DAVID BLOOM

# Andean tectonics related to geometry of subducted Nazca plate

TERESA E. JORDAN
BRYAN L. ISACKS
RICHARD W. ALLMENDINGER
JON A. BREWER*
*Department of Geological Sciences, Cornell University, Ithaca, New York 14853*
VICTOR A. RAMOS *Servicio Geologico Nacional, Buenos Aires, Argentina*
CLIFFORD J. ANDO* *Department of Geological Sciences, Cornell University, Ithaca, New York 14853*

## ABSTRACT

Seismological and geological data show that tectonic segmentation of the Andes coincides with segmentation of the subducted Nazca plate, which has nearly horizontal segments and 30° east-dipping segments. Andean tectonics above a flat-subducting segment between 28°S to 33°S are characterized by (from west to east): (1) a steady topographic rise from the coast to the crest of the Andes; (2) no significant Quaternary, and possibly Neogene, magmatism; (3) a narrow belt of eastward-migrating, apparently thin-skinned, Neogene to Quaternary shortening of the Andes; and (4) Plio-Pleistocene uplift of the crystalline basement on reverse faults in the Pampeanas Ranges. From about 15°S to 24°S, over a 30°-dipping subducted plate, a west to east Andes cross section includes: (1) a longitudinal valley east of coastal mountains; (2) an active Neogene and Holocene andesitic volcanic axis; (3) the Altiplano-Puna high plateau; (4) a high Neogene but inactive thrust belt (Eastern Cordillera); and (5) an active eastward-migrating Subandean thin-skinned thrust belt. Tectonics above a steeply subducting segment south of 33°S are similar west of the volcanic axis, but quite different to the east.

Early Cenozoic tectonics of western North America were quite similar to the Neogene Andes. However, duration of segmentation was longer and the width of deformation was greater in the western United States.

Patterns of crustal seismicity are systematically related to Plio-Quaternary structural provinces, implying that current deformational processes have persisted since at least the Pliocene. Horizontal compression parallel to the plate convergence direction is indicated to a distance of 800 km from the trench. Above flat-subducting segments, crustal seismicity occurs over a broad region, whereas over steep segments, it is confined to the narrow thrust belt. Strain patterns in the forearc region are complex and perhaps extensional, and a broad region of the Altiplano-Puna and Eastern Cordillera appears to be aseismic.

## INTRODUCTION

The Andes mountain system is commonly used as an illustration of a "simple" orogen formed by subduction of an oceanic plate beneath a continental margin (Dewey and Bird, 1970; James, 1971). Over much of its length, the Andes consist of a magmatic arc, flanked on the west by a trench and on the east by a foreland thrust belt and basin (Fig. 1). These characteristics of an "Andean-type margin" are recognized in the geological record of various convergent margins.

The Neogene Andes afford the outstanding opportunity to understand the coupling of subduction and continental orogenesis. They are primarily a noncollisional mountain belt formed along a long-lived, currently active subduction system. The Andes are an important exploration model for the generation of economic resources, both metals and hydrocarbons, in relation to plate interactions and paleogeographic controls.

Although the Andes are morphologically continuous along strike for more than 4,000 km (from about 5°S to 45°S), distinct broad-scale tectonic segments can be identified (Figs. 1 and 2). These tectonic segments are located above segments of similar scale in the subducted Nazca plate, defined by major along-strike variations in the dip of the Benioff zone. The coincidence of lateral variations in the geometry of the descending Nazca plate and in Andean physiography and geology is remarkable. In addition, the eastern limit of Benioff zone seismicity coincides with the eastern deformation limit of the overriding South American plate.

There must be two significant controls on lateral tectonic segmentation: modern plate interactions and pre-existing inhomogeneities in the South American plate. The western margin of the South American continent was intensely deformed during the Paleozoic and early Mesozoic, prior to the Andean Orogeny (Jurassic-Holocene). Apparent coincidences of ancient crustal boundaries with Neogene tectonic boundaries raise the possibility that features in the descending plate interact with pre-existing structure of the upper plate, in combination producing the segmentation of Andean tectonics and of subducted plate geometry.

The role of Nazca plate segmentation as a control on upper-plate segmentation is perhaps best studied between 18°S to 40°S (Fig. 2), in Chile, Argentina, and Bolivia, where the Andes are straight, and convergence directions of the Nazca and South American plates are at a high angle to the plate margin (Chase, 1978; Minster and Jordan, 1978), and an arid climate produces good exposure. Farther north, segment transitions in southern Peru and Ecuador coincide with major changes in the trend of the Andes and the continental margin, adding possible complications resulting from the shape of the plate margin. This paper will briefly summarize the seismological data and part of the extensive literature

---

*Present addresses: (Brewer) Department of Earth Sciences, Madingley Road, Cambridge CB3 OEZ, England; (Ando) Shell Development Company, P.O. Box 481, Houston, Texas 77001.

Geological Study of America Bulletin, v. 94, p. 341–361, 11 figs., March 1983.

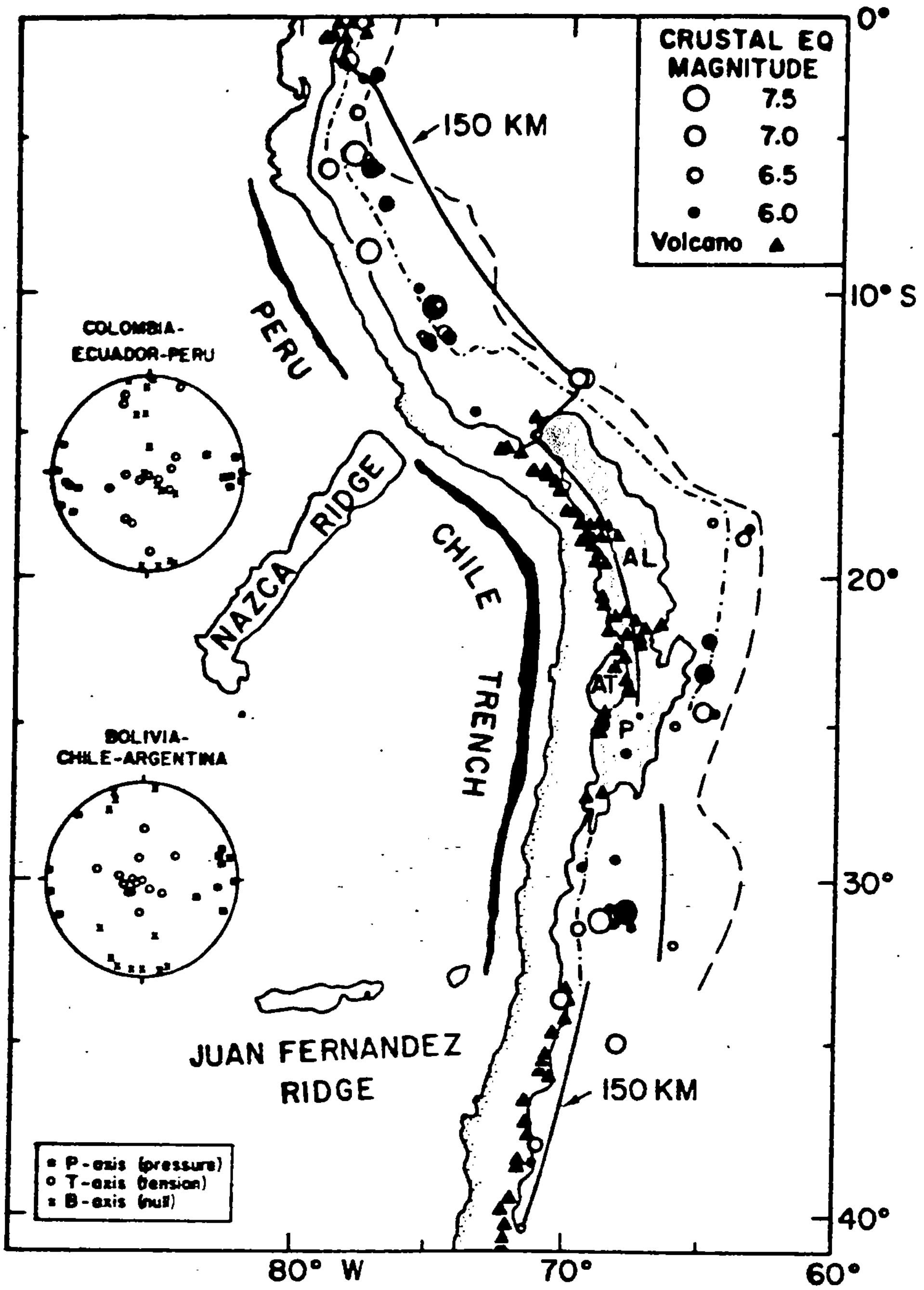

**Figure 1. Map of western South America and the eastern Pacific ocean floor, showing distribution of large crustal earthquakes, Holocene volcanoes (Simkin and others, 1981), and geologic provinces, relative to the geometry of the subducted Nazca plate (150-km contour on top of Benioff zone shown). Earthquakes shown have magnitudes greater than 5¾ (Gutenberg and Richter, 1954; Rothe, 1969; the *Seismological Notes*, or the *Bulletins of the Seismological Society of America*); those shown with black circles are included in equal-area projections at right (lower hemisphere of common focal sphere) of P, T, and B axes of focal mechanism solutions (Chinn, 1982). Geologic province boundaries are shown by dashed line (eastern limit of recognized Neogene deformation), dash-dotted line (boundary between foreland and hinterland, as defined in text), and light solid line (drainage divide along the Andean crest that also encloses the Altiplano (AL), Puna (P), and Atacama basin (AT)). The trench is mapped by the 6,000-m isobath.**

(mostly in Spanish, German, and French) on Neogene magmatic, stratigraphic, and structural history between 18°S and 40°S. Similarities between the modern Andes and the early Cenozoic western North America are also treated.

