TECTONICS, VOL. 12, NO. 1, PAGES 63-76, FEBRUARY 1993

BASEMENT SEISMICITY BENEATH THE ANDEAN PRECORDILLERA THIN-SKINNED THRUST BELT AND IMPLICATIONS FOR CRUSTAL AND LITHOSPHERIC BEHAVIOR

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Abstract. Data from a digitally recording seismic network in San Juan, Argentina, provide the first images of crustal scale basement faults beneath the Precordillera. This seismicity is near the boundary between the Precordillera (a thin-skinned thrust belt) and the Sierras Pampeanas (a region of thick-skinned basement deformation), two seismically active tectonic provinces of the Andean foreland. The seismicity data support models for this region in which crustal thickening, rather than magmatic addition or thermal uplift, plays the dominant mountain building role. The Precordillera seismicity occurs in three segments distributed north to south. The southern segment is an area of diffuse activity extending across the Precordillera and eastward into the Sierras Pampeanas that shows no patterns in map or cross section. The northern and central segments have well-defined dipping planes that define crustal scale faults extending from 5 to 35 km depth. It is clear from the relative fault geometries that the overlying Precordillera is not simply related to the basement activity. The seismicity here may result from reactivation of an ancient suture between the Precordillera and Pampeanas terranes or be occurring in basement of unknown affinity west of the suture. The seismicity provides the first constraints on basement fault geometries, and we present models integrating this information with the surface geology. These basement faults may have been responsible for the 1944 Ms 7.4 earthquake that destroyed the city of San Juan. The imaging of these faults suggests that seismic risk estimates for San Juan made on the basis of surface geologic studies may be too low.

INTRODUCTION

The Andes provide a unique laboratory to study mountain belt formation in a subduction-driven but noncollisional environment. The present orogen began in the Jurassic, driven by subduction of the oceanic Nazca plate beneath the continental South American plate. The modern Andes are due to Neogene tectonics characterized by along-strike segmentation of major features of the subducted and overriding plates [Barazangi and Isacks, 1976; Jordan et al., 1983] (Figures 1 and 2). In addition, the along-strike features of the two plates are correlated, both spatially and in their temporal development. Between 15°S and 24°S the Altiplano-Puna plateau, the Eastern Cordillera and Subandean Zone thrust belts, and an active volcanic arc are located above a moderately dipping Wadati-Benioff zone (WBZ). In contrast, a narrow thin-skinned thrust belt (Precordillera), a wide zone of basement uplifts (Sierras Pampeanas), and an extinct arc are located above an intermediate-depth subhorizontally subducting WBZ between 28°S and 33°S. Shutdown of volcanism, onset of Pampean and Precordilleran crustal deformation, and development of flat subduction are thought to coincide at 10-15 Ma [Jordan et al., 1983]. The Sierras Pampeanas and the Precordillera are thought to have a tectonic relationship similar to that of the Mesozoic Sevier and Laramide provinces of North America, which are also thought to have developed over a region of flat subduction [Dickenson and Snyder, 1978; Fielding and Jordan, 1988].

The Andean orogen is seismically active, and variations of crustal intraplate seismicity in the overriding plate correlate with the along-strike variations of tectonic style (Figure 2). Crustal seismicity is concentrated in a narrow band along the eastern margin of the foreland in areas over normal subduction, while above flat subduction a wide area of the foreland, with thin- and thick-skinned tectonic provinces, is highly active seismically. The easternmost limit of crustal seismicity coincides with the easternmost WBZ activity in both flat and steep subduction regions. The depth of crustal earthquakes also correlates with tectonic style. In regions of normal subduction, seismicity occurs in the upper and mid crust to depths of 25 km [Cahill et al., 1992], while in areas of flat subduction crustal events occur at mid and lower crustal depths to 40 km [Smalley and Isacks, 1990; Suárez et al., 1983]. This variation may be due to regional differences in lithospheric or crustal stress, strain rate, crustal geotherm, or rheology, both across and along the orogen.

GEOLOGY

Precordillera. The Precordillera is a thin-skinned thrust belt of Paleozoic clastics divided into three structural subprovinces: Western, Central, and Eastern (Figure 3) [Baldis, 1975; Ortiz and Zambrano, 1981; Baldis et al., 1982]. The Central and Western provinces form the foreland thrust belt found on the cratonic side of compressional orogens. These mountain belts are interpreted as the result of a crustal shortening across an orogen in which crustal thickening associated with A-type subduction occurs along a major intracontinental thrust [Bally, 1981]. Crustal material from the orogen proper is thrust cratonward over relatively undeformed foreland basement, pushing the foreland basin sediments into a thin-skinned thrust belt. This thrust belt is typically the cratonwardmost limit of deformation associated with an orogenic system. The development of these thrust belts generally follows a set of rules, derived from geologic studies [Chapple, 1978; Dahlstrom, 1970; Davis et al., 1983] and physical models of deformation [Panian and Pilant, 1990] describing the spatial and temporal evolution of their structures.

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Paper number 92TC01108.
0278-7407/93/92TC-01108$10.00

