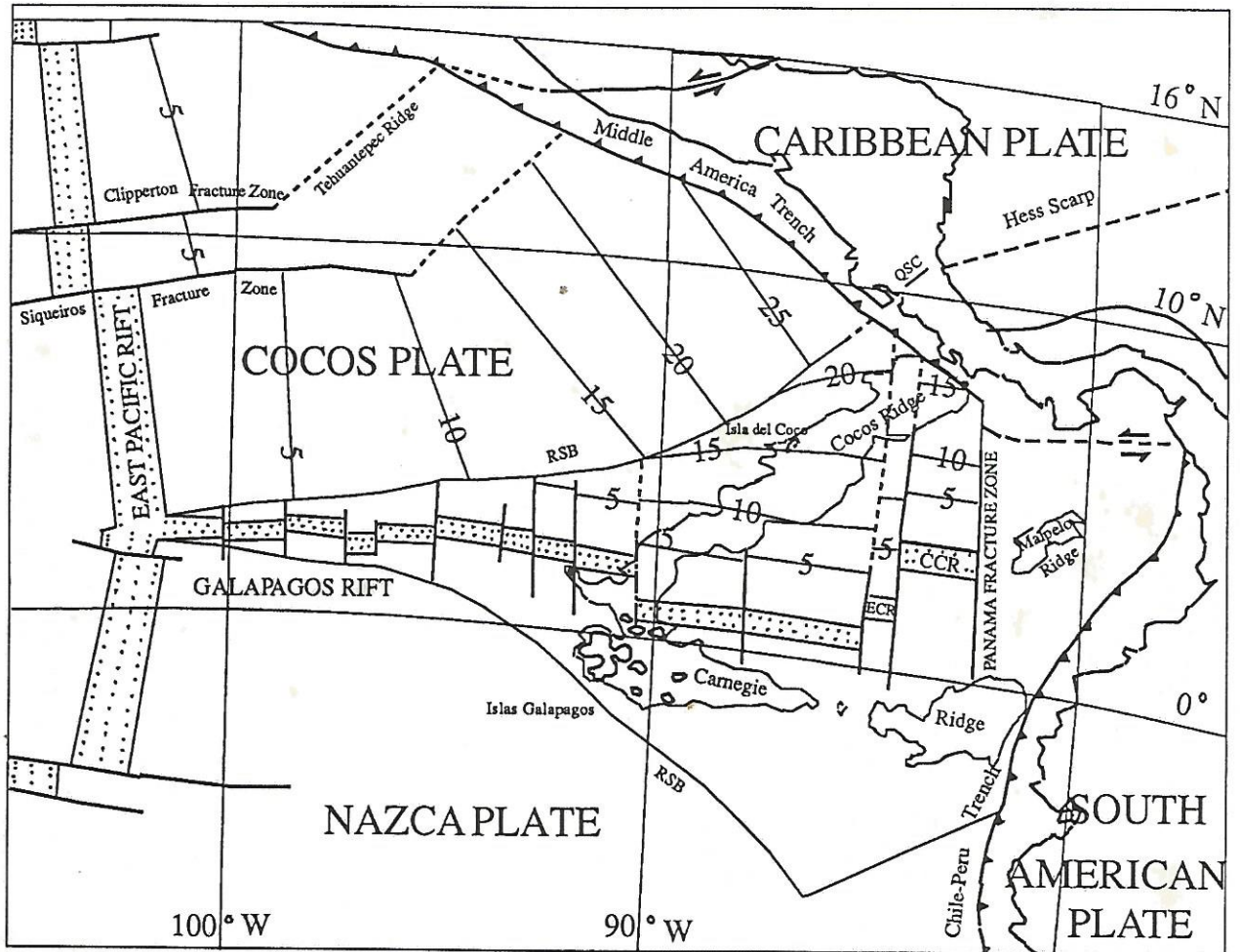


UNIVERSITY OF CALIFORNIA

SANTA CRUZ

CORRELATION BETWEEN THE AGE OF THE SUBDUCTING COCOS PLATE  
AND THE GEOMETRY OF THE WADATI-BENIOFF ZONE UNDER NICARAGUA  
AND COSTA RICA



A dissertation submitted in partial satisfaction of the  
requirements for the degree of

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in

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by

Jorge Marino Protti-Quesada

June 1991

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ABSTRACT

This work integrates six tectonic features related to the subduction of the Cocos plate under the Caribbean plate along the southern terminus of the Middle America Trench (Nicaragua and Costa Rica) into a self-consistent model. These tectonic features are: 1) The shallowing of Middle America Trench morphology from NW to SE; 2) The decrease of maximum depth of intraplate Wadati-Benioff zone earthquakes from NW to SE; 3) The shallowing of the Wadati-Benioff zone dip angle in the same direction; 4) The existence of a sharp contortion in the subducted Cocos plate; 5) The abrupt disappearance of intraplate earthquakes deeper than 50 km in central Costa Rica, east of 83° 55' W; and 6) The termination of the Central America Volcanic Chain in central Costa Rica.

The subduction of the Cocos Ridge under southern Costa Rica has traditionally been used as the mechanism to explain most of the above mentioned features. The Cocos Ridge started subducting only about one million years ago and therefore its subducted portion is no longer than 90 km. Even if the subduction of this ridge had started earlier, the presence of the Panama Fracture Zone limits its NE extension to less than 100 km from the trench, and therefore it can not be responsible for regional changes in the Wadati-Benioff zone several hundred kilometers away.

A new model that considers along-trench variations in age of the subducted Cocos plate may primarily explain the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica, and regional tectonic changes in the overriding Caribbean plate.

x

To Mama, Papa,  
Auxi, Beto, Mauri,  
Aldo, Bosco and Javier.  
I'm so lucky having  
such a great family!!!

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INTRODUCTION

Correlations between the age of the subducting plate and the geometry (angle, length and maximum depth) of Wadati-Benioff Zones have been made, on a large scale (subduction segments larger than 500 km), for subduction zones with very different tectonic settings and evolutions (Deffeyes, 1972; Vlaar and Wortel, 1976; Molnar et al 1979; Uyeda and Kanamori, 1979; Ruff and Kanamori, 1980; Sugi and Uyeda, 1984; Yamaoka et al., 1986; Jarrard, 1986). In general, those works indicate a direct correlation between the age of the plate, or a combination of age and convergence rate, with the Wadati-Benioff zone angle and length, explained by differences in the thickness, density and thermal condition of the oceanic lithosphere that affect the sinking and thermal assimilation of the slab.

Here I attempt to correlate the geometry of the Wadati-Benioff zone along a single subduction segment on a smaller scale (segments as small as 150 km) and with age differences of less than ~10 m.y. Such a detailed study has the potential of revealing clues about the processes and dynamics of subduction zones.

The region studied is the subduction zone along the southern terminus of the Middle America Trench (southern Nicaragua

and Costa Rica) where the Cocos Plate is being subducted under the Caribbean Plate (fig. 1). The existence, in that region, of age changes along the strike of the subduction zone in a relatively young lithosphere (not older than 40 m.y.), and the availability of a unique seismic data set collected by the local seismographic network made correlations on such a small scale possible. That local network is run jointly by the Observatorio Vulcanologico y Sismologico de Costa Rica, Universidad Nacional (OVSICORI-UNA) and the Charles F. Richter Seismological Laboratory, University of California at Santa Cruz (CFRSL-UCSC).

New results included in this work are integrated with previously known tectonic features to construct a model, based on age differences of the subducted plate, that could explain many tectonic features associated with the subduction process in this region. The model proposed herein attempts to be a contribution to the understanding of neotectonic processes in Costa Rica, and by extrapolation, to other subduction zones where young oceanic lithosphere is being subducted.

The new results presented in this work come from three interrelated studies: 1) a high-resolution three-dimensional plot of the top of the Wadati-Benioff zone from northern Nicaragua to southern Costa Rica; (2) a study of the stress distribution within the subducted Cocos plate under Costa Rica; and (3) a recognition, definition and map of the brittle coupling zone (the seismogenic interface of large thrust earthquakes) between the Cocos and Caribbean plates in Costa Rica.

The shape of the Wadati-Benioff zone gives qualitative information about density and temperature conditions as well

as their variations along the strike of the subduction and helps in the interpretation of regional geochemistry variations along the volcanic arc (i.e. Malavassi and Gill, 1990; Malavassi, 1991).

An understanding of the stress distribution within the subducted slab, through study of focal mechanisms of intermediate-depth earthquakes, is of scientific and practical importance. Scientifically, it provides information about the deformation mechanisms within the slab and helps in the interpretation of driving forces of plate tectonics. Practically, changes in the stress regime within the slab, in time and space, are considered to have potential applications for intermediate to short term earthquake prediction (Liu et al, 1990).

Knowing the deepest extension of the brittle coupling zone in a convergent plate boundary and the lateral extent of rupture zones of large thrust earthquakes is of extreme importance for seismic risk assessments and for crustal deformation studies.

The main motivation and purpose of this study is to create a neotectonic framework for understanding rupture processes associated with large underthrust earthquakes in Costa Rica that can be used for seismic risk assessments.

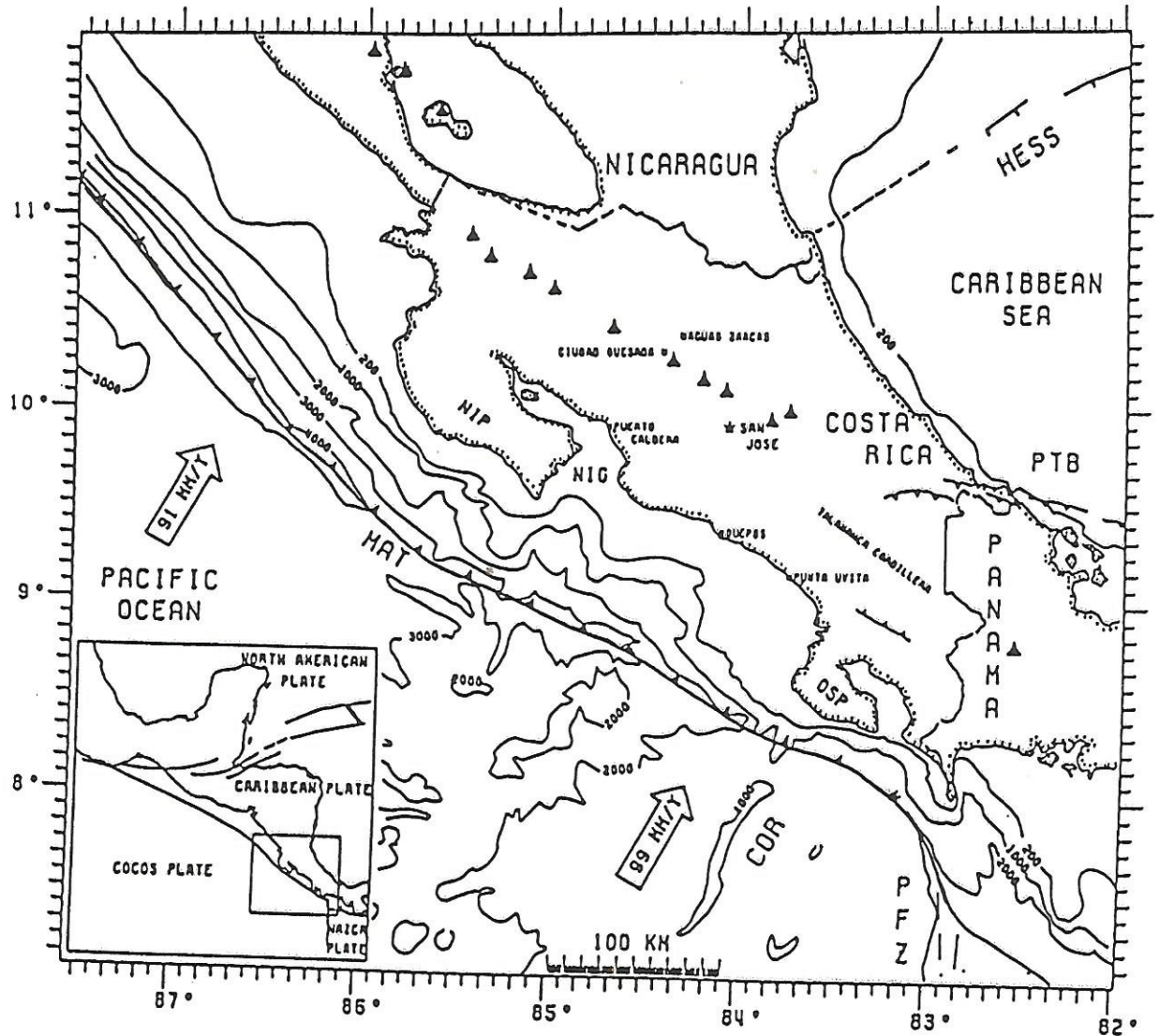


Figure 1. Tectonic setting of southern Central America. Convergence velocity between Cocos and Caribbean plates is after De Mets et al., 1990. Closed triangles are active volcanoes; bathymetry contours are given in meters. COR: Cocos Ridge; HESS: Hess Scarp; MAT: Middle America Trench; NIG: Nicoya Gulf; NIP: Nicoya Peninsula; OSP: Osa Peninsula; PFZ: Panama Fracture Zone; PTB: Panama Thrust Belt. The location of other places mentioned in the text are also given.

## TECTONIC SETTING

Costa Rica, as part of Central America, is located on the western margin of the Caribbean plate (fig. 1). There, the Cocos plate subducts under it along the Middle America Trench. The direction of convergence of these two plates is N 25-30° E and their relative velocity varies from 72±3 mm/year offshore northern Guatemala to 102±5 mm/year offshore southern Costa Rica (DeMets et al., 1990).

South of the border between Costa Rica and Panama is the Panama Fracture Zone. This right lateral transform fault is the plate boundary between the Cocos and Nazca plates. West of the Cocos-Nazca-Caribbean triple junction and SW of the Osa Peninsula, the Cocos Ridge is also being subducted under southern Costa Rica as part of the Cocos plate. The Cocos ridge is a trace of the Galapagos hot spot (Hey, 1977), and has an orientation N 45° E which indicates the direction of movement of the Cocos plate with respect to the underlying mantle.

In Costa Rica, off of the southern tip of the Nicoya Peninsula, the Middle America Trench shows a left bend from NW to SE, and its depth rapidly decreases to the SE from this point. East of Costa Rica is the Panama Block. The northern boundary of the Panama Block with the Caribbean plate is a convergent margin, the Panama thrust belt, that extends from the Caribbean coast of Colombia to south of Limon, inland within Costa Rica (Silver et al., 1990). The western limit of the Panama Block with the Caribbean plate, in Costa Rica, is an unclear and probably transitional boundary, with an unknown velocity vector. Results from

recent global positioning system campaigns in the region will help in deciphering these unknown vectors.