In addition to tectonic segmentation along boundaries that cross strike (that is, lateral segmentation), the subject of this paper, the Andes have tectonically distinct belts paralleling strike. We apply terminology developed in other mountain belts to these tectonic subdivisions (Figs. 1, 3, and 4): (1) The "forearc region," located between the Peru-Chile Trench and the continental drainage divide, includes the Coastal Ranges and Longitudinal Valleys of Chile and Peru. (2) The "magmatic arc," or "main cordillera," is the zone of active volcanoes and or the main continental drainage divide in the Western (Peru and Bolivia) or Principal and Frontal (Argentina and Chile) Cordilleras. (3) The "hinterland" lies between the magmatic arc and the foreland region. It includes the Altiplano of Bolivia and Puna of Argentina, and the Eastern Cordilleras of Peru, Bolivia, and Argentina. The term is ambiguous in the flat-subducting segments but includes parts of the Principal and Frontal Cordillera of Argentina. (4) The "foreland" is the region of youngest deformation in the Andes, bounded to the east by the undeformed craton. The Pampeanas Ranges and Bolivian Subandean belt represent end-member structural components of the foreland, which also includes the Argentine Precordillera and Peruvian Subandean zone. Together, the foreland and hinterland comprise the back-arc or retroarc province of the Andes.

## SEGMENTATION OF THE SUBDUCTED NAZCA PLATE

The descending Nazca plate south of Ecuador is divided into four major segments as inferred from the spatial distribution of intermediate-depth earthquakes (Stauder, 1973, 1975; Barazangi

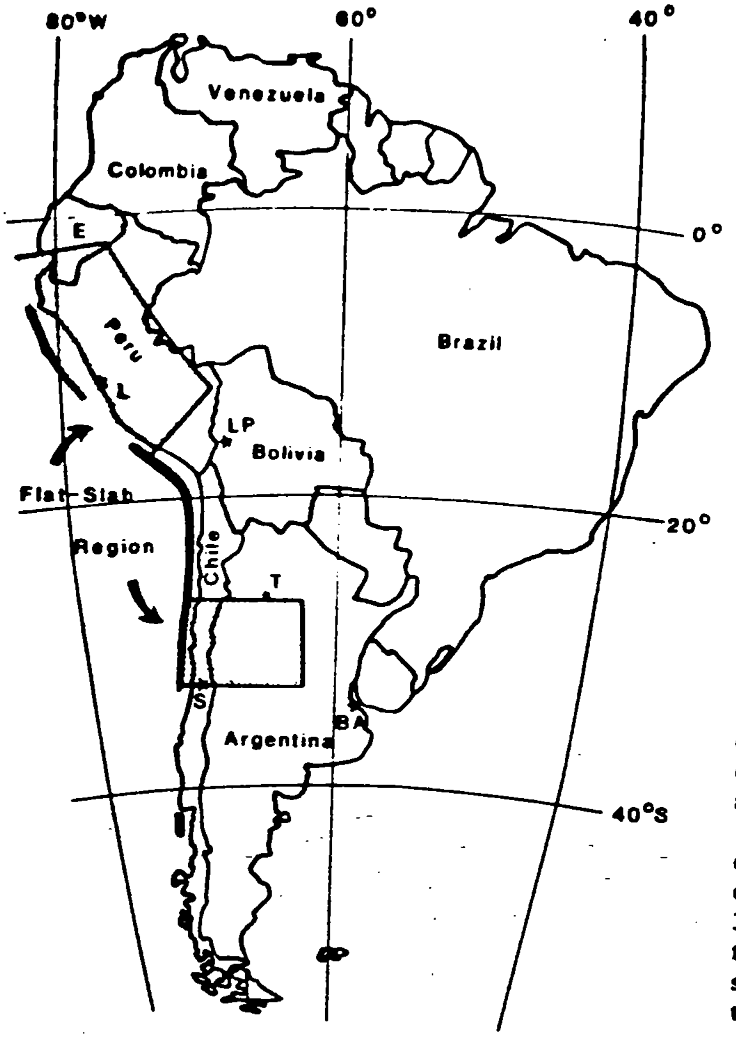

**Figure 2. Map of South America, showing locations of subhorizontal segments of subducted Nazca plate ("flat-slab regions") relative to political boundaries. E, Ecuador; L, Lima; LP, La Paz; T, Tucuman; S, Santiago; BA, Buenos Aires.**

and Isacks, 1976, 1979; Isacks and Barazangi, 1977). From about 2°S to 15°S and 27°S to 33°S, the Benioff zone dips only about 5° to 10° east, whereas from 15°S to 24°S and south of 33°S, the zone is inclined about 30° east (Figs. 1 and 2). The relatively abrupt transition between steep and flat parts of the subducting plate near 15°S was interpreted as a tear between the two segments by Barazangi and Isacks (1979), but Hasegawa and Sacks (1981) found evidence that it is instead a very sharp contortion of the plate. The geometry of the transition near 33°S is not as well known.

At the north end of the Chile-Argentina flat-subducted slab, there is a gap along strike (between 24°S–27°S) in the distribution of intermediate-depth (125–300 km) earthquakes (indicated by the break along strike of the 150-km contour of hypocentral depth in Figs. 1 and 4b). The mantle in this area appears to be virtually aseismic, based on a careful search for well-located events for the period 1950–1979. Continuity of forearc features and magmatic-arc features suggests that the major change from steep to flat subduction occurs near 27°S. Above the aseismic region, there is an area of complex transitional tectonics in the upper plate (see below).

The down-dip lengths of the two nearly flat segments of the subducted plate are similar, about 750 km measured from the axis of the trench to a depth of about 160 km (Fig. 3). The intervening more steeply dipping segment is slightly shorter, about 650 to 700 km to a depth of about 300 km. With a convergence rate near 10 cm/yr (Minster and others, 1974), these three segments would have been subducted since the late Miocene. Deep earthquakes beneath western Brazil and Bolivia may be within a piece of lithosphere detached from the shallower segments. These events, as well as the deep earthquakes beneath Argentina, are probably within lithosphere that left the surface in the middle Miocene (Wortel and Vlaar, 1978).

The segment south of 33°S is significantly shorter, less than 500 km measured downdip from the trench axis to 160-km depth. The length east of the magmatic axis is even shorter relative to the other three segments, since the forearc region of the southern segment is 100 to 200 km broader than the forearc segments to the north (Fig. 2). Vlaar and Wortel (1976) and Wortel and Vlaar (1978) attributed the decrease in slab length to a decrease in subducted plate age (and hence decreased resorption time) toward the south, approaching the Chile Rise. South of 42°S, the Benioff zone becomes even shorter, as the age of the plate decreases southward across the Medana fracture zone (Vlaar and Wortel, 1976). However, intersections between discontinuities in subducted plate age (fracture zones) and the trench do not coincide with the segment boundaries near 27°S and 33°S. Rather, the abrupt change in downdip length near 33°S may indicate that resorption is dependent upon the depth reached (and thus on the angle of subduction) as well as upon the time involved.

Of several coincidences between Nazca plate features and subducted plate segmentation, the most striking is the alignment of the east-trending Juan Fernandez ridge and the segment boundary near 33°S (Fig. 1). In contrast, Nazca plate fracture zones are oblique to the plate margin. The Nazca Ridge intersects the subduction zone significantly north of the transition between the Peru flat-slab and the more steeply dipping slab to the south, and its subducted extension trends northeast beneath Peru (Pilger, 1981). On the other hand, the flexure or tear in the plate beneath southern Peru coincides closely with the inflection in the large-scale shape of the trench axis (in map view) from a westward-convex curvature in the north to eastward-convex curvature in the south. This major change in curvature may strongly influence the geometry of the descending plate (Rodriguez and others, 1976). Small-scale segmentation of the subducted Nazca plate has been proposed (Rodriquez and others, 1976; Swift and Carr, 1975), but in our opinion it is beyond the resolution achievable with presently available earthquake locations.

