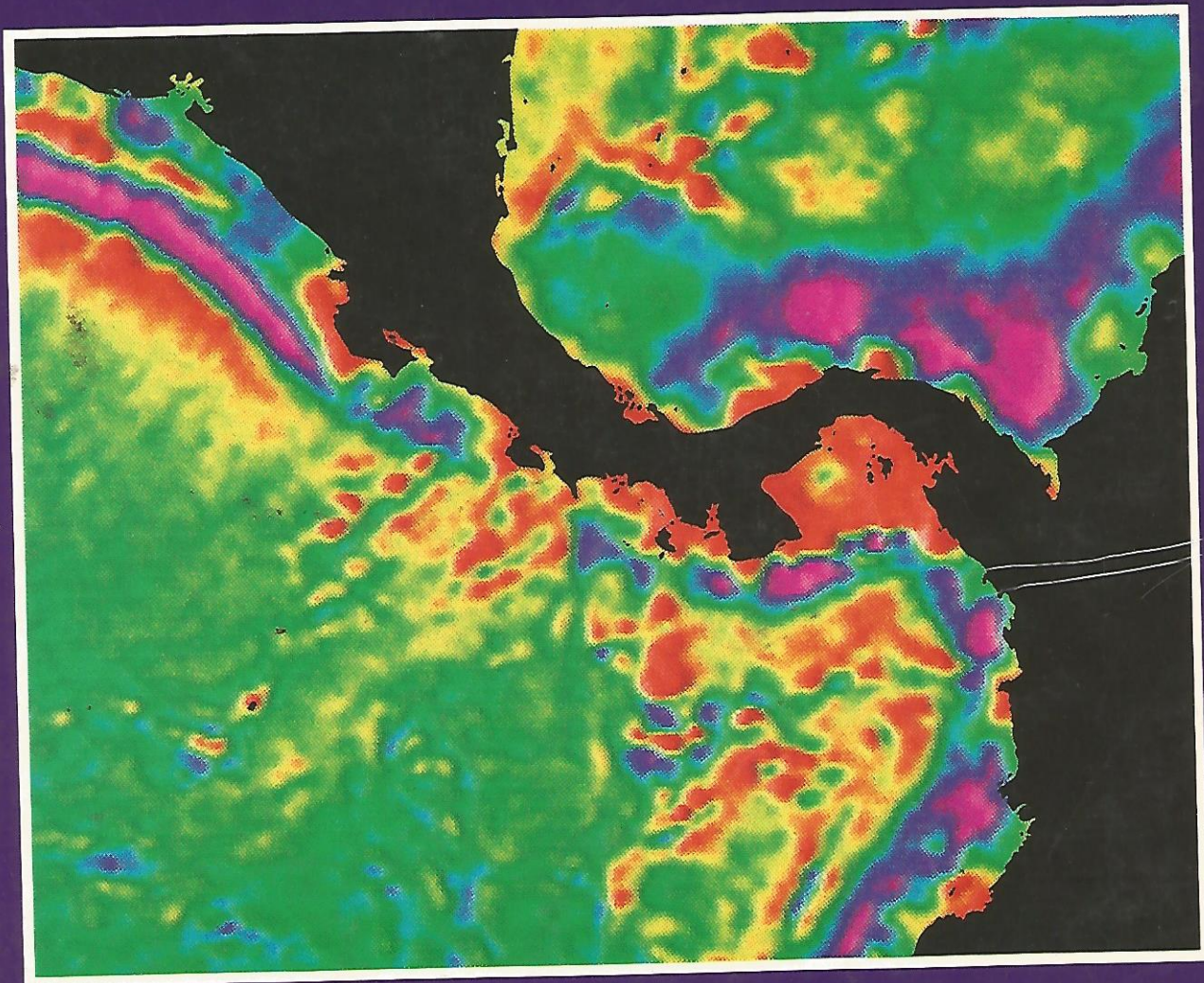


Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America

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SPECIAL PAPER

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Correlation between the age of the subducting Cocos plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica

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ABSTRACT

High-resolution seismicity data from Costa Rica and southern Nicaragua have been used to image the geometry of the Wadati-Benioff zone under southern Central America. The data include 9,514 events with computed horizontal and vertical errors smaller than 4 and 5 km respectively.

We found that under the Nicaragua–Costa Rica border the Wadati-Benioff zone contorts (from steep to shallow dip angles, northwest to southeast) but does not show evidence of a brittle tear, as postulated by others. Further to the southeast—northeast from Puerto Caldera—the Wadati-Benioff zone does, however, show a tear (the Quesada Sharp Contortion) at intermediate depths ($h > 70$ km). Overall the dip angle of the Wadati-Benioff zone decreases from 84° under Nicaragua to 60° under central Costa Rica. The maximum depth of intraplate Wadati-Benioff zone earthquakes also decreases from northwest (~ 200 km under Nicaragua) to southeast (~ 125 km under central Costa Rica). In southern Costa Rica, east of $83^\circ 55'W$, we find no evidence of the Wadati-Benioff zone below 50 km.

This geometry of the Wadati-Benioff zone and other tectonic features related to the subduction of the Cocos plate beneath the Caribbean plate have been integrated into a model that correlates them with along-trench variations in age of the subducted Cocos plate. These tectonic features are (1) the shallowing of the Middle America Trench bathymetry from northwest to southeast, (2) differences in coupling between Cocos and Caribbean plates, (3) the termination of the Central America Volcanic Chain in central Costa Rica, and (4) distinct stress field variations on the overriding Caribbean plate.

The subduction of the Cocos Ridge under southern Costa Rica is partially responsible for some of these features (shallowing of the Middle America Trench in southern Costa Rica) and for the high uplift rates of the outer arc. However, since the presence of the Panama Fracture Zone limits the subducted extension of the Cocos Ridge to less than 100 km from the trench, we propose that the overall geometry of the Wadati-Benioff zone is controlled by abrupt along-trench changes in the age of the subducted Cocos plate.

INTRODUCTION

This work presents new data that refine previously published geometries of the Wadati-Benioff zone along the southern terminus of the Middle America Trench, between Nicaragua and Costa Rica, where the Cocos plate subducts beneath the Caribbean plate (Fig. 1). This unique earthquake data set, collected by a local seismographic network, also allows the definition of new features of this subduction zone. The local network has been jointly operated since 1984 by the Observatorio Vulcanológico y Sismológico de Costa Rica, Universidad Nacional (OVSICORI-UNA), and the Charles F. Richter Seismological Laboratory, University of California at Santa Cruz (CFRSL-UCSC)

A new high-resolution three-dimensional plot of the top of the Wadati-Benioff zone from northern Nicaragua to southern Costa Rica is the main result presented in this chapter. This new definition of the Wadati-Benioff zone is combined with previously known regional tectonic features to construct a model that correlates them with abrupt age changes in the subducted Cocos plate. The amount and quality of located

earthquakes and the existence in this region of along-strike abrupt age changes in a relatively young lithosphere (less than ~40 m.y. old) made correlations on a small scale possible.

Correlations between the age of the subducting plate and the geometry (dip 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 (e.g., Sagg and Uyeda, 1984; Yamaoka et al., 1986; Jarrard, 1986). In general, these works indicate a direct correlation between the age of the plate, or a combination of age and convergence rate, with the Wadati-Benioff zone dip angle and its length. Such a correlation has been explained by differences in the thickness, density, and thermal state of the subducting lithosphere that affect the sinking or buoyancy of the slab and its thermal assimilation by the asthenosphere.

Here we attempt to correlate the geometry of the Wadati-Benioff zone along a single subduction zone on a smaller scale (segments as small as 150 km) and with age differences of less than ~20 m.y. Such a detailed study has the potential for revealing clues about the processes and dynamics of subduction zones.

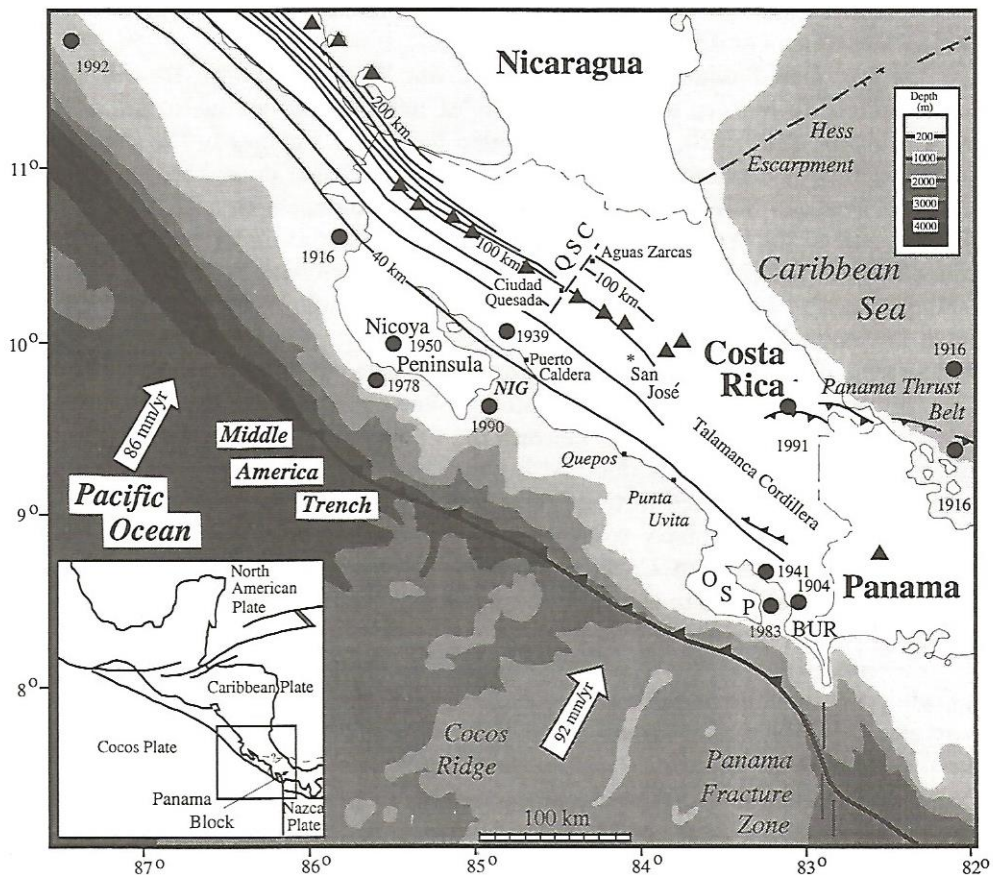


Figure 1. Tectonic setting of southern Central America and isodepth contours (in km) of the top of the Wadati-Benioff zone obtained in this study. Convergence velocities between Cocos and Caribbean plates are after DeMets et al., 1990. Closed triangles are active volcanoes, and solid circles show the location of large ($M_s \geq 7.0$) interplate earthquakes that occurred this century. NIG: Nicoya Gulf; OSP: Osa Peninsula; BUR: Burica Peninsula; QSC: Quesada Sharp Contortion. The locations 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). Here, the Cocos plate subducts under it along the Middle America Trench. The direction of convergence of these two plates is N 25 to 30° E, and their relative velocity varies from 69 ± 3 mm/year offshore of northern Guatemala to 95 ± 4 mm/year offshore of southern Costa Rica (De Mets et al., 1990).