#### PREVIOUS WORK

##### Geometry of the Wadati-Benioff zone

The geometry of the Wadati-Benioff zone in Central America has been deduced from both surface tectonic features (Stoiber and Carr, 1973,) and direct seismic observations (Pennington, 1981; Bevis, 1982; Burbach, 1983; Bevis and Isacks, 1984; Burbach et al., 1984; Burbach and Frohlich, 1986; Guendel and McNally, 1986c; Yamaoka et al., 1986). Guendel and McNally (1986c) mapped the "middle" of the seismic slab for the same region covered in this work. Their data base has been updated in this work with almost three times the number of earthquakes to map the top of the Wadati-Benioff zone. All previous work in the region, except for those by Yamaoka et al (1986) and by Guendel and McNally (1986c), have proposed segmentation of the subducted Cocos plate and the existence of tear faults which break the downgoing slab under the Nicaragua-Costa Rica border, and under the Nicoya Peninsula. The two works mentioned above suggested, in contrast, that smooth contortions of the slab explain the hypocentral distribution of intermediate-depth earthquakes in the region, without requiring tear faults.

## Deformation of the subducted Cocos plate

A relationship between stress distribution and Wadati-Benioff zone geometry was made by Frank (1968). By geometric modeling, he found that the slab dip which minimizes internal stress within the subducted plate is simply twice the radius of curvature of the plate boundary. Laravie (1975) and Yamaoka et al. (1986) successfully tested that hypothesis.

Work on the stress distribution within the subducted Cocos plate under Costa Rica has not been done before, probably because of the lack, before 1984, of well located intermediate-depth events. Guendel and McNally, 1986c, made a comparison, based on relocated WSSN earthquakes from 1964 to 1985, of the energy release within the subducted Cocos plate under Nicaragua with respect to that under Costa Rica. They found reduced seismic energy release under Costa Rica which they interpreted as being related to the subduction of the Cocos Ridge.

## Width of the brittle coupling zone

Mapping of the coupling zone has been done in many areas around the Circumpacific based on the deepest extension of the aftershock zones of large thrust earthquakes (i.e. Kelleher et al., 1974; Ruff and Kanamori, 1980), or on the depth of large ( $M > 6$ ) underthrusting earthquakes that have occurred at the downdip edge of the coupled plate interface (Tichelaar and Ruff, 1991, in press).

Given the lack of locally well recorded aftershock sequences of large thrust earthquakes in Costa Rica, with the

exception of the one in March 1990, [Protti and McNally, 1990], no attempt to do this kind of work in the region has been made.

The physics of the forces acting at the contact between the subducted and overriding plate were studied by Jischke (1975) who concluded that nonhydrostatic pressure force and viscous shear force are sufficient to maintain the contact between the two plates down to the base of the upper plate.

#### DATA ANALYSES

Table 1 gives the seismic data sets most frequently used for studies in Nicaragua and Costa Rica, and the new data sets used in this work.

##### Geometry of the Wadati-Benioff zone

For study of the geometry of the Wadati-Benioff zone, data sets DS04 to DS09 were used, for a total of 9930 events. This analysis does not include DS01 to DS03, used by Guendel and McNally 1986c, because it is deemed desirable to maintain consistency by using only earthquakes located by local networks. For Costa Rica only earthquake locations with horizontal and vertical errors smaller than 4 and 5 km respectively, were used. For Nicaragua no values of ERH or ERZ exist in the data base.

TABLE 1. Seismic data sets for Nicaragua and Costa Rica mentioned in the text.

| NAME<br>(1) | FROM<br>DD-MM-YY | TO<br>DD-MM-YY | MAG. |     | DEPTH |     | # OF<br>EVENTS | REGION<br>(2) | REMARK |
|-------------|------------------|----------------|------|-----|-------|-----|----------------|---------------|--------|
|             |                  |                | MIN  | MAX | MIN   | MAX |                |               |        |
| DS01        | 05-10-50         | 11-11-50       | 6.0  | 7.7 | 31    | 46  | 7              | NCR           | (a)    |
| DS02        | 06-05-51         | 23-12-72       | 5.0  | 7.3 | 1     | 180 | 73             | N             | (b)    |
| DS03        | 16-10-65         | 25-09-85       | 5.0  | 6.3 | 4     | 194 | 75             | CR            | (c)    |
| DS04        | 01-01-78         | 31-12-78       | 0.6  | 3.3 | 0     | 216 | 568            | N/NCR         | (d)    |
| DS05        | 01-05-78         | 15-10-78       | 1.7  | 7.0 | 0     | 221 | 421            | NCR           | (e)    |
| DS06        | 01-04-84         | 22-10-86       | 1.0  | 5.2 | 0     | 178 | 2601           | SN/CR         | (f)    |
| DS07        | 23-10-86         | 01-04-90       | 1.7  | 6.8 | 0     | 194 | 5748           | SN/CR         | (f)    |
| DS08        | 02-04-84         | 30-12-87       | 2.2  | 4.9 | 50    | 197 | 416            | SN/CR         | (g)    |
| DS09        | 15-10-87         | 05-07-88       | 1.6  | 4.7 | 0     | 184 | 176            | SN/NCR        | (h)    |

- (1) Names used in this work for simplicity.  
(2) N:Nicaragua; CR:Costa Rica; SN:southern Nicaragua; NCR:northern Costa Rica.  
(a) Relocations of the Nicoya 1950 sequence by Guendel and McNally, 1990.  
(b) Relocation of WWSSN data by Dewey and Algermissen, 1974.  
(c) Relocation of WWSSN data by Guendel and McNally, 1986a.  
(d) Events located in 1978 by the Nicaraguan network (Guendel and McNally, 1986c).  
(e) Relocations by Guendel and McNally (1986b), of events recorded by the Arenal network.  
(f) Events reported by OVSICORI-UNA (1984-1990).  
(g) Events from DS06 and DS07 relocated by M. Protti (this work) (Appendix A).  
(h) Events recorded in a joint project by OVSICORI-UNA and CRSL-UCSC with financial support of NSF (Appendix B).

Local networks are capable of locating earthquakes of smaller magnitude that are not even recorded by global networks. Several works have noted a tendency for local networks to yield a steeper dip of the Wadati-Benioff zone (e.g. Adams and Ware 1977; Hauksson, 1985; Jarrard 1986; Engdahl and Gubbins, 1987), but this is not significant for

this region. For example the Wadati-Benioff zone under Nicaragua (where the coverage of the network is not as good as in Costa Rica), from 0 to 100 km in depth there is no difference between the local results and the angle of subduction obtained with the relocations (Dewey and Algermissen, 1974) of globally recorded earthquakes. Deeper than 100 km the difference is only  $11^{\circ}$  (steeper for the local network). This results in less than 30 km of horizontal discrepancy at the maximum depth of 210 km. A qualitative description of this difference for Nicaragua, using the same data sets, was made by Burbach et al., (1984). For Costa Rica, where the local network is more dense and covers the entire slab, and where the Wadati-Benioff zone is not as deep as in Nicaragua, that difference becomes even more insignificant. The relative lack of moderate to large magnitude earthquakes within the slab under Costa Rica (Guendel and McNally, 1986c), makes both quantitative and qualitative comparisons difficult.

The location of seismographic stations and coverage of local networks is shown in fig. 2. Fig. 3, shows the epicentral distribution of all earthquakes included in this study.

To obtain a 3-D view of the top of the W-B zone two procedures were used. First, maps of seismicity with depth intervals of 20 km were plotted to obtain the general trend of the seismicity with depth (fig. 4). Second, cross-sections of seismicity were constructed, perpendicular to the general trend obtained by the first step; these produce sections almost perpendicular to the Middle America Trench (fig. 5). Fig. 6 shows cross sections of seismicity parallel to the Middle America Trench. Locations of all cross sections are shown in fig. 3. For Nicaragua, earthquakes within 37.5 km on each side of the profile line were plotted

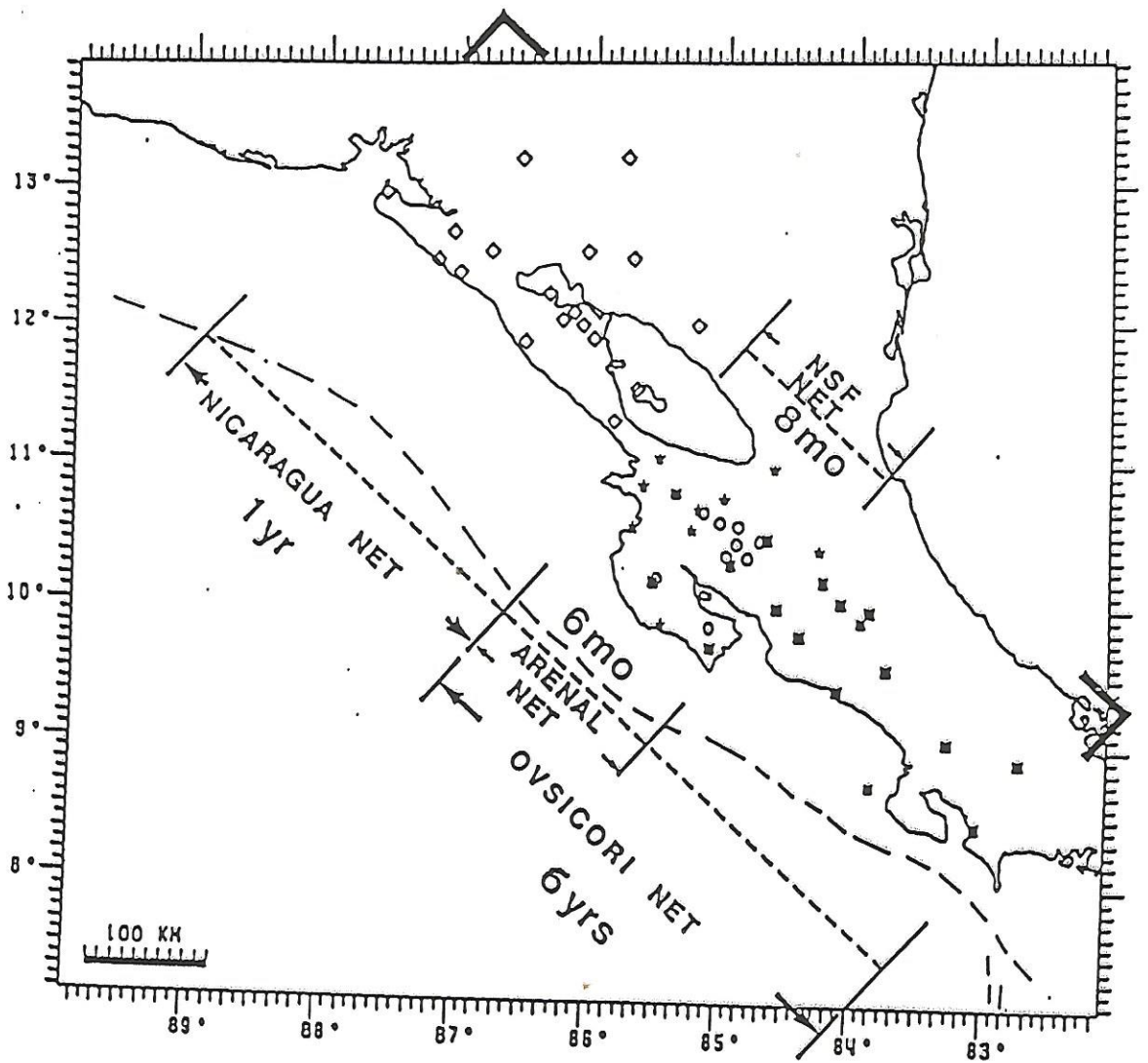


Figure 2. Map showing the location of seismographic stations and coverage of local networks from which data were used. Open diamonds: Nicaragua Network (Jan-Dec. 1978); open circles: Arenal Network (May-Oct. 1978); stars: Northern Costa Rica Network (Oct. 1987-May 1988); closed squares: Costa Rica Network (Apr. 1984-Mar. 1990).

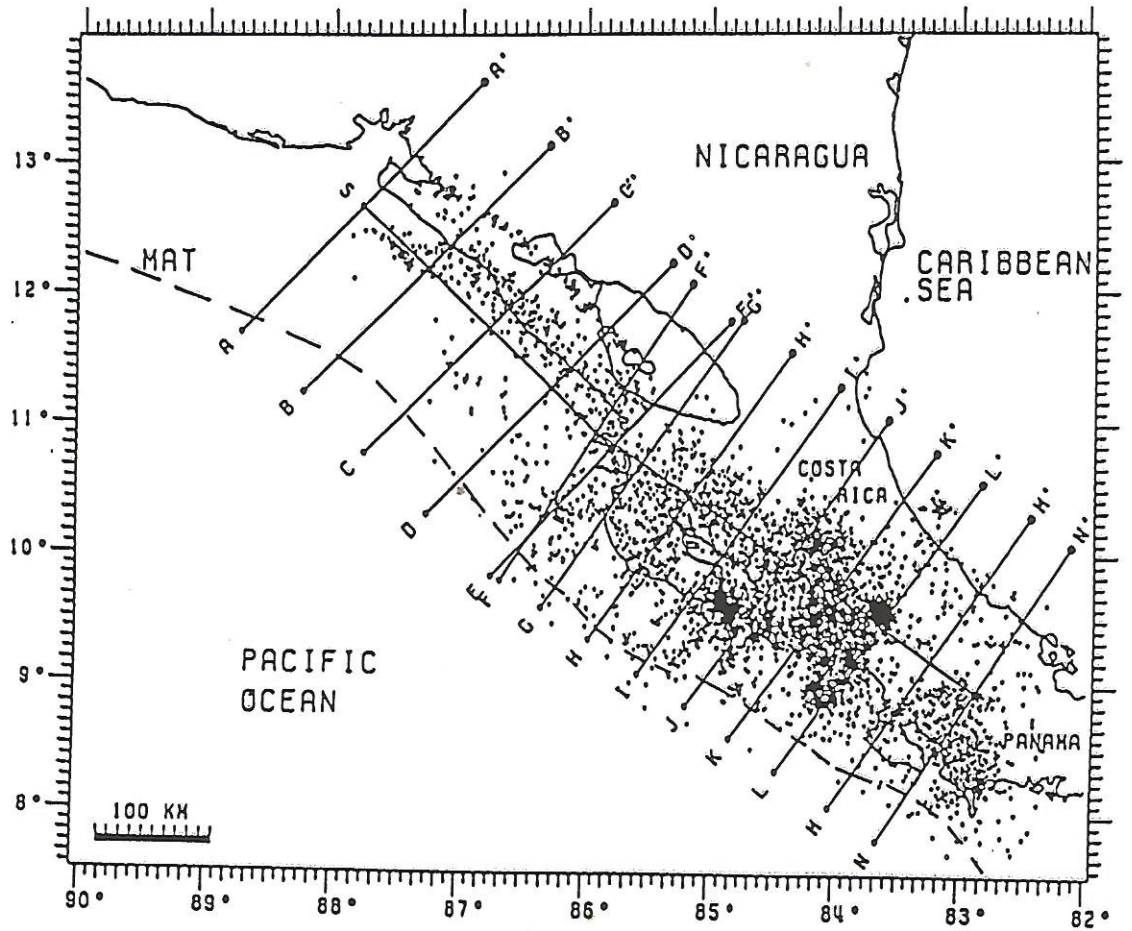


Figure 3. Map showing the epicentral distribution of all events used and the location of cross sections perpendicular (A-N) and parallel (S-T) to the Middle America Trench (MAT). The cross sections are shown in figure 5.