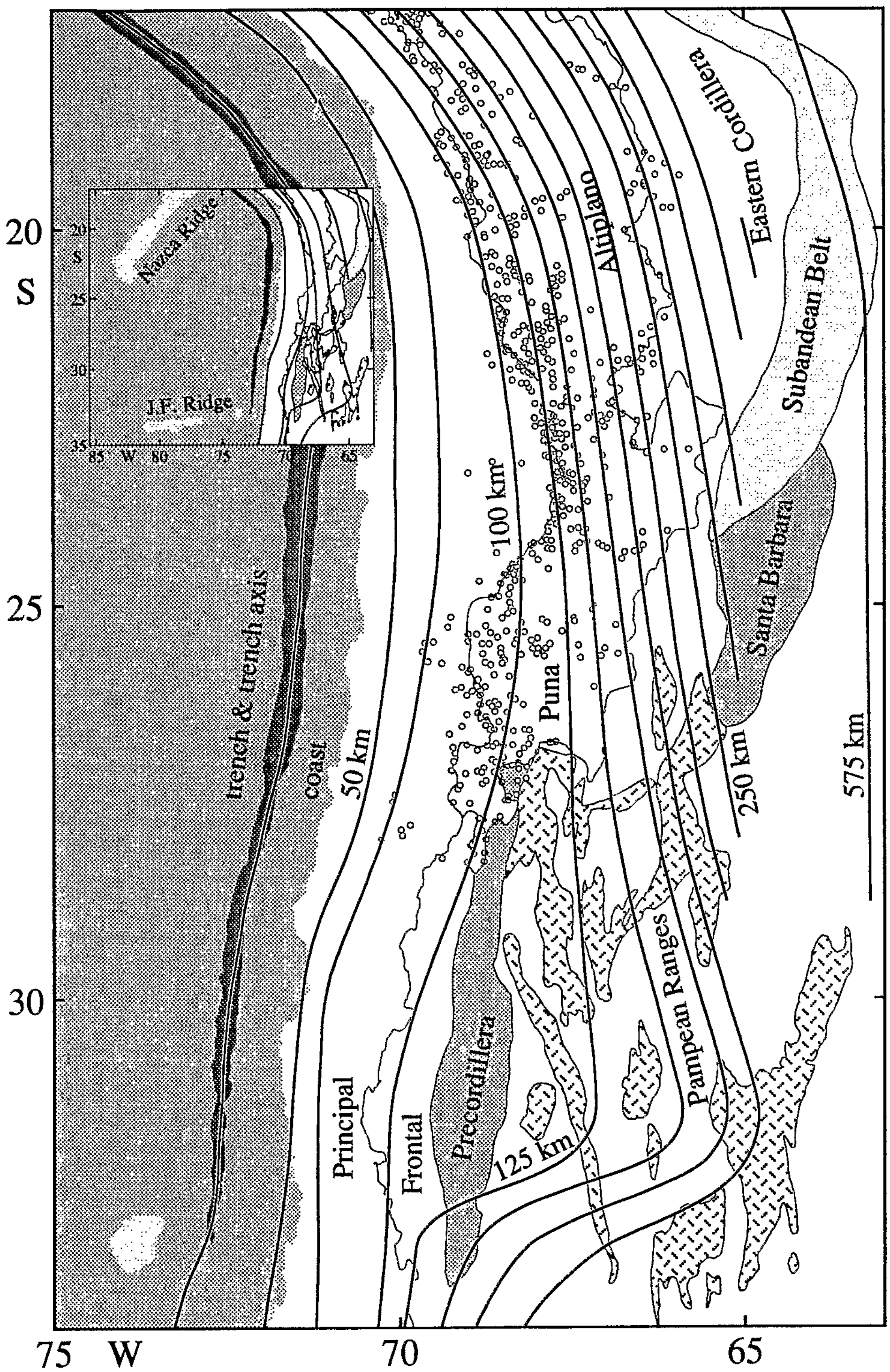


Fig. 1. Map of western South America illustrating upper plate tectonic features, volcanic arc, and contours of the Wadati-Benioff zone (WBZ). Along-strike segmentation of the upper plate tectonic provinces correlates with the along-strike segmentation of the WBZ [Jordan et al., 1983]. The distribution of Neogene volcanoes (open circles) [Isacks, 1988] shows an active magmatic arc over the steep WBZ segment and the absence of an active arc over the flat segment. The drainage divide, which defines the internally drained Puna/Altiplano plateau and then follows the crest of the Andes southward between the Principal and Frontal cordilleras, is also shown. The inset shows the major topographic features of the oceanic Nazca plate (Juan Fernandez and Nazca ridges).

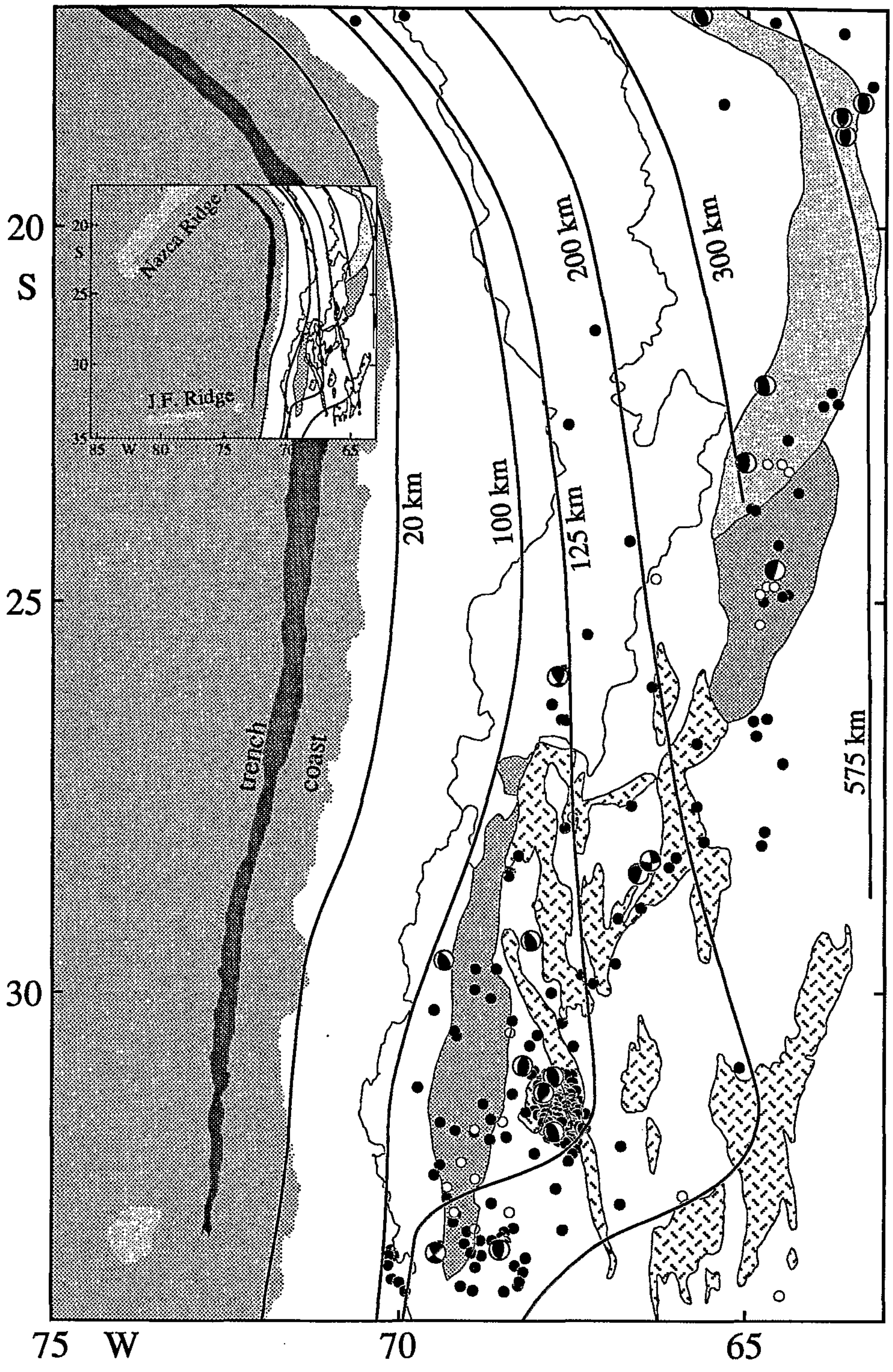


Fig. 2. Shallow intraplate seismicity (solid circles) and damaging historic earthquakes (open circles) [Zamarbide and Castano, 1978] of the Andean back-arc. Epicenters are selected from Preliminary Determination of Epicenters (1963, 1983-1990) and International Seismological Center (1964-1982) catalogs. Selected events were located with 15 or more P arrivals, are shallower than 50 km, and are east of the 100 km WBZ contour ensuring they are in South American lithosphere and are not interplate or WBZ events. A selection of focal mechanisms [Chinn and Isacks, 1983; Dziewonski et al., 1987; Kadinsky-Cade, 1985; Stauder, 1973] is also shown. The level of seismicity in the Pie de Palo area (31.5°S, 67.5°W) is so intense that only focal mechanisms with accurate source depths from synthetic modeling are shown. Tectonic provinces and inset are as in Figure 1.

