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

Todd Shearer
Department of Geology, Whitman College, Walla Walla, WA 99362
Faculty sponsor: Kevin Pogue, Whitman College

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.

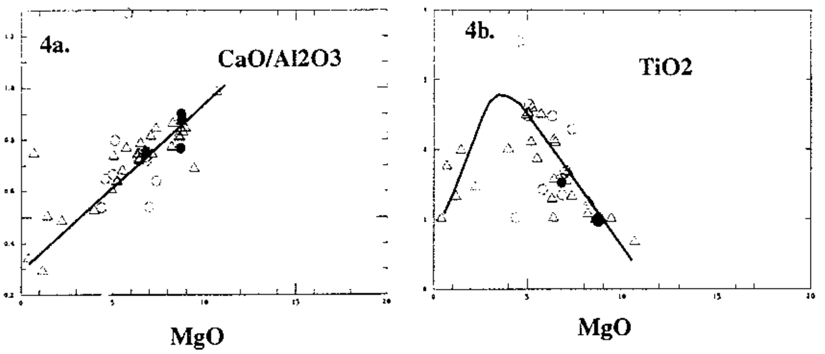
METHODS

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.

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.



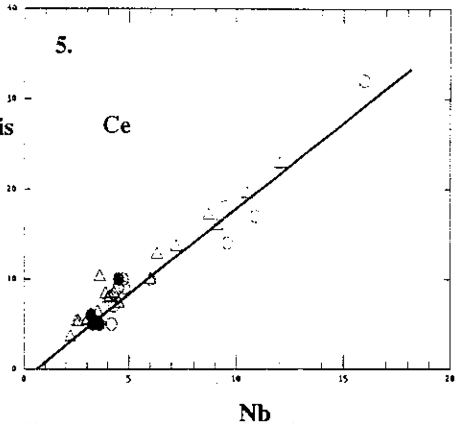


Figure 5: Bi-variate plot of highly incompatible elements shows retention of source ratio through fractionation. No distinctions between the CT and NT can be inferred.

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.