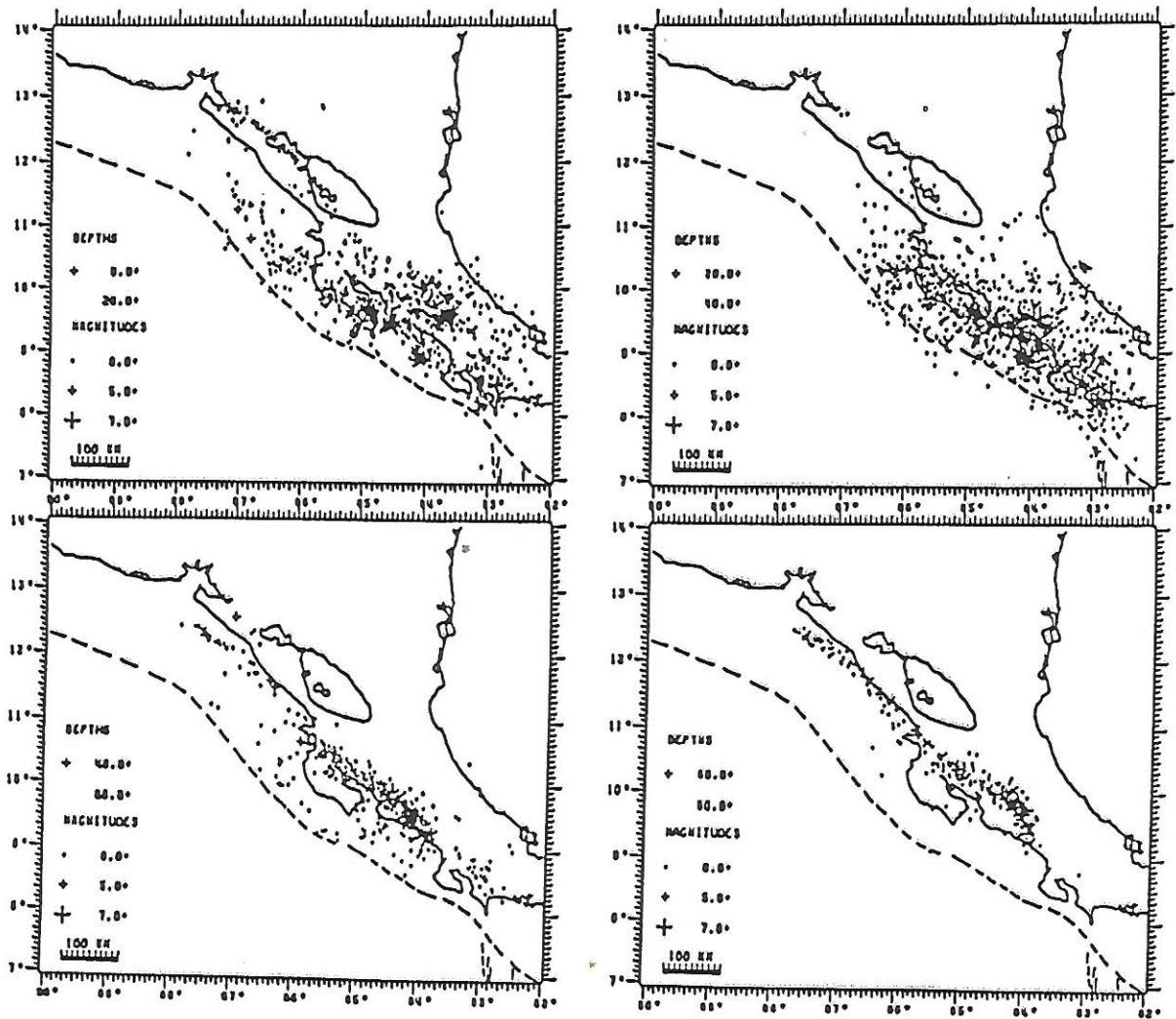


Figure 4. Maps showing the epicentral distribution of earthquakes at depth intervals of 20 km.

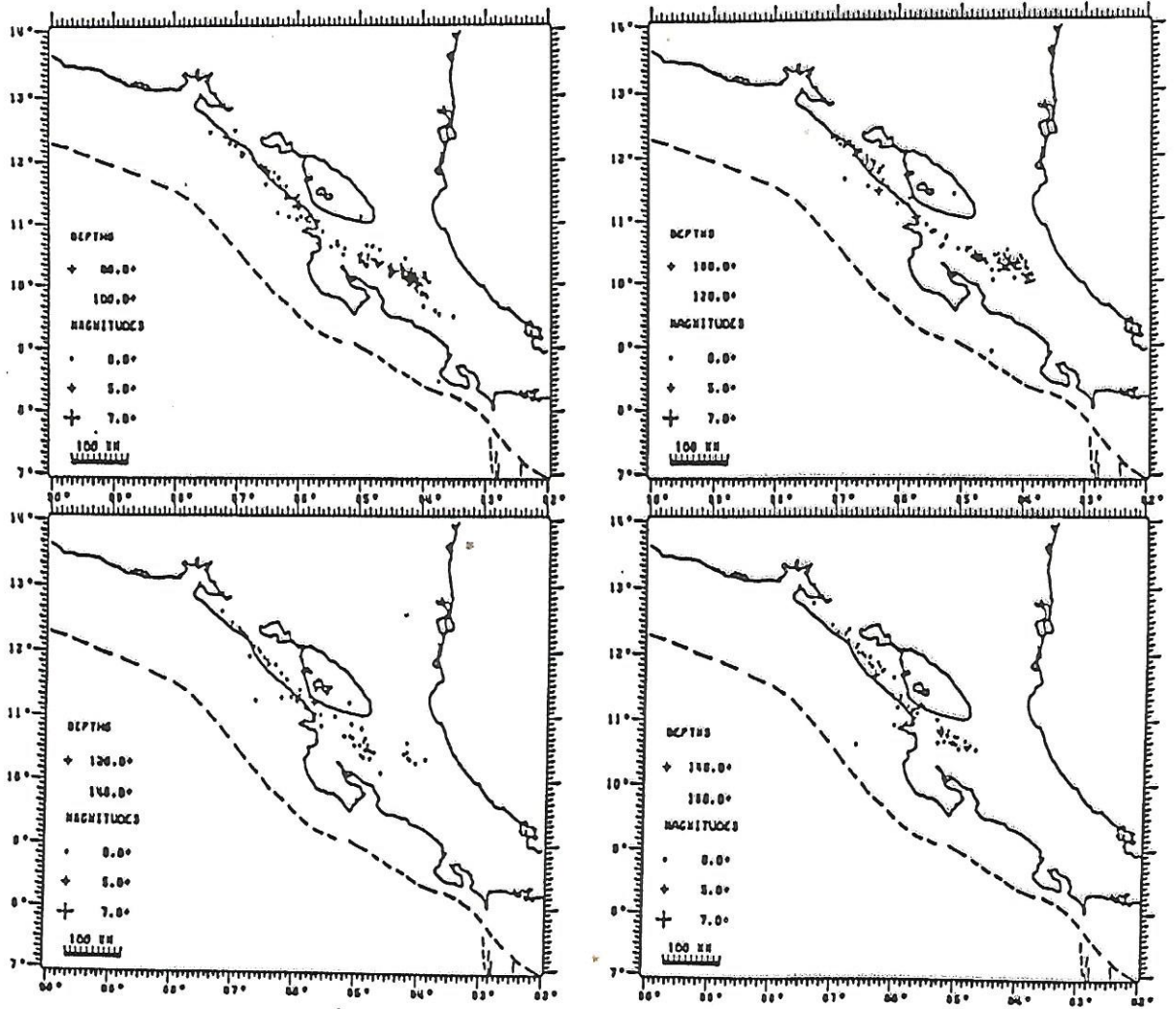


Figure 4. (cont.)

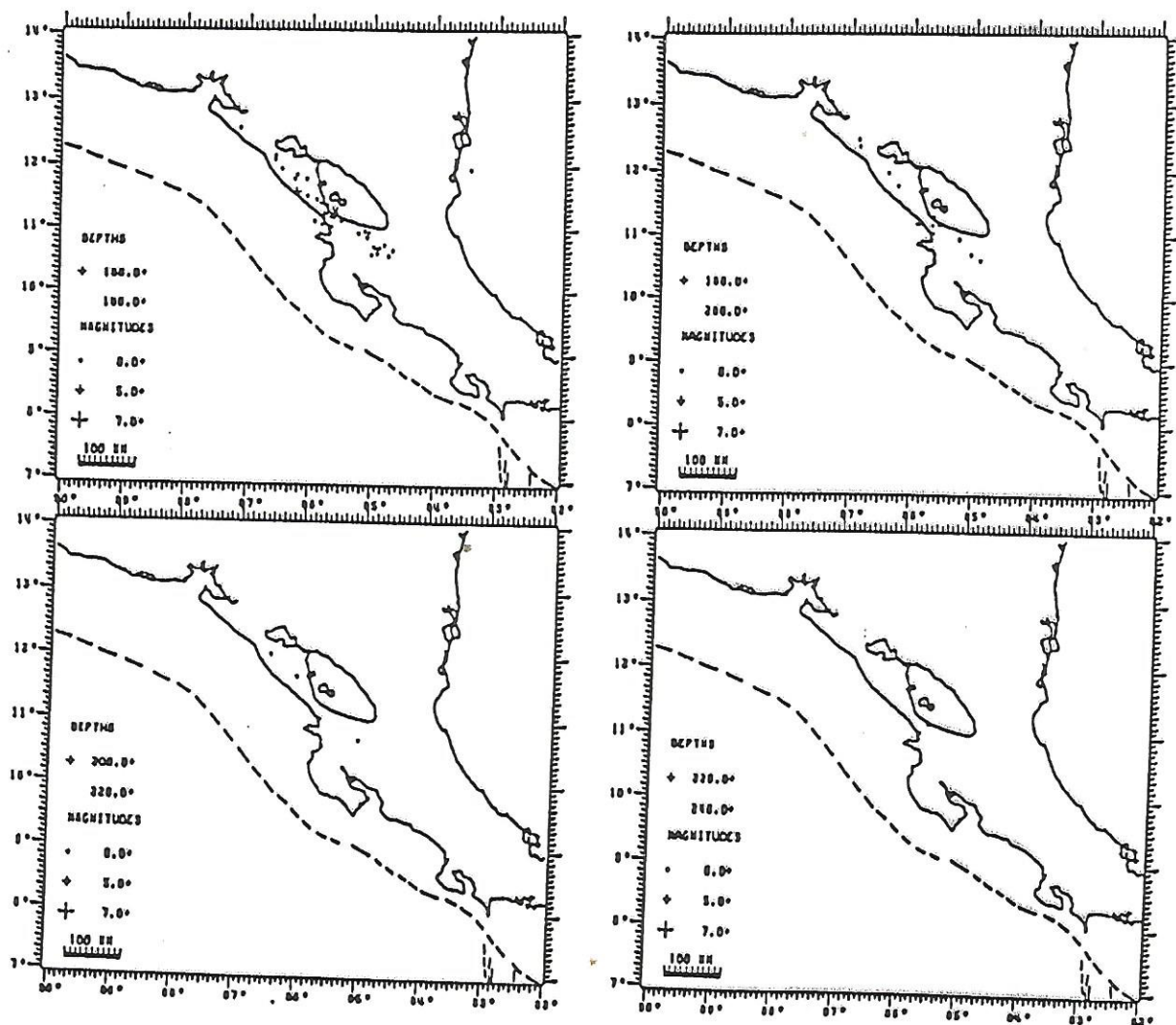


Figure 4. (cont.)

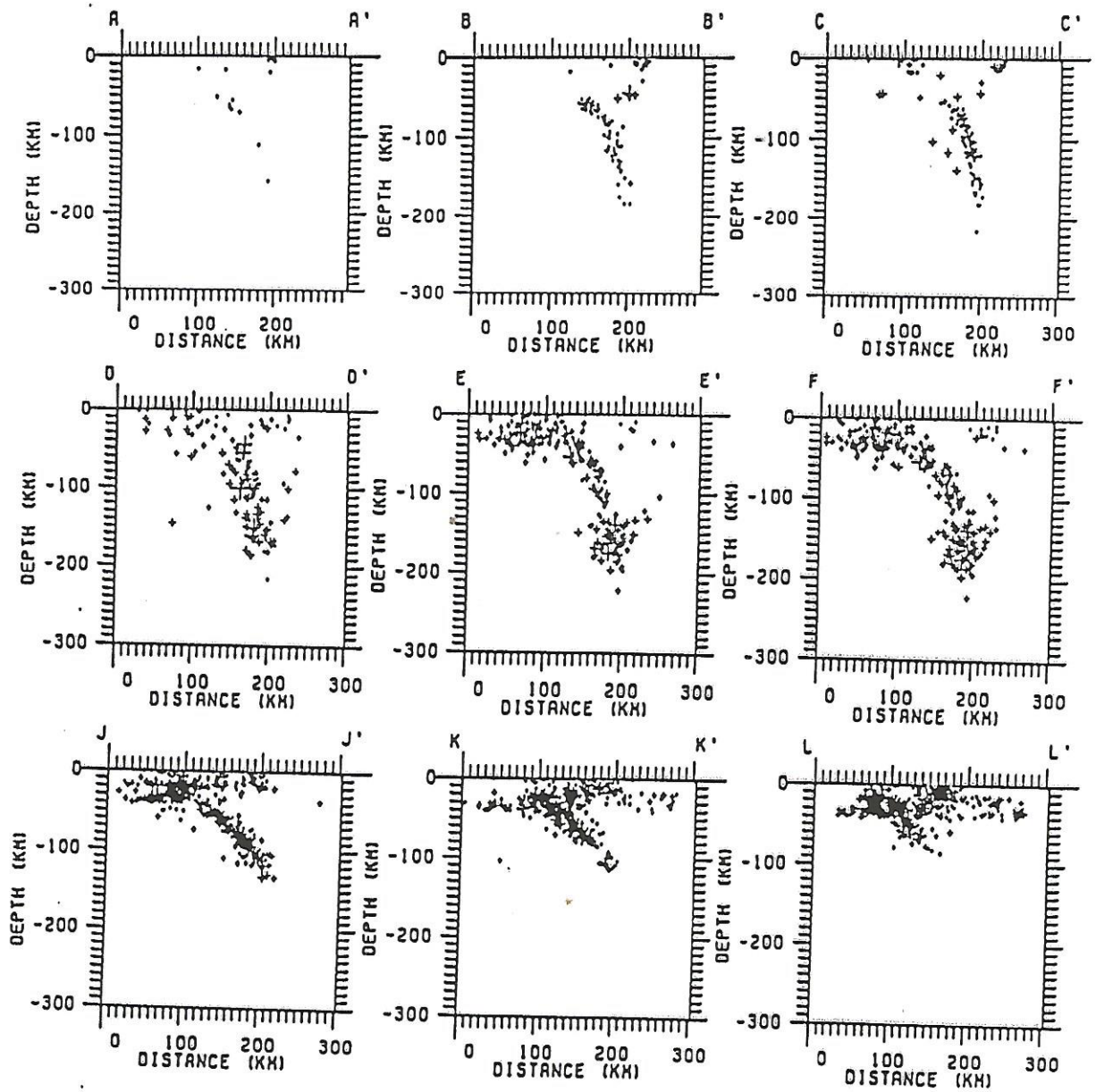


Figure 5. Depth distribution of earthquakes on cross sections perpendicular to the Middle America Trench. See figure 3 for location of the cross sections.