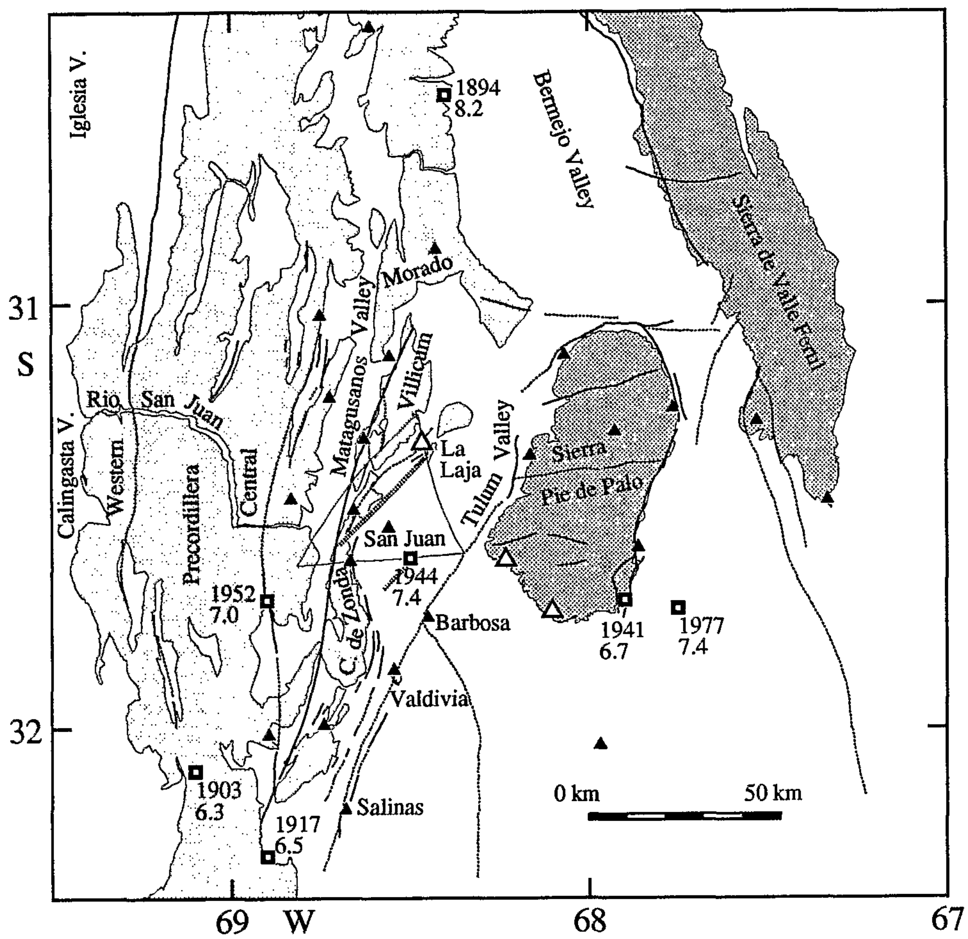


Fig. 3. Geology, mapped and inferred faults (solid and dotted bold lines), seismic station sites (small triangles: solid for stations, open for arrays of 8 to 11 stations with apertures of 1 m to 1 km), damaging historical seismicity (dated open squares, 1944 location from Kadinsky-Cade [1985]), the 1944 earthquake intensity VIII isoseismal (large triangle outline) [Castellanos, 1945], and two LANDSAT lineaments in San Juan (heavy gray lines). The LANDSAT lineament near La Laja includes the fault suffering offset in 1944. Mountain range patterns are light gray for sedimentary rocks (Precordillera) and dark gray for basement blocks (Sierras Pampeanas); intermontane valleys are in white. The Eastern Precordillera is the chain of mountains east of the Matagusanos Valley (Sierras Chica de Zonda, Villicum, Morado, and extensions north and south). West of the Precordillera are the Calingasta and Iglesia valleys.

The Central Precordillera is a typical foreland thin-skinned thrust belt. The Eastern Precordillera was first described as the easternmost part of this thrust belt [Ortiz and Zambrano, 1981], but it appears to break two rules of thin-skinned thrusting. First, the Eastern Precordillera is thrust westward, away from the craton. Second, the basal unit of the Eastern Precordillera is over 2 km down-section with respect to the basal unit of the Central and Western precordilleras, suggesting the décollement cuts downsection in the transport direction [Baldis and Bordonaro, 1984]. Previous cross sections of the Eastern Precordillera, based on geologic [Instituto Nacional de Prevención Sísmica (INPRES), 1982; Whitney, 1991] or geologic and low-resolution seismicity and shallow seismic reflection studies [Allmendinger et al., 1990; Fielding and Jordan, 1988], show the observed east-dipping basal thrusts of the Eastern Precordillera as upward continuations of inferred east-dipping Pampean basement faults.

Sierras Pampeanas. East of the Precordillera are the Sierras Pampeanas, a province of Precambrian metamorphic basement block uplifts [Caminos et al., 1982; Cingolani and Varela, 1975]. Such deformation cratonward of the thin-skinned thrust belt is unusual and found only in regions overlying subhorizontal subduction, a correlation also thought to hold in extinct orogens [Dickenson and Snyder, 1978]. The Pampeanas mountains are generally north-south trending blocks with a distinct morphology consisting of a steep fault-bounded front side and a gently dipping back side. The fault is typically moderately dipping, thrust or reverse type, and has large amounts (up to several kilometers) of structural relief [Jordan and Allmendinger, 1986]. The back side is a late Paleozoic erosional basement surface [Caminos, 1979; Rassmuss, 1916; Dalla Salda and Varela, 1984; Toselli et al., 1985]. Wide, shallow basins of unmetamorphosed, relatively undeformed Carboniferous and younger sediments separate the blocks [Salfity and Gorustovich, 1983].

Boundary region. The Bermejo and Tulum valleys separate the two provinces (Figure 3). As one crosses between the provinces the nature of the basement is a major unanswered question. Unfortunately, basement in the boundary region is buried by Paleozoic rocks of the Precordillera or young sediments of the Bermejo and Tulum valleys. Three small fault-bounded outcrops of Pampean basement follow an inferred basement fault extending southwest from Pie de Palo and come within 10 km of the Eastern Precordillera (Cerros Barbosa, Valdivia, and Salinas; Figure 3), and no basement outcrops are found farther west [Zambrano, 1969]. No occurrences of the Paleozoic Precordillera section are known east of the Eastern Precordillera. A melange associated with a Devonian strike-slip suturing of the two terranes is exposed along the east side of the Eastern Precordillera [Ramos et al., 1986; Ortiz and Zambrano, 1981]. If the basement changes from Pampean to an unknown and probably allochthonous basement under the Precordillera, the change occurs west of the three basement outcrops described. The location of a basement suture with respect to the melange is problematic as the thin-skinned thrust belt sediments are decoupled from the basement across the basal décollement.

SEISMICITY

Seismicity in San Juan occurs in two zones: in the crust and in the subhorizontal Nazca plate at about 100 km depth [Barazangi and Isacks, 1976; Smalley and Isacks, 1990; Pujol et al., 1991] (Figure 4). The crustal seismicity also occurs in two zones: in the Sierras Pampeanas basement block uplift Sierra Pie de Palo [Regnier et al., 1992] and in the thin-skinned Precordillera.

Previous studies have shown seismicity in the Precordillera is concentrated at mid to lower crustal depths of 10 km to 40 km, placing the activity in the basement beneath the sediments of the thrust belt [Smalley and Isacks, 1990]. Our preliminary locations agree with this result, but our improved final locations have a depth range of 5 km to 35 km. The earlier studies resolved the overall map and depth range of seismicity here but were unable to resolve structures in the seismicity pattern. These results were nevertheless used to build models in which the Eastern Precordillera is not part of the thin-skinned thrust belt but results from underlying Pampean deformation. In these models, the east dipping basal

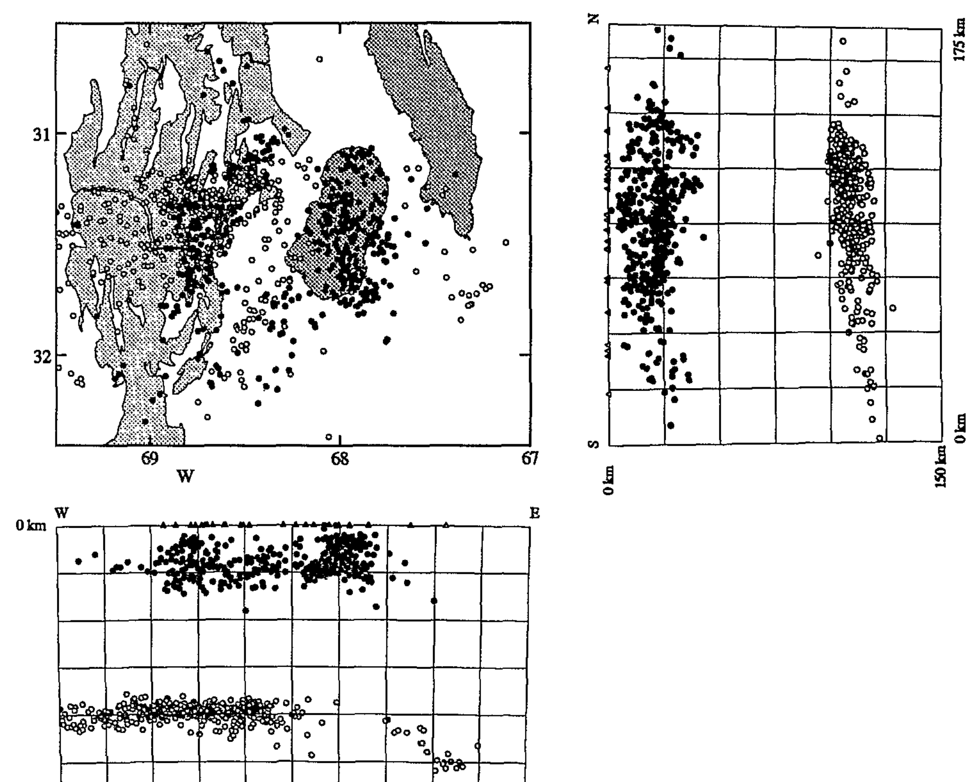


Fig. 4. Selected shallow (solid circles) and intermediate-depth (open circles) earthquakes from this study located using Joint Hypocentral Determination [Pujol et al., 1991] and a laterally homogeneous layered crustal/upper mantle velocity model. Cross sections show the seismicity has a bimodal depth distribution (crustal and Wadati-Benioff zone). Map shows that crustal seismicity distribution is also bimodal and associated with the Pampean range Sierra Pie de Palo and the eastern side of the Precordillera. In the Precordillera all A, B, and C quality events are shown (~220). For Pie de Palo only A events plus B and C events from a 1-month window around an M_L 5.3 event are shown (~720). A small subset of A and B intermediate-depth events (~500) is also shown.

thrust of the Eastern Precordillera is interpreted as a simple continuation of a Pampean style, east dipping crustal scale basement fault to the surface [Allmendinger et al., 1990; Fielding and Jordan, 1988].