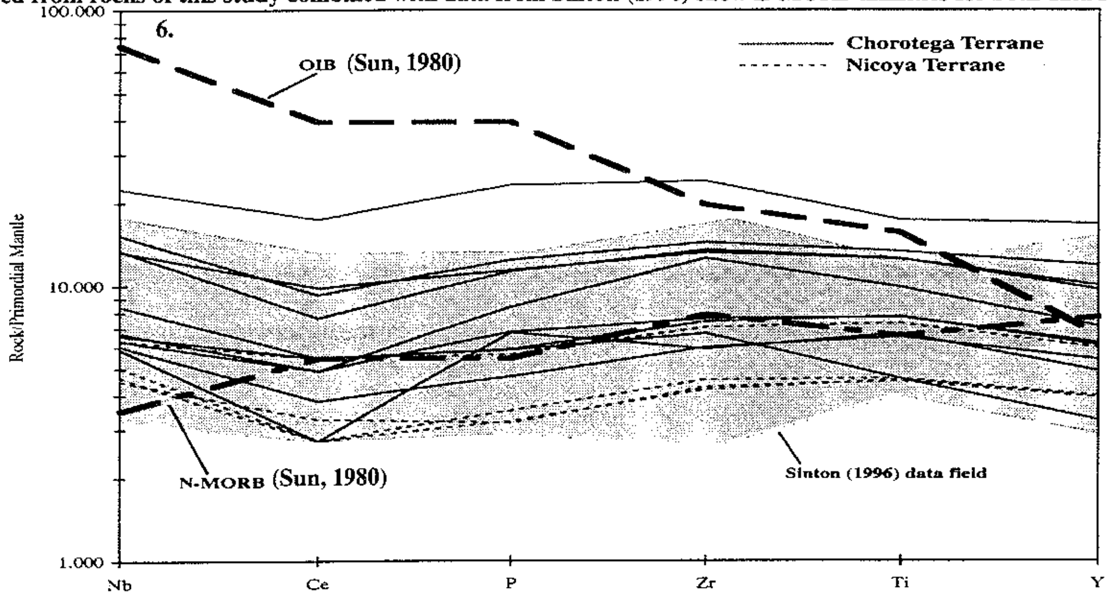
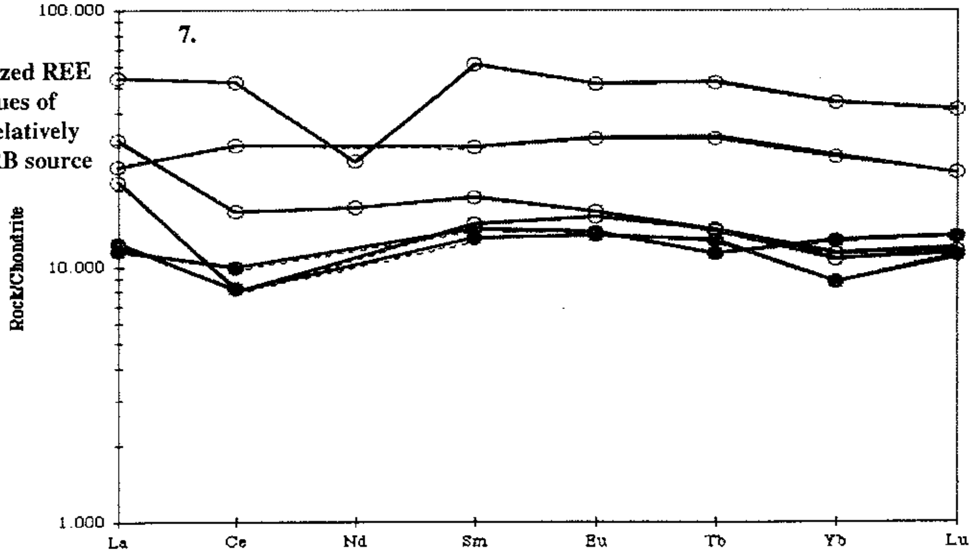


Figure 7: Chondrite normalized REE diagram using chondrite values of McDonough *et al.* (1995). Relatively flat patterns suggest E-MORB source for this study (see legend on preceeding page).



Dislocation Modeling. A dislocation model created by Ward and Barrientos (1986), models elastic deformation due to a buried point source, and is designed to mimic deformation produced from the rupture of a fault. The program allows the user to input grid dimensions, number of planes, strike, dip, rake, length, and width of faults. The subsequent output file produces a three dimensional (X,Y,Z) data set showing the vertical displacement due to a buried point source. The data set is then translated into a three-dimensional graph showing areas of uplift or subsidence using Delta*Graph* to interpolate and contour.

RESULTS AND DISCUSSION

Detecting current rates of forearc deformation using geodetic survey techniques requires a combination of high precision and sufficient time. This insures measured uplift is greater than experimental errors. Because the last survey was completed in 1955, enough time has passed so actual uplift overprints any errors. A series of six permanent survey benchmarks and GPS monuments were surveyed along lines roughly parallel and perpendicular to subduction on a Pleistocene marine terrace (Fig. 1). Elevations for each site and errors from each of the three survey techniques show the differences in precision (Table 1). Elevations determined by geometric leveling and GPS have millimeters of error, while trigonometric leveling has centimeters of error. A benefit of geometric leveling is the high level of precision, less instrument error, and the ability to field check data. But since terrain is steep and vegetation thick, geometric surveying is very slow; a meager 600m was completed in four days. In addition, to maintain high levels of precision, shots were kept under 30m. For distances greater than 30m the refraction from temperature and heat make readings difficult and inaccurate.