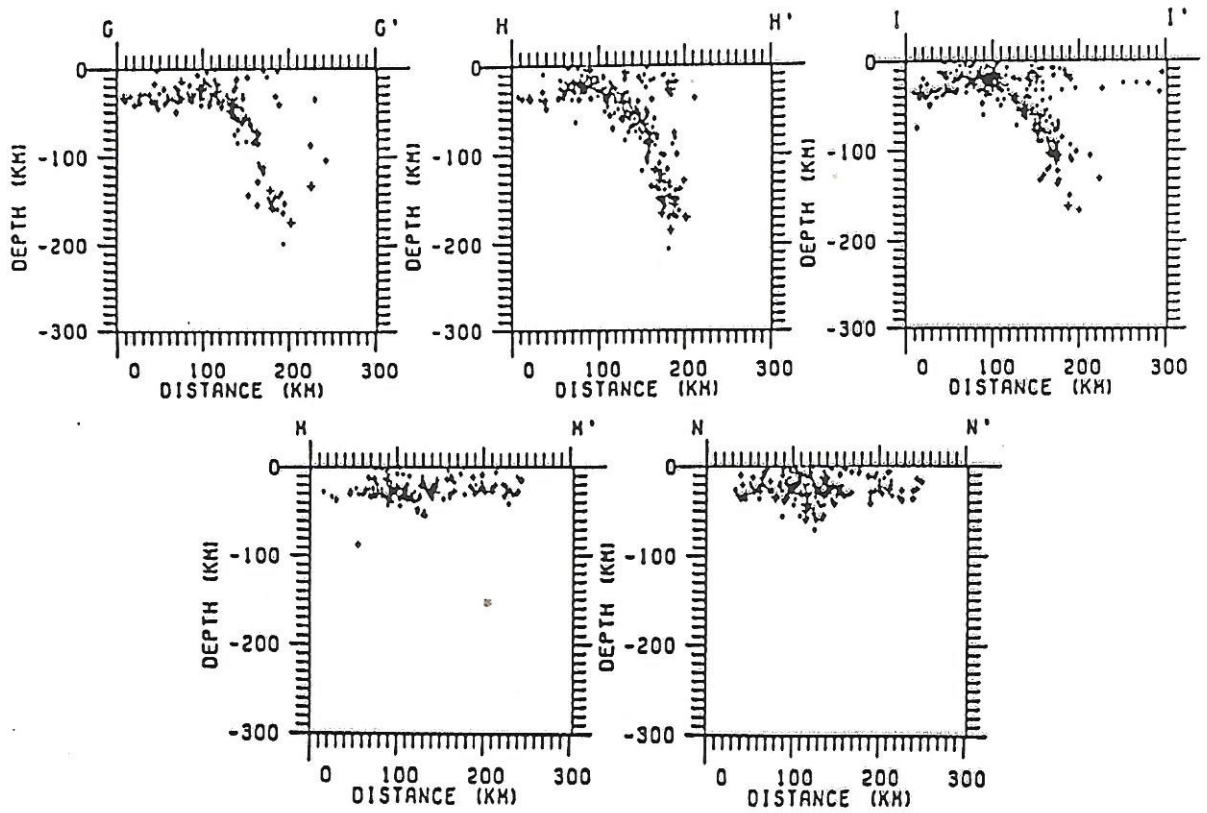


Figure 5. (cont.)

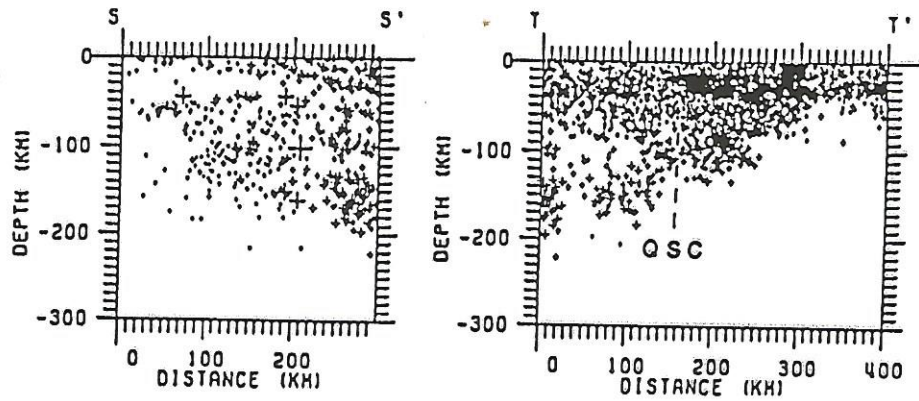


Figure 6. Depth distribution of earthquakes on cross sections parallel to the Middle American Trench. Also shown is the depth projection of the Quesada Sharp Contortion (QSC) discussed later in the text. See figure 3 for location of the cross sections.

in the cross sections, while for Costa Rica, that distance was only 25 km on each side. Given the amount of data used, no overlap of the cross-sections was needed. Cross sections for Nicaragua are wider since the Nicaragua database is not as large and complete as the Costa Rica database, and therefore the resolution in the geometry obtained for the slab under Nicaragua is not as good as it is for Costa Rica. Another advantage of the Costa Rica data set is that it has been collected by networks which extend closer to the trench, overlying most of the seismic slab. In Nicaragua most of the seismic slab lies under offshore areas, reducing the possibility of better resolution.

The top of the Wadati-Benioff zone was drawn on each cross section and projected to the surface in intervals of 20 km starting at 40 km depth. The slices of seismicity (fig. 4) were also used for the interpolation of the projected depths and construction of the isodepth contours. This helps reduce the effect of apparent location produced by the perpendicular projection of earthquakes in cross-sections.

#### Tension and compression axes within the subducted Cocos plate

Intraplate Cocos, tension and compression axes have been mapped along Costa Rica from mechanisms of earthquakes at depths between 50 and 200 km (there is no seismic activity deeper than 200 km beneath Costa Rica).

Data set DS08 (fig. 7) (Appendix A) was used for this particular study. Focal mechanisms for each earthquake were constructed by plotting polarities of p-waves in lower hemisphere equal-area stereographic nets. Those events that

occurred in spatial and temporal clusters were combined in composite focal mechanisms. The events were then grouped and mapped in two different sets: (1) vertical to subvertical compression axes; and (2) vertical to subvertical tension axes.

#### Width of the brittle coupling zone

Data sets DS05 to DS09 and profiles (G-N), shown in fig. 3, were used for the study of the width of the BCZ in Costa Rica. The contact between the deepest seismicity on the upper plate and the top of the intraplate seismicity within the Cocos plate was projected to the surface.

This method presents an inconvenience in that the level of intraplate seismicity within the Caribbean plate in Costa Rica varies considerably from NW to SE (Guendel et al 1989), making difficult, in some cases, delineation of the bottom of the brittle upper lithosphere. In northern Costa Rica the Caribbean intraplate seismicity is much lower than in the central part. In the southern part that seismicity is difficult to interpret due to the absence of a well defined Wadati-Benioff zone.

The threshold detection of the permanent seismographic network (OVSI-CORI-UNA) is not the same for the entire country. The low intraplate seismicity in northern Costa Rica is not an artifact of the magnitude threshold as it was also found with the data collected with a portable network (11 stations) (fig. 2) installed for 9 months (Oct. 1987 to Jul, 1988) through that region (data set DS09, Appendix B).

## INTERMEDIATE DEPTH SEISMICITY (APR. 84-JUL. 89)

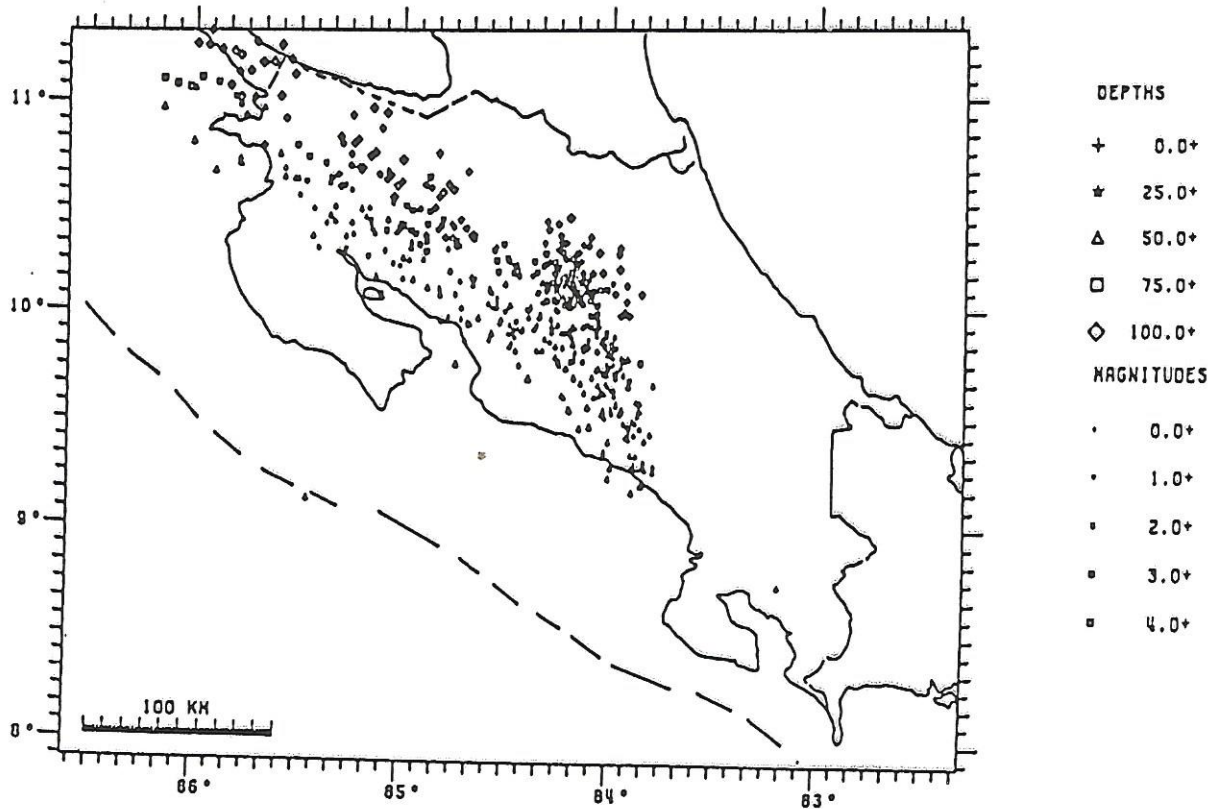


Figure 7. Epicentral distribution of earthquakes, with focal depth greater than 50 km, used for the study of compressional and tensional axes within the subducted Cocos plate (data base DS08 in table 1). Note the sudden termination of the seismicity within the slab east of the 84° meridian.

## RESULTS AND DISCUSSION

## Geometry of the Wadati-Benioff zone

Even though Guendel and McNally, (1986c), studied the geometry of the subducted slab for the same region included in this work (Nicaragua to Costa Rica), the two studies differ in that for the first work, the "middle" part of the seismic slab (looking in cross section) was mapped, while in the present work, the top of the Wadati-Benioff zone zone has been used to define the geometry. Also, for this work almost 3 times the number of earthquakes, not available for the first study, have been included in the data base, mostly from southern Nicaragua and all of Costa Rica.

The geometry of the Wadati-Benioff zone obtained by Guendel and McNally, 1986c, is shown in fig. 8, and the new geometry is shown in fig. 9. Also shown, for reference, are the volcanic chain, the Middle America Trench and the Cocos Ridge.

For Nicaragua and northern Costa Rica the general shape of the seismic slab obtained in this work does not differ substantially from that obtained by Guendel and McNally, 1986c. This is because almost the same data base was used in both works for Nicaragua. Since, in this work, what was mapped was the top of the Wadati-Benioff zone, the major difference in the results of the two studies is the relative location of the isodepths and the maximum depth of the seismic slab. The general shape of the smooth contortion in the Nicaragua-Costa Rica border remains almost the same. By using the data base DS09 in this work, a more detailed sampling of the Wadati-Benioff zone under the border was

obtained. This data was collected specifically for that purpose, under a collaborative research between OVSICORI-UNA and CFRL-UCSC, with the financial support of NSF.

Given the extra amount of data used, I was able to identify a sharp contortion (segmentation) in the slab under central Costa Rica (fig.9), hereby called the Quesada Sharp Contortion (QSC) since it lies under Ciudad Quesada (fig. 1). For the final analyses I adjusted the zones covered by profiles 'I' and 'J' (fig. 3) in such a way that the boundary between the zones was coincident with the location obtained for the Quesada Sharp Contortion, avoiding in this way the overlapping of the two Wadati-Benioff zone segments and therefore obtaining a more realistic picture in cross section. The Quesada Sharp Contortion is recognizable, by means of seismicity, only below depths of 70 km. It extends N 34° E from NE of Puerto Caldera to Aguas Zarcas de San Carlos (fig. 1). The horizontal displacement of the isodepths along this feature is on the order of 15 km, higher than the statistical errors inherent in the earthquake locations selected for this work ( $ERH \leq 4$  km,  $ERZ \leq 5$  km). NW of this contortion the deeper portion of the seismic slab dips about 80° and reaches maximum depths ranging from 200 km near the border between Nicaragua and Costa Rica, to 135 km under Ciudad Quesada. To the SE that portion of the Wadati-Benioff zone dips about 60° and the seismicity does not extend below depths ranging from 125 km, behind the volcanic chain, to 50 km, east of Quepos. The location of the sharp contortion on a cross section parallel to the Middle America Trench is shown in fig 6. On both sides of the Quesada Sharp Contortion the maximum depth of earthquakes on the Wadati-Benioff zone shallows up from NW to SE at a similar rate of 7 km per each 10 km of horizontal distance parallel to the trench axis.