DATA COLLECTION AND ANALYSIS

A digitally recording portable seismic network (PANDA [Chiu et al., 1991]) was operated in San Juan, Argentina, from August 1987 to May 1988 and recorded nearly 20,000 earthquakes. The network consisted of 26 sites in a 100 km by 150 km area including parts of the Precordillera and Sierras Pampeanas and the boundary between them (Figure 3). Three of the sites contained small aperture arrays for a total of 48 three-component stations. Stations sent data by frequency modulation telemetry to a central site where it was digitized at 100 samples per second. Earthquakes were identified and saved automatically using an event detection algorithm based on coincidence of triggers at specified groups of stations. Because recording and digitizing are performed at a central site, there were no interstation timing problems and the data were available in real time. To guarantee recovery of absolute time, we recorded an analog Inter-Range Instrumentation Group (IRIG) time code from a satellite clock.

Each station had six channels for use with two three-component sensors and could be operated with (1) identical sensors (4.5 Hz, Mark Products® L-28 geophones) in a dual gain mode to obtain wide dynamic range (~90 dB), (2) identical sensors at the same gain to form small-aperture arrays, or (3) two different sensors (e.g., a geophone and force balance accelerometer). Half the stations are capable of repeating data from one other station, and several repeat-only stations were capable of repeating a two-station data stream. This ability to repeat the telemetered signals meant network design was not constrained by topography and could be optimized for coverage of the seismic target areas.

Preliminary processing included event classification and quality grading followed by location using automatically determined P and S times [Smalley et al., 1989]. Events were graded on the basis of the number of well-recorded P arrivals, counting multistation arrays as one station. Events with over 19 well-recorded P arrivals received quality grades of A; 11 to 18, B; 7 to 10, C; and less than 7, D. Events for this study were selected based on the preliminary processing and were reprocessed to verify times and phase characteristics of the automatically determined arrivals and to pick additional arrivals. Impulsive P and S arrivals were easily measured to 0.01 s; i.e., the first sample containing the arrival can be clearly and unambiguously identified. For emergent arrivals and small events with poor signal to noise ratios, the problem becomes identification of the arrival, as the precision remains 0.01 s. Such P arrivals can typically be identified within 1/2 cycle or 0.05 s at the predominant frequencies for local events. Similar considerations apply to identification of S buried in large amplitude P coda or mixed with converted phases, which limits identification to within one cycle or 0.1 s.

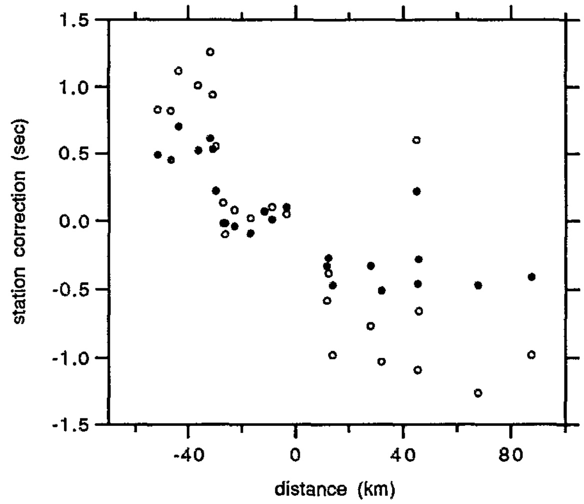


Fig. 5. Cross section (azimuth N105°E) of Joint Hypocentral Determination station corrections for P (solid circles) and S (open circles) showing general decrease from west to east (the outliers, one P and one S, on the east are located on unconsolidated sandy sediments south of Sierra Pie de Palo, Figure 3).

Initial locations were found with HYPOINVERSE [Klein, 1978] and a laterally homogeneous three-layer crustal velocity model (Table 1). As the geology has large-scale lateral heterogeneities across the network (metamorphic basement on the east and sedimentary rocks on the west) and the set of stations recording each event is not homogeneous (approximately half the selected events are "C" quality and recorded only by stations in the Precordillera) the station subset used to locate an event strongly influenced the result. We made a simple test using events recorded by the whole network by comparing locations obtained using all the stations

TABLE 1. Three-Layer Over Half-Space Model For Crustal Velocity

Depth, km	Velocity, km/s
0.0	5.88
10.0	6.20
32.0	7.30
45.0	8.10

Three-layer over half-space model for San Juan area from the Instituto Nacional de Prevencíon Sísmica (INPRES). Data used to generate model could not resolve velocity differences between the Precordillera and Sierras Pampaneas provinces resulting in a single velocity model for both. The velocity of the top layer is based on shallow refraction data in the Tullum and Bermejo valleys [Bollinger and Langer, 1988]. Velocities in the bottom two layers are based on regional earthquake studies [Volponi, 1968].

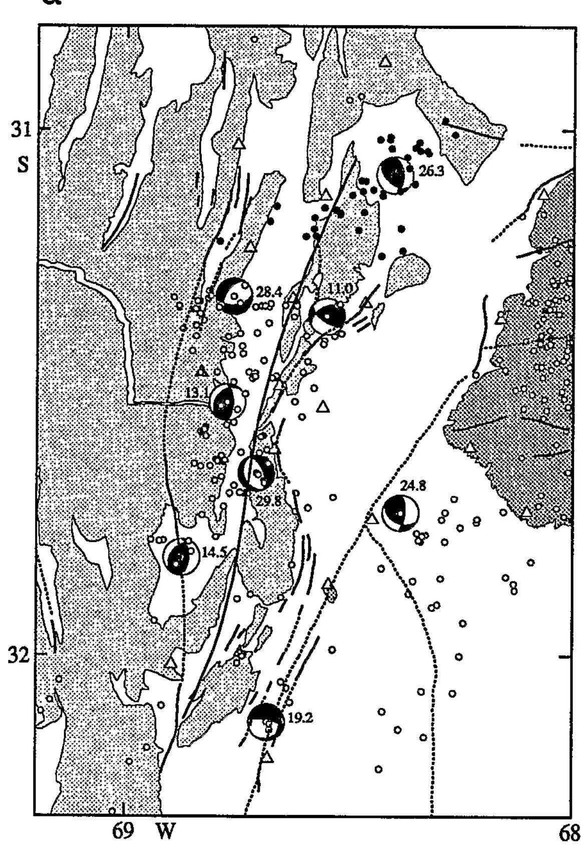
to locations obtained using only stations in the Precordillera. The most important variation was a consistent depth difference of about 5 km, with the full network locations having shallower hypocenters. To address this problem and retain as many well located events as possible, events with greater than 10 P and 10 S arrivals were selected for relocation by joint hypocentral determination (JHD) [Pujol et al., 1991] and the whole data set was relocated using the JHD station corrections. The JHD locations are uniformly shifted a few kilometers west and shallower than the HYPOINVERSE locations. Most importantly, however, effects of inhomogeneous station sets are removed. The JHD station corrections have a clear pattern that correlates with the change in surface geology across the network (Figure 5). This correlation is also found in station corrections obtained using events from only the WBZ or only Sierra Pie de Palo [Pujol et al., 1991]. The station corrections indicate that arrivals on the west side of the network are delayed with respect to those on the east. Such a delay can be caused by a lower average velocity to the west or, for intermediate-depth events, a thickening of the crust to the west. The agreement of station corrections obtained from the two crustal source areas with those from the intermediate-depth seismicity suggests the velocity effect predominates and this is our preferred interpretation. From here on we will consider only the final JHD locations.