South of the border between Costa Rica and Panama is the Panama Fracture Zone. This right-lateral transform fault is one of the plate boundaries between the Cocos and Nazca plates. West of the Cocos-Nazca-Caribbean triple junction and southwest of the Osa Peninsula, the Cocos Ridge is being subducted beneath 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. Cocos plate generated at the East Pacific Rise subducts under Nicaragua and northern Costa Rica, whereas Cocos plate generated at the Galapagos Spreading Center subducts under central and southern Costa Rica.

In Costa Rica, off the southern tip of the Nicoya Peninsula, the Middle America Trench axis shows a prominent left bend from northwest to southeast, and its depth rapidly decreases southeast of 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, which 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, could be the northwest extension of the April 22, 1991, Valle de la Estrella earthquake (Fig. 1) rupture zone.

PREVIOUS WORK

The Wadati-Benioff zone geometry in southern Central America has been deduced from both surface tectonic features and direct seismic observations. Stoiber and Carr (1973), based on differences in the strikes and position of volcanic lineaments, proposed tear faults in the subducted plate under central Nicaragua, under the Nicaragua-Costa Rica border, and under Irazu-Turrialba volcanoes. Burbach et al. (1984) and Burbach and Frohlich (1986) combined ISC (International Seismological Center) relocated events with locally recorded events and proposed a tear under the Nicoya Peninsula. Bevis and Isacks (1984) used hypocentral trend surface analysis for teleseismically recorded events and found no evidence for pronounced discontinuities in the region. Wolters (1986), using PDE (Preliminary Determination of Epicenters) data, mapped limits of seismic sections ("not necessarily breaks") under central Nicaragua and under the Nicoya Peninsula. Yamaoka et al. (1986), using ISC locations to fit an inextensible spherical shell, concluded that no tearing of the slab was needed to fit the data. "Güendel (1986), using mainly local data, mapped the

mean depth of the Wadati-Benioff zone for the same region covered in this chapter and suggested that smooth contortions of the slab fit the hypocentral distribution of intermediate-depth earthquakes in the region, without requiring tear faults.

The data set used by Güendel (1986) has been updated in this chapter, with almost three times the number of earthquakes, to map the top of the Wadati-Benioff zone. We refined the smooth contortion under the Nicaragua-Costa Rica border and defined a tear under central Costa Rica.

DATA ANALYSIS

Data used and location errors

Both teleseismic and local data sets have been used for studies conducted in Nicaragua and Costa Rica (Table 1). Data from four local seismographic networks are used in this chapter (Fig. 2): Arenal (1978), Nicaragua (1978), OVSICORI-UNA (1984-1990), and a temporal network (October 1987-July 1988) funded by the National Science Foundation (NSF) as part of a joint research project between OVSICORI-UNA AND CFRSL-UCSC. Three of these networks overlap in northern Costa Rica.

To study the geometry of the Wadati-Benioff zone, data sets DS04 to DS09 were used, for a total of 9,514 events (Fig. 3). This analysis does not include DS01 to DS03, used by Güendel (1986), because it is deemed desirable to maintain consistency by using only earthquakes located by local networks. The majority of these data sets (88%) was recorded by OVSICORI-UNA's network, and we have complete location parameters for them (e.g., 77% of the events were located with 11 or more readings including P and S; 50% are within an azimuthal gap less than 225°; 63% are at an epicentral distance of less than 40 km to the nearest station; 85% have root mean square (RMS) equal to or smaller than 0.30 seconds; 93% have horizontal errors equal to or smaller than 6 km; and 84% have vertical errors equal to or smaller than 6 km). For Costa Rica we only used earthquakes located with horizontal and vertical errors smaller than 4 and 5 km respectively. For Nicaragua no values of horizontal and vertical errors exist in the data base; however, the data correspond to a time period (1978) when the network was fully operational (David Harlow, personal communication, 1985).

Local versus global earthquake locations

Local networks are capable of locating earthquakes of magnitudes smaller than those global networks are capable of recording. Several works have pointed out a tendency for local networks to yield a steeper dip of the Wadati-Benioff zone (e.g., Adams and Ware, 1977; McLaren and Frohlich, 1985); however that tendency is not significant for the region of our study. McLaren and Frohlich (1985) showed that the maximum errors occur for earthquakes deeper than 200 km and where the local network does not extend above the deepest part of the seismic slab. In the Wadati-Benioff zone under

TABLE 1. SEISMIC DATA SETS FOR NICARAGUA AND COSTA RICA MENTIONED IN THIS CHAPTER

Name*	From (DD-MM-YY)	To (DD-MM-YY)	Mag.		Events	Region†	Remarks§
			Minimum	Maximum			
DS01	05-10-50	11-11-50	6.0	7.7	7	NCR	a
DS02	06-05-51	23-12-72	5.0	7.3	73	N	b
DS03	16-10-65	25-09-85	5.0	6.3	75	CR	c
DS04	01-01-78	31-12-78	0.6	3.3	568	N, NCR	d
DS05	01-05-78	15-10-78	1.7	7.0	421	NCR	e
DS06	01-04-84	22-10-86	1.0	5.2	2,601	SN, CR	f
DS07	23-10-86	01-04-90	1.7	6.8	5,748	SN, CR	f
DS08	15-10-87	05-07-88	1.6	4.7	176	SN, NCR	g
DS09	02-04-84	30-12-87	2.2	4.9	416	SN, CR	h

*Names used in this chapter for simplicity.

†N = Nicaragua; CR = Costa Rica; SN = southern Nicaragua; NCR = northern Costa Rica.

§a = Relocations of the Nicoya 1950 sequence by Güendel, 1986; b = Relocation of WWSSN data by Dewey and Algermissen, 1974; c = Relocation of WWSSN data by Güendel, 1986; d = Events located in 1978 by the Nicaraguan network (Güendel, 1986); e = Relocations by Güendel, 1986, of events recorded by the Arenal network; f = Events reported by OVSICORI-UNA (1984–1990); g = Events recorded in a joint project by OVSICORI-UNA and CFRSL-UÇSC with financial support of NSF (Protti, 1991); h = Relocated events from DS06 and DS07 (Protti, 1991).

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 relocations of globally recorded earthquakes (Dewey and Algermissen, 1974). Deeper than 100 km the difference in dip angle is only 11° , being steeper for the local network, resulting in less than 30 km of horizontal discrepancy at a 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). In Costa Rica, where the local network is denser and covers the entire seismic slab and where the Wadati-Benioff zone is not as deep as in Nicaragua, this difference becomes less significant. The relative lack of moderate- to large-magnitude earthquakes within the slab under Costa Rica makes both quantitative and qualitative comparisons difficult.

Wadati-Benioff zone

To obtain a three-dimensional view of the top of the Wadati-Benioff zone, two procedures were used. First, maps of seismicity with depth intervals of 20 km were plotted to obtain the general trend of seismicity as a function of depth. Second, cross sections of seismicity were constructed perpendicular to the general trend obtained in the first step, producing sections almost perpendicular to the Middle America Trench (Fig. 4). We also constructed cross sections parallel to the Middle America Trench (Fig. 5). Given the amount of data used, no overlap in the cross sections was needed. Cross sections for Nicaragua are wider, since the Nicaragua data base is not as large or as complete as the Costa Rica data base. Therefore, 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 resides in the fact that it has been

collected by networks that extend closer to the trench, overlying most of the seismic slab. In Nicaragua most of the seismic slab lies outside the network coverage.

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 the 40-km depth contour. The slices of seismicity from the first step were also used for the interpolation of the projected depths and for the construction of the isodepth contours.

DISCUSSION

Proposed subduction segments

We have divided the subduction zone from Nicaragua to Costa Rica into four segments: Nicaragua and northern, central, and southern Costa Rica (Fig. 6). This subdivision is based on the geometry of the Wadati-Benioff zone and on other tectonic features (Table 2) that differ from segment to segment (Protti, 1991).

Comparison to previous results

Although Güendel (1986) studied the geometry of the subducted slab for the same region presented in this chapter (from Nicaragua to Costa Rica), the two studies differ. In Güendel (1986) the mean depth of the seismic slab was projected to the surface, whereas in the present study the top of the Wadati-Benioff zone has been used to define the geometry. Also, for this chapter almost three 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.

For Nicaragua and northern Costa Rica the general shape of the seismic slab obtained in this work does not differ sub-

stantially from that obtained by Güendel (1986). This is because almost the same data set was used in both works for Nicaragua. The major difference in the results of the two studies in this region is the relative location of the isodepths and the maximum depth of the seismic slab. This difference arises because in this study we mapped the top of the Wadati-Benioff zone. The general shape of the smooth contortion in the Nicaragua–Costa Rica border remains almost the same (Fig. 1). A more detailed sampling of the Wadati-Benioff zone under the border was obtained by using data base DS08, collected specifically for that purpose.

Quesada Sharp Contortion

Given the total amount of data used, we were able to identify a tear in the slab under central Costa Rica (Fig. 7), hereafter called the Quesada Sharp Contortion because it lies under Ciudad Quesada (Fig. 1). For the final analyses we adjusted the zones covered by profiles I-I' and J-J' (Fig. 3) in such a way that the boundary between the zones included in these cross sections was coincident with the location obtained for the Quesada Sharp Contortion. In this way we avoided the overlapping of the two Wadati-Benioff zone segments and ob-