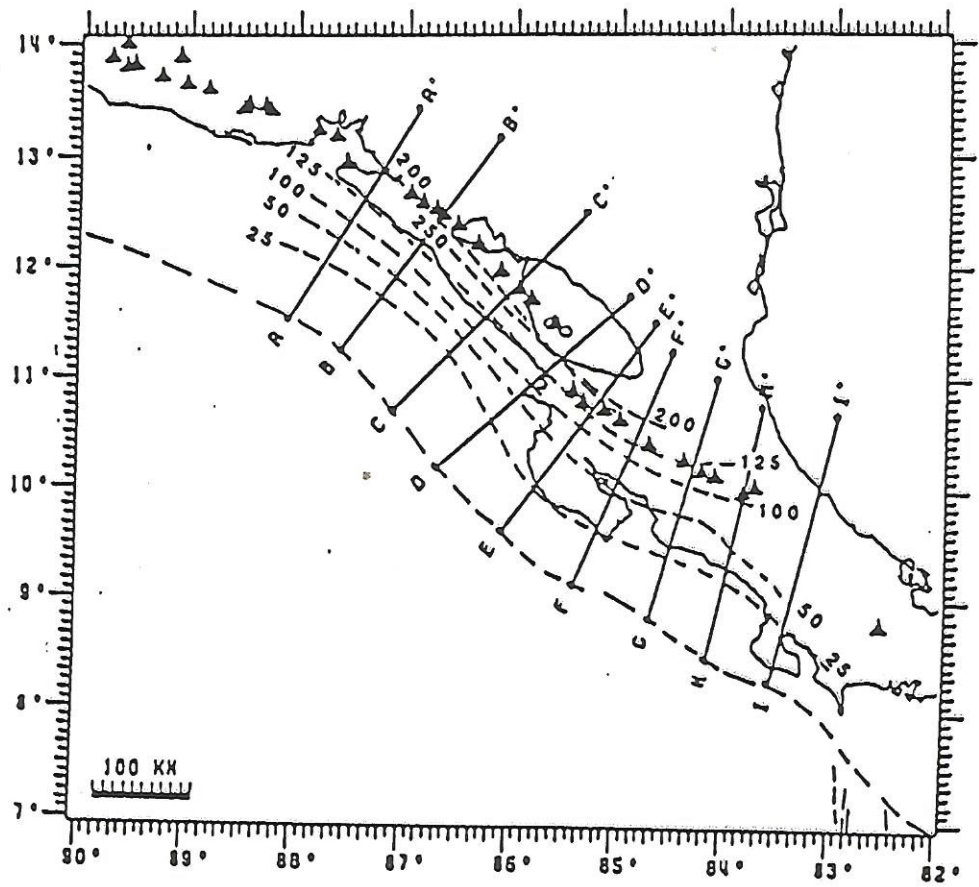


Figure 8. Geometry of the Wadati-Benioff zone obtained by Guendel and McNally, 1986c, and location of the cross sections used in their study.

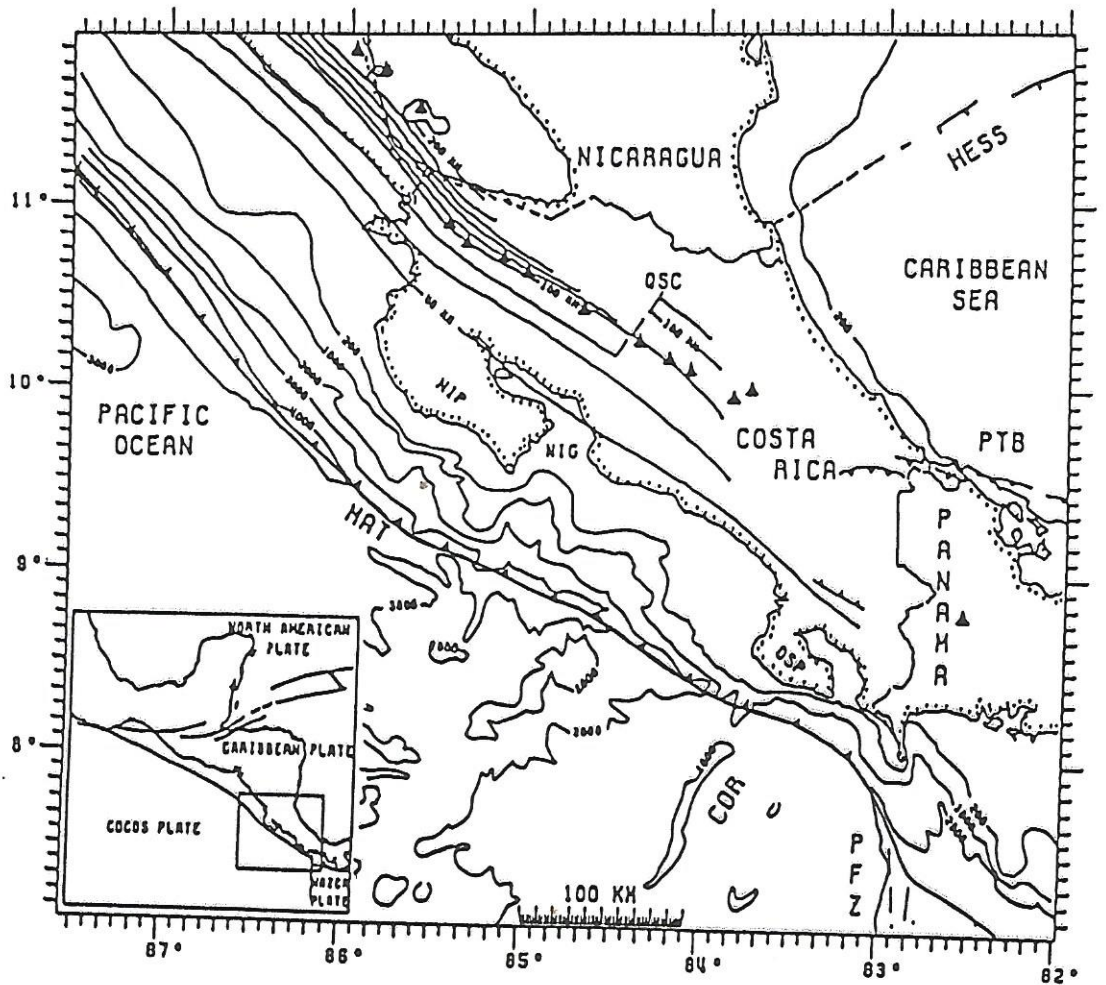


Figure 9. Geometry of the top of the Wadati-Benioff zone obtained in this work. The Quesada Sharp Contortion (QSC) represents the boundary between two segments of the subducted Cocos plate with very different geometry. Note the shallowing of the deepest part of the seismic slab from Nicaragua to the QSC, and the sudden end of the seismic slab east of the 84° meridian.

The subduction zone from Nicaragua to Costa Rica has been divided into four segments: Nicaragua, Northern, Central and Southern Costa Rica (fig. 10). This subdivision is based on the geometry of the Wadati-Benioff zone and on other tectonic features different for each segment. Table 2 lists these parameters for each subduction segment.

Another remarkable feature of the Wadati-Benioff zone under Costa Rica is its abrupt termination at  $83^{\circ}55'$  W, coincident with the SE end of the Central America active volcanic chain. No evidence of Wadati-Benioff zone seismicity deeper than 50 km was found SE of Punta Uvita.

It is noteworthy that even though there is an abrupt displacement of the volcanic chain from Nicaragua to Costa Rica (fig. 9), no major change in the geometry of the seismic slab was found, moreover, no appreciable changes in the orientation of the volcanic chain occurs where the Quesada Sharp Contortion is located. However, even though there is no change in the orientation of the volcanic chain across the Quesada Sharp Contortion, Malavassi and Gill (1990) and Malavassi (1991) have found important changes in the geochemical composition of Tertiary and Quaternary lavas across the contortion. In addition, there are important geochemical signatures of the Aguas Zarcas cones (near Aguas Zarcas, fig. 1) under which the Quesada Sharp Contortion has its maximum expression.

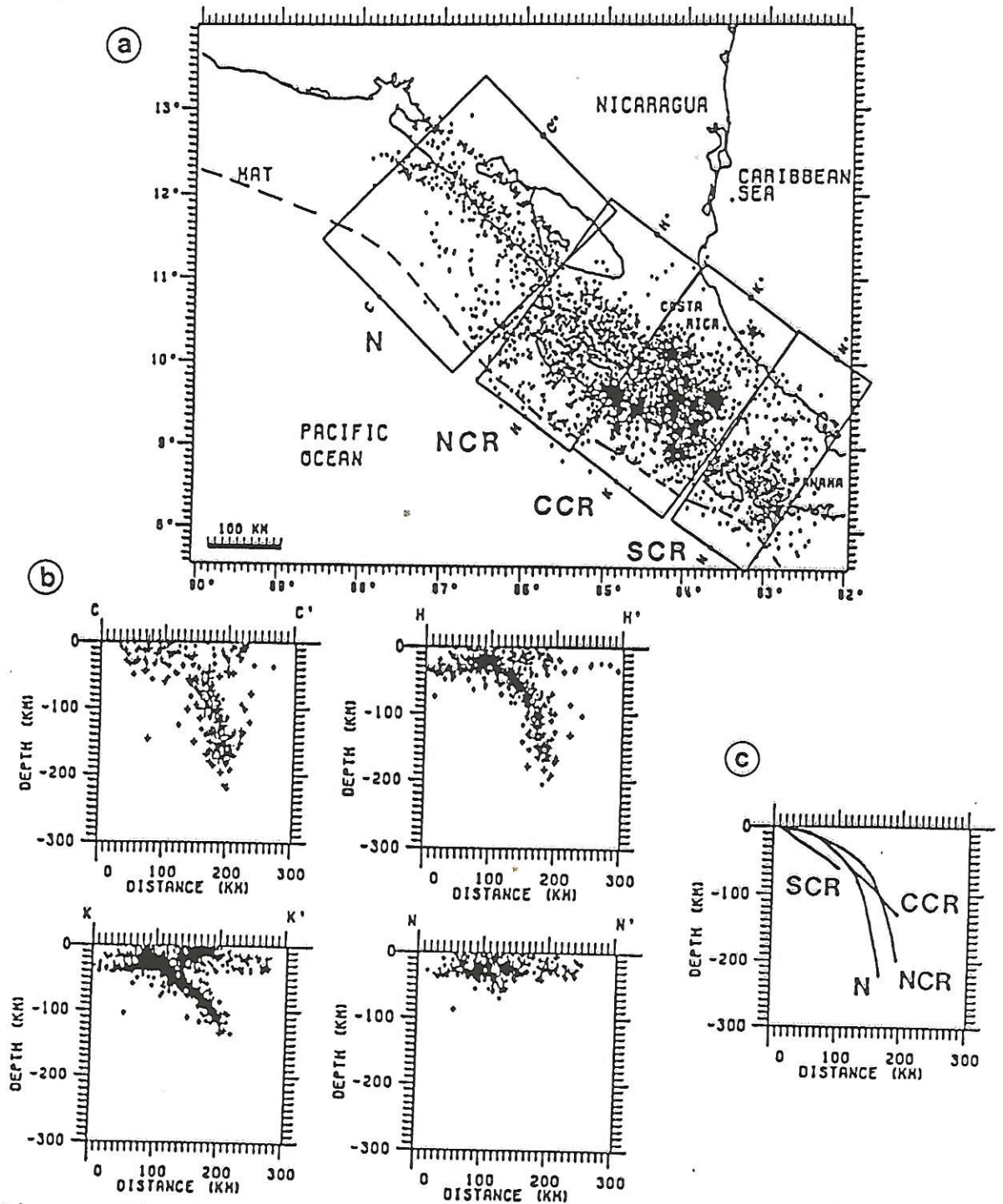


Figure 10. Subduction segments described in the text: N: Nicaragua; NCR: Northern Costa Rica; CCR: Central Costa Rica; SCR: Southern Costa Rica. a) Map showing the area and seismicity covered by each segment; b) Depth distribution of seismicity for each segment; c) Overlapping of all segments with the trench axis as common point.

Table 2. Parameters for each subduction segment described in the text (shown on map view and on cross section in fig. 10). The NW boundary of the Nicaragua segment was arbitrarily set at the border between Nicaragua and Honduras. Ages of the Cocos plate are projections of spreading rates obtained from the Plate-Tectonic Map of the Circum-Pacific Region. Convergence rates are after DeMets et al., 1990; the dip ranges for the Wadati-Benioff zone (WBZ) are the same used by Jarrard (1986); and the strain classification is also that suggested by Jarrard (1986). The numbers assigned in this work for strain class are based on the stress analysis made by Malavassi (1991).

| SUBDUCTION PARAMETERS                   | NICARAGUA         |      | NORTHERN COSTA RICA |      | CENTRAL COSTA RICA |      | SOUTHERN COSTA RICA |      |
|---|-------------------|------|---------------------|------|--------------------|------|---------------------|------|
|   | NW                | SE   | NW                  | SE   | NW                 | SE   | NW                  | SE   |
| LENGTH ALONG THE TRENCH (km)            | ~250              |      | ~150                |      | ~160               |      | ~120                |      |
| TRENCH DEPTH(m)                         | 5000              | 4500 | 4500                | 3400 | 3400               | 2000 | 2000                | 2000 |
| TRENCH AZIMUTH                          | N 40° W<br>(320°) |      | N 50° W<br>(310°)   |      | N 65° W<br>(295°)  |      | N 65° W<br>(296°)   |      |
| ARC-TRENCH GAP (km)                     | 185               |      | 160                 |      | 160                |      | 125                 |      |
| HIGHEST PEAK ON INNER ARC (m)           | 1745              |      | 2028                |      | 2919               |      | 3819                |      |
| AGE AT THE TRENCH (m.y.)                | 25-30             |      | 25-30               |      | 20-22              |      | 13-17               |      |
| AGE AT THE TIP (m.y.)                   | 30-35             |      | 30-35               |      | 20-22              |      | 17-19               |      |
| CONVERGENCE RATE (mm/y) (+4)            | 85                | 91   | 91                  | 95   | 95                 | 99   | 99                  | 102  |
| WBZ LENGTH (km)                         | 260               | 310  | 310                 | 260  | 240                | 170  | 100                 |      |
| WBZ HORIZONTAL EXTENT (km)              | 180               | 180  | 180                 | 170  | 210                | 110  | 110                 |      |
| DIP (0-60 km)                           | 25°               |      | 23°                 |      | 24°                |      | 30°(?)              |      |
| DIP (0-100 km)                          | 34°               |      | 32°                 |      | 30°                |      |                     |      |
| DIP (>100 km)                           | 84°               |      | 80°                 |      | 60°                |      |                     |      |
| MAX. DEPTH (km)                         | 160               | 220  | 200                 | 135  | 125                | 50   | 45                  |      |
| STRAIN CLASS                            | 3                 |      | 4                   |      | 5                  |      | 6-7                 |      |
| SLAB PULL FORCE (*10 <sup>12</sup> N/m) | 11.0              |      | 11.0                |      | 8.1                |      | 3.7                 |      |
| LARGEST EARTHQUAKE (Ms)                 | 7.0               |      | 7.7                 |      | 7.0                |      | 7.6                 |      |

Since we are using flat layers in the crustal velocity structure, without lateral variations (Matumoto et al, 1977), the depth resolution for earthquakes offshore is not as good as it is for events within the network. Therefore, the dip of the shallow part of the Wadati-Benioff zone was assumed constant from the trench axis to the shallower part of the resolved seismic slab (35-40 km) (i.e. the deepest extension of the brittle coupling zone as will be defined later). Given the bend of the trench axis, the subduction angle seems to change from  $23^{\circ}$  in northern Costa Rica, to  $30^{\circ}$  in southern Costa Rica. Whether or not this feature is real cannot be ascertained until better depth resolution is obtained for events offshore.

#### Tension and compression axes within the subducted Cocos plate

The general findings concerning the stress regime within the subducted Cocos plate indicate that downdip extension is predominant below depths of around 75 km. Above these depths, however, a change from vertical and subvertical extension to vertical and subvertical compression was found NW and SE of about  $9^{\circ} 45'N$ ;  $84^{\circ} 15'W$ , respectively, between depths of 50 and 75 km.