DISCUSSION

Our data provide the first view of seismicity in the Precordillera with sufficient resolution to image fault-like features (Figures 6 and 7). The activity is concentrated beneath the Eastern Precordillera, the Matagusanos Valley, and the easternmost Central Precordillera. Almost no activity is found westward in the Central and Western precordilleras or eastward in the Tulum Valley. Seismicity in the Precordillera is also not evenly distributed north-south, as north of 31°S it is relatively aseismic. The sharpness of the termination of activity at 31°S, which is shared by the Pie de Palo and WBZ activity, is an important observation although its significance is poorly understood [Smalley and Isacks, 1987, 1990]. The crustal seismicity has a roughly north-south striking pattern extending from approximately 31°S to near 32.25°S where the termination of activity is poorly defined. This seismicity is also clearly divided into segments: northern, central, and southern.

The northern segment, between Sierra de Morado and La Laja, forms a northeast-southwest striking linear pattern (Figure 6). In cross section we see a narrow, linear, dipping feature over a wide range of azimuths. The distribution of hypocenters is therefore almost pencil-like. If the distribution is interpreted as a line in a plane, the shallowest apparent dip is the true dip of the plane, and the cross-section trend is normal to the strike of the plane. Alternatively, if the seismicity is a linear distribution not related to a plane, the cross section showing the shallowest dip gives the plunge of the line and the projection direction is normal to the trend. As

a



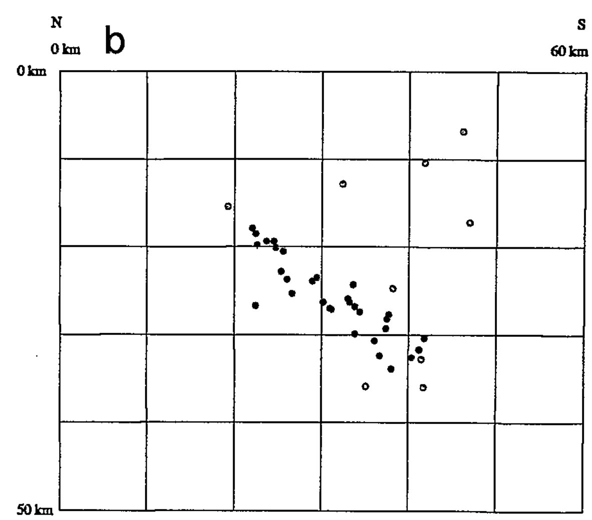
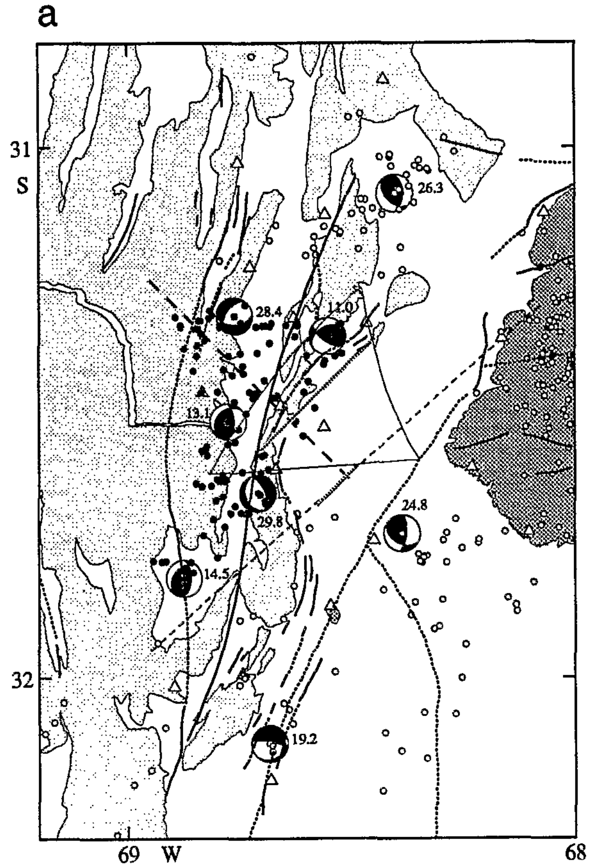


Fig. 6. (a) Map and (b) one-to-one cross section of locations for northern segment (solid circles). A cross section striking S4°E has the shallowest dip (31°S) and is interpreted as a N86°E striking fault plane dipping south. (The strike of the cross section is the strike of the vertical plane onto which the data are projected). Map features are as in Figure 3, the numbers by the focal mechanism solutions are event depths in kilometers. Solid circles on the map indicate events selected for display in the cross section. In the cross section there is an additional division of events represented by solid and patterned circles. The solid circles indicate events used in the least squares fit to a plane, and the patterned circles are the remaining events selected in the map view that were removed before the fit was made.



faults are generally thought to be two-dimensional we have selected the planar interpretation. A least squares fit of the hypocenters to a plane gives a strike of N86°E and dip of 31°S for the best fit plane. This agrees with the strike and dip found in the planar interpretation of the cross sections.

The central segment (Figure 7) is the triangle of activity beneath Sierras Villicum and Chica de Zonda. In cross section (Figure 7b) we see a northwest dipping plane plus a cluster of activity in the footwall. A least squares fit to a plane, after removing the footwall activity, gives a strike of N45°E and dip of N35°W for the best fit plane. The clear gap in activity between 15 and 19 km depth may be related to the sediment-basement contact, estimated to be deeper than 8 to 10 km beneath the Matagusanos Valley [Fielding and Jordan, 1988], or to the décollement beneath the Central and Western precordilleras estimated at 15 km depth [Allmendinger et al., 1990].

Additional structure in the Central segment is also suggested in the cross section and map, but the small number of events limits resolution. For example, two cross-section features suggest back thrusting in the hanging wall block. They project upwards, opposite the dip of the main fault, from about 10 km and 15 km depth. The activity in the footwall narrows to a minimum width, with a roughly vertical distribution, when the cross section is rotated 15° counterclockwise (Figure 7c), suggesting a vertical fault plane with a strike of N30°E. Figure 7 also shows that the eastern boundary of the seismicity is not one straight line but two parallel segments offset by a step. This step is found where the seismicity pattern crosses beneath the Eastern Precordillera at the north end of Sierra Chica de Zonda. Associated with this step are changes in the strike of the Eastern Precordillera and