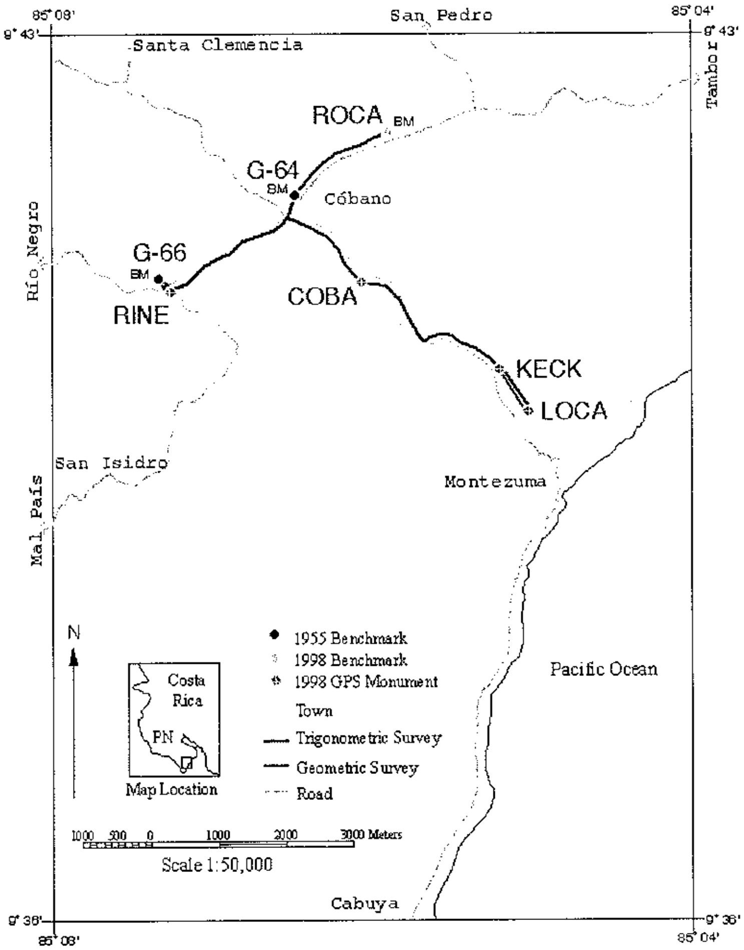


Figure 1. Map of study area.
PN=Península de Nicoya.

Table 1. Monument elevations (m) for 1998. Elevations with no error represent an arbitrary elevation where the survey began. Spaces marked -- represent no data collected.

Method	LOCA	KECK	COBA	G-64	RINE	G-66	ROCA
Geometric	150.0000	173.2170 ± 0.7 mm	--	--	180.0000	178.7103 ± 16μm	--
Trigonometric	150.0000	173.2458 ± 4.8mm	179.2469 ± 8.3mm	160.9935 ± 9.6cm	177.424 ± 12.6cm	176.1363 ± 12.7cm	148.2395 ± 7.9cm
GPS	157.4312 ± 22cm	180.9064 ± 6.6mm	186.8024 ± 4.0mm	--	187.9357 ± 5.7mm	--	--

Considering time constraints, completing the proposed survey line using geometric leveling appeared impossible, so a switch was made to the quicker trigonometric survey style. Completing 2km in a day was common, topography was no longer a hindrance, and the equipment was more portable, making trigonometric surveying a better choice. A total of 8.5 km was completed for the base-line survey. Longer shots, up to 400m, made the technique faster, but the ability to cover more ground came at a cost as trigonometric surveying is less precise than geometric surveying (Table 1).

Initial plans designated LOCA as the starting point for all surveys, but the large error associated with the GPS solution for the LOCA monument forced us to designate KECK as the starting point instead (Table 1). The large error is believed to be associated with a movement of the antenna and failure to record proper antenna height rather than instrument error. Subsequent solutions for KECK, COBA, and RINE show expected errors of approximately ± 5.0mm and are considered accurate.

