# Seismological evidence on the geometry of the Orogenic System in central-northern Ecuador (South America)

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# Seismological evidence on the geometry of the orogenic system in central-northern Ecuador (South America)

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**Abstract.** Analysis of the spatial distribution of seismicity beneath central Ecuador from a temporary network gives new insights on two main points of the Ecuadorian tectonics. Major structures in the Ecuadorian Andes are East-dipping Late Jurassic to Paleogene sutures reactivated by present-day compression. The oceanic plate is plunging continuously down to a depth of about 200 km with a dip of 25°-35°. We also show that the coastal plain acts as a buttress transmitting stresses to the Andes, beneath which deformation is concentrated.

## 1. Introduction

The Andes are regarded as a tectonically thickened magmatic arc, resulting from the eastward subduction of the Nazca oceanic plate beneath the South American continental plate. The Andean orogeny is bounded to the West by the trench, and to the East by an east-verging fold and thrust belt (Subandean Zone) [Mégard, 1989; Allmendiger et al., 1997]. The Northern Andes (Ecuador, Colombia) differ from the Central Andes (Peru, Bolivia, northern Chile) by the presence of oceanic terranes accreted in their western part [Gansser, 1973; Reynaud et al., 1999] and by a poorly developed subandean fold and thrust belt to the East [Rivadeneira and Baby, 1999].

The Andes of Ecuador are made of two cordilleras (Figure 1) separated by the Interandean Valley. The Western Cordillera and the Coastal Plain are made of oceanic terranes accreted from Late Jurassic to Eocene. The first accretion, of Late Jurassic-Early Cretaceous age (≈ 140-130 Ma), involved continental and oceanic terranes, remnants of which crop out along a suture located on the western slope of the Eastern Cordillera [Litherland et al., 1994] (1 in Figure 1). Then, Cretaceous oceanic plateaus and island arcs were accreted during Late Cretaceous times (≈ 85 to 65 Ma) [McCourt et al., 1998; Reynaud et al., 1999]. The resulting sutures are located along the Western Cordillera [McCourt et al., 1998] (2 in Figure 1). The western part of the Western Cordillera and the Coastal Plain are made of oceanic plateaus and island arcs accreted during the Early Tertiary (≈ 58-38 Ma) [Jaillard et al., 1997; Hughes and Pilatasig, in press] (suture 3 in Figure 1). The metamorphic Eastern Cordillera is in tectonic contact with the Subandean zone by means of a major NNE-trending, west-dipping reverse fault system [Litherland et al. 1994] (B in Figure 1). Finally, the Subandean zone is separated from the Oriente Basin by a NNE-trending, steep West-dipping reverse fault (A in Figure 1) [e.g. Mégard, 1989; Rivadeneira and Baby, 1999].

The processes and geometry of the accretions are debated. For some authors, they occurred along West-dipping planes and were locally associated with Eastward obduction [Bourgois et al., 1987; 1990; Tibaldi and Ferrari, 1993]. Others support an East-dipping geometry of the sutures expressing the paleo-subduction planes [e.g. Mégard, 1989; Jaillard et al., 1997; Taboada et al., 2000].

Finally, because of scarce data, the geometry of the oceanic slab is poorly constrained. According to most authors, the slab is subducting eastwards with a 25 to 40° dip [Lonsdale, 1978; Pennington, 1981; Prévot et al., 1996; Taboada et al., 2000]; whereas Gutscher et al. [1999, 2000a, 2000b] propose a 100 km deep flat slab beneath the Ecuadorian Andes, as far as 500 km from the trench.

This paper presents seismological data from a temporary network, which bring new information regarding (1) the dip of the sutures and (2) the geometry of the subducting slab.

## 2. Data

From December 1994 to May 1995, a network of 54-1Hz seismic stations (19 3-C, 35 1-C) ran in the northern part of the Ecuadorian Andes, between 80°W - 77.4°W and 0.1° S - 1.5° S, within the Ecuadorian network (27 telemetred 1C, 1Hz stations) of the Instituto Geofísico of Quito.