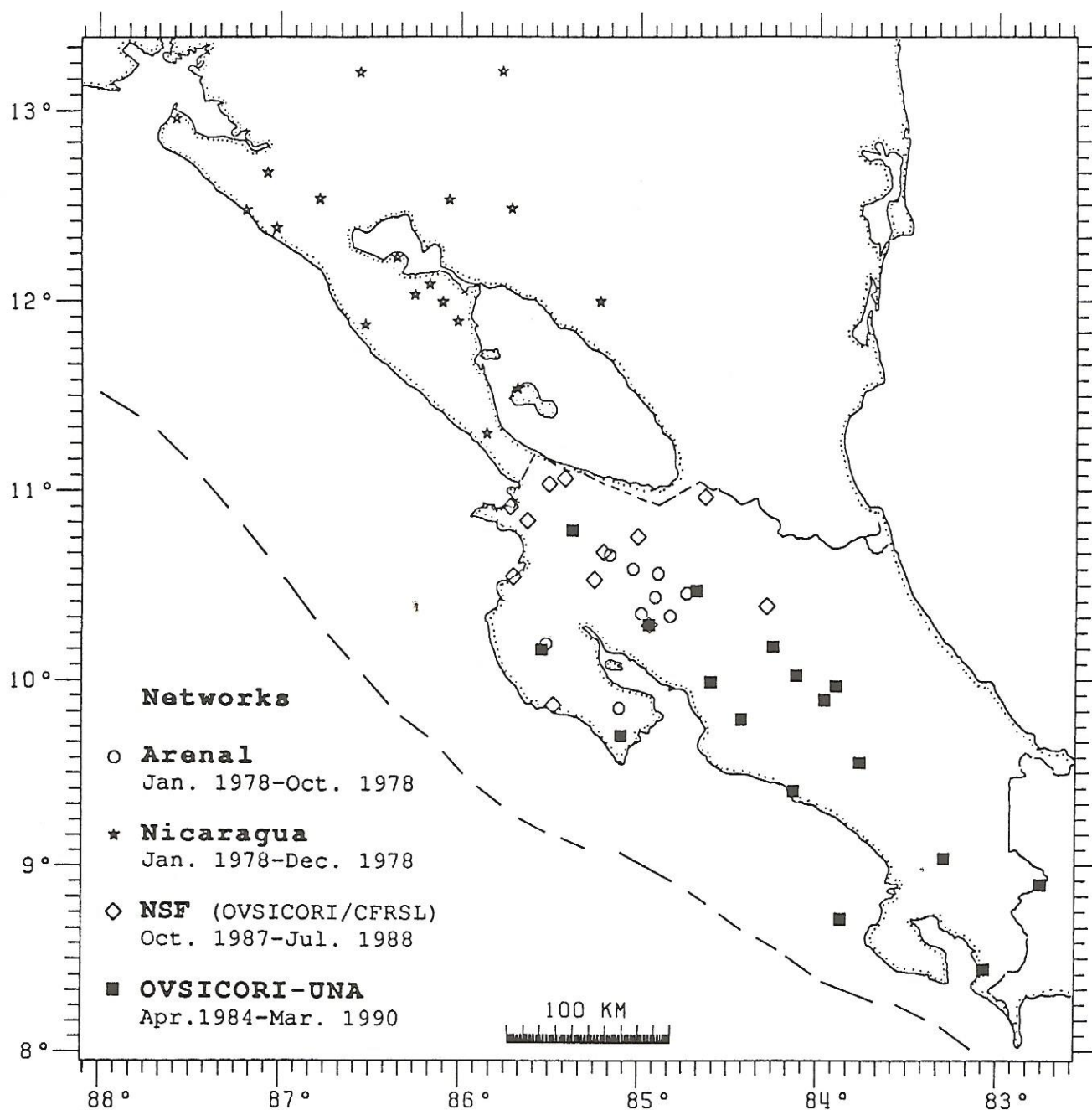


Figure 2. Map showing the location of seismicographic stations and period of operation of local networks from which data was used.

tained 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 northeast of Puerto Caldera to Aguas Zarcas de San Carlos (Fig. 1). The horizontal offset 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). To the northwest of this contortion a 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 southeast of the Quesada Sharp Contortion 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, northeast of Quepos. On both sides of the Quesada Sharp Contortion the maximum depth of earthquakes in the Wadati-Benioff zone shallows up from northwest to southeast at a rate of 7 km per each 10 km of horizontal distance parallel to the trench axis (Fig. 5).

SE termination of the seismic slab

Another remarkable feature of the Wadati-Benioff zone under Costa Rica is its abrupt termination at 83°55'W (Fig. 5), coincident with the southeast end of the Central America

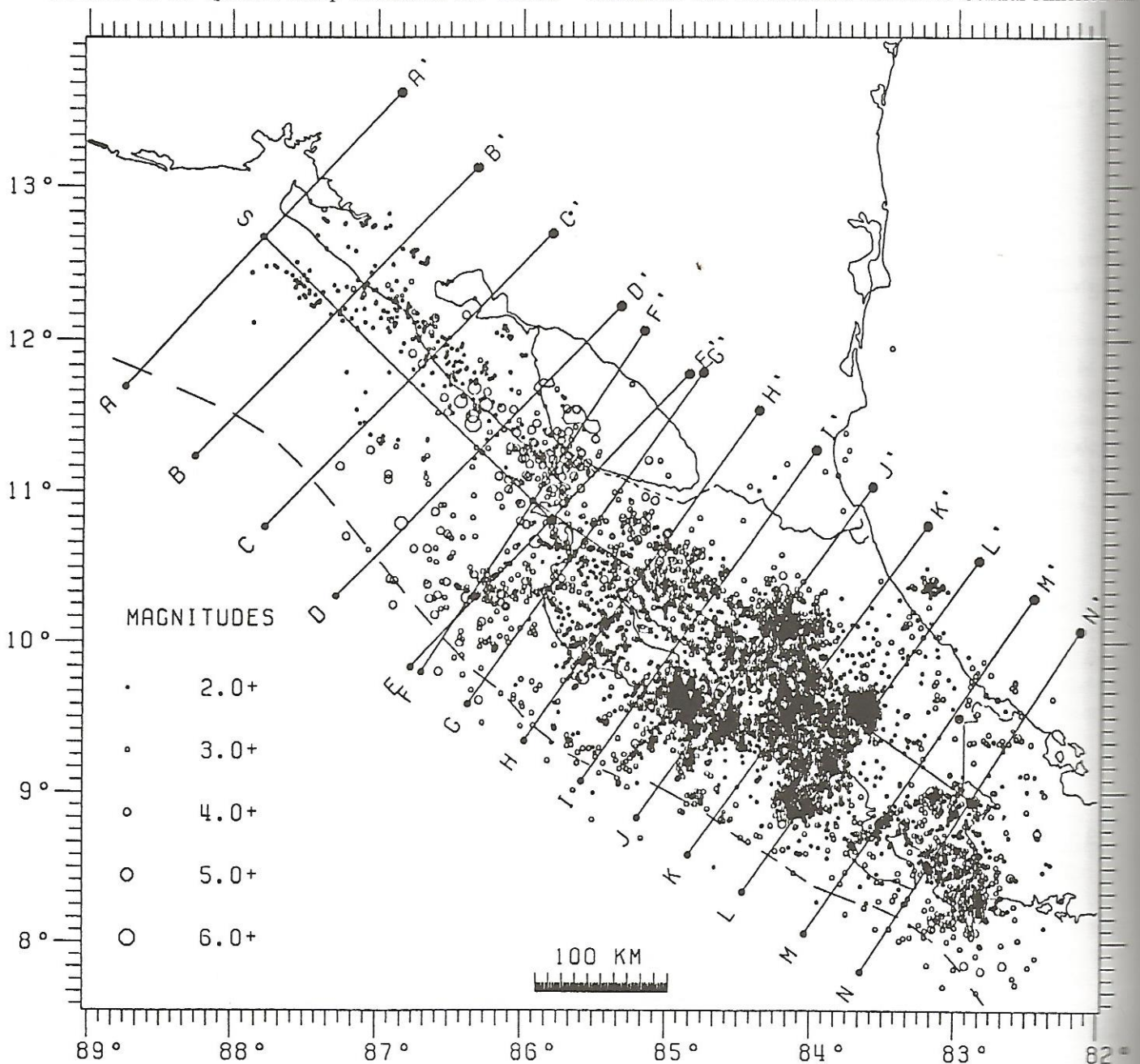


Figure 3. Map showing the epicentral distribution of all events used and the location of cross sections perpendicular (A through N) and parallel (S-T) to the Middle America Trench. The cross sections are shown in Figures 4 and 5.