## SEGMENTATION OF UPPER-PLATE GEOLOGY IN ARGENTINA-CHILE-BOLIVIA

The regional geologic framework of the Andes in southern Peru, Bolivia, Chile, and Argentina has been extensively described (see reviews in Harrington, 1956; Herrero-Ducloux, 1963; Aubouin and others, 1973; Laubacher, 1978; Martinez and Tomasi, 1978; Zeil, 1979; Dalmayrac and others, 1980a and 1980b). Precambrian and presumed Precambrian basement occurs widely east of the magmatic arc and in a thin strip (the "Arequipa Massif") along the Pacific coast (Fuller, 1968; Cobbing and others, 1977). Several late Precambrian and Paleozoic tectonic cycles of laterally variable character and the Jurassic to Quaternary Andean orogeny are superimposed. The older structures, partly striking across Andean trends, may have strongly influenced later structures (Cobbing, 1972; Turner and Mon, 1979; Rolleri and Fernandez Garrasino

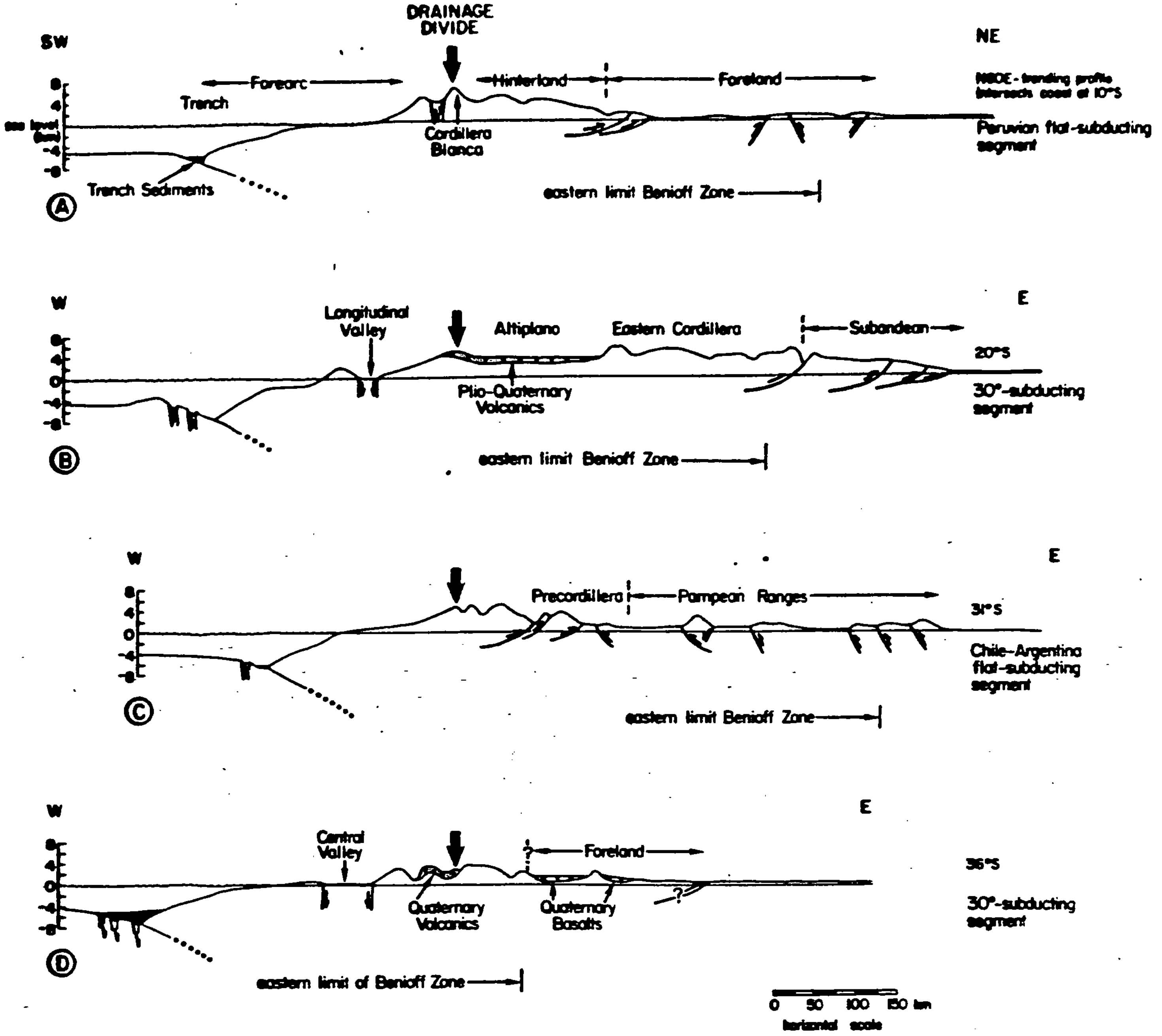

**Figure 3. Topographic profiles (about 25 times vertical exaggeration) drawn across Andes perpendicular to tectonic strike, contrasting two regions with nearly horizontal Benioff zone (A, C) with two regions where Benioff zone dips more steeply (B, D). Geometry of Pliocene or Quaternary faults shown schematically. Eastern limit of intermediate depth events of Benioff zone indicated. Compiled from Carte Geologique de l'Amerique du Sud (1964), Operational Navigation Charts (1973), Schweller and others (1981), and references in text.**

1979; Allmendinger and others, 1981). However, space limitations permit only a description of the Neogene tectonics.

The timing of major uplift of the Andes is uncertain, but uplift during and after the Miocene is commonly postulated (Hollingworth and Rutland, 1968; Mortimer, 1973; Paskoff, 1977; Zeil, 1979; Naranjo and Paskoff, 1980). In cross section for areas above the 30°-dipping Benioff zone, the outer trench slope has normal faults, a major valley divides coastal mountains from the Andes range with its active volcanoes, and the foreland is primarily deforming by thin-skinned shortening. In contrast, cross sections over a flat-subducting Nazca plate include less faulting in the outer trench slope, no longitudinal valley, no active volcanoes, and fore-segments of the forearc and magmatic arc coincide more closely with boundaries of the subducted plate than do lateral hinterland and foreland boundaries.

### Chile Trench and Forearc

The Chile trench, outer-trench slope, and continental slope are abruptly segmented along strike (Scholl and others, 1970; Schweller and Kulm, 1978; Schweller and others, 1981). From 22°S to 27°S, the Chile trench is 7,000 to 8,000 m deep and contains only isolated pockets of sediment. Its outer trench slope is broken by horsts and grabens paralleling the trench axis with 500 to 1,000 m of offset