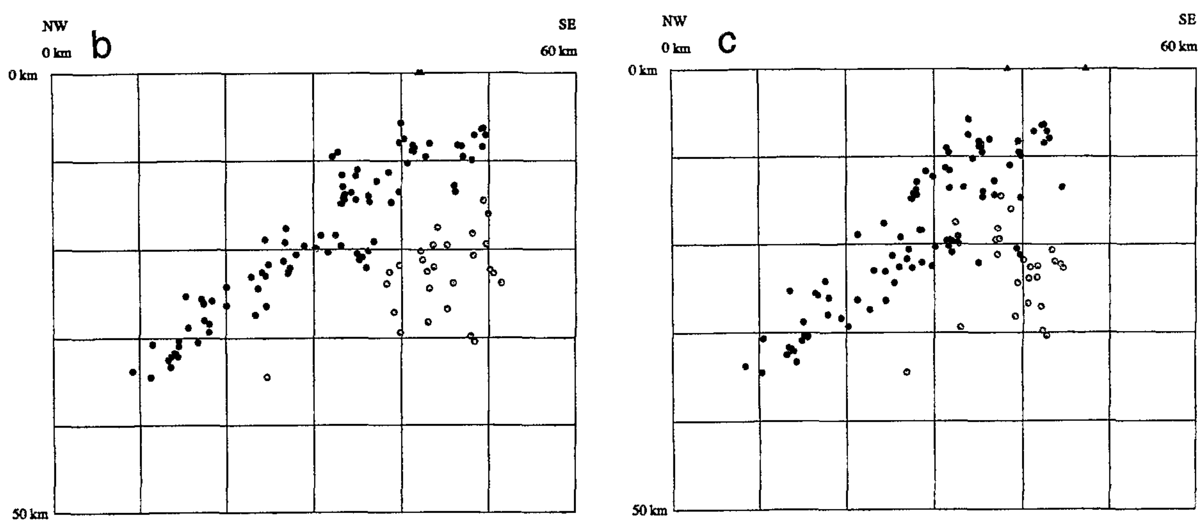


Fig. 7. (a) Map and (b,c) cross sections of locations for central segment (solid circles). A cross section (b) striking N45°W has the steepest dip (35°NW) and a good planar distribution indicating a fault plane striking N45°E and dipping NW. The surface intercept of the proposed fault (long southwest to northeast dashed line), and the cross section strike (northwest to southeast dashed line through center segment) are shown on the map. The projection of the ends of the LANDSAT lineament near La Laja are shown in the cross section by the small triangles. Map and earthquake symbols are as in Figure 6. A tightening of the activity in the footwall block into a less well-defined vertical plane is seen when the cross section is rotated to a strike of N60°W (c) indicating a vertical plane that strikes N30°E.

the minimum depth of the earthquakes. To the northeast of this step the shallowest seismicity is about 10 km deep, while to the southwest seismicity continues upward to about 5 km depth. Finally, the surface intercept of the plane defined by the seismicity overlaps a LANDSAT lineament related to agricultural exploitation of a line of springs, the Médanos de Oro, in the southwestern Tulum Valley (Figure 7a).

The southern segment is the poorly defined area of sparse seismicity in the south lacking clear patterns in map or cross-section views. Seismicity in the Tulum Valley southwest of Pie de Palo is mostly east of the line of basement outcrops and the inferred basement fault that both strike southwest from the western side of Pie de Palo. This seismicity is therefore in Pampean basement and not considered part of the Precordillera activity.

The northern and central segments clearly define distinct faults that may be used to estimate maximum magnitudes, or characteristic events, for this area. The Ms 7.4 San Juan earthquake of 1944 (location 31.6°±0.4°S, 68.5°±0.6°W [Kadinsky-Cade, 1985], which produced a maximum intensity of IX in San Juan [Instituto Nacional de Prevención Sísmica (INPRES), 1977]), may have occurred on one or more of these fault-like features. The large uncertainty in the location of the 1944 earthquake precludes associating the event with any specific fault. The area of the plane in the central segment, or the central and northern segments combined, is within the range of areas for Ms 7.0-8.0 events [Kanamori and Anderson, 1975]. These planes may have ruptured in a multiple event in 1944, similar to the multifault ruptures proposed for the 1977 Caucete earthquake that occurred nearby beneath Sierra Pie de Palo in the Sierras Pampeanas [INPRES, 1977; Volponi, 1979; Kadinsky-Cade, 1985] or the 1988 Tennant Creek, Australia, earthquake [Bowman, 1991]. Although the depth of the 1944 earthquake is poorly controlled, it probably occurred in the basement (the International Seismological Center reports a depth of 50 km) because no significant surface faulting occurred. Six centimeters of coseismic dip-slip movement, which increased to 30 cm over a period of weeks, was observed on a 6 km long fault in soft sediments near La Laja [Castellanos, 1945; Groeber, 1944] (Figure 3). The offset on this fault was east side up, similar to the offset on the basal thrusts of the Eastern Precordillera. This is opposite the direction expected from thrust movement on the northwest dipping basement fault defined by the seismicity and supports the interpretation of Castellanos [1945] that surface faulting was a secondary feature. The planar features imaged in the basement, whose areas are in the range associated with M 7+ earthquakes, and any masking of surface faulting by the overlying sediments reinforces the idea that seismic risk in San Juan may be higher than that estimated from surface geologic information alone [INPRES, 1982].

While there is clearly a spatial relation between the basement seismicity and the Eastern Precordillera, the structures implied by the seismicity do not correlate with features of the surface geology such as segmentation of the Eastern Precordillera into individual ranges. The strikes, dips,

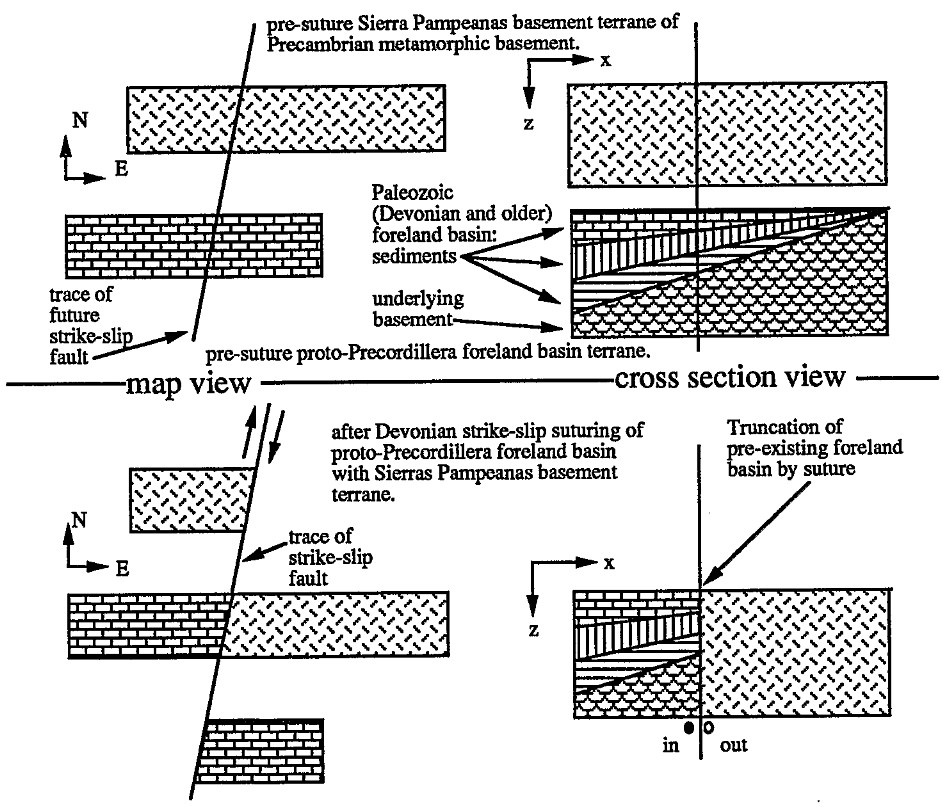


Fig. 8. Map and cross section views showing the proto-Precordillera and Sierras Pampeanas terranes before and after a Devonian strike-slip suturing of the Precordillera terrane, composed of an early Paleozoic foreland basin, to the western margin of South America [Ramos et al., 1986]. Note the truncation of the foreland basin by the suture zone. (Actual sense of strike-slip offset is unknown.)

and surface projections of the seismically defined faults also do not match the faults and structures of the Eastern Precordillera. In addition, immediately north of the termination of seismicity near 31°S the depth to basement in the Bermejo Valley deepens dramatically to the north or northeast [Jordan and Allmendinger, 1986]. We will discuss the importance of this in more detail below.

The strikes of the seismically defined planes in the central segment are also subparallel to the western side of Pie de Palo and to the inferred fault and line of small fault-bounded basement outcrops striking southwest from Pie de Palo. The seismicity beneath the Eastern Precordillera and Matagusanos Valley may represent compressional reactivation, in a roughly east-west direction, of faults along a north/northeast-south/southwest trending, originally strike-slip, suture zone between the Sierras Pampeanas and Precordillera terranes (Figure 8). This geometry would also allow strike-slip movements, but such deformation has not been recognized in the Eastern Precordillera.

The incongruence of the basement faults and the surface geologic structures suggests a nonunique class of models relating the two deformations (Figure 9). The intrinsic three-dimensionality makes it difficult to illustrate the full geometry in two-dimensional cross section, so we will present our models in three-dimensional perspective view. In these models an inferred sharp change in the depth to basement, related to the suture between the Precordillera and Sierras Pampeanas basements, truncates the foreland basin of the Precordillera (Figure 8). The relative location of the basement faults with respect to the suture and to the Precordillera sedimentary section determine if the sedimentary section is passively carried on the hanging wall block of the basement fault or if the sedimentary section participates in the same deformation as the basement.