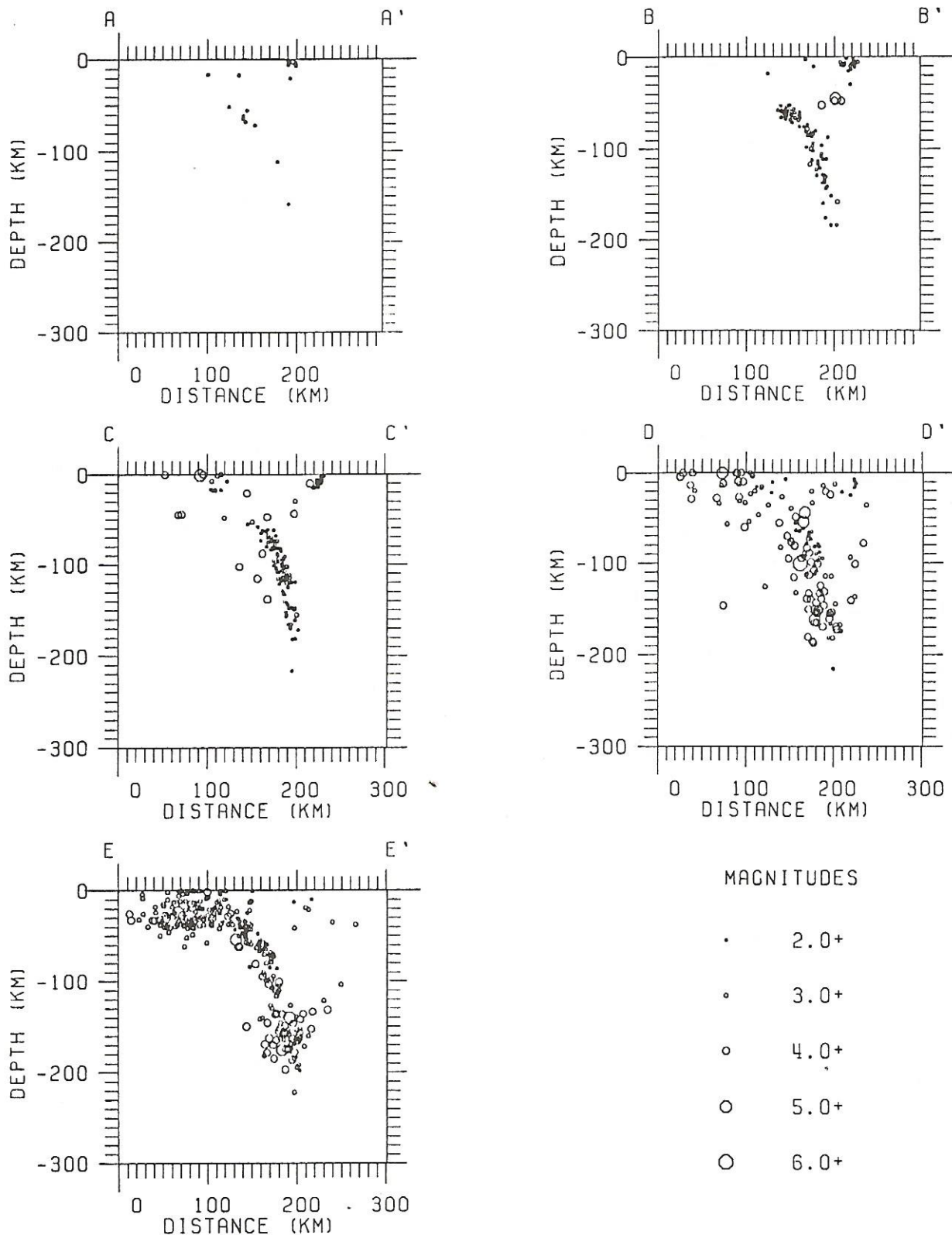
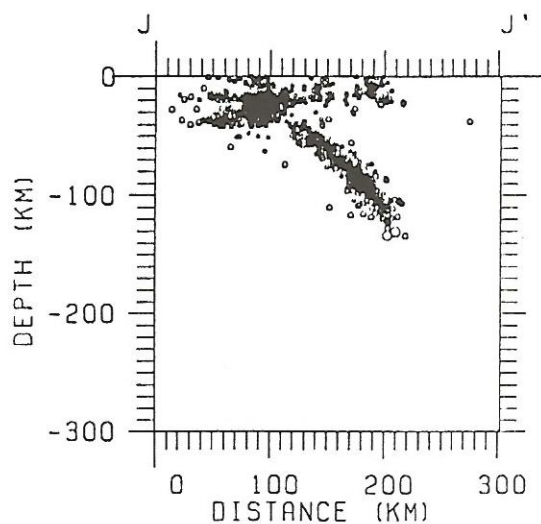
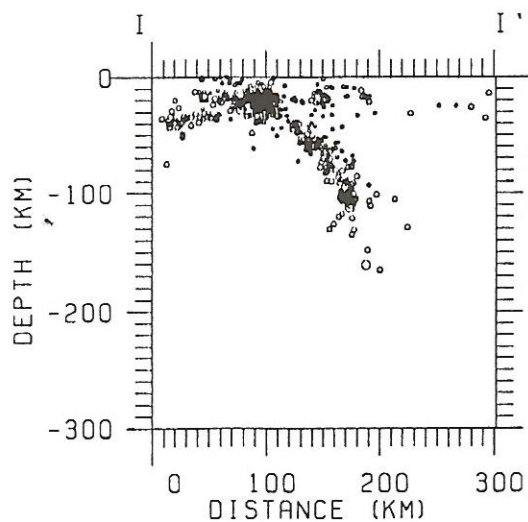
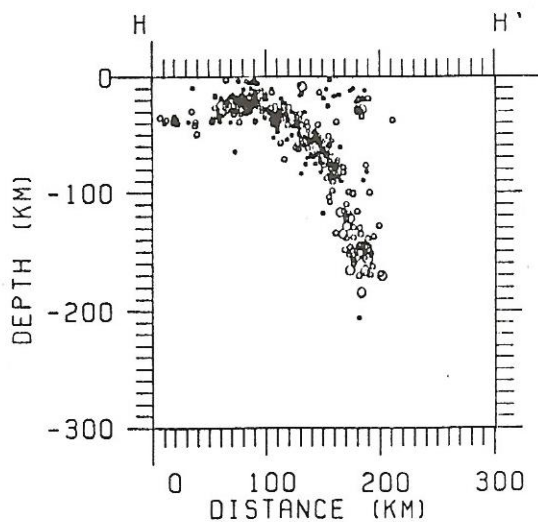
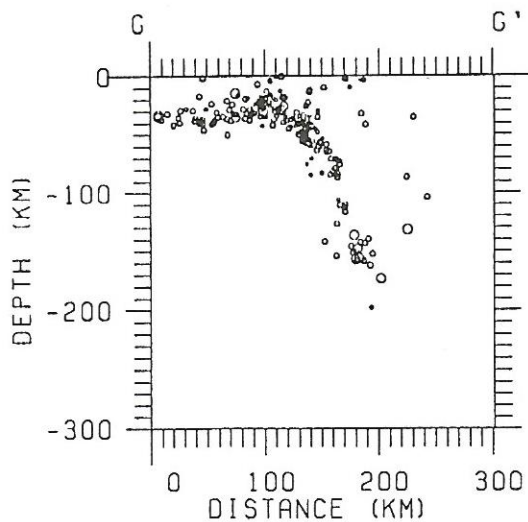
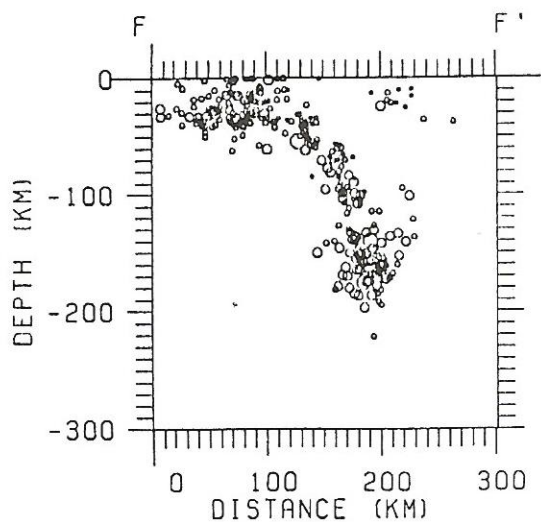
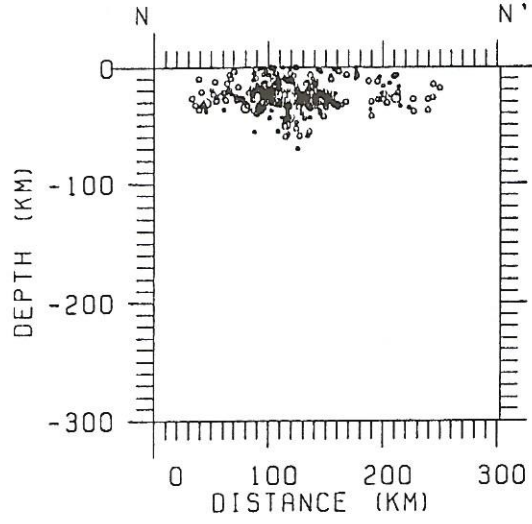
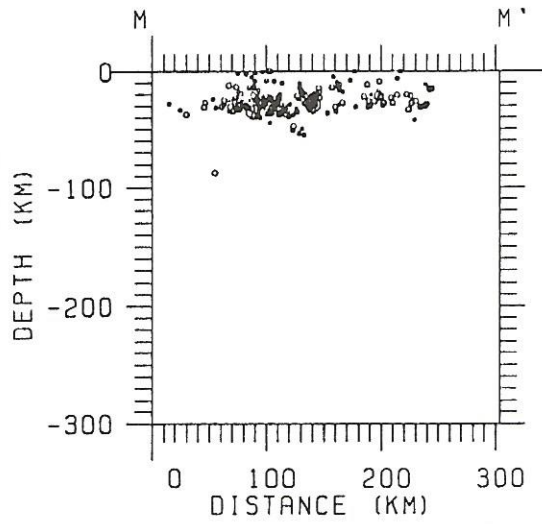
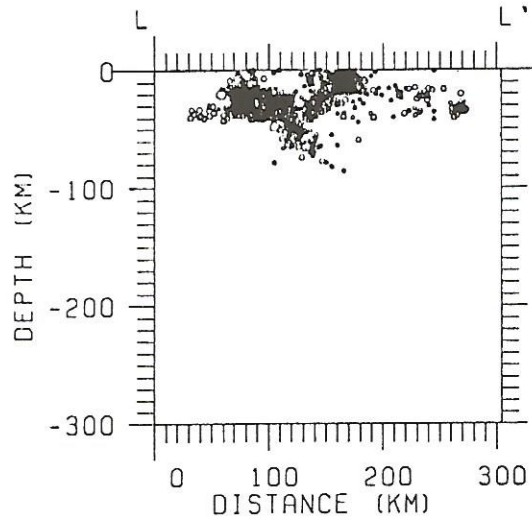
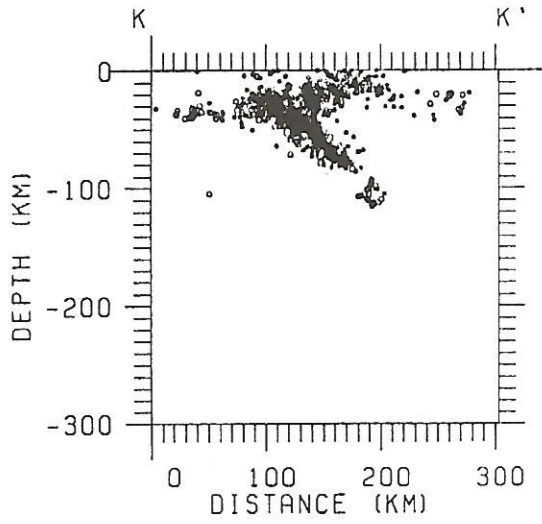


Figure 4 (on this and following two pages). Depth distribution of earthquakes on cross sections perpendicular to the Middle America Trench. See Figure 3 for location of the cross sections. For Nicaragua, earthquakes within 37.5 km on both sides of the profile line were plotted on the cross sections, whereas for Costa Rica that distance was only 25 km on each side.



MAGNITUDES

- 2.0+
- 3.0+
- ◊ 4.0+
- 5.0+
- 6.0+



MAGNITUDES

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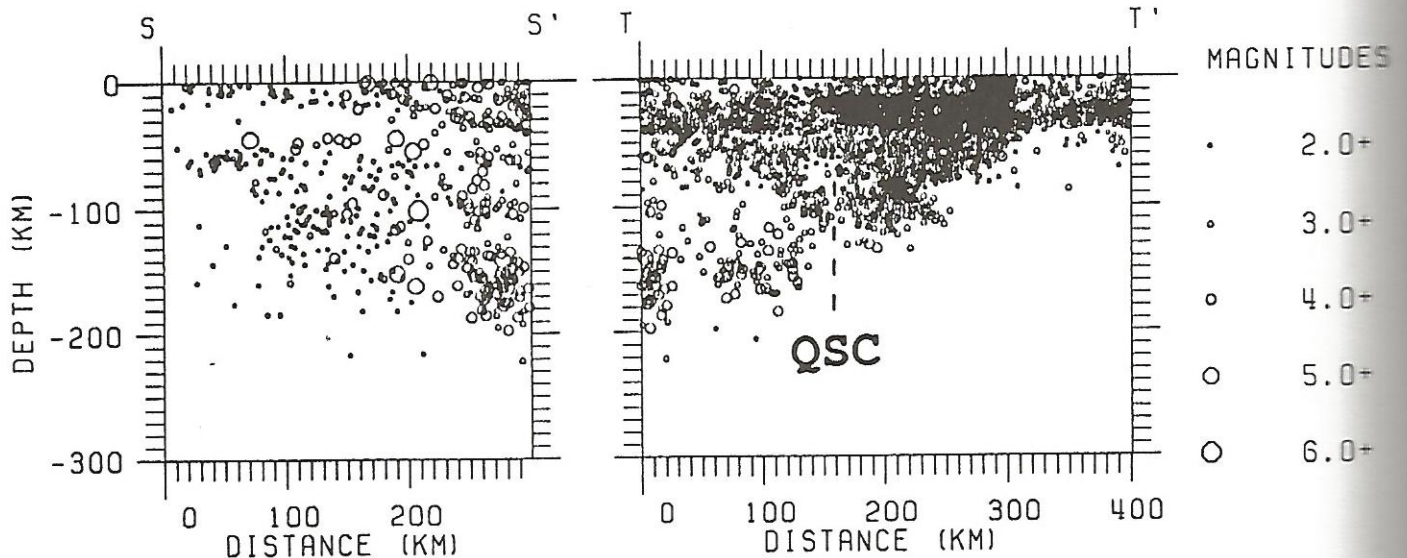


Figure 5. Depth distribution of earthquakes on cross sections parallel to the Middle America Trench. Also shown is the depth projection of the Quesada Sharp Contortion (QSC) discussed in the text. See Figure 3 for location of the cross sections.

tive volcanic chain. No evidence of Wadati-Benioff zone seismicity deeper than 50 km is found southeast of Punta Uvita (cross sections M-M' and N-N' on Figs. 3 and 4).