Direct elevation comparisons are poor indicators of precision. By looking at the difference in elevation between monuments, the effects of assigned elevations are removed (Table 2). It is important to remember that 1998 surveys are "floating" with respect to the 1955 survey. We were unable to directly tie into the 1955 survey, so absolute uplift rates are unobtainable. Portions of the 1998 survey connected monuments G-66 and G-64 from the 1955 survey. Monument G-66 was in excellent shape, while G-64, in the town of Cobano, was vandalized. An estimated 10cm of concrete was removed as vandals successfully extracted a metal pin used for centering. Fortunately, trigonometric leveling data shows less relative uplift at G-64 than G-66, indicating uplift decreases away from Cabo Blanco at the tip of the Península de Nicoya (Table 3 and Fig. 2). The relative elevation difference between the surveys of 1955 and 1998 indicates an arcward tilting of the Península de Nicoya at and angular rotation rate of 0.09°/k.y. This value is significantly higher than the angular rotation rate 0.02°/k.y. from Marshall and Anderson (1995). The discrepancy could either be recording aseismic accumulation of strain or be an artifact of the method's precision.

Table 2. Elevation differences (m) between monuments for the 1998 surveys. Spaces marked -- represent no data collected.

Method	LOCA-KECK	KECK-COBA	COBA-RINE	RINE-G-66	COBA-ROCA
Geometric	23.2170	--	--	-1.2897	--
Trigonometric	23.2458	6.0011	1.8245	-1.2861	-31.0073
GPS	23.4752	5.8960	1.1333	--	--

Table 3. Elevations and differences (m) between monuments for the 1955 and 1998 survey.

Location	1955	1998
G-64	158.1007	160.9935 ± 9.6cm
G-66	172.9787	176.1363 ± 12.7cm
Δ H	14.8780	15.1428

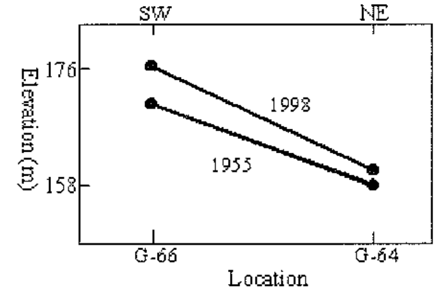


Figure 2. Graphical representation of Table 3, showing decreasing amounts of uplift towards the arc.

Forward modeling of deformation resulting from a buried point source reveals a constant increase in uplift from the trench to 60 km, at which point uplift of the forearc dramatically increases (Fig. 3). Maximum uplift is located at 80 km, and coincides with the coastline of the Península de Nicoya. Continuing arcward, uplift steadily decreases, forming the Golfo de Nicoya. All modeled elastic coseimic deformation is the result of a single rupture along the fault and follows a 40 year earthquake cycle.

The large magnitude of uplift arcward from the trench forms the forearc, while subsidence represents the forearc basin of the Nicoya subduction zone. Theoretical uplift and subsidence is a response to the accumulation and release of strain in the forearc, but doesn't allow for the effects of underplating bouyant seamounts, which is thought to play a significant role in forearc deformation along this section of the coast. Modeled forearc deformation simulated the rupture of a two planes, one dipping 8°, and extending from 10 km northeast of the trench to the southwestern side of the Península de Nicoya, and a second plane dipping 25°, and extending from the southwestern of the peninsula to the Golfo de Nicoya. The dimensions of the modeling plane are believed to be accurate as they correlate with plate geometry described by Protti (in press).