Arrival times were read using the Sismalp library [Fréchet and Thouvenot, 1992]. Hypocenters were located using the HYPOINVERSE program [Klein, 1978]. We used a flat layered velocity model, built the following way : (1) between 0 and 75 km depth we used the velocity column located underneath the Interandean Valley of the 3D model from the inversion results

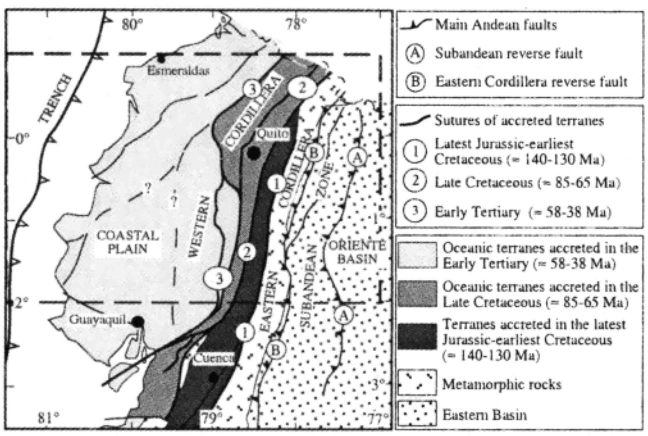


**Figure 1.** Sketch map of Ecuador with main morphological zones. Numbers refer to Late Jurassic to Early Tertiary sutures. Letters refer to main Andean faults. The dashed rectangle delimits the studied area.

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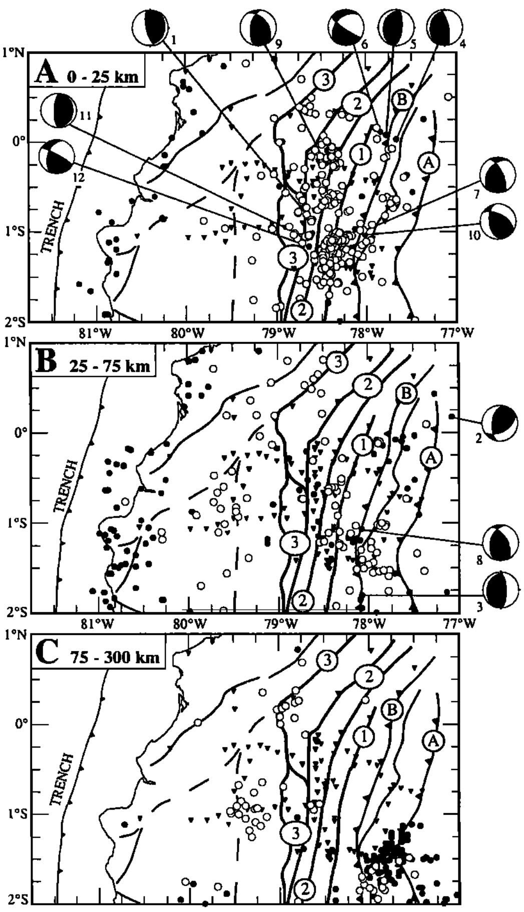


**Figure 2.** Maps showing the seismicity distribution in depth ranges A, 0-25 km; B, 25-75 km; and C, 75-300 km. Open circles represent events located using the temporary network data. The circle size equals the maximum estimated location error (5 km). Filled circles represent earthquake locations from Engdahl et al. [1998]. Down closed triangles represent seismic stations. Focal mechanisms were obtained using parameters of Table 1. Numbers and letters as in Figure 1

of Prévot et al. [1996], as about 75% of the events are located beneath the Interandean Valley, and (2) below 75 km we used a velocity of 8.61 km/s, the velocity of the block adjacent to the previously mentioned column, where most of the deeper events occur. Each layer has a Vp/Vs ratio of 1.737 obtained independently of the earthquake locations with a (S-S) versus (P-P) diagram. No changes were observed in the seismicity distribution by relocating the earthquakes using successively the maximum velocity, the minimum velocity, and the average velocity of each layer of the 3D model of Prévot et al. [1996]. Thus, the picture revealed by the seismicity distribution does not seem to be affected by lateral variations of the velocity model and is not an artifact of the location process.