If the fault defined by the seismicity passes beneath the sedimentary section, basement shortening will not directly shorten the sediments above the fault. In this case, normal cratonward growth of the thin-skinned thrust belt is interrupted by the wall of Pampean basement at the ancient strike-slip suture zone where the foreland basin is truncated. The wall forms a buttress pushing up the west-verging Eastern Precordillera, which may also be uplifted and rotated as a unit atop the hanging-wall block. The thin-skinned thrusting is therefore significantly modified by truncation of the foreland basin along the suture boundary. Except for the effects due to the anomalous termination of the foreland basin, however, the Precordillera is a normal foreland thrust belt driven cratonward by the orogen proper. Last, as the sedimentary cover in the Tulum Valley is relatively thin, 1-2 km [unpublished seismic refraction data, Argentine national oil company, Yacimientos Petrolíferos Fiscales, (YPF)], and there are no major surface features in the Eastern Precordillera or Tulum Valley associated with projections of the basement faults to the surface, the offset on these faults must be relatively small, especially in comparison to the large offsets found in the Sierras Pampeanas province. The northeast portion of the central segment, where the seismicity is east of the Eastern Precordillera, may represent this case.

If the fault is on the foreland basin side of the suture and sufficiently close to it, basement shortening will carry the sediments on the hanging wall side eastward into the abutment of Pampean basement at the suture. In this case, shortening in the sedimentary section associated with the Eastern Precordillera is a direct result of the basement shortening. The southwest portion of the central segment, where the easternmost limit of seismicity crosses westward beneath the Eastern Precordillera, may represent this case. In this area a band of deformation subparallel to the strike of the edge of the seismicity is found across the Eastern Precordillera in LANDSAT images and may represent surficial structure related to the basement deformation.

In both models, back thrusts in the hanging wall block could exaggerate, or be responsible for, the Eastern Precordillera, outcropping with or as the basal faults of the

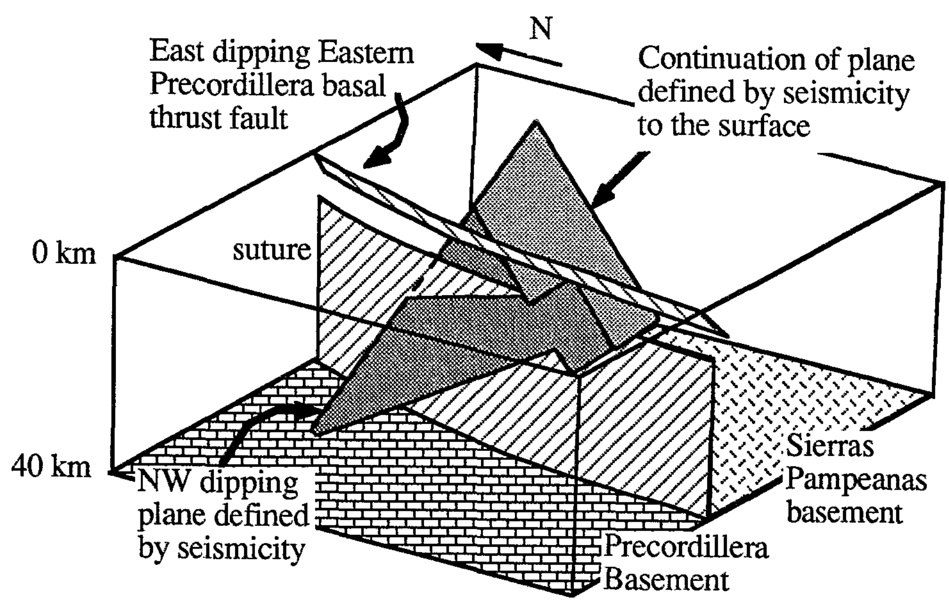


Fig. 9. Schematic three-dimensional perspective view illustrating tectonic model for relationship between basement faults and surficial geology. Note change in depth of the shallowest seismicity as the plane defined by the seismicity crosses beneath the Eastern Precordillera.

Eastern Precordillera. East-dipping faults observed along the eastern side of the Eastern Precordillera, such as the fault showing displacement associated with the 1944 earthquake, may be same dip bending moment thrusts [Whitney, 1991] or a second set of back thrusts related to the basement buttress. The uplift and rotation of sediments in the hanging wall may also explain the apparent down section change in stratigraphic level of the décollement between the Central and Eastern precordilleras.

While seismicity cannot identify the type of basement, comparing the Precordillera activity with that of the Pampean range Sierra Pie de Palo immediately to the east shows that the rate of earthquake occurrence and the seismicity pattern of the two areas are very different. One explanation is that the activity level is related to the time since the last large or characteristic event. In the Eastern Precordillera, the last large event was the 1944 Ms 7.4 San Juan earthquake, while beneath Pie de Palo it was the 1977 Ms 7.4 Caucete earthquake. Although the times involved here are much longer than those associated with normal aftershock activity, ongoing activity beneath Pie de Palo (Regnier et al., 1992) is very similar to the first month of the 1977 event aftershock activity [Bollinger and Langer, 1988] and to the activity during 1980, 1984, and 1985 [Smalley and Isacks, 1990]. The seismicity is therefore remarkably persistent and, like the immediate aftershocks, may continue to represent the redistribution of stress from the 1977 event onto a network of smaller faults. Neither the activity before the Caucete earthquake nor that of the other Pampean ranges is known well enough to determine if the activity level and pattern associated with Pie de Palo is the normal background activity in the Sierras Pampeanas. In the Eastern Precordillera, the time since the last large earthquake is greater than that for Pie de Palo, and stresses transferred to the region surrounding the mainshock fault may have been relieved by past seismicity. The stresses may concentrate near the main fault again, which is therefore imaged in the seismicity. Activity associated with the Precordillera, both before and for the first 30 years after the 1944 earthquake, is also too poorly known to determine the activity pattern as a function of time in the earthquake cycle. No seismicity pattern is visible using Preliminary Determination of Epicenters and International Seismological Center data because too few events are reported. Another major difference between the two regions is the seismic depth distribution. Beneath Pie de Palo, seismicity is concentrated in a pronounced subhorizontal midcrustal layer near 25 km depth, and the maximum depth is 30 km (Regnier et al., 1992). This midcrustal concentration is absent in the Precordillera activity, and the maximum depth is 35 km. The very different seismicity patterns suggest that the two areas have distinct basements with different crustal rheology.

The focal mechanisms presented here are the first single-event mechanisms from the Precordillera (Figures 6 and 7). Although there are strike-slip and normal mechanisms, most of the mechanisms are thrusts, as expected for regional east-west compression. In the central segment, focal mechanisms of events shallower than about 20 km and deeper than about 30 km indicate thrust faulting, while events between 20 km and 30 km depth indicate normal faulting. We were unable to obtain focal mechanism solutions for events deeper than 30 km, but the first motions at the closest stations, those plotting in the center of the focal sphere, are compressions, suggesting a return to thrust faulting deeper than 30 km. The events in this study are all small, less than $M_L = 4$, so the fault areas and source volumes involved are also small. The earthquakes may therefore be sampling small-scale variations of the deviatoric stress field from the regional stress field. The orientation of the deviatoric stress field at short wavelengths can vary widely from the regional stress field because of roughness on the surfaces of the major faults or the fractal nature of fault systems producing a mix of focal mechanism types.

Along-strike tectonic variations. Simple subduction models and the associated tectonics are typically two-dimensional, modeling upper plate deformation as a series of linear tectonic provinces perpendicular to the convergence direction with no along-strike structures. While this is valid at large scales, many subduction systems have along-strike and therefore three-dimensional variations. The Precordillera and Sierras Pampeanas terranes are examples of such regional-scale variations. Within these terranes, which are two-dimensional on a regional scale, we find along-strike variations on the scale of individual mountain blocks and ranges.