Fig. 11, shows the geographic distribution of vertical to subvertical extension and compression axes; the contour depths of the top of the Wadati-Benioff zone are also plotted for reference. Fig. 12 shows the projection of these results in cross-sections perpendicular (profiles A to D on fig. 11) and parallel (profile L on fig. 11) to the trench.

## COMPOSITE T AND P AXES SOLUTIONS

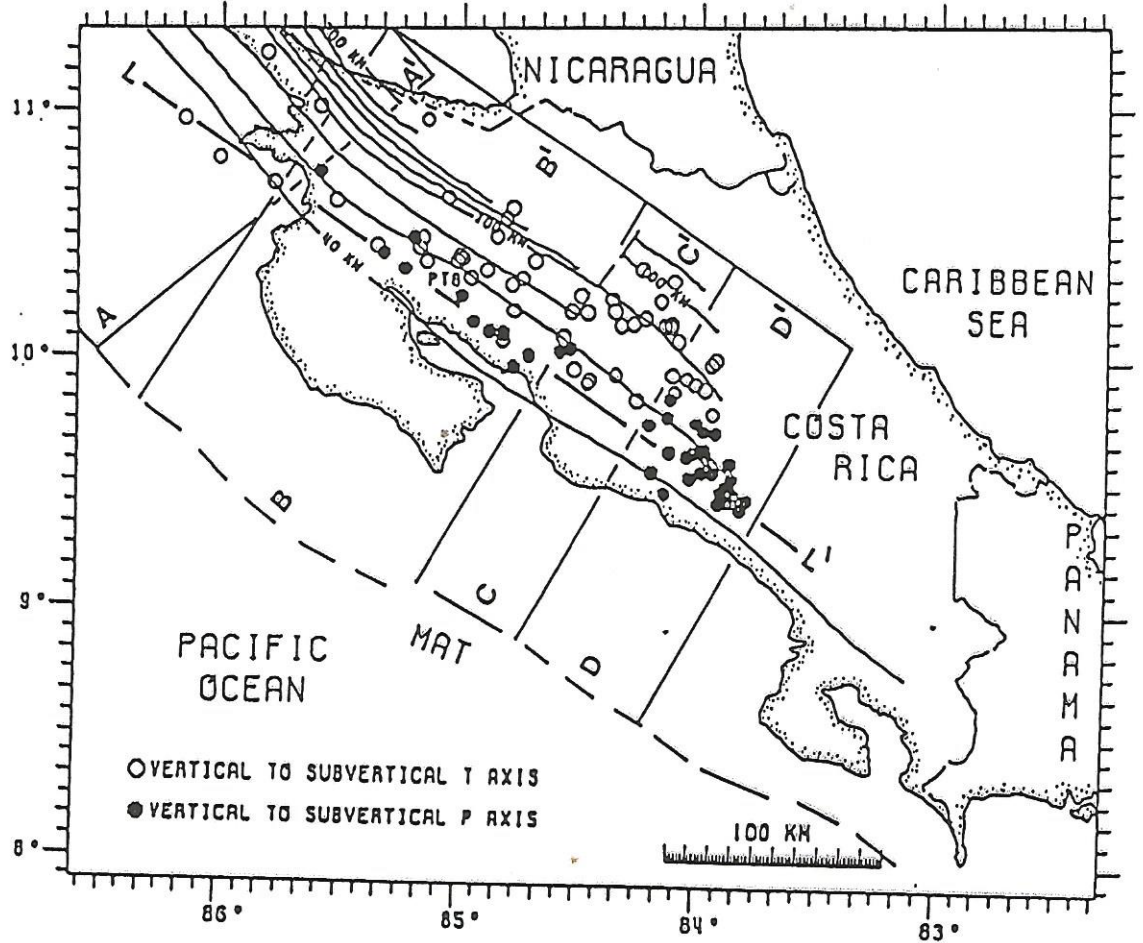


Figure 11. Map showing the distribution of events within the Cocos plate with vertical to subvertical tension (T) and compression (P) axes. The isodepth contours of the top of the Wadati-Benioff zone are shown for reference. Boxes A-D enclose events shown in cross sections in figure 12. Cross section L-L' is also shown in figure 12.

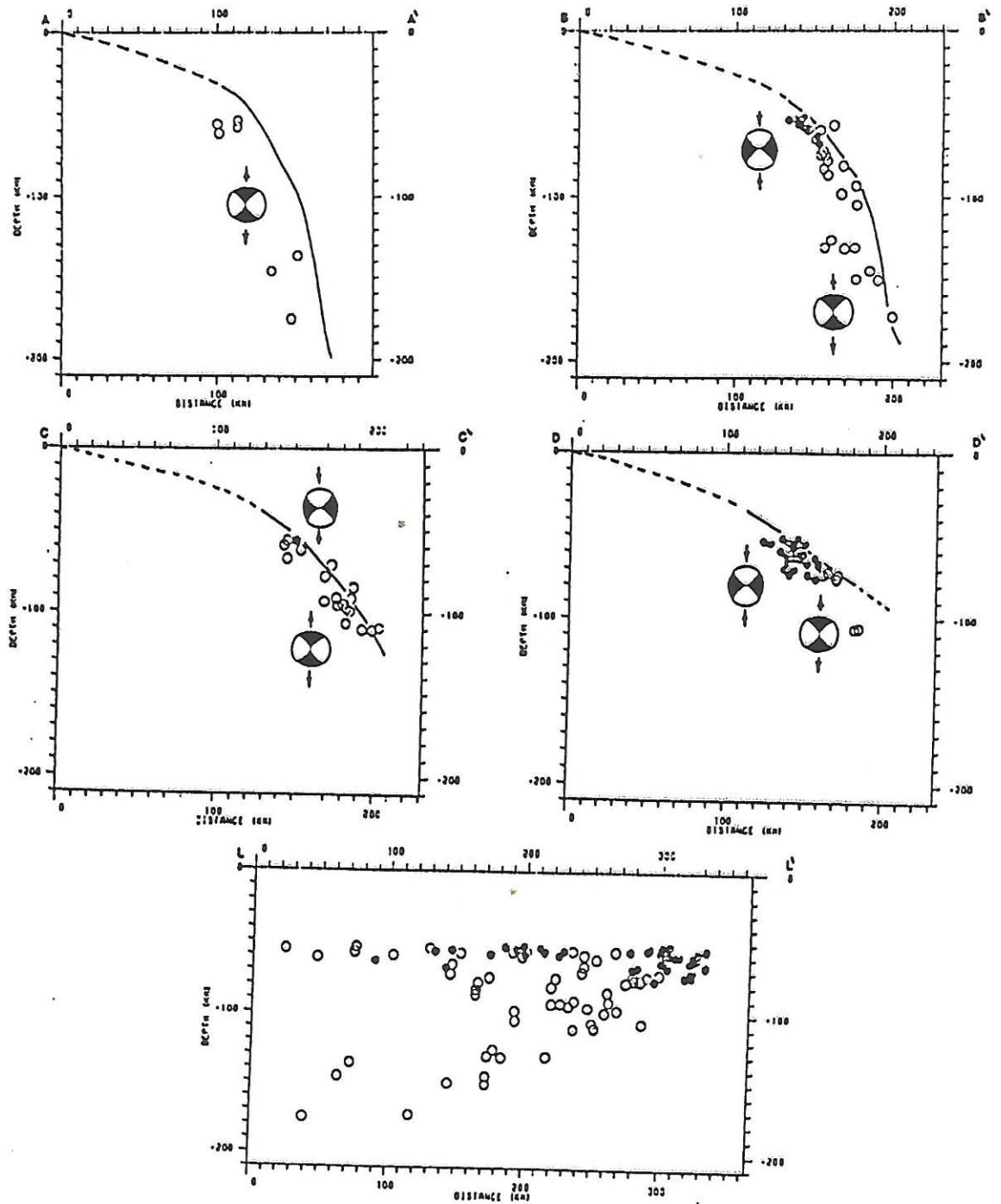


Figure 12. Cross sections of seismicity within the Cocos plate showing distribution of events with vertical to subvertical tension (T) and compression (P) axes. Location of cross sections is given in figure 11.

It is important to mention that by means of focal mechanisms (of events deeper than 50 km), no evidence was found of either tearing along the Quesada Sharp Contortion, or changes in the general internal deformation of the slab.

#### Width of the brittle coupling zone

To define the width of the brittle coupling zone the following assumptions were made: (1) the deepest extension of the brittle coupling zone is defined as the contact between the deepest intraplate seismicity in the overriding plate (brittle lithosphere) and the upper extension of the clearly distinguishable intraplate seismicity within the subducted plate; and (2) even low-magnitude (i.e. 2-3) earthquakes can reflect the limit between brittle and plastic lithosphere. The results of this definition of the brittle coupling zone are shown in fig. 13.

It has been shown that long-term plastic behavior of the lower lithosphere can change to elastic behavior when it is subjected to high stresses in a very short time (non-Newtonian behavior), for example, by rapid slip during a large earthquake (i.e. the case of the McQuarie earthquake) (Anderson and Zhang, 1990). The effect of this is a considerable increase in the width of the fracture zone and, as a result, a much larger moment release in long period waves. The experience in the most recent large thrust earthquake in Costa Rica, the March 25, 1990 earthquake (ML=6.8, Ms=7.0) at the entrance of the Nicoya Gulf, shows that the rupture did not propagate down-dip and that the aftershock zone did not extend beyond 35 km in depth (Protti and McNally, 1990).

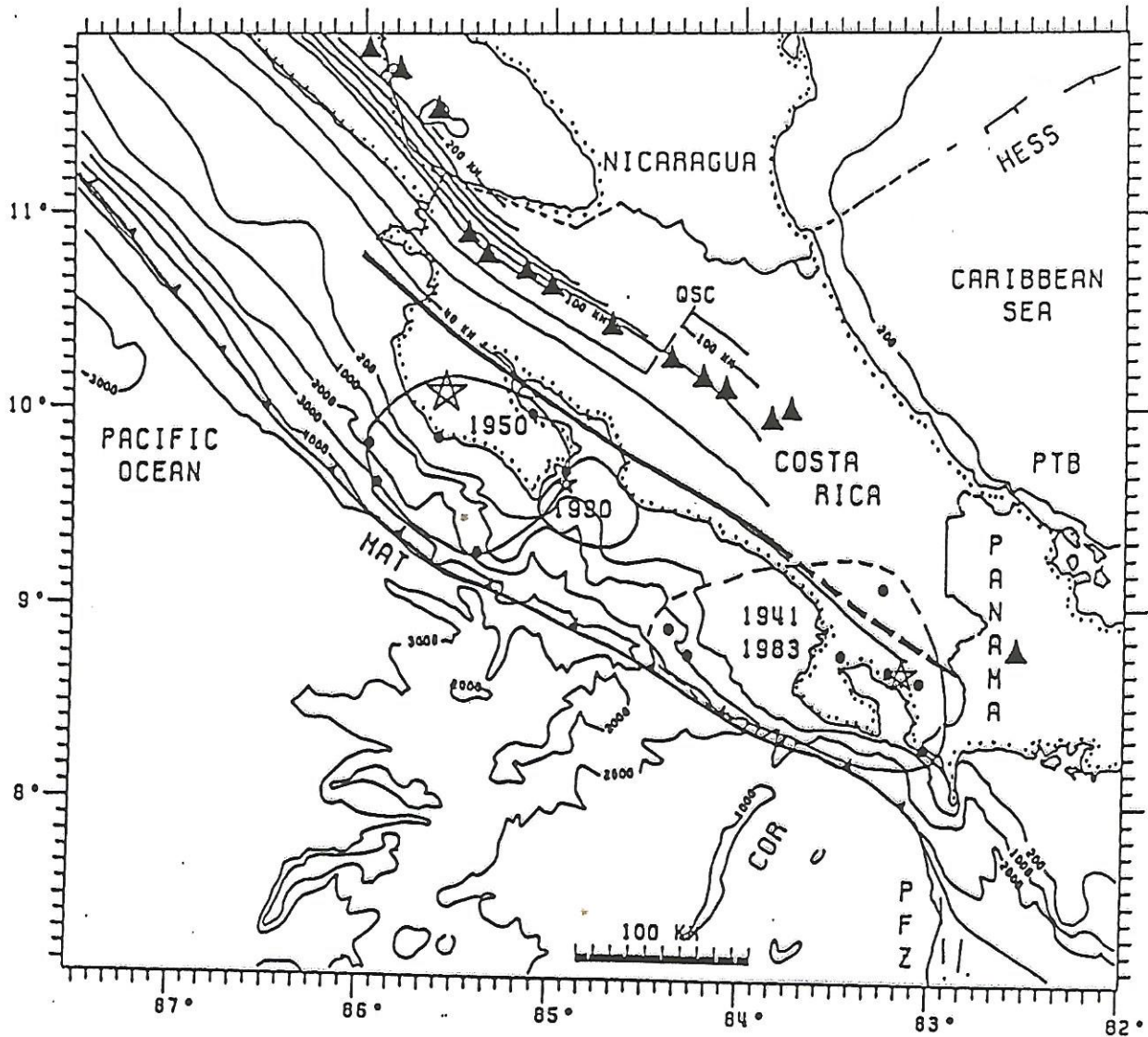


Figure 13. Map showing the maximum down-dip extension of the brittle coupling zone (thick line) between Cocos and Caribbean plates, under Costa Rica. Also shown for reference are the isodepth contours of the Wadati-Benioff zone and the aftershock zones of the 1941 and 1983 Golfito earthquakes (Kelleher et al., 1973; and Guendel and McNally, 1986b), the 1950 Nicoya earthquake (Guendel and McNally, 1986b), and the 1990 earthquake at the entrance of the Nicoya Gulf (Protti et al., 1991, in prep.).

Since the practical application of this procedure of mapping the brittle coupling zone is to estimate the largest potential earthquake for seismic risk assessments, and since the short period waves are the main source of damage, I believe this approximation of the width of the brittle coupling zone, based on long-term brittle behavior, can be valid.

The deepest extension of the brittle coupling zone, obtained in this work, is shown in fig. 13. Considering the limitations of this method, the preliminary results presented here have to be analyzed critically. These results and interpretations can be improved considerably with a better velocity structure. This will allow a better depth resolution, especially for earthquakes in the upper 40 km and for the offshore regions. In addition more large thrust earthquakes need to be analysed in order to test the validity of the method. A correlation and test with other subduction zones, where good local data is available, may also be useful.

#### THE NEW MODEL

##### Age and geometry changes along the trench

The updip projection of the Quesada Sharp Contortion coincides with an abrupt change in the bathymetry of the Cocos plate along a NE alignment. Such alignment extends from the Cocos-Nazca-Pacific triple junction, on the East Pacific Rise, to where the sharpest bend in the Middle America Trench occurs offshore the southern tip of the

Nicoya peninsula (fig. 14). This bathymetric change (the northern "rough-smooth boundary" of HEY, 1977) reflects an age and, therefore, a density contrast on the Cocos plate on either side of the alignment (younger and lighter lithosphere on the SE side) (fig.14). No relative displacement of lithospheric blocks has occurred across this boundary nor seismicity occur on it; therefore it can not be considered a fault, but it has been misinterpreted as a left lateral strike-slip fault in previous works, i.e. Mann and Corrigan, (1990).