1063 events, in the magnitude range 2.2 - 5.1, have been located. Magnitudes were computed from earthquake signal duration using a locally determined empirical relationship. From the initial set of events, 567 were selected using the following criteria: P-arrival times ≤ 6, S-arrival times ≥ 1, RMS ≤ 0.4, ERH and ERZ ≤ 5, and condition number ≤ 90. The average parameters of the selected events are: RMS = 0.26 ; ERH = 1.7 and ERZ = 2. Moreover, thanks to the relatively dense station distribution, about 75% of the shallow events are located at a distance from the nearest station that is less than 1.5 times their depth, providing a quite good control on the depth of most of the selected events. We can thus estimate the maximum location error to be no more than 5 km.

This data set is complemented by the 1964 - 1995 events (Mw ≥ 5.2), relocated by Engdahl et al. [1998].

## 3. Seismicity patterns

About 50% of the total seismic activity is concentrated in a narrow area between 1°S - 1.25°S and 78.25°W - 78.6°W and 0-25 km depth, known as the Pisayambo nest. Except for this nest, seismic activity is mostly shallow: about 50% of the remaining events are shallower than 25 km.

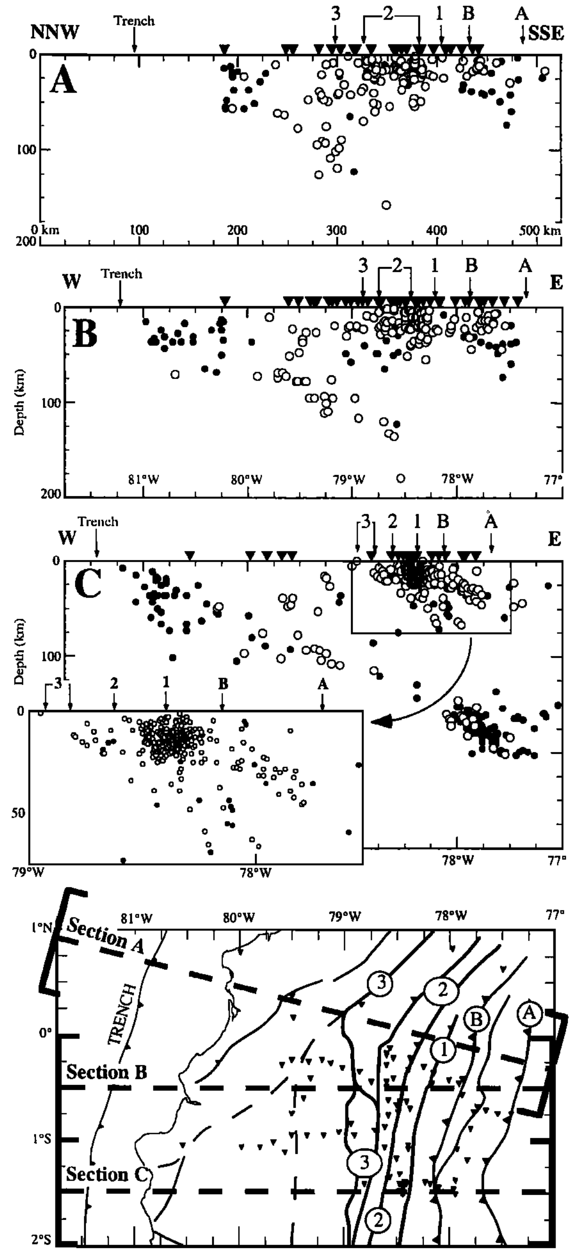


**Figure 3.** Projections of hypocenters onto vertical planes. Thick dashed lines in bottom map show traces of planes on the surface. Earthquakes were selected between the brackets shown at the ends of each cross-section. Earthquake and station symbols as in figure 2. The circle size equals the maximum estimated location error (5 km). Numbers and letters above sections as in Figure 1. Note that the continuous slab is observed only when hypocenters from the temporary network (i.e. open circles) are used.

