonometric Leveling. Trigonometric leveling is a second-order leveling method with the precision of ± 1cm. The technique uses an electronic theodolite, which measures an angle from a vertical axis between the center of the geoid and the instrument. Additional equipment includes an electronic distance meter (EDM), which uses a single frequency infrared light to detect the distance to a point, and a target/prism used for sighting and reflecting infrared beams. The theodolite and EDM are set up at one point while the prism is moved to another location, and measurements are taken. Later, the difference in elevation is calculated using the angle from the vertical (measured using the theodolite), the distance to the prism (measured using the EDM), and simple trigonometric functions.

Global Positioning System Campaign. Four permanent monuments were installed along the proposed survey lines and then occupied for three to five days by a Trimble 4000 SSI dual-frequency geodetic receiver in a static style campaign. Daily data sets were stored with the receiver and processed using GPS Inferred Positioning System (GIPSY) by Paul Lungren at the Jet Propulsion Laboratory in Pasadena, CA. All geographical coordinates and elevations are based on the global reference WGS-84.