Relation of Wadati-Benioff zone geometry to volcanic arc

It is noteworthy that even though there is an abrupt displacement of the volcanic chain from Nicaragua to Costa Rica (Fig. 1), no major changes in the geometry of the seismic slab were found. In addition, no appreciable changes in the orientation of the volcanic chain axis exist across the Quesada Sharp Contortion. Nevertheless, and even though there are no changes in the orientation of the volcanic chain axis across the Quesada Sharp Contortion, Malavassi (1991) found important changes in the geochemical composition of Tertiary and Quaternary lavas across the contortion. In addition, he also found important geochemical signatures in the Aguas Zarcas cones (near Aguas Zarcas, Fig. 1), beneath which the Quesada Sharp Contortion has its maximum morphological expression. It is important to mention that by means of focal mechanisms (for events deeper than 50 km), no evidence has been found of either tearing along the Quesada Sharp Contortion or changes in the general internal deformation of the slab (Protti, 1991).

Variations in the shallow dip of the subduction zone

Because our earthquake location procedure uses a flat-layer velocity model (Matumoto et al., 1977), without lateral variations, the depth resolution for earthquakes offshore is not as good as for those events within the network. Therefore, the dip of the shallow part of the Wadati-Benioff zone is assumed constant from the trench axis to the shallower part of the resolved seismic slab (35 to 40 km) (i.e., the deepest extension

of the brittle coupling zone as defined by Protti, 1991). Given the bend of the trench axis off the southern tip of the Nicoya Peninsula, the subduction angle seems to change from 23° in northern Costa Rica to 30° in southern Costa Rica. Whether or not this feature is real cannot be ascertained until better depth resolution is obtained for events offshore (i.e., through a better crustal model).

MODEL FOR ALONG-STRIKE CHANGES IN THE WADATI-BENIOFF ZONE GEOMETRY AS A FUNCTION OF CHANGES IN AGE OF THE SUBDUCTED PLATE

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 northeast alignment. This 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 of the southern tip of the Nicoya Peninsula (Fig. 9); here the Fisher seamounts (von Huene et al., this volume) are being subducted as part of the Cocos plate. This bathymetric change (the northern "rough-smooth boundary" of Hey, 1977), mainly marked by the 3,000-m depth contour, reflects an age and, therefore, a density contrast on the Cocos plate on either side of the alignment (younger and lighter lithosphere on the southeast side) (Fig. 9). The ages shown in Figures 9 and 10, near the East Pacific Rise and the Galapagos Spreading Center, were obtained directly from the magnetic anomalies reported in the plate tectonic map by the Circumpacific Council for Energy and Mineral Resources (southeast quadrant) (1981). Farther from

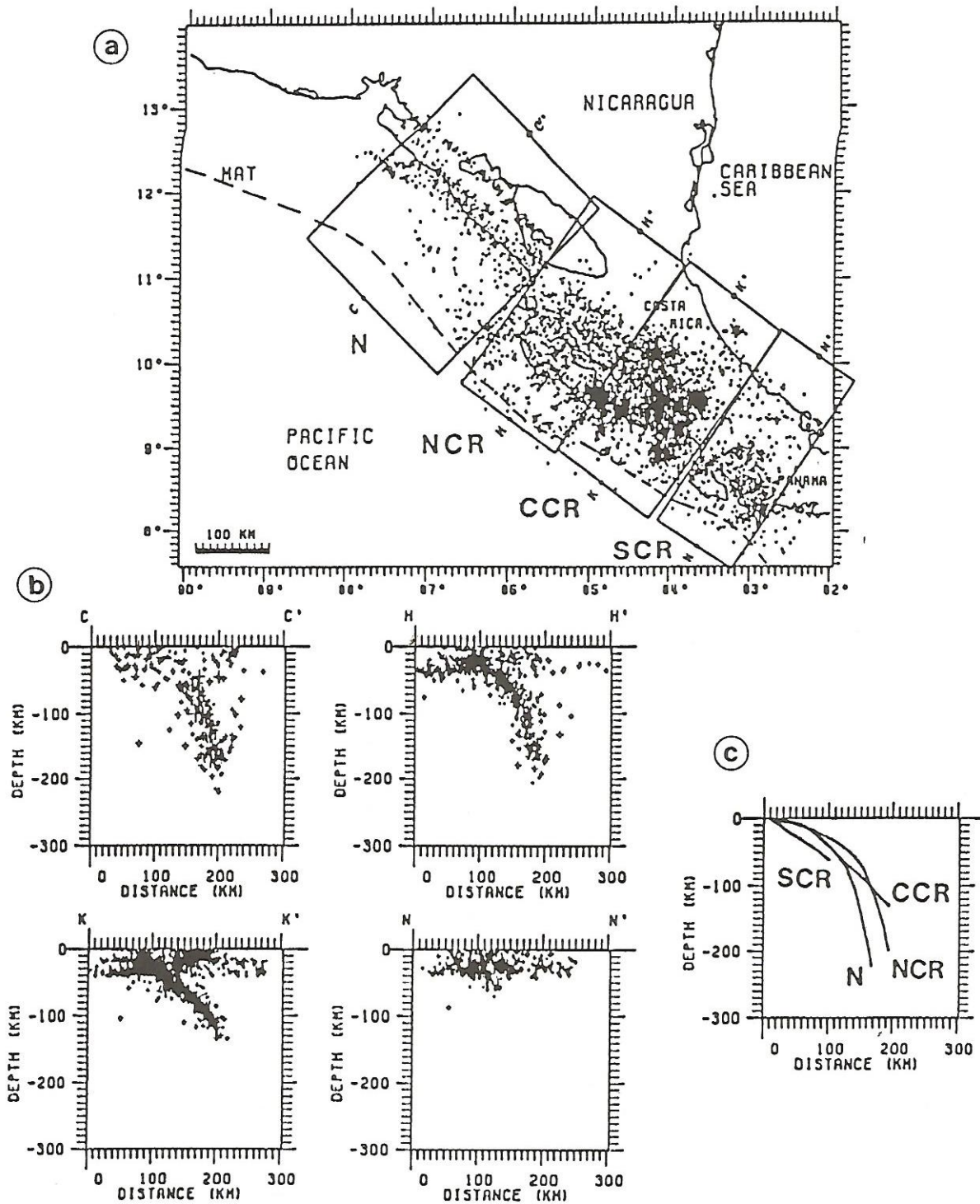


Figure 6. Subduction segments described in the text: N: Nicaragua; NCR: northern Costa Rica; CRR: central Costa Rica; SCR: southern Costa Rica. a, Map showing the area and seismicity covered by each segment; b, depth distribution of seismicity for each segment; c, overlapping of all segments with the trench axis as common point.

TABLE 2. PARAMETERS FOR EACH SUBDUCTION SEGMENT DESCRIBED IN THIS CHAPTER*

Subduction Parameters	Nicaragua		Northern Costa Rica		Central Costa Rica		Southern Costa Rica	
Length along trench (km)	~250		~150		~160		~120	
Trench depth (m)	NW-5,000	SE-4,500	NW-4,500	SE-3,400	NW-3,400	SE-2,000	NW-2,000	SE-2,000
Trench azimuth	N 40° W (320°)		N 50° W (310°)		N 65° W (295°)		N 65° W (296°)	
Arc-trench gap (km)	185		160		160		125	
Highest peak on inner arc (m)	1,745		2,028		2,919		3,819	
Age at trench (m.y.)	25–30		25–30		20–22		13–17	
Age at tip (m.y.)	30–35		30–35		20–22		17–19	
Convergence rate (mm ± 4/y)	NW-81	SE-86	NW-86	SE-89	NW-89	SE-92	NW-92	SE-95
WBZ length (km)	NW-260	SE-310	NW-310	SE-260	NW-240	SE-170	NW-100	
WBZ horizontal extent (km)	NW-180	SE-180	NW-180	SE-170	NW-210	SE-110	NW-110	
Dip (0–60 km)	25°		23°		24°		30°(?)	
Dip (0–100 km)	34°		32°		30°			
Dip (>100 km)	84°		80°		60°			
Maximum depth (km)	NW-160	SE-220	NW-200	SE-135	NW-125	SE-50	NW-45	
Strain class	3		4		5		6-7	
Slab pull force (*10 ¹² N/m)	11.0		11.0		8.1		3.7	
Largest earthquake (Ms)	7.2		7.7		7.0		7.6	

*Shown on map view and on cross section in Figure 6. 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 (see text and Figs. 9 and 10). Convergence rates are after De Mets et al., 1990; the dip ranges for the Wadati-Benioff zone (WBZ) are those used by Jarrard, 1986; and the strain classification is also that suggested by Jarrard, 1986. Values for strain class and slab pull force are from Protti, 1991.

the spreading centers (i.e., near the trench) the age was obtained following Hey (1977), Lonsdale and Klitgord (1978), Klitgord and Mammerickx (1982), and Mammerickx and Klitgord (1982) and from projections of spreading rates and spreading patterns of both rifts. The age obtained for the oceanic plate subducting under the Nicoya Peninsula is a conservative value (it could be over 40 m.y. old according to Klitgord and Mammerickx, 1982). The emphasis of this chapter is on relative age differences (or age contrasts across boundaries) rather than absolute ages, not available yet for this region.

The rough-smooth boundary marks the boundary between Cocos lithosphere created at the East Pacific Rise, to the north, and that created at the Galapagos Rift System, to the south. The northeast section of the rough-smooth boundary, which turns into the Quesada Sharp Contortion, is a relic of the fracture along which the Farallon plate broke into Cocos and Nazca plates between 25 m.y. (Hey, 1977) and 28 m.y. ago (Lonsdale and Klitgord, 1978). As a consequence of this opening, the age of the subducted plate under the Nicoya Peninsula is older and, in the direction of subduction, increases more rapidly than under the central Costa Rica. To clarify this, we have unbent the Wadati-Benioff zone, and with it our esti-

mated ages, to a dip of 0° (Fig. 10). This age distribution correlates not only to the steeper angle in the northwest segment and the shallower angle found in the southeast segment but also with an almost constant Wadati-Benioff zone dip angle in central Costa Rica, in contrast to the downdip increase in the angle under Nicaragua and northern Costa Rica. According to our age estimates the age contrast at the tip of the Wadati-Benioff zone (across the Quesada Sharp Contortion) is on the order of 5 to 10 m.y. (Figs. 9 and 10) and could be even larger. The age at the tip, shown in Figure 10, 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).

Age variations of this order are effective only in changing the Wadati-Benioff zone geometry for subduction of young, rapidly cooling lithosphere (less than 40 to 50 m.y. old) as in this case. Older lithosphere is almost thermally stable and does not experience major density and thickness changes (Leeds, 1975; Parsons and Sclater, 1977; Wortel, 1980; Sacks, 1983). Also, these changes in age have to occur abruptly across fracture zones, transform faults, ridges, or boundaries between plates generated at different spreading centers like the rough-smooth boundary.