**Table 1.** Parameters of focal mechanisms shown on Figure 2 (from Dziewonski et al. [1981], except event 1 from Pennington [1981]). Locations from Engdahl et al. [1998].

| n° | Date | Lat. | Long. W | Dep km | $M_w$ | NP1 Strike-dip | NP2 Strike-dip |
|---|---|---|---|---|---|---|---|
| 1 | 76/10/06 09:12 | 0.726 S | 78.732 | 3.9 | 5 8 | 161-72 | 013-20 |
| 2 | 83/05/19 19:07 | 0.179 N | 77.071 | 25.5 | 5.2 | 060-49 | 189-54 |
| 3 | 84/04/28 20:12 | 1.813 S | 78.090 | 46 9 | 5.6 | 199-26 | 358-65 |
| 4 | 87/03/06 01:54 | 0.038 N | 77 662 | 12 8 | 6.4 | 198-20 | 348-73 |
| 5 | 87/03/06 04:10 | 0.081 N | 77.777 | 17.8 | 7 1 | 195-27 | 007-64 |
| 6 | 87/03/06 08:14 | 0 113 N | 77.852 | 5.7 | 6.0 | 226-40 | 125-81 |
| 7 | 87/09/22 13:43 | 1.010 S | 78.030 | 4.7 | 6.3 | 218-42 | 334-68 |
| 8 | 87/09/22 16.21 | 1.070 S | 78.082 | 48.4 | 5.9 | 197-42 | 330-59 |
| 9 | 90/08/11 02:59 | 0.166 S | 78.480 | 16.8 | 5.2 | 323-45 | 190-55 |
| 10 | 92/12/26 14:57 | 1.029 S | 78.024 | 6.1 | 5.8 | 200-46 | 300-80 |
| 11 | 96/03/28 23:03 | 1.065 S | 78 666 | 18.5 | 5.8 | 008-21 | 182-69 |
| 12 | 96/08/25 14:08 | 1.159 S | 78.643 | 15.0 | 5.4 | 172-48 | 300-55 |

### 3.1. Upper plate seismicity

The shallow (0-25km) low magnitude seismicity is concentrated beneath the Andean Cordillera, especially between the Early Tertiary suture (3) and the Eastern Cordillera reverse fault (B) (Figure 2A). There is an outstanding lack of shallow seismicity between the trench and the western slope of the Andes, except for a strip of magnitude ≥ 5 events restricted to the coastal line area. A lower level of activity is also observed in the Sub-Andean zone, between faults B and A (Figure 2A), while there is no activity in the Oriente Basin, East of fault A.

At intermediate depths (25 to 75 km), seismic activity is distributed throughout the area. There are almost no M≥ 5 events in the Coastal Plain (Figure 2B).

Beneath the Andes, the shallow to intermediate events are clearly bounded by two east-dipping lines which intersect the surface at the location of suture 3 and fault B (Figure 3). Moreover, parallel linear patterns can also be observed, which cut the surface at the locations of sutures 2 and 1 (Figure 3C). Although less clear north of 1°S, these linear patterns extend down to depths ranging between 50 km and 70 km (Figure 3C). There is no seismic expression of fault A (Figure 3).

### 3.2. Lower plate seismicity

The Wadati-Benioff zone dips with an angle evolving from 35° in the North to 25° in the South, reaching a depth of at least 150 km in the North and 200 km in the South (Figure 3). The image obtained by combining the 1964 - 1995 world-wide relocations by Engdahl et al. [1998] and the locations from our temporary experiment show that the subducting slab is continuous down to the deepest earthquake locations (Figure 3). Note that the slab continuity shows up only when using the locations of the temporary network (Figure 3), and that using only events strong enough to be recorded world-wide led Gutscher et al. [1999, 2000a, 2000b] to evidence a flat slab.

## 4. Discussion

### 4.1. Upper plate structures

Disagreements about the dip orientation of the main Andean faults arise from the fact that outcrops present subvertical fault planes [e.g. McCourt et al., 1998]. Our results strongly support the interpretation of East dipping suture planes. The seismic activity exhibits parallel linear features dipping eastward with an angle of about 35°, which intersect the surface at the locations of sutures 1, 2, and 3. These features clearly show up south of 1°S (Figure 3C) and can be inferred north of 1°S (Figures 3A and 3B). We interpret this seismic activity as the reactivation of the sutures linked to the Late Jurassic to Early Tertiary accretions of oceanic terranes.