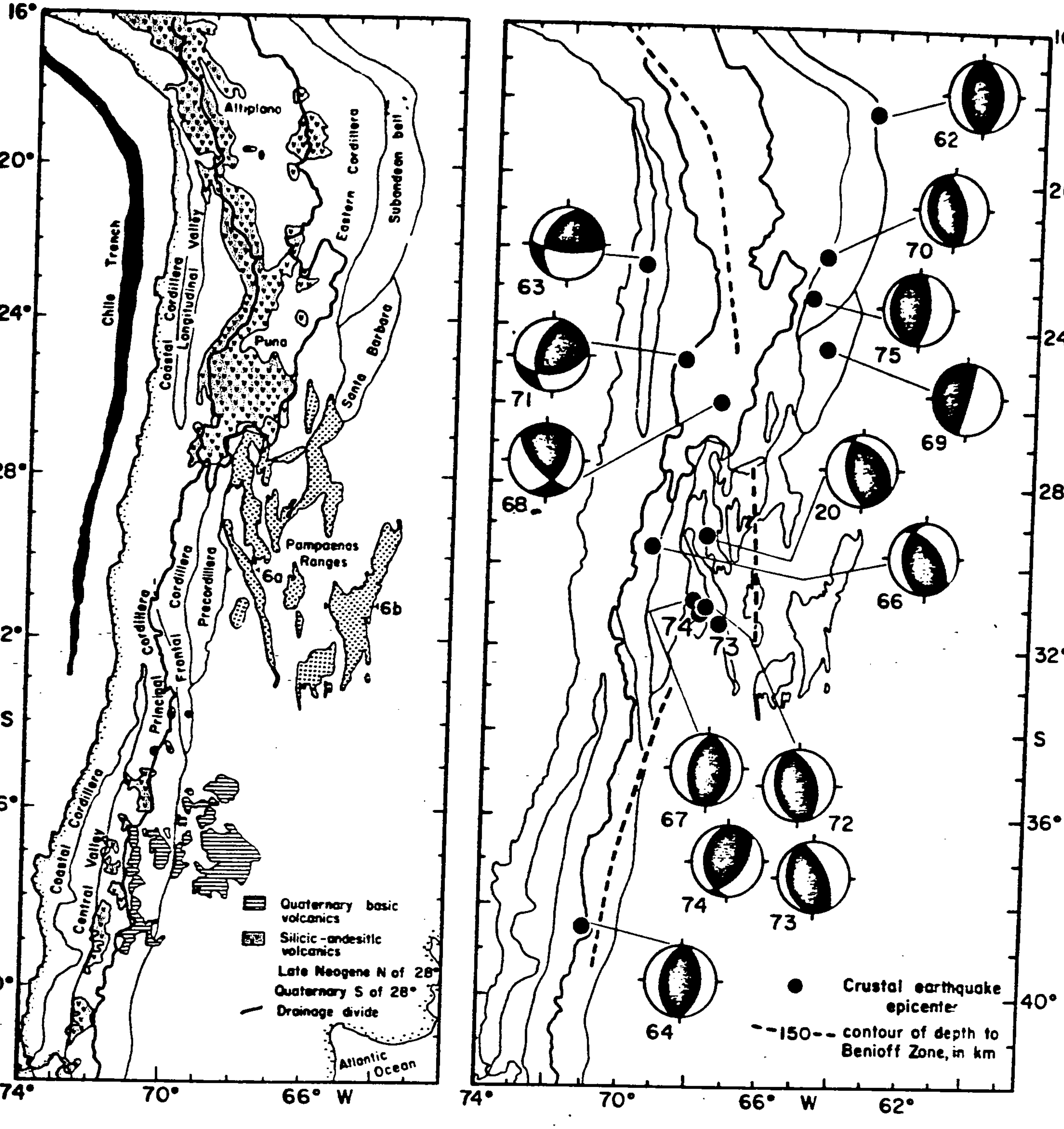

Figure 4. (a) Tectonic provinces and young volcanic cover of the central Andes in Chile, Bolivia, and Argentina. Primary Pacific drainage divide (heavy line) marks Andean crest and forms western boundary of Altiplano-Puna. Eastern boundary of Altiplano-Puna here defined by the divide between the Atlantic Ocean and internal Puna-Altiplano drainage. Trench identified by 6000 m isobath. (From Operational Navigation Charts, 1973; Tectonic Map of South America, 1978; Carte Geologique de l'Amerique du Sud, 1964.) (b) Equal area projections of focal mechanisms for well-determined shallow earthquakes for same area as "a." Numerals beside focal mechanism solutions identify earthquakes listed in Chinn (1982). Flat-slab area between about 28° S and 33° S indicated by eastward shift of 150-km contour on the top of the Benioff zone.

about 6,400 m deep, with up to about 350 m of sediment smoothing over structural irregularities. There are only minor block faults on the outer trench slope, and the continental slope is gentler than in

broad, flat basin about 5,000 m below sea level, with an additional kilometre or more of sediment fill (Fig. 3D). As in the northernmost segment, the outer trench slope is highly faulted, orrelate with changes of the degree of curvature and faulting of the eaward trench slope, and lateral transitions in seaward trench lope curvature correlate with boundaries of the segmented sublucting Nazca plate (Schweller and others, 1981).

The map view (Fig 4) of the shape of the trench and the eading edge of the upper plate clearly reflects the major segmentaion. From 18°S to 27°S, the trench and coastline are quite straight. etween 27°S and 33°S, the trench and coastline (and the trend of he Andean Cordilleras) are distinctly convex toward the west. outh of 33°S, the distance between the trench and the drainage ivide increases. This seaward or westward projection of the leading dge of the plate is reflected by the increased widths of the forearc Fig. 3) and the interplate boundary, which dips more gently south f 33°S than north of 33°S (Chinn, 1982).

In the forearc region, Quaternary landforms are commonly ought to express extensional structures (Katz, 1971; Paskoff, 977), although Thomas N. (1970) and Rutland (1971) interpreted resent morphology to be on compressional structures. Paskoff 1977) suggested notable neotectonic uplift and subsidence from 8°S to 26°S and from 33°S to 46°S but Quaternary stability from bout 26°S to 33°S, corresponding closely to the flat-subducting gment. The Coastal Cordillera is separated from the Principal ordillera by a narrow elongate depression called the "Central ongitudinal) Valley," except between 26°S and 33°S (Fig. 4) 'Angelo and Aguirre, 1969; Kausel and Lomnitz, 1969; Thomas ., 1970; Paskoff, 1977). Mortimer and Saric Rendic (1975) proosed that the Central Valley acts as a neutral zone between an tensional tectonic regime to the west and a compressional regime the east.

## agmatic Arcs

In Chile, from at least 20°S to 35°S, the calc-alkaline volcanic is migrated steadily eastward from the Jurassic into the Tertiary, companied by an eastward increase in $K_2O$ content in plutonic cks (Aguirre and others, 1974; Clark and others, 1976; Roobol d others, 1976; Coira and others, 1982). Back-arc spreading and lcanism were apparently widespread in the Cretaceous (Dalziel d others, 1974; Ramos and others, 1982; Coira and others, 1982).

**Volcanism over 30°-dipping Benioff Zones and Transition ne.** During the Quaternary, andesitic stratovolcanoes were active ng the Bolivia-Chile-Argentina borders between 17°30'S and °S, where elevations reach 5,500 to 7,000 m. Quaternary basaltic desite stratovolcanoes were active between 33°15'S and 52°20'S, ere peak elevations diminish southward from over 6,000 m to low 4,000 m south of 36°S (Lopez-Escobar and others, 1976; wrie and Hey, 1981). South of 35°S, a Miocene to Holocene salt province east of the andesitic axis reaches nearly to the lantic coast (Fig. 4) (Yrigoyen, 1950; Gonzalez Diaz, 1978; Ulia, 1978).

Oligocene and abundant Miocene volcanism was active north 28°S and south of 33°S (Aguirre and others, 1974; Clark and ers, 1976; Vergara, 1978; Charrier and Munizaga, 1979; Coira others, 1982). The Neogene volcanic history is best illustrated m 22°S to 26°S (Coira and others, 1982), but studies to the north south suggest similar trends (Clark and others, 1976; Kussmaul others, 1977; Baker and Francis, 1978; Zeil, 1979). From the gocene through most of the Miocene, intermediate composition gmatism was prolific from the Longitudinal Valley of Chile to eastern Puna-Altiplano, comprising both stratovolcanoes and ash-flow tuff fields, interrupted by deformation phases in the late Oligocene and middle to late Miocene. By the latest Miocene (about 5 to 6 m.y. B.P.), the andesitic to dacitic volcanic belt had narrowed to approximately the present magmatic axis. Common late Pliocene and Quaternary basalts and ash-flow tuffs east of the andesitic axis reflect renewed widening of the volcanic belt (Aguirre and others, 1974; Clark and others, 1976; Kussmaul and others, 1977; Chong D., 1977; Paskoff, 1977; Coira and others, 1982).

**Volcanism over the Flat Benioff Zone.** A distinct Quaternary volcanic gap exists between about 28°S and 33°15'S (Fig. 1) (Aguirre and others, 1974; Paskoff, 1977). Comparatively minor quantities of incompletely dated and described Neogene volcanics occur between 28°S to 33°S, dated locally in the Precordillera as mid-Miocene (Aparicio, 1975; Leveratto, 1976). In the volcanic gap, Paleozoic strata, Mesozoic strata and volcanic units, and Cretaceous and lower Tertiary granitic plutons reach typical crest elevations of 5,000 to more than 6,000 m, including Cerro Aconcagua (7,021 m).

## Hinterland and Foreland: The Andes of Argentina-Bolivia

In the eastern Andes and foreland regions, four distinct cross-sectional segments can be recognized (from north to south): (1) the Bolivian Altiplano, the Eastern Cordillera, and the Subandean zone, between about 15°S and 23°S (see Figs. 3 and 4); (2) a "transition zone" comprising the Argentine Puna, Eastern Cordillera, and Santa Barbara system between 23°S and 27°S; (3) the Frontal Cordillera, the Precordillera, and Pampeanas Ranges between 27°S and 33°S; and (4) the eastern parts of the Cordillera Principal and areas of widespread basaltic volcanism south of 33°S (to 46°S). Segment 3 coincides with the nearly flat segment of the subducted Nazca plate, whereas segments 1, 4, and probably 2 coincide with 30°-dipping segments of the subducted plate.

**Tectonics over 30°-dipping Subducted Slab: Subandean Belt, Eastern Cordillera, and Altiplano (15°S–23°S).** The 100- to 200-km-wide Subandean thin-skinned thrust belt forms low mountains on the eastern flank of the Andes of Bolivia and northernmost Argentina (Figs. 1, 2, 3, and 4). Upper Paleozoic to Tertiary strata dominate, with exposure to lower Paleozoic. Structures trend northwest in central Bolivia, but change abruptly at 18°S to a north-northeast trend that continues into northern Argentina. Asymmetric, eastward-verging folds and west-dipping thrust faults are characteristic, accommodating at least 30 to 80 km of horizontal shortening (Fig. 5a) (Martinez and others, 1972; Mingramm and Russo, 1972; Martinez and Tomasi, 1978; Mingramm and others, 1979). Folding and thrusting of formerly undeformed rocks in the Subandean zone apparently did not begin until the end of the Miocene and continued at least into the Pleistocene (Martinez and Tomasi, 1978; Mingramm and others, 1979). Earthquakes indicate ongoing shortening (see below), and there are a few reports of folds or thrusts involving Holocene strata (Lohmann, 1970).