The rough-smooth boundary marks the boundary between lithosphere created at the East Pacific Rift, to the north, and that created at the Galapagos Rift System, to the south. The NE part of the rough-smooth boundary, part of which is the Quesada Sharp Contortion, is a relict of the fracture along which the Farallon plate broke into the Cocos and Nazca plates 22 m.y. ago (Hey, 1977). As a consequence of that opening, the subducted plate under the Nicoya peninsula becomes older downdip. In contrast, on the segment SE of the Quesada Sharp Contortion the age of the plate is not only younger, but it maintains the same age in the downdip direction. To clarify this, fig. 15 shows the estimated age of the slab after unbending up the Wadati-Benioff zone to a dip of  $0^{\circ}$ . This may explain not only the steeper angle of the NW segment with respect to that of the SE segment, but also the almost constant Wadati-Benioff zone angle in central Costa Rica, in contrast to a downdip increase in the angle under Nicaragua and northern Costa Rica. A similar association between decrease in age of the slab and shallowing of the Wadati-Benioff zone, for northern and central Chile, was made by Jordan et al. (1983).

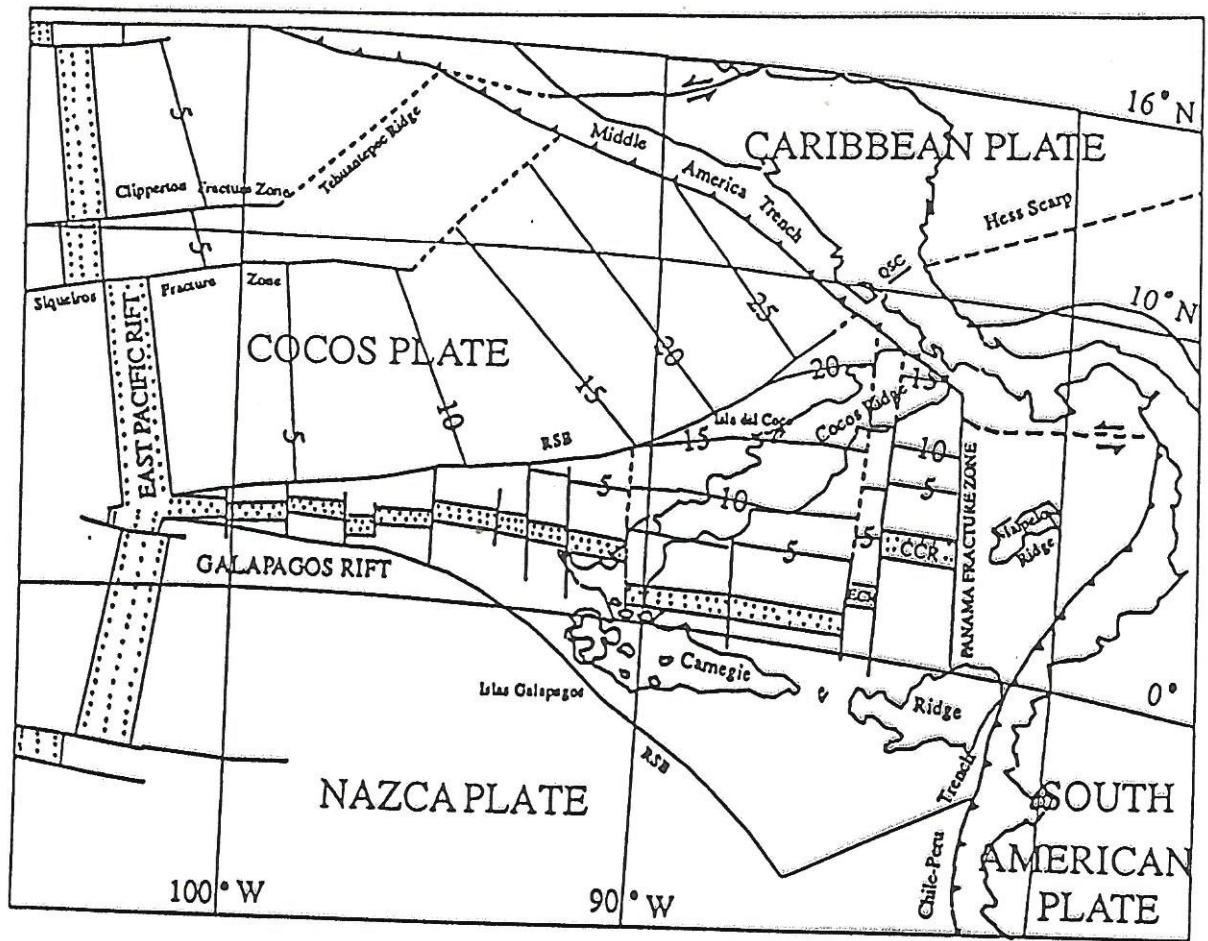


Figure 14. Distribution of lithospheric age, in m.y., of the Cocos plate. Base map is a segment of the Plate-Tectonic map of the Circum-Pacific region, southeast quadrant. The isochrons were drawn following the pattern of magnetic anomalies reported in that map, and from the projection of the spreading rates of the East Pacific Rise and the Galapagos Rift. Dotted bands represent oceanic lithosphere created during the last million year. Cocos, Malpelo and Carnegie ridges are shown by the 2000 m depth contour. RSB are the Rough-Smooth boundaries of Hey, 1977. The northern RSB divides lithosphere of the Cocos plate created along the Galapagos Rift from that created along the East Pacific Rise. The southern RSB is the analogous boundary for the Nazca plate. QSC is the Quesada Sharp Contortion; CRR and ECR are the Costa Rica and Ecuador rifts, respectively.

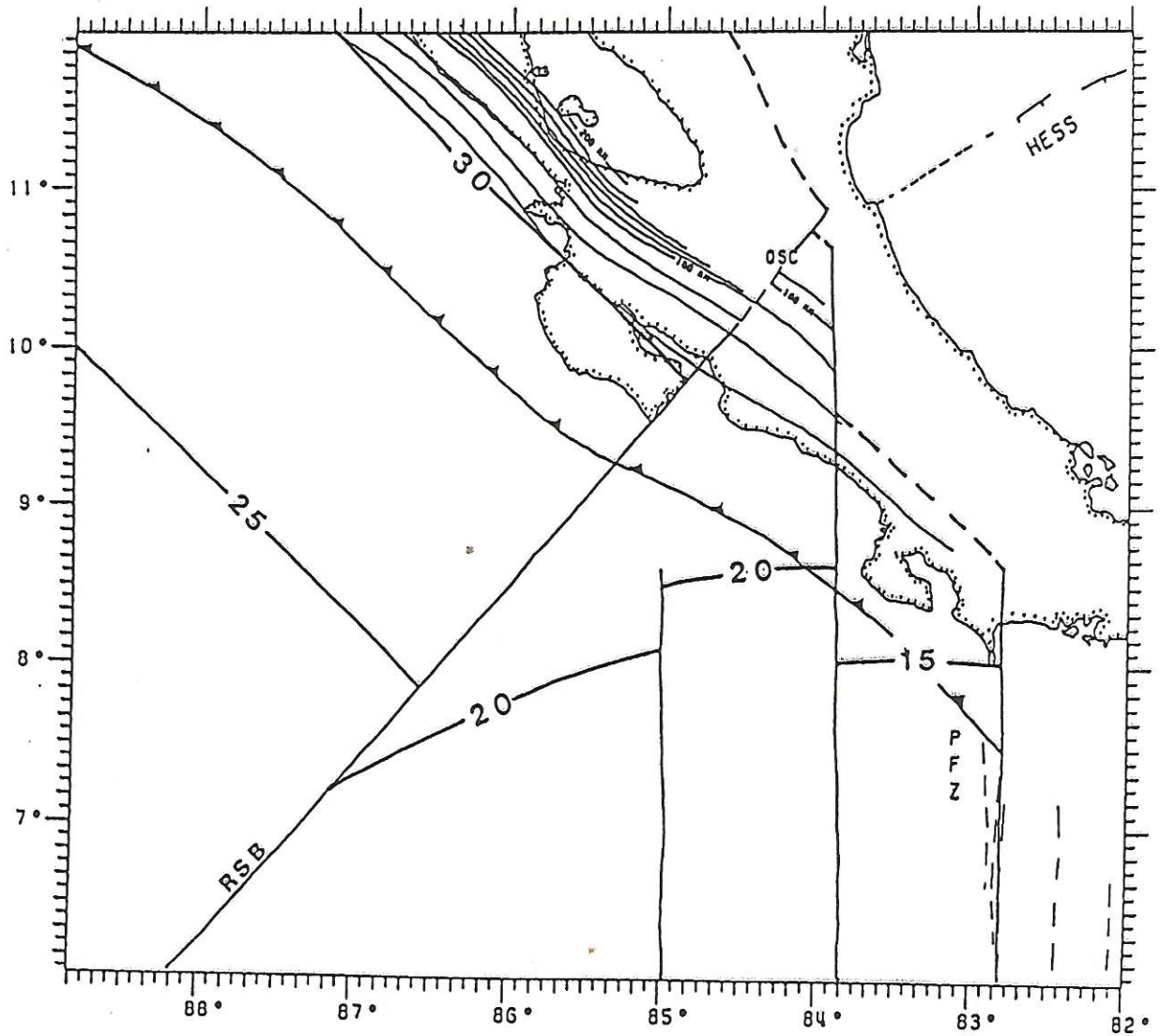


Figure 15. Projection of lithospheric ages, in m.y., of Cocos plate after unbending the seismic slab. These projections of age are based on the spreading rates of the East Pacific Rise and the Galapagos Rift. Dashed line is the maximum extension of the seismic slab. NW of the Quesada Sharp Contortion (QSC) the subducted Cocos plate is not only older than under Central Costa Rica, but also its age increases in the direction of subduction, while to the SE the age remains almost constant along the QSC. Also shown for reference are the isodepth contours of the Wadati-Benioff zone. MAT: Middle America Trench; PFZ: Panama Fracture Zone; RSB: rough-smooth boundaries; HESS: Hess scarp.

### Maximun depth of the seismic slab

The proposed age contrast explains also the deeper Wadati-Benioff zone under Nicaragua with respect to that under central Costa Rica, since the deepest seismicity on the subducted slab, which reflects the transition from brittle to ductile deformation of the slab as a response to gradual slab heating (Isacks et al., 1968; McKenzie, 1969), is also a function of the slab age (Vlaar and Wortel, 1976; Wortel and Vlaar 1978). A correlation of slab length with convergence rate was also found by Isacks et al. (1968).

The slab length is a function of both convergence rate and slab age (Deffeyes, 1972; Molnar et al., 1979). This conclusion was confirmed by Jarrard (1986) applying stepwise multiple regression to a larger and revised data base. In the case treated in this work the differences in convergence rates are not significant ( $\sim 5$  mm/y according to DeMets et al., 1990), and the faster rate occurs where the Wadati-Benioff zone is shorter, contrary to what the model predicts. Thus the slab age is the main parameter controlling the geometry of the Wadati-Benioff zone in this region.

A similar correlation between convergence rate and slab age with slab dip was found by Ruff and Kanamori (1980) and Jarrard (1984). However, Jarrard (1986), with more data, found that the correlation is poor, with negligible regression coefficients that improve only a little when considering only oceanic upper plates.

An correlation analogous to the one presented in this work, was found by Farrar and Lowe (1978), for Peru-Chile, under

similar conditions, i.e. the same convergence rates but contrasts in slab ages and slab lengths.

The shallowing of the maximum depth of the Wadati-Benioff zone from Nicaragua to the Quesada Sharp Contortion, along lithosphere of the same age, may be produced by lateral thermal assimilation since the slab is being exposed to mantle heat flow from three directions: top, bottom and laterally along the "tear" on the Quesada Sharp Contortion.

Following Hey (1977), Lonsdale and Klitgord (1978), the Circum-Pacific Council for Energy and Mineral Resources's plate tectonics map (1981 and 1987); Klitgord and Mammerrickx (1982); and Mammerricks and Klitgord (1982), and being conservative, the age contrast, at the tip of the Wadati-Benioff zone (along the Quesada Sharp Contortion), is on the order of 5 to 10 m.y. (see fig. 14 and 15). The age at the tip, shown in fig. 15, is the present age based on projections of spreading rates, and not the effective age when the tip was at the trench as used by Jarrard, (1986).

Small age variations like this are only effective in changing the Wadati-Benioff zone geometry for subduction of young lithosphere (less than 40-50 m.y.) as in this case. Older lithosphere is almost stable and does not experience major density and thickness changes (Leeds, 1975; Parsons and Sclater, 1977; Sacks, 1983).

#### Slab pull force, trench depth and upper plate deformation

The deeper trench off Nicaragua and the Nicoya peninsula (relative to that in central and southern Costa Rica) may also be a result of a larger slab pull (Hilde and Uyeda,

1983; Jarrar, 1986) induced by the steeper Wadati-Benioff zone under Nicaragua and northern Costa Rica (young lithosphere resists subduction; England and Wortel, 1980; Sacks, 1983). England and Wortel (1980) modified the slab pull force ( $F_s$ ) per unit length of trench segment model of Richter and McKenzie (1978), for a non-vertical dip of the slab. Jarrard (1986), following England and Wortel (1980) and using their estimates of physical constants, gives:

$$F_s = K_1 S^3 V_c \sin(i) [1 - \exp(-K_2 / S^2 V_c \sin(i))]$$

where,  $K_1 = 2.37 \cdot 10^6 \text{ kg m.y km}^{-4} \text{ s}^{-2}$ ;  $K_2 = -1.74 \cdot 10^5 \text{ km}^3 \text{ m.y.}^{-1}$ ;  $i$  is the shallow subduction angle (0-60 km);  $V_c$  is the convergence rate in km/m.y.; and  $S$  is the subducted lithosphere thickness in km, obtained from:

$$S = 8.18(T)^{1/2}$$

for  $T$  (age of the lithosphere in m.y.) younger than 70 m.y.,  
or

$$S = 91.3 - 74.9 \exp(-T/62.8)$$

for lithosphere older than 70 m.y.

These formulae and the values given in table 2 for the studied region give slab pull forces of  $11.0 \cdot 10^{12} \text{ N/m}$  for Nicaragua and northern Costa Rica;  $8.1 \cdot 10^{12} \text{ N/m}$  for central Costa Rica; and  $3.7 \cdot 10^{12} \text{ N/m}$  for southern Costa Rica. These values are in agreement with the relative trench depth (difference between the abyssal plain depth and the maximum trench depth) in the respective subduction segments

according to the graphical comparison given by Jarrard (1986).

The strength regime on the overriding plate also shows variations from Nicaragua to Southern Costa Rica in the same direction that the Cocos plate age decreases. Using the seven-class strain classification system suggested by Jarrard (1986), and based on the stress analyses made by Malavassi (1991) for Nicaragua and Costa Rica, I have assigned the following values: Nicaragua, class 3 (mildly tensional); northern Costa Rica, class 4 (neutral, mildly tensional to mildly compressional); central Costa Rica, class 5 (mildly compressional); and southern Costa Rica, class 6-7 (moderately compressional to very strongly compressional). An inverse correlation is, therefore, found between the age of the subducted Cocos plate and the strain class. This correlation was previously found with global data by Molnar and Atwater (1978) and confirmed by Jarrard (1986). A low subduction angle also facilitates the transmission of compressive stress to the overriding plate by increasing contact area between the plates (Cross and Pilger, 1982; Jarrard, 1984 and 1986). A decrease in the subduction angle towards SE also correlates with the strain class in this region.