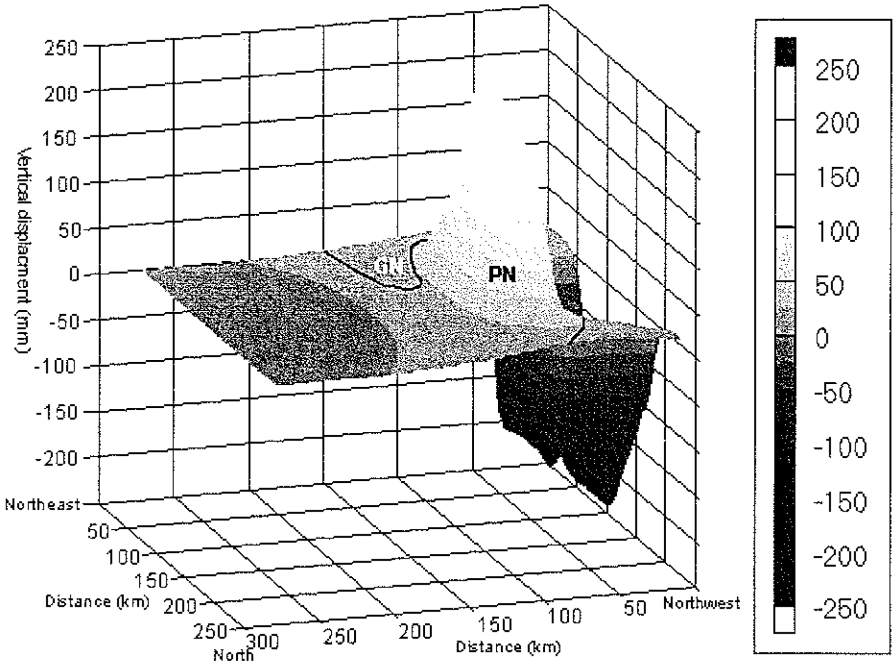


Figure 3. PN=Península de Nicoya, GN=Golfo de Nicoya. Three dimensional dislocation model of the uplfited forearc (Península de Nicoya) and subsided forearc basin (Golfo de Nicoya). View direction is south, shown by arrow on map below, with subduction of the Cocos plate to the northeast beneath the Carribean plate.

CONCLUSIONS

The main objective of completing a base-line survey is a success since a total of 8.5 km of trigonometric leveling is completed and ready to be reoccupied following a large seismic event. Future surveys can easily tie into this survey given the addition of six permanent monuments, three of which have absolute elevation as determined by GPS.

A comparison of survey techniques shows geometric leveling provides the greatest accuracy, but is too slow given the topography and vegetation. Trigonometric surveys are the fastest, but don't provide enough precision. On the other hand, GPS is both time effective and provides enough precision for geodetic point surveying to determine small amounts of deformation. When time and accuracy are important, a static style GPS campaign can cover a significant amount of terrain and provide enough resolution to determine small amounts of uplift.

Both the 1955 and 1998 surveys are snapshots in time, and when compared show the interseismic strain accumulation, manifested as uplift, within a single earthquake cycle. Because the surveys are contained within a single earthquake cycle, uplift rates spanning thousands of years cannot be determined. Relative elevation differences between the two surveys suggests arcward tilting of the peninsula at an angular rotation rate of 0.09°/k.y. The observed angular rotation of the peninsula towards the arc supports conclusions made by Marshall and Anderson (1995). This style of deformation is correlative with forward modeling predictions of an uplifted forearc high, subsided forearc basin, and resumed uplift at the foot of the arc. The plate geometry for the theoretical deformation indicates the Cocos plate is dipping 8° between the trench and the coast of the peninsula, where it steepens to 25°. Mechanisms for forearc deformation include interseismic accumulation of strain, coseismic release of strain, and/or underthrusting of buoyant oceanic seamounts from the Cocos Ridge.

REFERENCES CITED

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1990, Current plate motions: Geophysics Journal International, v. 101, p. 425-478.

Marshall, J.S., and Anderson, R.S., 1995, Quaternary uplift and seismic deformation, Península de Nicoya, Costa Rica: Geological Society of America Bulletin, v. 107, no. 4, p. 463-467.

Protti, M., Güendel, F., and Malavassi, E., In Press, Lo que Sabemos y lo que Podríamos Esperar de la Brecha Sísmica de Nicoya: Revista de Vulcanologia, Sismologia y Tectonica, OVSICORI-UNA, Heredia, Costa Rica.

Ward, S.N., and Barrientos, S.E., 1986, An inversion for slip distribution and fault shape from geodetic observations of the 1983, Borah Peak, Idaho, earthquake: Journal of Geophysical Research, v. 91, no. 5, p. 4909-4919.