Where well documented near 22°S, the western boundary of the Subandean belt is a west-dipping, high-angle reverse fault (Fig. 5a) (Martinez and others, 1972; Mingramm and others, 1979). To the west, the high Eastern Cordillera exposes chiefly Ordovician and Devonian strata in Bolivia, and weakly metamorphosed Precambrian strata and intrusives, Ordovician strata, and upper Mesozoic continental deposits in Argentina (Turner and Mon, 1979). These are cut by thrusts and high-angle reverse faults whose trends also change abruptly from northwest north of 18°S to north-

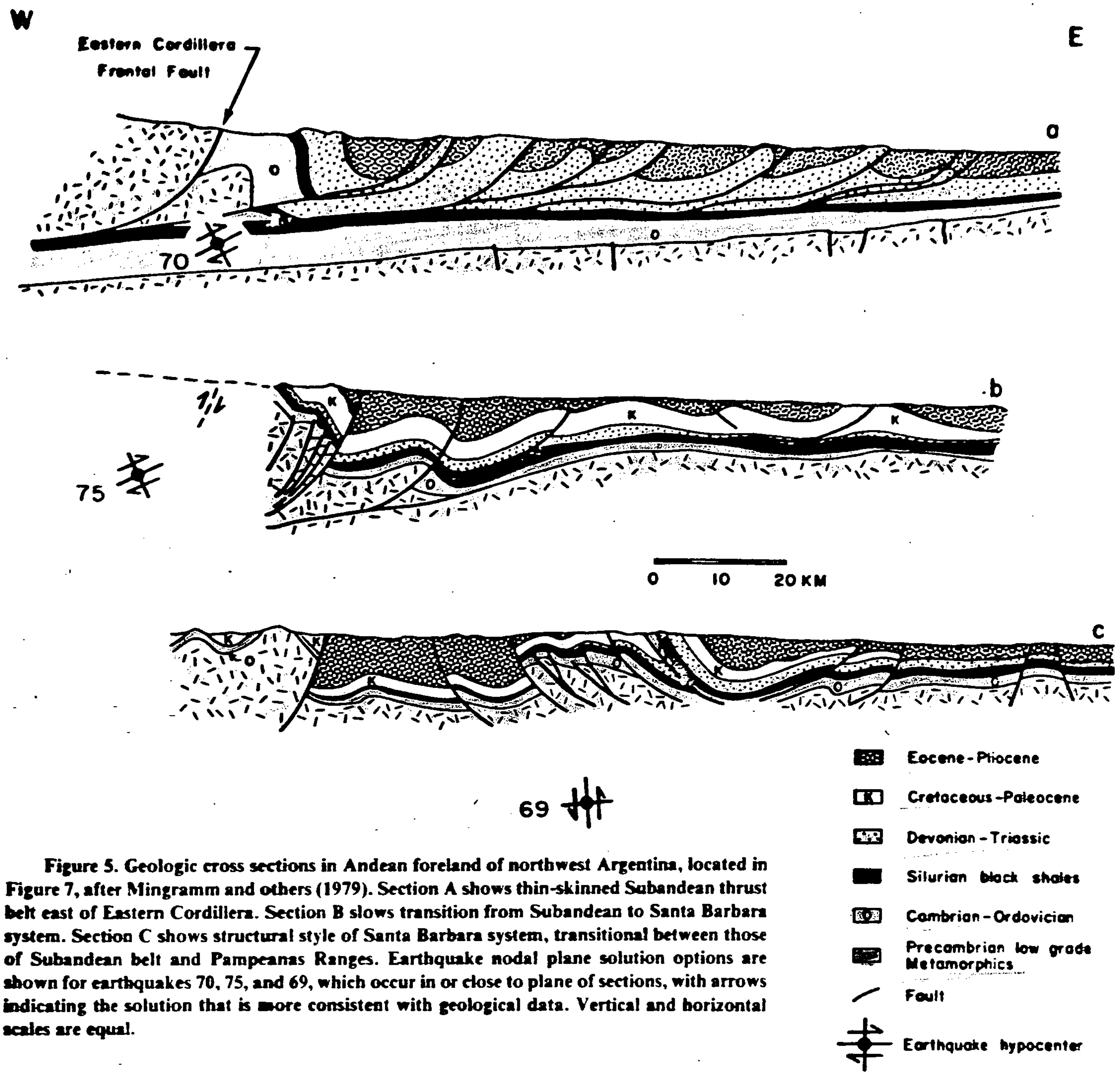

Figure 5. Geologic cross sections in Andean foreland of northwest Argentina, located in Figure 7, after Mingramm and others (1979). Section A shows thin-skinned Subandean thrust belt east of Eastern Cordillera. Section B slows transition from Subandean to Santa Barbara system. Section C shows structural style of Santa Barbara system, transitional between those of Subandean belt and Pampeanas Ranges. Earthquake nodal plane solution options are shown for earthquakes 70, 75, and 69, which occur in or close to plane of sections, with arrows indicating the solution that is more consistent with geological data. Vertical and horizontal scales are equal.

northeast to the south (Turner, 1972; Martinez and Tomasi, 1978; Turner and Mon, 1979). Mingramm and others (1979) inferred that the subhorizontal detachments of the Subandean zone deepen westward and cut into basement below the Eastern Cordillera (Fig. 5a). Miocene deformation was apparently most important (Turner and Mon, 1979; Russo and Serraiotto, 1979), although poor age control on Neogene strata limits the resolution of deformation age.

The Altiplano and Puna, discussed more extensively below, form a distinctive high-elevation plateau with basins enclosed within an internal drainage system outlined by the major drainage divides shown in Figures 1, 4, 7, and 8. The basin elevations range from 3.7 to 4.4 km. The Miocene and Pliocene volcanic histories of the Altiplano and Puna were apparently similar, but the Puna is distinguished by its morphology and trend.

The Altiplano-Puna became a major continental basin in the Paleogene and was first gently folded in the Oligocene (Zeil, 1979). Major folds and high-angle reverse faults are inferred to be of Miocene age with local Pliocene deformation (Schwab, 1972; Laubacher, 1978; Martinez and Tomasi, 1978; Zeil, 1979; Coira and others, 1982). Large volumes of Miocene and younger ash-flow tuffs and andesitic volcanic rocks characterize the Altiplano and Puna. Final uplift in the Plio-Pleistocene has been inferred, and Quaternary normal faults are reported at the northern end of the Altiplano (Laubacher, 1978; Martinez and Tomasi, 1978).

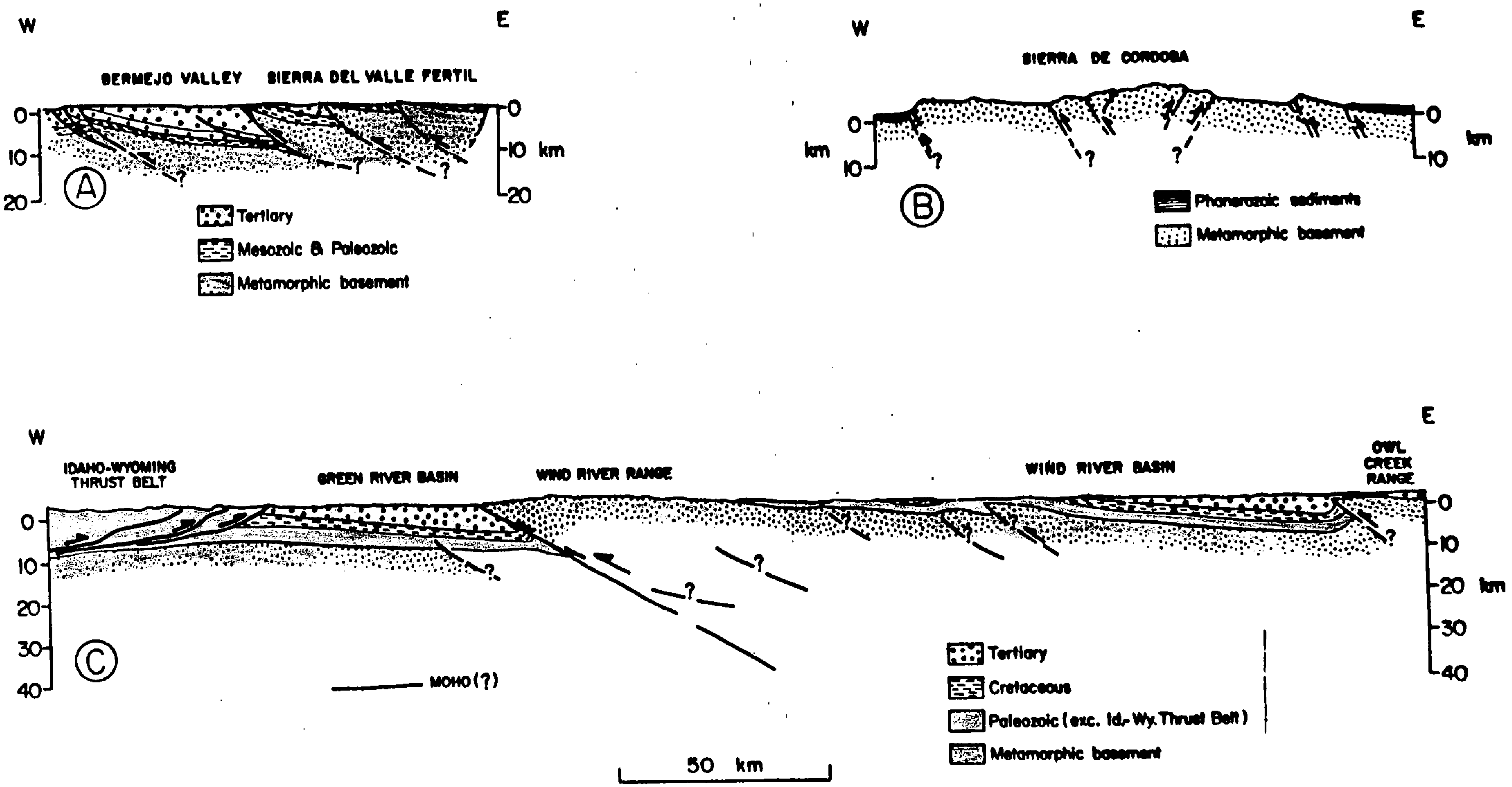

Figure 6. Comparison of structural geometry of uplifts in (A) western and (B) eastern Pampeanas Ranges (located in Fig. 4) to (C) Wind River Mountains in Laramide province of North America (located in Fig. 10). A is from Vasquez and Gorrono (1980), B is from Gordillo and Lencinas (1979), and C is compiled from Royse and others (1975), Case and Keefer (1966), Brewer and others (1980), and Lynn (1980).