Maximum depth of the seismic slab

The proposed age contrast also correlates with the deeper Wadati-Benioff zone under Nicaragua and with the shallower one under central Costa Rica. Such a correlation is to be expected since the deepest seismicity, which reflects the transition from brittle to ductile deformation in the slab as a response to gradual heating (Isacks et al., 1968; McKenzie, 1969), is also a function of the slab age (Vlaar and Wortel, 1976; Wortel and Vlaar, 1978). The slab length is also a func-

tion of convergence rate (e.g., Jarrard, 1986), but in our case differences in convergence rates are not significant (~ 5 mm/yr according to De Mets et al., 1990), and the faster rate occurs where the Wadati-Benioff zone is the shortest, contrary to what the model predicts. Thus, the slab age is the main parameter controlling the length and maximum depth of the Wadati-Benioff zone at the southern terminus of the Middle America Trench. 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 accounted for

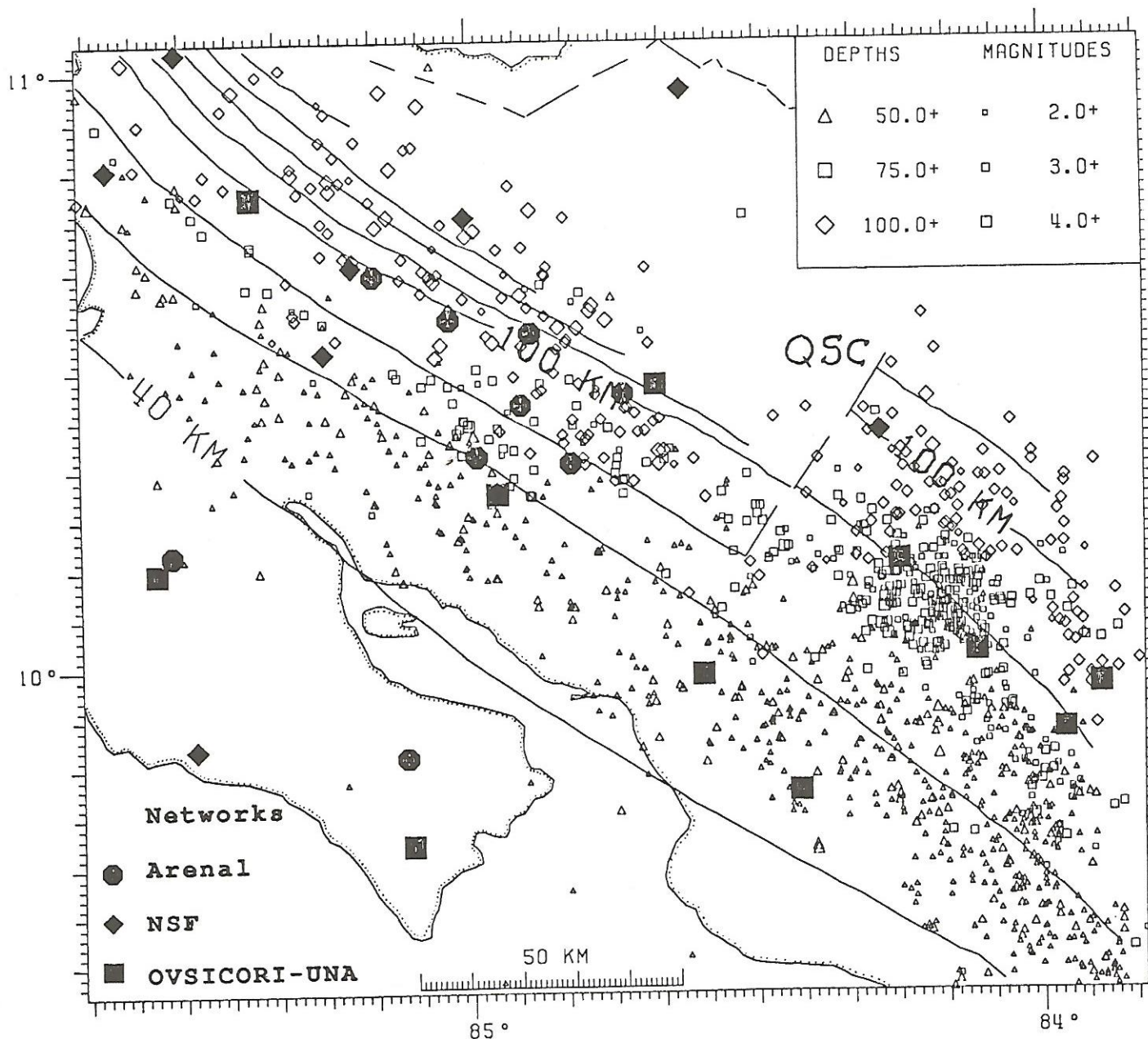


Figure 7. Detailed map of northern and central Costa Rica showing seismicity, station distribution, and the geometry of the top of the Wadati-Benioff zone obtained in this work. The Quesada Sharp Contortion (QSC) represents the boundary between two segments of the subducted Cocos plate with different ages and geometries. The different-sized squares that indicate magnitudes refer to the size for all of the symbols.

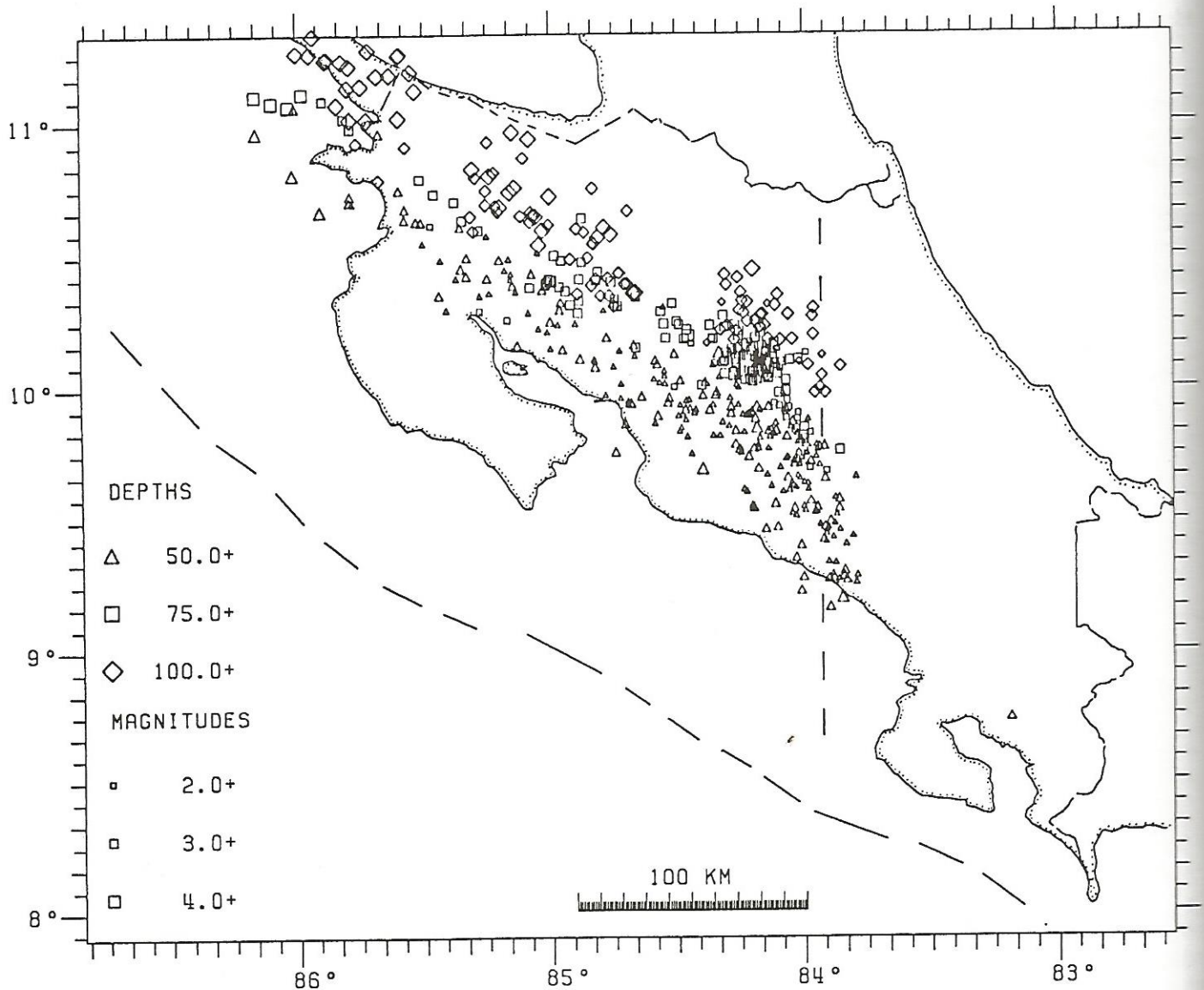


Figure 8. Epicentral distribution of earthquakes with focal depth greater than 50 km (DS09 of Table 1). Note the sudden termination of the seismicity within the slab east of the 83°55'W meridian. The different-sized squares that indicate magnitudes refer to the size for all of the symbols.

by lateral thermal assimilation, since the slab is being exposed to mantle heat flow from three directions: top, bottom, and laterally along the tear of the Quesada Sharp Contortion.

Southeast end of the seismic slab

The abrupt termination of the Wadati-Benioff zone at 83°55'W (Figs. 1 and 8) correlates with and is parallel to another along-trench age change (~5 m.y.) on the Cocos plate across a north-south transform fault that originated at the Cocos-Nazca spreading center. This fault marks the west limit of the Costa Rica rift and the east limit of the Ecuador rift (CRR and ECR on Fig. 9). East of the location where this fracture is being subducted, the oceanic plate is very young (~15 m.y.); its thermal structure is probably beyond the brittle-plas-

tic limit, and it therefore cannot deform elastically (i.e., lack of earthquakes beyond 50-km depth). We predict that this segment of the Cocos plate has to be subducting with a shallower angle than its western counterpart and probably bends upward, continuing an almost horizontal path like that found under Peru (Isacks and Barazangi, 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—and thus does not allow for an asthenospheric wedge between the plates. This driving mechanism precludes the oceanic plate from reaching the depth needed for the dehydration of the slab, thus inhibiting the subduction-related volcanic activity in southeastern Costa Rica. The underriding of the Cocos plate in southern

Costa Rica may also be responsible for the high compressive stress regime on the upper plate, which probably contributed to the genesis of the April 22, 1991 ($M_w = 7.6$), Valle de la Estrella earthquake (Fig. 1).