Leveling Techniques Applied to the Southern Part of the Nicoya Peninsula in Northern Costa Rica

Enrique Hernández R.
Observatorio Vulcanológico y Sismológico de Costa Rica
Universidad Nacional (OVSICORI-UNA), Apartado 2346-3000, Heredia, Costa Rica
Faculty Sponsor: Dr. Jorge Marino Protti, Universidad Nacional, Costa Rica

INTRODUCTION

Seismic activity along the Pacific coast of Costa Rica results from the subduction of the Cocos plate under the Caribbean plate. The zone of instability product of this collision represents a region of constant crustal deformation and therefore requires extensive geodetic studies. The construction of a geodetic network with permanent benchmarks will allow the recording and quantification of vertical and horizontal movement in the region due to future large earthquakes associated with this process.

The region between the coastal town of Montezuma and Cóbano, in the southern part of the Nicoya peninsula in Costa Rica constitutes the area where we started, during our Keck project, the first stage of monumentation and leveling. Our work focused on a set of sites along two lines parallel and perpendicular to the subduction direction. This work was part of a larger project that pretends to build and level a baseline across the peninsula with the goal of documenting crustal deformation in the region associated to the earthquake cycle.

We built 6 new monuments, conducted 600 m of geometrical leveling, almost 8.5 km of trigonometric leveling, and occupied 4 monuments with global positioning systems (GPS). This way we initiated a component of a project that will collect geodetic and geophysical information all over the Nicoya peninsula.

As part of this project we compare the resolution and precision obtained by three different geodetic techniques in order to define which one will be the most appropriated to be apply to the rest of the peninsula.

METHODS

Before we started the fieldwork, we collected all available geodetic information from the region. This information included topographic sheets, an inventory of previously occupied monuments and their descriptions, and gathered the precise elevation of measured benchmarks. We obtained all this information from the Costa Rica National Geographic Institute (IGN).

After all data was collected we conducted a field check of reported benchmarks but, out of nearly 20 sites, we were able to find only two. These two monuments were labeled by IGN as G-64, located near the school in Cóbano, and G-66 located 2.4 km SW from G-64. Since we only found the concrete pier but not its brass plate, we had to rebuild G-64 installing a stainless steel pin. The monuments of the G series were built and geometrically leveled in 1955.

When you are interested in measuring elevation of benchmarks you have to first decide what king of exactness you require, then you choose what technique to apply (De Obaldia.et al.,1991). This led us to apply three different techniques and conduct and analysis and comparison of them:

Geometric leveling. Depending on the application, this technique receives three different names: leveling by heights, geodesic leveling and precision leveling (Jordan ,1996). Sights on a horizontal plane characterize this technique. The instrument is selected based on the application and required exactness. In our fieldwork we used a Nak2 Wild level, with a GpM3 micrometric parallel plate, which transforms the level into a first order level. This is an automatic level, which does not require centering the bubble each time you take a reading. We also used stuffs with invar tapes that are not susceptible to thermal contraction or expansion. Geodesic leveling is used at two different scales. Large-scale regional networks are occupied, in the case of Costa Rica, by IGN or the National Cadastre and are called official networks. Small or local scale networks are constructed and occupied for specific projects by institutions like OVSICORI-UNA with the goal of documenting crustal deformation.

Trigonometric leveling. In this leveling technique, sights are taken along inclined lines and therefore requires the use of instruments capable of measuring vertical angles and distances, values needed to compute the elevation difference between two points. Although this technique is not as precise as geometric leveling, it can reach the exactness of 5 to 10 mm per leveled kilometer (De Obaldia.et al.,1991). We used a Wild 2000 electronic theodolite, which gives vertical angles to half a second, and a WILD 3000 electronic distancemeter which can reach up to 14 km and have an mean error +-(5mm+1ppm).

Global positioning system (GPS). GPS gives tridimentional position of points in a geometrical and very precise way (Hollmann and Welsch.,1995).Conventionally all positions are given in global geocentric coordinates under the WGS84 reference frame. For our GPS occupations we utilized dual-frequency (L1 and L2) 4000 SI Trimble receivers and ground plate antennas. We monumented four sites (LOCA, KECK, COBA and