**Tectonics over the Flat-subducted Slab: Pampeanas Ranges, Precordillera and Frontal Cordillera (28°S–33°S).** In sharp contrast to thin-skinned thrusting to the north and west, the foreland from 28°S to 33°S is dominated by a broad region of crystalline basement uplifts in the Pampeanas Ranges (Fig. 4). These massive mountain blocks commonly reach 2 to 4 km and locally 6 km elevation, with intervening broad, flat plains at less than 1 km elevation. The ranges, often 75 to 100 km long and 25 to 75 km wide, are uplifted on north- to north-northwest–trending reverse faults that dip about 60° beneath the uplifts (Gordillo and Lencinas, 1979; Caminos, 1979b; Lucero M., 1979; Flores, 1979; Criado Roque and others, 1981). Vertical throws of at least 6 km separate the mountain blocks from the intervening broad basins. The faults place Precambrian and Paleozoic crystalline basement rocks over upper Cenozoic strata, with associated drag folds (Fig. 6) (Gordillo and Lencinas, 1979). Principal deformation of the Pampeanas Ranges is poorly dated, but it is thought to be Pliocene and Pleistocene in age (Gordillo and Lencinas, 1979; Lucero M., 1979; Caminos, 1979b; Flores, 1979). Earthquake focal mechanisms indicate active compression in the region, with fault planes apparently dipping 40° to 60°.

To the west, the Precordillera and Frontal Cordillera (Fig. 4) appear to be a narrow Neogene to Quaternary thin-skinned thrust belt. The complex pre-Andean structural history is recorded in a Paleozoic sequence, including oceanic slices and late Paleozoic batholiths (Furque and Cuerda, 1979; Caminos, 1979a). The Principal Cordillera, in the southwest part of this segment, is dominated by Mesozoic volcanic and sedimentary sequences (Yrigoyen, 1979). West-dipping reverse faults, locally observed to be low angle, were active in the mid-late Miocene along the boundary between the Principal Cordillera and Frontal Cordillera. A set of imbricate west-dipping reverse faults separating the Frontal Cordillera and Precordillera developed during the late Pliocene to early Pleistocene, indicating eastward-migrating thrusting (Gonzalez Bonorino, 1950; Caminos, 1979a). In the Precordillera, lower Paleozoic rocks locally overlie Tertiary on 40° to 50° west-dipping reverse faults, and Holocene uplift continues (Furque and Cuerda, 1979). In the easternmost Precordillera, reverse faults verge to the west (Ortiz and Zambrano, 1981).

**Transition Zone Overlying Inferred 30°-dipping Slab (23°S–28°S).** The foreland of the transition zone is deformed by large, broad, predominantly west-verging folds cored by lower Paleozoic rocks and bounded by reverse faults on one or both sides (Santa Barbara system) (Fig. 7). The Eastern Cordillera of the transition zone contains thick deposits of Cretaceous red beds lying unconformably on low-grade metasediments of the Precambrian-Cambrian Puncoviscana Basin. A northern wedge of Sierras Pampeanas crystalline basement uplifts constitutes a third part of the transition zone (Mon, 1972, 1976a; Mon and Urdaneta, 1972; Turner and Mon, 1979; Reyes and Salfity, 1973; Rolleri, 1976; Allmendinger and others, 1981). In all of these regions, a significant component of strike-slip faulting is evident, with left-lateral sense on northwest-trending faults and right-lateral sense on east-northeast–trending faults (Baldis and others, 1976; Ramos, 1977; Salfity, 1979). In the Puna, Miocene to Quaternary volcanic rocks coincide with several of these transverse structural zones.

The structural style of the transition zone, with characteristics of the thrust belt to the north and of the basement uplifts to the south, is partly controlled by the local paleogeography. Well-defined areas of thrusting are localized in Cretaceous basin fill, whereas steeper reverse faulting coincides with relative sedimentary thins. The transition from deepest exposures in the north of Pre-

basement of gneisses and intrusives corresponds to a transition from generally low-angle to high-angle reverse faults (Mon, 1972; Allmendinger and others, 1981).

The transitional region terminates southward in a diffuse, northeast-trending zone known as the Tucuman, Hualfin, and Aconquija lineaments (Mon, 1976a, 1976b; Ramos, 1977; Salfity, 1979; Turner and Mon, 1979). This zone appears to be one of distributed right-lateral shearing rather than strike-slip faulting along a single fault. Ordovician litho-tectonic assemblages are displaced across this zone, but the age and significance of the apparent offset is not yet known. The zone also coincides with the southern boundary of the Puna (Fig. 4).

The high basins of the Puna are located between the active volcanic axis and the transitional foreland province just described (Fig. 1 and 4). At the western edgeof the Puna, the main volcanic axis changes trend sharply at 23.5°S. To the north the axis trends north-northwest, but to the south, it trends north-northeast. Farther south, the axis changes to north-south (Fig. 4). This jog forms the eastern boundary of the lower (2.3 km) Atacama basin of Chile. The Altiplano and Puna "boundary" lies east of this jog. A particularly extensive east-west zone of Miocene-Quaternary volcanics and a pronounced westward encroachment of Atlantic Ocean drainage occur at the Altiplano-Puna boundary.

Unlike the Altiplano, the Puna is characterized by many small intermontane basins and mountain blocks with north-south to north-northeast–south-southwest trends and 1 to 2 km relief. Ranges are probably bounded by high-angle reverse faults that were active in the Neogene, deforming units as young as about 9 to 10 m.y. old (Schwab, 1970, 1972, 1973; Turner and Mendez, 1979; Coira and others, 1982).

**Southern Region over 30°-dipping Subducted Segment (33°S–38°S).** Whereas a main subducted plate segment boundary is at 33°S, the pronounced change in foreland geology occurs at about 34°30′S (Fig. 4). Between 33°S and 34°30′S, deformation patterns are typical of, but less developed than the Precordillera and the Pampeanas Ranges to the north. The large morphostructural blocks of the Pampeanas Ranges cease at 33°S, but minor exposures of similar crystalline basement persist to the south (Criado Roque and Ibanez, 1979). Active gentle folding of Neogene strata is reported along strike of the Precordillera (Regairaz and Videla Leanie, 1968) and seismic-reflection data reveal west-dipping thrusts and eastward-vergent folds (Bettini, 1980). The Frontal Cordillera Neogene structural province continues to about 34°30′S. Early Miocene volcanism occurred in the western Andes, and Middle to late Miocene magmatism and Quaternary volcanics are common in the Principal Cordillera.

In contrast, south of 34°30′S, there are voluminous Quaternary volcanics extending from the Principal Cordillera to more than 100 km east of the Andes foothills (Fig. 4). Little is known about the chemistry or tectonic affinity of these basalts and andesites, which form several prominent volcanic centers with as much as 3 km relief above the surrounding plains. Mid-Tertiary folding and faulting and Miocene folding accompanied by significant salt tectonics are reported in the Principal Cordillera, and younger folding and thrusting are likely. In the broad volcanic foreland, there is little reported evidence of post-Miocene compression; minor faulting and gentle arching of strata are suggested (Membru and Uliana, 1978). The common southeast-to-east orientation of these structures suggests control by older basement trends.