Cocos-Caribbean coupling and seismic risk

The differences in coupling between the Cocos and Caribbean plates, for Nicaragua and Costa Rica, can also be correlated with 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, corresponding to the subduction segments described in Table 2: northwestern Costa Rica (from Papagayo Gulf to the southeastern end of the Nicoya Peninsula), central Costa Rica (from the entrance of the Nicoya Gulf to northwestern Osa Peninsula), and southeastern Costa Rica (from Osa Peninsula to the inland projection of the Panama Fracture Zone). Historically, large ($M_s > 7.0$) underthrust earthquakes have occurred along the northwestern and southeastern segments but not within the central segment (Table 2).

The boundary between the northwestern and the central segment is the updip projection of the Quesada Sharp Contortion (i.e., the down dip projection of the rough-smooth boundary), marking a difference in the ocean-floor relief. Under the northwestern segment, relatively smooth plate is being subducted, 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 seamounts (von Huene et al., this volume), which reduces the coupling area to a set of smaller patches that can break by moderate ($M_s \leq 7.0$) earthquakes. Von Huene et al. (this volume) suggest that these seamounts act as asperities for large subduction earthquakes. We suggest that the small size of these asperities inhibits the nucleation of large subduction earthquakes and therefore reduces the seismic potential of the central segment. Based on this interpretation, the central segment can be classified as Kurile type according to the asperity model of Lay et al. (1982). The March 25, 1990, $M_s = 7.0$, earthquake at the entrance of the Nicoya Gulf (Protti and McNally, 1990) (Fig. 1) occurred at

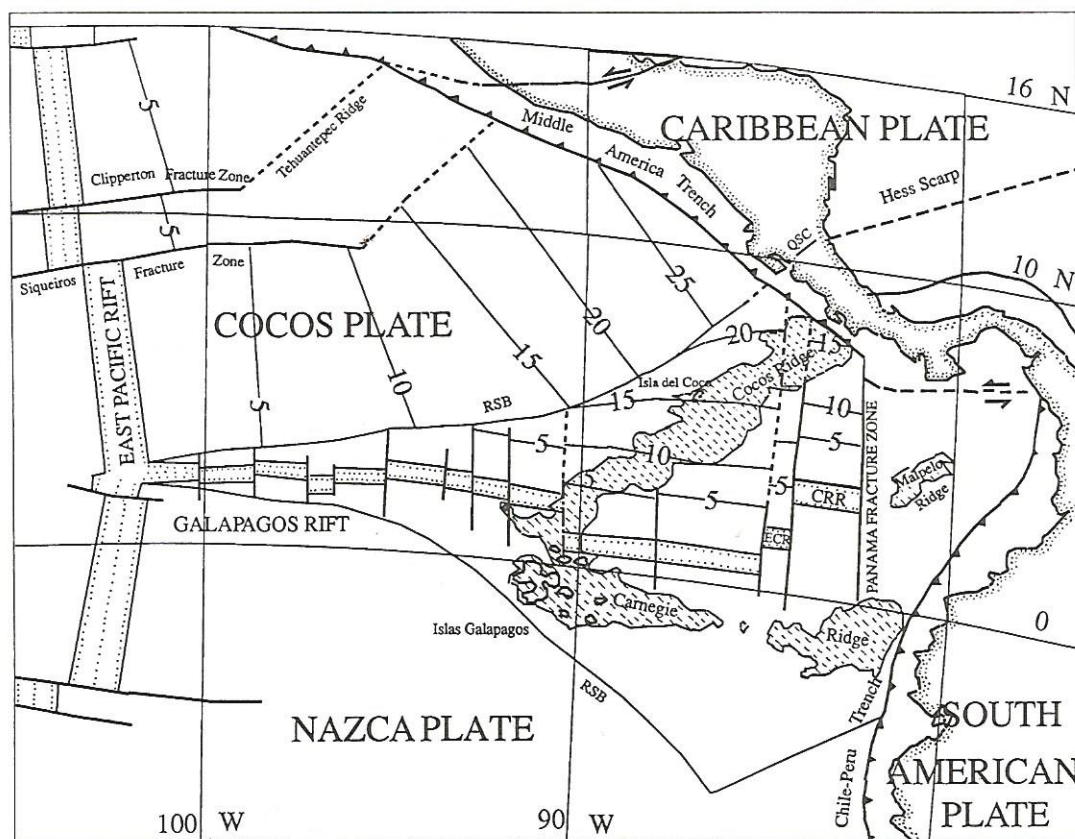


Figure 9. Distribution of lithospheric age, in m.y., of the Cocos plate. Base map is a segment of the plate-tectonic map of the Circum Pacific region, southeast quadrant (Circumpacific Council for Energy and Mineral Resources, 1981). The isochrons were drawn following the pattern of magnetic anomalies reported in that map and from projections of spreading rates of the East Pacific Rise and the Galapagos Rift. Dotted bands represent oceanic lithosphere created during the last million years. Cocos, Malpelo, and Carnegie Ridges are shown by the 2,000-m depth contour. The two 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.

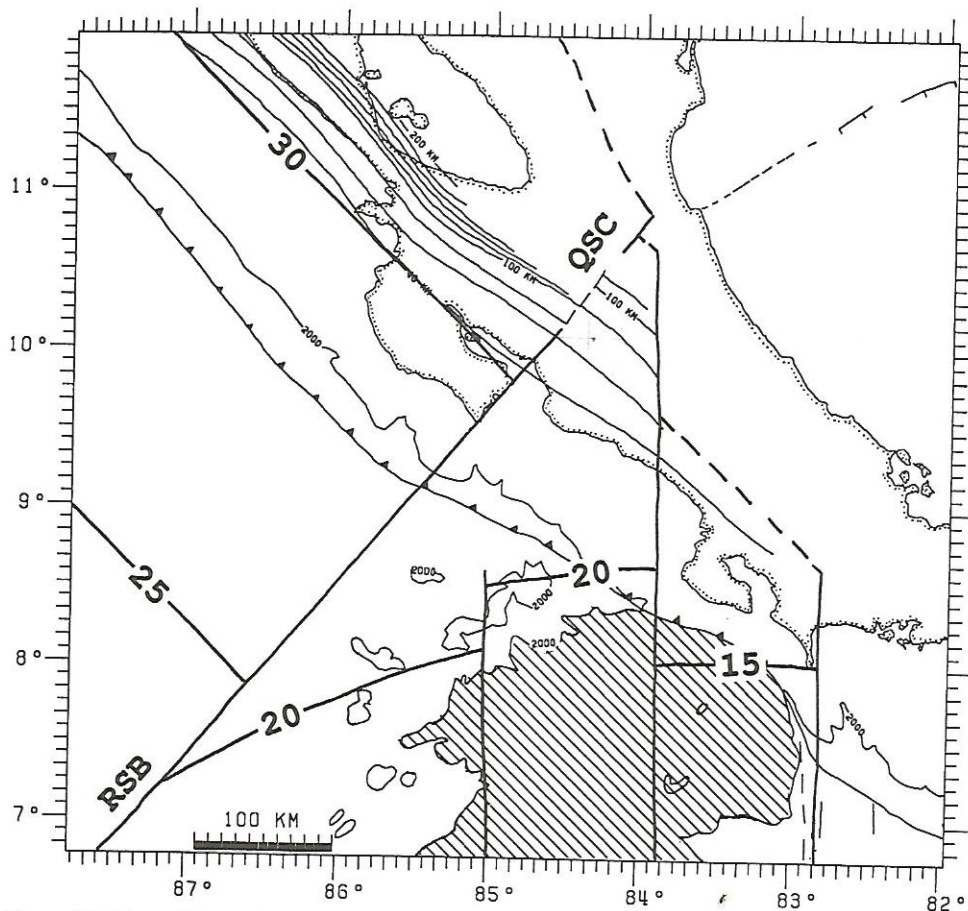


Figure 10. Map with projected lithospheric ages, in m.y., of the Cocos plate after unbending the seismic slab to a 0° dip angle. These projections of age are based on the spreading rates of the East Pacific Rise and the Galapagos Rift. Dashed line is the maximum extension of the seismic slab. Northwest of the Quesada Sharp Contortion (QSC) the subducted Cocos plate is older than under central Costa Rica. Also shown for reference are the isodepth contours (in kilometers) of the Wadati-Benioff zone. The Cocos Ridge is represented by the area enclosed by the 2,000-m depth contour; RSB is the rough-smooth boundary. Compare this figure with Figure 8.

the northwestern 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 northwestern and central segments: Even though it occurred right at the boundary between the segments, no aftershocks occurred toward the northwest (Protti and McNally, 1990) where a much stronger coupling exists (a locked gap) (Nishenko, 1989). Rather, all aftershocks occurred southeast of where the fracture initiated. Teleseismic analyses of the rupture propagation of that earthquake (Pacheco and Protti, 1990) agree with this interpretation.

The southeastern segment once again has a stronger coupling, relative to the central segment, as a result of the subduction of the Cocos Ridge, which is not only more buoyant but is also a much higher and more constant bathymetric anomaly. The expected existence of deeper roots beneath the Nicoya and Osa Peninsulas, practically absent in the central segment, may also contribute to the stronger coupling of the northwestern and southeastern segments with respect to the central one.

The roots of these peninsulas may not only act as bumps at the base of the overriding plate but also increase the vertical load on the coupling interface.

Analogous regions

The main correlation we are making in this chapter is of Wadati-Benioff zone geometries with abrupt changes in age of the oceanic plate. These abrupt changes occur across fracture zones, transform faults, ridges, or boundaries between plates generated at different spreading centers like the rough-smooth boundary.

Our model could be applied to 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 controls the Quesada Sharp Contortion, with abrupt changes of age, is on the same order as in Costa Rica.

Another possible analogy for the Costa Rica case may be represented by the differences in the subduction geometry found on either side of the Tehuantepec Ridge (Bevis and

Isacks, 1984). Across this ridge the plate shows a strong difference in bathymetry that may correspond with an abrupt change in age.

Southern Chile is another region where this model can be tested. We believe that a sharp contortion or tear might exist under southern Chile, where an abrupt jump in age on the order of 10 m.y. occurs across the Valdivia Fracture Zone on relatively young (20 to 30 m.y.) oceanic lithosphere of the subducted Nazca plate.

Another promising region in looking for the same Wadati-Benioff zone geometry variations discussed in this chapter is the South Sandwich subduction zone. A major change in trench depth across a fracture zone separating crust of very different ages is found there (Jarrard, 1986).

Furthermore, an analogous correlation to the one presented in this chapter was found by Farrar and Lowe (1978) for Peru and Chile. In that subduction zone conditions similar to those in Costa Rica are present, that is, the same convergence rates but abrupt contrasts in slab ages and slab lengths.

Subduction of the Cocos Ridge

The Cocos Ridge, here considered as the bathymetric high on the Cocos plate enclosed by the 2,000-m contour, subducts under southern Costa Rica. This ridge is one of the traces of the Galapagos hot spot (Hey, 1977) and therefore represent a thermal and density anomaly within the Cocos plate. Its buoyancy and bathymetric characteristics are responsible for the fast uplift rates of Osa and Burica Peninsulas (e.g., Corrigan et al., 1990; Gardner et al., 1992). Another effect that the subduction of the Cocos Ridge has in southern Costa Rica, as mentioned above, is an increase in the coupling between oceanic and upper plate.