These sutures have been deformed only in their upper part and are reactivated by compressional and strike-slip movements due to the ocean-continent convergence [Jaillard et al., 1997]. Tectonic analysis demonstrated that the dextral strike-slip fault which bounds to the East the Western Cordillera of Central Ecuador (0° - 2.5°S), crosscuts and reactivates the Late Cretaceous sutures [Winter and Lavenu, 1989; Winter et al., 1993; McCourt et al., 1998]. Similarly, in the Eastern Cordillera of Northern Ecuador (0° - 1°N), a dextral strike slip fault reactivates the Late Jurassic-Early Cretaceous suture [Tibaldi and Ferrari, 1992; Ego et al., 1996]. Such a deformation regime probably triggered the creation of double-verging flower structures, as observed in the Western Cordillera.

Conversely, there is a general agreement on the West-dipping geometry of the two eastern Andean major faults (A and B) [e.g. Mégard, 1989; Litherland et al., 1994]. However, our data show that fault B may also be related to an East-dipping seismically active deep plane (Figure 3C). Since the eastern areas underwent dominantly transpressional deformations [Rivadeneira and Baby, 1999], the superficial West-dipping fault B could merge into the deep East-dipping major plane, as frequently observed in flower structures. While fault A cannot be related to any seismic plane, almost no seismicity occurs East of that fault (Figures 2 and 3). This fault seems therefore to be the eastern limit of the Andean deformation, thus confirming the lack of fold and thrust belt in the eastern areas of Ecuador [Rivadeneira and Baby, 1999].

Focal mechanisms exhibit a plane dipping westward with an angle of roughly 60° and a plane dipping eastward with an angle of roughly 40° (Figure 3, Table 1). They are therefore compatible with both interpretations, depending on which plane is chosen as the fault plane. Thus, they do not conflict with our interpretation of east-dipping planes related to sutures 1, 2 and 3 as well as to fault B.

The absence of activity east of fault A together with the significant lack of seismicity shallower than 25 km between the trench and the western slope of the Western Cordillera indicates that deformation is concentrated beneath the Andes. The lack of shallow coastal seismicity suggests that the basement of the Coastal plain presently acts as a rigid, virtually undeforming body that transmits to the Andes the stress originating along the interplate coupling surface.

Seismic activity between 25-50 km depth beneath the coastal zone suggests a 40 to 50 km-thick crust, which supports the oceanic plateau nature of the accreted terranes indicated by geochemical studies [Reynaud et al., 1999; Mamberti, 2001], although Tertiary shortening may partly account for the currently observed thickness.

The strong seismic activity observed beneath the Andes to depths of 50 to 75 km suggests a 50 to 75 km thick crust beneath the chain, in accordance with the at least 50 km deep Moho determined by Prévot et al. [1996] from seismic wave inversion. Thus, although their mean elevation is lower, the crustal root of the Ecuadorian Andes is comparable to the continental root of high plateaus like the Altiplano. This apparent contradiction is accounted for by the higher density of the oceanic material underplated beneath Ecuador.

### 4.2. Lower plate structure

The spatial distribution of the lower plate seismicity shows a continuously plunging slab down to a depth of about 200 km with an angle varying from 35° in the North to 25° in the

South. This is in accordance with the results of Lonsdale [1978], Pennington [1981] and Prévot et al. [1996], who determined a 25° and 30° dipping slab between 1°N - 2°S, and 1.5°N - 2.5°S, respectively, plunging continuously down to a depth of at least 200 km.

Our results contradict the interpretation of Gutscher et al. [1999, 2000a, 2000b] who proposed that the slab becomes flat at a depth of 80-100 km and extends eastwards as far as 500 km from the trench. As already pointed out, this apparent flat slab is an artifact due to the fact that they used only events recorded worldwide. Consequently, the present adakitic arc magmatism of Ecuador is probably not due to slab melting as proposed by Gutscher et al. [2000b]. As to why only small events occur between depths of about 80 and 150 km is beyond the scope of this paper.

## 5. Conclusions

Analysis of the spatial distribution of the seismicity from a local temporary network installed in central-northern Ecuador provides important insights on two tectonic issues that are currently debated:

(1) major active structures in the Andes of Ecuador are Late Jurassic to Early Tertiary East-dipping sutures reactivated by present day compression;

(2) the down-going plate is plunging with a dip of 25°-35°and is continuous down to a depth of about 200 km.

This data set also shows that deformation is concentrated beneath the Andes, while the Coastal plain acts as a buttress transmitting the stress to the Andes. Finally, there are elements favoring a crustal thickness of about 40-50 km under the coastal plain and of 50-70 km beneath the Andes.

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