The significant structural break at 34°30′S apparently coincides with the northern limit of the important Mesozoic Neuquen basin. Late Paleozoic–early Mesozoic mountain building may also

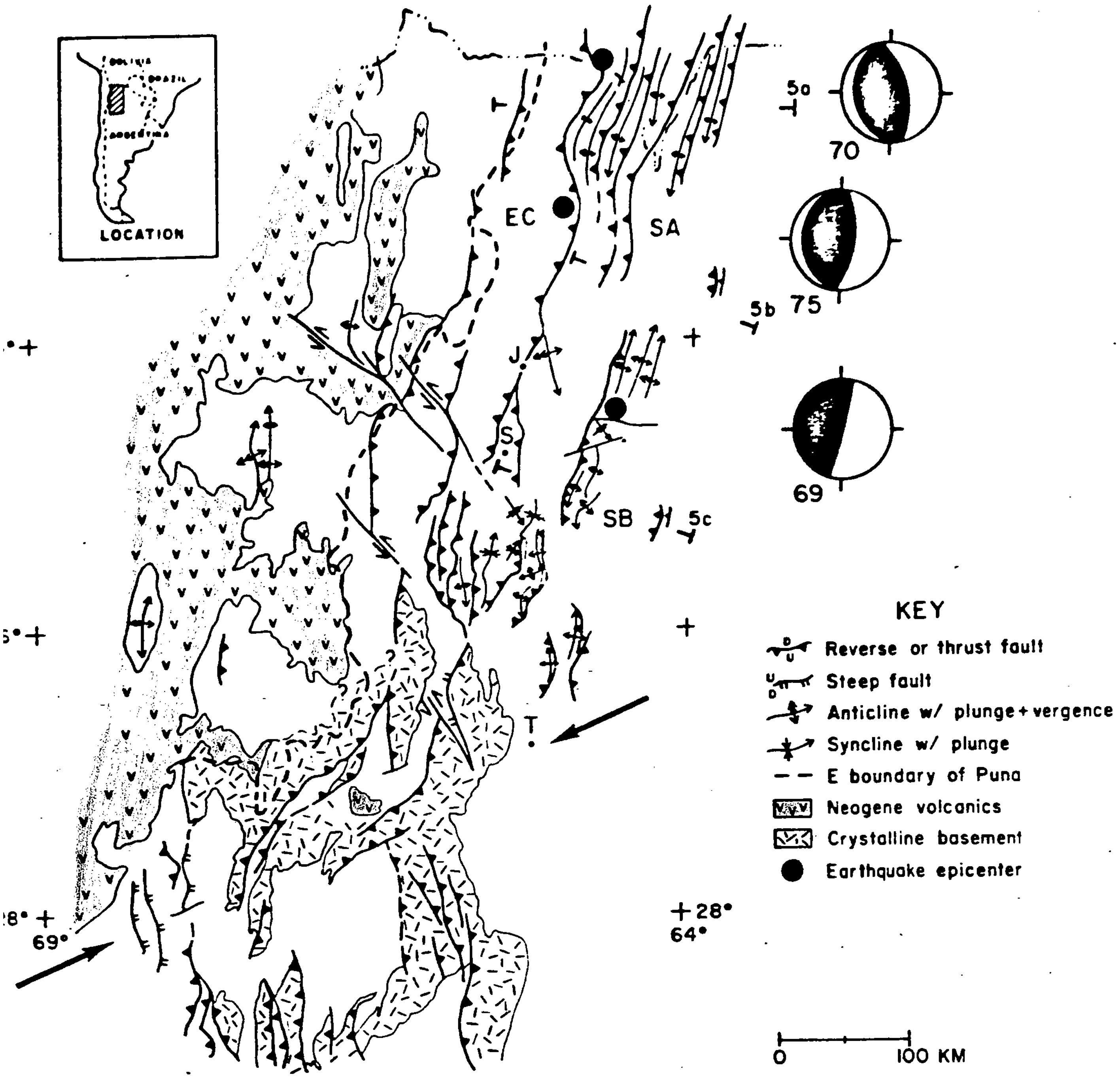

**Figure 7.** Generalized tectonic map of transition zone and adjacent regions of northwest Argentina. Crystalline basement exposures licate the northern Pampeanas Ranges. The Aconquija/Tucuman lineaments, shown by heavy arrows, are interpreted as a broad zone of ;ht-lateral shearing. Unpatterned areas are metamorphics, Phanerozoic sedimentary rocks, and intrusives. The Puna has extensive lcanic cover, west of dashed drainage divide. Structures not shown in Puna except for prominent west-verging folds in Tertiary strata. :, Eastern Cordillera; SA, Subandean belt; SB, Santa Barbara system; J, Jujuy; S, Salta; T, Tucuman. Section lines a, b, and c refer to gure 5. Focal mechanisms are referred to in text by number, with epicenters shown by nearby filled circles. The Argentina-Bolivia ternational boundary is shown at the top of the figure. Data from analysis of LANDSAT imagery, field observations by the authors, and ips by Gonzales Bonorino (1972), Maisonave (1979), Ruiz Huidobro (1968, 1972, and 1975), Turner (1964a and 1964b, 1967, 1971, and 73), and Vilela and Garcia (1978).

tersects the modern Andes near 34°30'S (Dalziel and Elliott, 82).

## mparison to Peru

The tectonic framework of both Andean and older orogenic ases in Peru and Bolivia is described in numerous recent geological studies (Audebaud and others, 1973; Megard, 1978; Marocco, 1978; Laubacher, 1978; Dalmayrac, 1978; Martinez and Tomasi, 1978; Dalmayrac and others, 1980a). Above another nearly horizontal segment of the Benioff zone in central Peru (Fig. 1, 2, and 3), Neogene deformation in the hinterland and foreland is characterized by open cylindrical and locally asymmetric folding, monoclinal

---

fle
bet
on
rer,
de
and
und

flat
Arg
diff
due
the
that
Per
pea
pro
or c
sub

fron
inte
follo
(No
try
Chil
strai
volc
In A
20-m
cene
1975

CRU
TEC

Ame
Chin
solut
work
dept
mech
quak

Area

segm
comp
post-
slab
parti
time

ping
conc
ern p
Suba
lera a
In the

flexuring, and northeast-vergent reverse faults (reported dips between 50° and 80°). Locally, basement-cored uplifts are bounded on the southwest side by west-verging reverse faults (Ham and Herrera, 1963; Megard, 1978). Basement involvement in foreland deformation in Peru appears most pronounced between about 7°S and 13°S (Ham and Herrera, 1963; Bellido and others, 1972; Martinez and Tomasi, 1978).

However, foreland basement deformation above the Peruvian flat-subducted slab is probably not as extreme as over the Chile-Argentina flat-slab (Ham and Herrera, 1963; Megard, 1978; Gordillo and Lencinas, 1979; Caminos, 1979b). This difference may be due to subtle differences in subduction geometry, or may imply that the horizontal-subduction geometry in Chile-Argentina is older than in Peru. Perhaps, if present subduction geometries continue, Peruvian foreland uplifts will become similar to the present Pampeanas Ranges. Alternatively, the differences in the two foreland provinces may partly or largely reflect differences in the thickness or character of the South American crust, rather than differences in subduction history.

Indirect evidence for the history of the flat subduction comes from the volcanic age sequence in the magmatic arc. In Peru, intense volcanic and plutonic activity from 8 to 11 m.y. B.P. was followed by waning but still significant activity until 5 m.y. B.P. (Noble and McKee, 1977). Therefore, the Peruvian flat-slab geometry was probably fully developed by about 5 m.y. B.P. Over the Chile-Argentina flat-slab, the young volcanic history is less constrained. In Chile, only minor amounts of Miocene and Pliocene volcanics have been mapped between 28°S and 33°S (Fuller, 1968). In Argentina, volumetrically minor volcanics, locally with 16- to 20-m.y. K-Ar dates and elsewhere assigned Pliocene and Pleistocene ages, are scattered across the flat-subducting region (Aparicio, 1975; Leveratto, 1976).

## CRUSTAL EARTHQUAKES AND ACTIVE TECTONICS OF THE UPPER PLATE

Shallow earthquakes in the continental crust of western South America manifest ongoing tectonic activity. Chinn (1982) and Chinn and Isacks (unpub. data) determined new focal mechanism solutions for shallow earthquakes in the Andean crust, updating the work of Stauder (1973, 1975). They also report accurate focal depths for many of the earthquakes large enough to obtain focal-mechanism solutions. In this paper, their data and published earthquake locations are integrated with Neogene tectonic information.

### Areal Distribution

Upper-plate seismicity is most active above the flat-subducted segments in Peru and Argentina (for example, compare Fig. 8, the compilations of 1955–1978 earthquakes of all sizes, and Fig. 1, post-1925 larger earthquakes). The largest events occurred in flat-slab segments, with magnitude 7 to 7½. The seismicity clusters in particular areas, but the persistence of such localization on geologic time scales is not known.

In contrast, South American crust above the more steeply dipping subducted-slab has fewer and smaller earthquakes that are concentrated in the foreland. The Bolivian Altiplano and the northern part of the Argentine Puna appear nearly aseismic, whereas the Subandean foreland thrust belt and the easternmost Eastern Cordillera and southern part of the Argentine Puna are moderately active. In the southern more steeply dipping segment, especially south of 34°30'S, activity is sparse and appears to be located mainly along or near the magmatic arc.

In general, the forearc crust (upper plate) appears to have a lower seismicity than the hinterland and foreland, although the hinterland of the Altiplano and Eastern Cordillera is also relatively aseismic. A forearc quiet zone is suggested by the gap (Fig. 8) between the seismicity in the eastern Andes and a western band of the very active seismicity that is mainly located along the forearc interplate boundary. Detailed studies of specific areas (Sacks and Linde, 1978; Dewey and Spence, 1979) also suggest a forearc quiet zone. Near-coastal events whose focal mechanism solutions are not compatible with interplate slippage have hypocentral depths within the subducted rather than the upper plate (Chinn, 1982), also indicating relative quiescence of the forearc region of the upper plate.