Several dates have been suggested for the initiation of the subduction of the Cocos Ridge under southern Costa Rica: 0.5 Ma from onland work on the Pacific coast of Costa Rica and elastic deformation modeling (Gardner et al., 1992), 1 Ma from ocean-floor magnetic anomalies and plate reconstructions (Lonsdale and Klitgord, 1978), and 3.6 Ma from onland work on the Caribbean coast of Costa Rica and Panama (Collins et al., this volume). We believe the younger ages are correct since they better fit physical models of crustal deformation. Uplift of the Caribbean basins of Costa Rica and Panama can be accounted for by shortening and underthrusting along the Panama Thrust belt as observed after the April 24 1991, Valle de la Estrella earthquake. With 1 m.y. of subduction of the Cocos Ridge, its subducted portion would not be longer than 100 km. The presence of the Panama Fracture Zone, which truncated the Cocos Ridge around 9 m.y. ago (Lonsdale and Klitgord, 1978), also limits the northeastern extension of the subducted Cocos Ridge to ~100 km. This leads us to suggest that it is the subduction of young lithosphere across the transform fault that offsets the Costa Rica and Ecuador rifts that produces the shallow subduction under southern Costa Rica and not the subduction of the Cocos Ridge as postulated by several workers,

including ourselves (e.g., Adamek et al., 1987; Güendel et al., 1989; Corrigan et al., 1990; Kolarsky et al., this volume). Geochemical signals of igneous rocks outcropping in the Talamanca Cordillera indicate that the subduction of young lithosphere started in southern Costa Rica approximately 6 or 7 m.y. ago (de Boer et al., this volume).

CONCLUSIONS

A new model, based on age variations of the subducted Cocos plate along the Middle America Trench, correlates well with the complex geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica (the Quesada Sharp Contortion, changes in dip angle, length and maximum depth of the seismic slab) as well as with regional tectonic features on the overriding Caribbean plate, such as distinct stress field variations and the termination of the Central America Volcanic Chain. This model better correlates the changes in the Wadati-Benioff zone geometry than previous models based on the subduction of the Cocos Ridge.

The difference in coupling between the Cocos and Caribbean plates along the southern terminus of the Middle America trench can be associated with bathymetric features on the subducted Cocos plate. These bathymetric features are also related to age and genetic differences within the Cocos Plate.

All of the above conclusions make Nicaragua-Costa Rica a potential area in which to study subduction processes and effects in a small area with variations from mildly tensional- to compressional-type subductions. This subduction zone represents almost the entire spectrum from Marianas- to Chilean-type subductions of Wilson and Burke (1972) and Uyeda and Kanamori (1979).

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REFERENCES CITED

- Adamek, S., Tajima, F., and Wiens, D. A., 1987, Seismic rupture associated with subduction of the Cocos Ridge: *Tectonics*, v. 6, p. 757-774.
- Adams, R. D., and Ware, D. E., 1977, Subcrustal earthquakes beneath New Zealand: Locations determined with a laterally inhomogeneous velocity model: *New Zealand Journal of Geology and Geophysics*, v. 20, p. 59-83.
- Bevis, M., and Isacks, B. L., 1984, Hypocentral trace surface analysis: Probing the geometry of the Benioff zones: *Journal of Geophysical Research*, v. 89, p. 6153-6170.
- Burbach, G. V., and Frohlich, C., 1986, Intermediate and deep seismicity, and lateral structure of the subducted lithosphere in the Circum-Pacific region: *Reviews of Geophysics*, v. 20, p. 833-874.
- Burbach, G. V., Frohlich, C., Pennington, W. D., and Matumoto, T., 1984, Seismicity and tectonics of the subducted Cocos plate: *Journal of Geophysical Research*, v. 89, p. 7719-7735.
- Circumpacific Council for Energy and Mineral Resources, 1981, Plate-tectonic map of the Circum-Pacific region, southeast quadrant: *American Association of Petroleum Geology*, scale 1:10,000,000.
- Corrigan, J., Mann, P., and Ingle, J. C., 1990, Forearc response to subduction of the Cocos Ridge, Panama-Costa Rica: *Geological Society of America Bulletin*, v. 102, p. 628-652.
- De Mets, C., Gordon, R. G., Argus, D. F., and Stein, S., 1990, Current plate motions: *Geophysical Journal International*, v. 101, p. 425-478.
- Dewey, J. W., and Algermissen, S. T., 1974, Seismicity of the Middle America arc-trench system near Managua, Nicaragua: *Bulletin of the Seismological Society of America*, v. 64, p. 1033-1048.
- Farrar, E., and Lowe, R. M., 1978, Age-length dependence of inclined seismic zones: *Nature*, v. 273, p. 292-293.
- Gardner, T. W., and six others, 1992, Quaternary uplift astride the aseismic Cocos Ridge, Pacific coast, Costa Rica: *Geological Society of America Bulletin*, v. 104, p. 219-232.
- Güendel, F., 1986, Seismotectonics of Costa Rica: An analytical view of the southern terminus of the Middle America Trench [Ph.D. thesis]: Santa Cruz, University of California, Santa Cruz, 157 p.
- Güendel, F., and 14 others, 1989, First results from a new seismographic network in Costa Rica, Central America: *Bulletin of the Seismological Society of America*, v. 79, p. 205-210.
- Hey, R. N., 1977, Tectonic evolution of the Cocos-Nazca spreading center: *Geological Society of America Bulletin*, v. 88, p. 1404-1420.
- Isacks, B. L., and Barazangi, M., 1977, Geometry of Benioff zones: Lateral segmentation and downwards bending of the subducted lithosphere, *in* Talwani, M., and Pitman, W. C., III, eds., *Island arcs, deep sea trenches, and back-arc basins*: Maurice Ewing ser., vol. 1, Washington, D.C., American Geophysical Union, p. 99-114.
- Isacks, B. L., Oliver, J., and Sykes, L. R., 1968, Seismology and the new global tectonics: *Journal of Geophysical Research*, v. 73, p. 5855-5899.
- Jarrard, R. D., 1986, Relations among subduction parameters: *Reviews of Geophysics*, v. 24, p. 217-284.
- Klitgord, K. D., and Mammerickx, J., 1982, Northern East Pacific Rise: Magnetic anomaly and bathymetric framework: *Journal of Geophysical Research*, v. 87, p. 6725-6750.
- Lay, T., Kanamori, H., and Ruff, L., 1982, The asperity model and the nature of large subduction zone earthquakes: *Earthquake Prediction Research*, v. 1, p. 3-71.
- Leeds, A. R., 1975, Lithospheric thickness in the western Pacific: *Physics of the Earth and Planetary Interiors*, v. 11, p. 61-64.
- Lonsdale, P. F., and Klitgord, K. D., 1978, Structure and tectonic history of the eastern Panama basin: *Geological Society of America Bulletin*, v. 89, p. 981-999.
- Malavassi, E., 1991, Magma sources and crustal processes at the southern terminus of the Central American volcanic arc [Ph.D. thesis]: Santa Cruz, University of California, Santa Cruz, 148 p.
- Mammerickx, J., and Klitgord, K. D., 1982, Northern East Pacific Rise: Evolution from 25 m.y. B.P. to the present: *Journal of Geophysical Research*, v. 87, B8, p. 6751-6759.
- Matumoto, T., Othake, M., Latham, G., and Umaña, J., 1977, Crustal structure of southern Central America: *Bulletin of the Seismological Society of America*, v. 67, p. 121-134.
- McKenzie, D. P., 1969, Speculations on the consequences and causes of plate motions: *Geophysical Journal of the Royal Astronomical Society*, v. 18, p. 1-32.
- McLaren, J., and Frohlich, C., 1985, Model calculations of regional network locations for earthquakes in subduction zones: *Bulletin of the Seismological Society of America*, v. 75, p. 397-413.
- Nishenko, S. P., 1989, Circumpacific seismic potential 1989-1999: U.S. Geological Survey, National Earthquake Information Center open file report 89-86, 168 p.
- Pacheco, J., and Protti, M., 1990, The March 25, 1990, earthquake sequence at the entrance of the Nicoya Gulf, Costa Rica: Teleseismic source parameters and rupture history: *EOS (American Geophysical Union Transactions)*, v. 71, p. 1438.
- Parsons, B., and Sclater, J. G., 1977, An analysis of the variation of ocean floor bathymetry and heat flow with age: *Journal of Geophysical Research*, v. 82, p. 803-827.
- Protti, M., 1991, Correlation between the age of the subducting Cocos Plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica [M.Sc. thesis]: Santa Cruz, University of California, Santa Cruz, 66 p.
- Protti, M., and McNally, K., 1990, The March 25, 1990 (ML=6.8, Ms=7.0) earthquake sequence at the entrance of the Nicoya Gulf, Costa Rica: A near field study: *EOS (American Geophysical Union Transactions)*, v. 71, p. 1438.
- Sacks, I. S., 1983, The subduction of young lithosphere: *Journal of Geophysical Research*, v. 88, p. 3355-3366.
- Silver, E. A., Reed, D. L., Tagudin, J. E., and Heil, D. J., 1990, Implications of the north and south Panama thrust belt for the origin of the Panama orocline: *Tectonics*, v. 9, p. 261-281.
- Stoiber, R. E., and Carr, M., 1973, Quaternary volcanic and tectonic segmentation of Central America: *Bulletin of Volcanology*, v. 37, p. 304-325.
- Suarez, G., Monfret, T., Wittlinger, G., and David, C., 1990, Geometry of subduction and depth of the seismogenic zone in the Guerrero gap, Mexico: *Nature*, v. 345, p. 336-338.
- Sugi, N., and Uyeda, S., 1984, Subduction of young oceanic plates without deep focus earthquakes: *Bulletin de la Societe Gologique de France*, v. 26, p. 245-254.
- Uyeda, S., and Kanamori, H., 1979, Back-arc opening and the mode of subduction: *Journal of Geophysical Research*, v. 84, p. 1049-1061.
- Vlaar, N. J., and Wortel, M.J.R., 1976, Lithospheric aging, instability, and subduction: *Tectonophysics*, v. 32, p. 331-351.
- Wilson, J. T., and Burke, K., 1972, Two types of mountain building: *Nature*, v. 239, p. 448-449.
- Wolters, B., 1986, Seismicity and tectonics of southern Central America and adjacent regions with special attention to the surroundings of Panama: *Tectonophysics*, v. 128, p. 21-46.
- Wortel, R., 1980, Age-dependent subduction of oceanic lithosphere [Ph.D. thesis]: Utrecht, The Netherlands, State University of Utrecht, 147 p.
- Wortel, M.J.R., and Vlaar, N. J., 1978, Age-dependent subduction of oceanic lithosphere beneath western South America: *Physics of the Earth and Planetary Interiors*, v. 17, p. 201-208.
- Yamaoka, K., Fukao, Y., and Kumazawa, M., 1986, Spherical shell tectonics: Effects of sphericity and inextensibility on the geometry of the descending lithosphere: *Reviews of Geophysics*, v. 24, p. 27-53.