In San Juan a sharp east-west striking linear feature cuts across the Sierras Pampeanas-Precordillera boundary near 31.1°S. On Pie de Palo, it is defined by steeply dipping faults that strike east-west across the northern boundary of the range. These faults are downthrown on the north and show evidence of Quaternary activity [Bastias and Weidmann, 1983; Zambrano, 1969]. Inferred and mapped continuations of these faults are found in the Sierra de Valle Fértil, in other Pampean ranges to the east, and in the Precordillera to the west [Zambrano, 1969]. An along-strike change in the structure of the Eastern Precordillera, from thrusts in the south to folds in the north, also occurs near 31.1°S where the southern end of Sierra de Morado bifurcates. The Central and Western precordilleras also have many faults with evidence of Holocene activity south of 31.1°S, but few Holocene faults are found to the north [Bastias and Weidmann, 1983]. Several unusual closed basins are also found in the Central Precordillera north of 31.1°S, and farther west a major structural high separates the Calingasta and Iglesia valleys at about 31°S.

The across-strike feature is also coincident with the major change in basement depth across the southern margin of the Bermejo Valley. Unpublished YPF seismic reflection data suggest a depth to basement in the footwall block beneath Sierra de Valle Fértil of 8 km or 17 km [Jordan and Allmendinger, 1986]. The difference depends upon interpretation of a 9 km thick package of reflectors at the bottom of the seismic section. A minimum structural relief of 11 km therefore exists between the peaks of Sierras Pie de Palo and Valle Fértil and the footwall basement block under Sierra de Valle Fértil. The basement surface in the Bermejo Valley therefore dips almost opposite the inferred southward dip of the seismically defined fault in the northern segment.

The basement block in the Bermejo Valley must play an important but poorly understood role in the regional tectonics. It is triangular shaped and known to be bounded by crustal-scale faults on the east, where it is the footwall block beneath Sierra de Valle Fértil, and on the south, where it terminates in vertical east-west striking faults crossing the north end of Sierra Pie de Palo. A crustal-scale thrust fault is also thought to exist along the west side [Allmendinger et al., 1990]. The valley may be floored by a crustal block being pushed or rotated out the bottom of the crust due to the regional east-west shortening and the weight of sediments in the Bermejo

Valley. South of the Bermejo Valley, shortening is expressed in the uplifted mountain block Sierra Pie de Palo. In the valleys on either side of Pie de Palo, basement is shallow, typically only 1 to 2 km [Gray de Cerdan, 1969; YPF, unpublished refraction and reflection data].

Beneath and west of the network a roughly east-west oriented linear concentration of WBZ seismicity (Figures 3 and 4) coincides with an along-strike continuation of the Juan Fernandez ridge of the oceanic Nazca plate [Smalley and Isacks, 1987]. The WBZ here is subhorizontal, and subduction of buoyant aseismic ridges has been proposed as a possible cause for such flat subduction [Cross and Pilger, 1979; Pilger, 1981]. As the seismicity follows an along-strike projection of the ridge, it supports the proposal that the ridge continues in the subducted plate.

The intermediate-depth and crustal seismicity also exhibit poorly defined southern boundaries near 32.25°S and share the sharp boundary near 31°S that is coincident with the transverse features of the upper plate geology described above. The crustal seismicity is concentrated beneath Pie de Palo, just east of an intense nest of intermediate-depth seismicity beneath La Laja. The intriguing spatial correlations between the large-scale mountain block structures and crustal seismicity of the upper plate with the intermediate-depth seismicity suggests an interaction of a subducted extension of the Juan Fernandez ridge with the upper plate through a lithospheric scale structure in the upper plate that is aseismic between 35 km and 95 km.

CONCLUSIONS

The high resolution afforded by a temporary seismic network in San Juan, Argentina, images a segmented pattern of crustal scale basement faults beneath the eastern part of the Precordillera tectonic province of the Andean foreland. The geometry of these faults does not correlate with the surface geology and shows that a simple structural relationship does not exist between the basement deformation and deformation in the overlying sediments. Improved locations (due to network density, use of three-component sensors, and application of the JHD method) allowed us to develop new models for the anomalous structures of the Eastern Precordillera and the relation of the Eastern Precordillera deformation to underlying basement deformation expressed in the seismicity. The two end-member models are (1) the deformations are unrelated and their spatial overlap is a coincidence and (2) the Eastern Precordillera and the basement seismicity are related through Neogene reactivation of a Devonian strike-slip suture between the Sierras Pampeanas and Precordillera. Figure 10 is an orogen-wide cross section combining the seismicity results with other established features of the Andean orogen. The basement faults may also have been responsible for the 1944 San Juan earthquake and may continue to pose significant seismic risk in the San Juan area. Lack of surface effects from large events in the basement suggests that the overall seismic risk in San Juan may be higher than that estimated from surface geologic studies alone. The data also suggest complex structural relationships between previously unidentified surface geologic features in the San Juan area and the Precordillera basement faulting.

Acknowledgments. We are indebted to J. C. Castano, and R. Recio of the Instituto Nacional de Prevención Sísmica (INPRES) in San Juan, Argentina, for scientific and logistical support. We also thank our engineer G. Steiner (CERI),

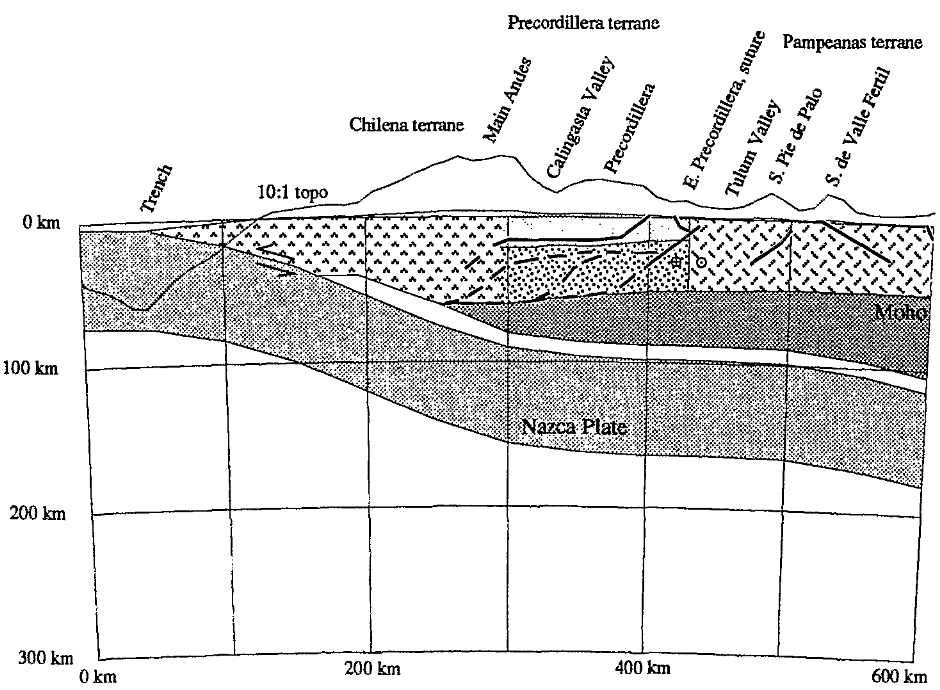


Fig. 10. One-to-one cartoon showing relationship of fault system imaged with our data to Precordillera-Sierras Pampeanas suture and formation of anomalous structures of the Eastern Precordillera. The major terranes of the Andes at 31°S (Chilenia, the Precordillera and the Sierras Pampeanas), their boundaries, and important geographic features are identified.

technicians J. Bollwerk (CERI), and F. Bondoux (ORSTOM), and field personnel J. Vlasity (CERI), D. Vlasity (CERI), T. Cahill (Cornell), C. Avila (INPRES), and M.C. Reta (INPRES). We are grateful to Mike Ellis, Rick Allmendinger, and Terry Jordan for many interesting discussions and useful comments. Constructive reviews by David James and Katherine Kadinsky-Cade helped improve the paper. This work was supported by National Science Foundation grants EAR-8608301 and EAR-8804925, the Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM), and the State of Tennessee Centers of Excellence Program.

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(Received July 19, 1991;
revised May 4, 1992;
accepted May 11, 1992.)