Based on the interpretations of England and Wortel (1980), the values of slab pull forces obtained above also predict extension in the upper plate for Nicaragua and northern Costa Rica, and compression for central and southern Costa Rica. This is in agreement with the strain classes assigned to these segments (table 2).

Wdowinski et al. (1989), developed a model to calculate the deformation of the overriding plate by using a thin viscous

sheet model and quantitatively found that the stress regime in the upper plate depends on the angle of subduction, the thickness of the overriding lithosphere, and the ratio of asthenospheric to lithospheric viscosities. That work does not make the compressive and extensive regimes dependent on the subduction angle but analyzes angle variations within the same overall strain environment. Applying the model to the Andes and the Aegean arcs, Wdowinski et al. (1989), found that within compressional environments (Andean type) an increase in the subduction angle increases the width of the compressional regime on the overriding plate, but in extensional regimes with an even larger subduction angle, like the Aegean, the band of compressive regime is limited to a narrow zone close to the trench. The segments studied in this work are too small to attempt a similar analysis.

On the other hand, the strong correlation between strain class and absolute motion of the overriding plate, found by Jarrard (1986), is not applicable to the region of this study since: 1) the absolute motion of the upper plate is the same for the four segments described above; and 2) the model suggests an extensional environment for all four segments.

#### Forearc width

The longer arc-trench gap in Nicaragua relative to that in northern Costa Rica may indicate an older age for the Nicaragua arc. At a globally obtained increase rate of the forearc width of 1 km/m.y. (Dickinson, 1973), the difference in age of the Nicaragua and northern Costa Rica arcs will be of about 25 to 30 m.y. Using the regression for arc age and dip angle obtained by Jarrard (1986), this difference in age

will produce a difference in the intermediate dip of only  $3^\circ$ , suggesting that a smooth contortion of the plate will be able to accommodate that dip difference, without the necessity of tearing the slab.

#### The SE end of the seismic slab

The abrupt termination of the Wadati-Benioff zone at  $83^\circ 55'W$  (see fig. 7 and 9) can be explained by another along-trench age change ( $\sim 5$  m.y.) on the Cocos plate across a NS fracture originated at the Cocos-Nazca spreading center. That fracture marks the west limit of the Costa Rica rift and the east limit of the Ecuador rift (CCR and ECR on fig. 14). East of the subducted part of that fracture, the Cocos plate is so young ( $\sim 15$  m.y.) that its temperature is probably beyond the brittle-plastic limit and therefore it does not deform elastically. This segment of the Cocos plate has to be subducting with a shallower angle than its western counterpart, and probably bends upwards continuing an almost horizontal path like that found under Peru (Barazangi and Isacks, 1976; Isacks and Baranzangi, 1977) and southern Mexico (Suarez et al, 1990). In such horizontal paths, the subducted plate underrides the base of the upper plate, in this case the roots of the plutonic Talamanca Cordillera; it does not leave an asthenospheric wedge between the plates, and may not reach the depths needed for the dehydration of the slab, thus inhibiting the subduction-related volcanic activity in that region. The quiet seismic behavior, explained above, of this plate portion makes it difficult to find evidence (by means of seismicity) of such a flattening.

Lundgreen and Dixon (1990) modeled the subduction of the Woodlark Rift beneath the Solomon Islands, where, like in

southern Costa Rica, subduction of young lithosphere occurs. They made a comparison of the seismicity with a simple model of lithosphere strength in which seismicity in the subducted slab is restricted to a region above the transition from brittle to ductile strength of olivine. That transition is a function of the temperature (i.e. age) of the subducted lithosphere. Their results suggest that the maximum depth of earthquakes follows the 700°C isotherm, consistent with intraplate seismicity. These results indicate that the subducted Cocos plate reaches that temperature at a much lower depth under southern Costa Rica, than in central and northern Costa Rica. Since mantle temperature variations are not expected in such a small scale, variations in age of the Cocos plate are chiefly responsible for the shallowing of the maximum depth of the seismic slab from northern to southern Costa Rica.

Attempts to estimate the lithospheric age for the transition from slab pull-down to resisting subduction have failed (Molnar and Atwater, 1978; England and Wortel, 1980) probably because of uncertainties in key variables (Jarrard, 1986) and/or variations in mantle density for each subduction zone. It seems that if my projections of age are correct, ~15 m.y. represents the age at which that transition occurs under the southern terminus of the Middle America trench. Therefore for the southern Costa Rica segment, the slab pull force obtained below ( $3.7 \times 10^{12}$  N/m) is cancelled by the buoyancy forces that oppose subduction.

#### The subduction of the Cocos Ridge

The subduction of the Cocos Ridge under southern Costa Rica has traditionally been used as the mechanism to explain some

of the above mentioned features (Vogt et al., 1976; Pennington, 1981; Burbach, 1983; Burbach et al., 1984; McGeary et al., 1985; Guendel and McNally, 1986c; Adamek et al., 1987; Guendel et al., 1989; Corrigan et al., 1990). Since the Cocos Ridge started subducting only about one million years ago (Lonsdale and Klitgord, 1978; Corrigan et al., 1990), its subducted portion is no longer than 90 km. Even if the subduction of the Cocos Ridge started earlier, the presence of the Panama Fracture Zone limits its NE extension to less than 100 km from the trench (see figs. 14 and 15), and therefore it can not be responsible for regional changes in the Wadati-Benioff zone several hundred kilometers away. Shallow subduction (or at least shallow maximum depth of the seismic slab) induced by the subduction of more buoyant and thermally hotter ridge has been documented in other regions (i.e. Kelleher and McCann, 1976; Barazangi and Isacks, 1979; Pilger, 1981; Pennington, 1981; Cross and Pilger, 1982; Lundgreen and Dixon, 1990), but that mechanism does to apply for Costa Rica.

In summary, age variations of the Cocos plate along the Middle America trench better explain the changes in the Wadati-Benioff zone geometry for Nicaragua and Costa Rica than previous models based on the subduction of the Cocos Ridge.

The other previously suggested independent variables that affect the seismic slab geometry (convergence rate, absolute motion of the upper plate, mantle flow) (Jarrard, 1986) are almost constant for this region, indicating that age must be the main factor controlling the Wadati-Benioff zone geometry under Nicaragua and Costa Rica.

### Analogous regions

A possible analogy for the case of Costa Rica could be the differences in the subduction geometry found on either side of the Tehuantepec Ridge where segments of the Cocos plate with different ages and relative buoyancy are being subducted (Bevis and Isacks, 1984).

The model presented in this work can also explain the isodepth contours of the Wadati-Benioff zone under Ecuador, which are almost perpendicular to the trench (Bevis and Isacks, 1984). There the southern counterpart of the rough-smooth boundary that produces the Quesada Sharp Contortion is being subducted.

Another region where this model can be tested is Chile. In northern and central Chile three major tears or plate contortions have been identified (Isacks and Barazangi, 1977; Garcia-Gonzalez, 1990), and under southern Chile subduction of oceanic lithosphere of the same ages as in Costa Rica is taking place. I predict that a sharp contortion or tear exists under southern Chile, where a jump in age on the order of 10 m.y. occurs across the Valdivia Fracture Zone on relatively young (20-30 m.y.) oceanic lithosphere of the subducted Nazca plate.

If good local data existed for the South Sandwich subduction zone, where there is a major change in trench depth across a fracture zone separating crust of very different ages (Jarrard, 1986), it could be another region to look for the same Wadati-Benioff zone geometry variations discussed in this work.

### Cocos-Caribbean coupling

The differences in coupling between Cocos and Caribbean plates, in Nicaragua and Costa Rica, can also be explained based on the characteristics of the subducted ocean floor.

Based on historical and instrumentally recorded seismicity in Costa Rica, three main segments with different coupling are recognized, coincident with the subduction segments described in table 2: NW Costa Rica (from Papagayo Gulf to the SE end of the Nicoya peninsula), Central Costa Rica (from the entrance of the Nicoya Gulf to NW Osa peninsula), and SE Costa Rica (from Osa peninsula to the inland projection of the Panama Fracture Zone). Historically large ( $M_s > 7.0$ ) subduction type earthquakes have occurred on the NW and SE segments but not on the Central one.

The boundary between the NW and the Central segment is the updip projection of Quesada Sharp Contortion (i.e. the down dip projection of the rough-smooth boundary), marking a difference in the ocean floor relief. Under the NW segment a relatively smooth plate is subducting, facilitating a larger area of contact with the overriding plate and therefore increasing the potential for large earthquakes. Under the Central segment, the subducted plate consists of isolated sea mounts (fig. 16), that reduce the coupling region to a set of smaller areas that can break by moderate ( $M_s \leq 7.0$ ) earthquakes. The SE segment has a stronger coupling, relative to the Central one, due to the subduction of the Cocos Ridge which is not only more buoyant, but also a more constant bathymetric anomaly. The stronger coupling of the NW and SE segments may also be due to a combination of the above described reasons along with the possible existence of deep roots of the Nicoya and Osa peninsulas, practically

absent in the Central segment. Those peninsulas may not only act as a bump at the base of the overriding plate, but also may increase the vertical load on the coupling interface (stronger coupling would occur right under the peninsulas and not under the accretionary wedge where the shear stress is much lower [Jarrard, 1986]). The results for the maximum extension of the coupling zone obtained in this work (fig. 13) do not show major variations for the three above mentioned segments.

Based on this interpretation, the Nicoya and Osa rupture zones can be classified as Aleutian type, and the central Costa Rica segment as Kurile type, according to the asperity model of Lay et al., (1982).

The March 25, 1990, earthquake at the entrance of the Nicoya Gulf (Protti and McNally, 1990) occurred at the NW end of the Central segment and may represent the largest earthquake that can be generated in that segment. That earthquake is a good indicator of the coupling differences between the NW and Central segments since, even though it occurred right at the boundary between the segments, no aftershocks occurred towards the NW (Protti and McNally, 1990) where a much stronger coupling exists (a locked gap) (Nishenko, 1989). All aftershocks however, occurred SE of where the fracture initiated. Teleseismic analyses of the rupture propagation of that earthquake (Pacheco and Protti, 1990), agree with this interpretation.

The relatively low coupling on the Nicaragua segment (no earthquakes larger than  $M_s=7.0$ ) may be due to the absence of a well developed outer arc in that region.

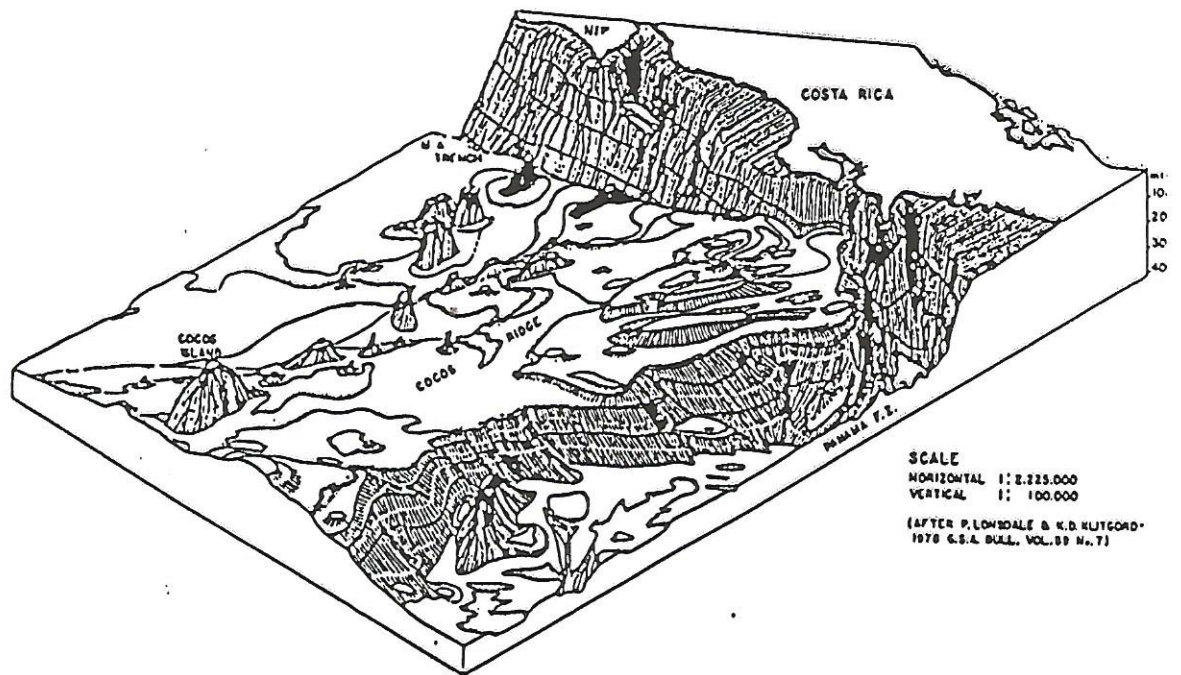


Figure 16. Block diagram showing bathymetric anomalies on the Cocos plate as it approaches the Middle America Trench (from Guendel and McNally, 1986a). Note the contrast between the relatively smooth ocean floor subducted under the Nicoya peninsula (NIP) with respect to the rough bathymetric high of the Cocos Ridge. Note also the subduction of isolated sea mountains under central Costa Rica.

Ruff and Kanamori (1980), using global data, found a correlation between the strength of coupling with the age of the oceanic lithosphere and rate of subduction. Their work indicates that the coupling increases as the age decreases and rate increases. Additional new and revised data used by Jarrard, (1986) confirms that interpretation.

Since for Costa Rica both a decrease in age and an increase in rate occur towards the SE, a stronger coupling should be expected in that direction, but it does not occur. Therefore, the present work suggests that variations in the relation between coupling with age of the subducted plate and rate of subduction, can occur due to bathymetric characteristics of the subducted plate.

All of the above conclusions make Nicaragua-Costa Rica a potential area to study subduction processes and effects in a small area with transitional variations from mildly tensional to compressional type subductions, representing almost the whole range from Marianas to Chilean type subductions of Wilson and Burke (1972) and Uyeda and Kanamori (1979).

#### CONCLUSIONS

A new model, based on age variations of the subducted Cocos plate along the Middle America Trench, explains the following characteristics of subduction zone in Nicaragua and Costa Rica: (1) the Quesada Sharp Contortion; (2) the difference in geometry (angle, length and maximum depth) of the Wadati-Benioff zone across the Quesada Sharp Contortion,

and in southern Costa Rica; (3) the sharp left-bend of the Middle America trench south of the Nicoya peninsula (by tectonic erosion? and/or by the movement of much shallower ocean bottom into the trench in the SE part); and (4) the rapid shallowing of the Middle America trench SE of that bend.

The difference in coupling between Cocos and Caribbean plates along the southern terminus of the Middle America trench can be explained by bathymetric features on the subducted Cocos plate.

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