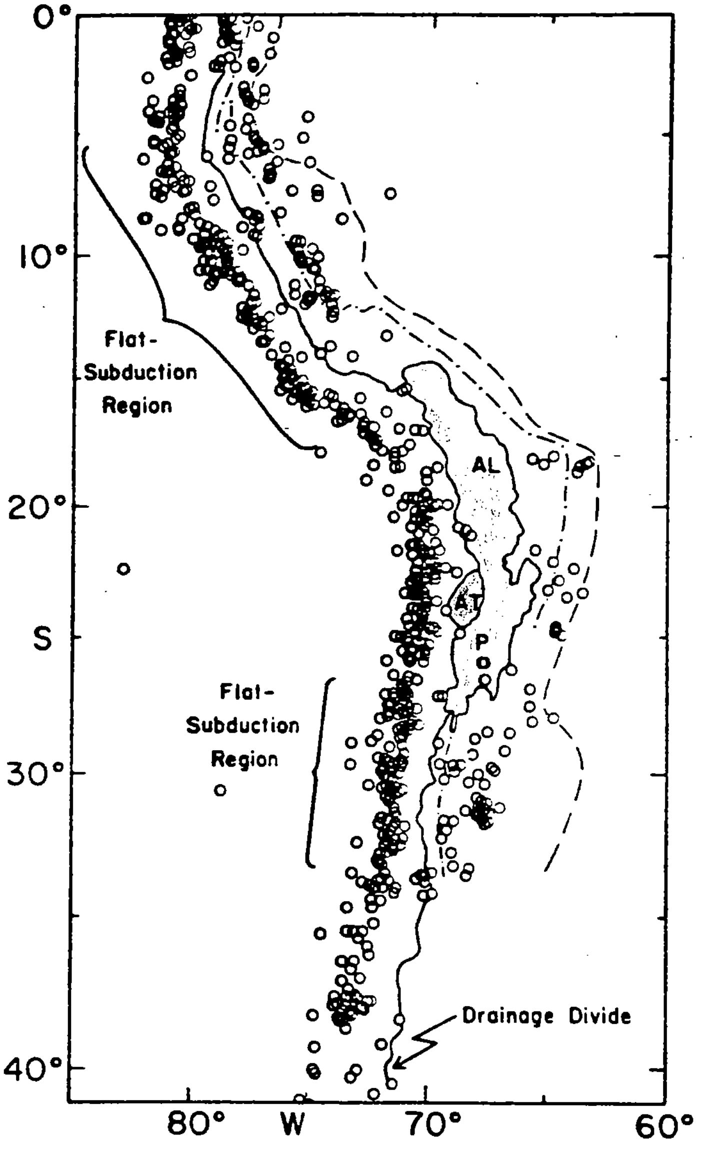

**Figure 8.** Epicenters of all earthquakes with depths less than 60 km. The data include relocations of L. R. Sykes for the period 1950 to 1960 and locations of the Preliminary Determination of Epicenters (PDE) of the U.S. Geological Survey for the period 1962 through July 1978, with the number of stations used in the PDE locations greater than or equal to 20. Drainage divide and structural boundaries identified in Figure 1. AL, Altiplano; P, Puna; AT, Atacama basin.

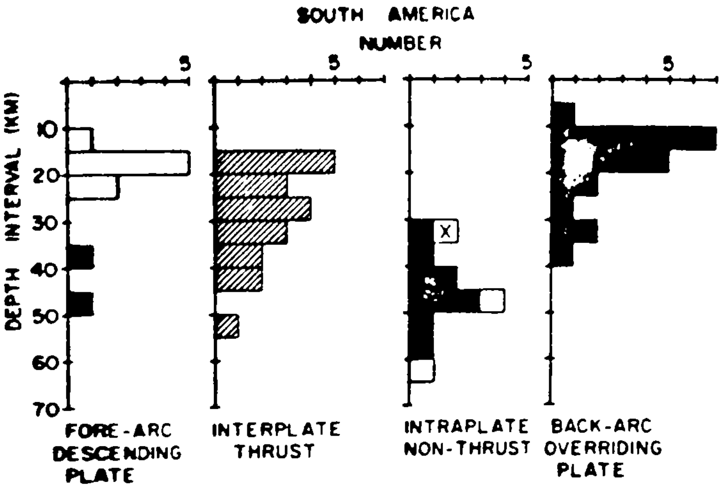

**Figure 9. Distribution of well-determined focal depths of shallow earthquakes in western South America. Depths determined by comparisons of synthetic and observed P-wave forms recorded by long-period seismographs of the WWSSN. Solid bars are in-plate compression; open bars are in-plate extension; diagonal lines are interplate thrust; and X, none of the preceding. These interpretations are based on the orientation of focal mechanism solutions. The four plots represent tectonic groupings according to location. The "forearc" include events mainly near the trench, while the "intraplate non-thrust" include events located near the interplate boundary (from Chinn, 1982).**

Yamashima and others (1978) present evidence that a quiescent forearc zone is a general feature of upper-plate seismicity in subduction zones.

### Focal-Mechanism Solutions: Predominance of Horizontal Compression

A strong horizontal east-west grouping of the "P" or compressional axes of the focal-mechanism solutions exists for the upper-plate earthquakes within the entire region from Ecuador to Argentina (Fig. 1) and in the foreland and Eastern Cordillera of Colombia (Pennington, 1981). Although dip-slip solutions predominate, strike-slip orientations are found in parts of Peru, Ecuador, and Colombia where the trend of the Andes is most transverse to the regional stress orientation. The average stress direction (obtained from the focal-mechanism data) and the inferred direction of relative motion across the Nazca–South American plate boundary are subparallel (Chase, 1978; Minster and Jordan, 1978). This coincidence suggests that the over-all convergence of the two plates is an important determinant of the stress within the upper plate in contrast to more localized and variable effects of uplift, magmatic intrusion, or other upper-plate processes.

Focal-mechanism solutions of several earthquakes located along the magmatic arc of Chile-Argentina reflect the over-all east-west compressive stress (Fig. 4b, events 64 and 71). The one earthquake studied by Chinn (1982) that was possibly located in the forearc upper plate (event 63, Fig. 4b) had a combined thrust and strike-slip solution with a compressive axis oriented obliquely (northwest-southeast) to the trend of the subduction zone. However, the 30-km depth places it ambiguously close to the plate boundary. It was also located directly below the surface trace of the Atacama fault (Arabasz, 1971), but neither of the two nodal planes can be easily associated with this fault.

### Depths

Deformation at middle- and upper-crustal depths is demonstrated by reliable determinations of depths of crustal earthquakes by analyses of long period *P*, *pP*, and *sP* phases (Chinn, 1982; Fig. 9). Most depths are between 10 and 25 km, but a significant minority occur at depths of 25 to 35 km; the deepest determination is 36 km for an event in the Ecuadorian Subandean zone. Depths of many of the events are clearly below the sedimentary section and indicate compressional deformation of the basement. Specific examples, especially for Bolivia and Argentina, are discussed below.

### Relationships of Seismicity to Late Cenozoic Deformation of the Upper Plate

Comparison of the distributions of seismicity and of late Neogene crustal deformation indicates a correlation between the two phenomena. In the areas of significant seismicity characterized by focal mechanism solutions with horizontal compressive axes, the latest Neogene structures are dominated by reverse faulting and folding indicative of important crustal shortening. In contrast, the relatively aseismic areas, including the forearc zone, the Altiplano, and parts of the Bolivian Eastern Cordillera and the Argentine Puna, are characterized by a relatively stable neotectonic regime or by one that appears to be dominated by relative vertical movements. As noted above, the forearc regions in the flat-slab areas in Peru and Chile appear to be relatively stable, although vertical movements and tilting of blocks may occur. In the forearc zones above the more steeply dipping subducting slabs, the Longitudinal or Central Valley and associated coastal ranges exhibit differential vertical movements, but the type and extent (or even the existence) of Neogene horizontal deformation are not well established.

Evidence for extensional stress is reported for the Peruvian Cordillera Blanca (Dalmayrac, 1974; Yonekura and others, 1979; Dalmayrac and Molnar, 1981), for the northern Altiplano and part of the Eastern Cordillera of northern Bolivia and southern Peru (Megard and Philip, 1976; Mercier, 1981), and for the southern boundary of the Puna (Turner, 1967). However, in none of these cases is there clear evidence for large amounts of crustal extension, and in each case there is an ambiguous but close relationship to crustal compression.

The spectacular normal faulting west of the Cordillera Blanca (Fig. 3a) is apparently related to the uplift of the very young batholith forming the Cordillera (ages as young as 2.7 m.y.; Stewart and others, 1974). One of the largest known crustal earthquakes, the Ancash earthquake of 1946, was located east of the Cordillera Blanca. It produced one of the few published cases of possible surface faulting in the Andes and was interpreted as normal faulting by Silgado (1951) and Richter (1958). However, Megard and Philip (1976) emphasize evidence found within the batholith itself for compressive deformation. Dalmayrac and Molnar (1981) emphasize the extensional stress implied by the normal faulting, but they consider the extension to be an effect of uplift and crustal thickening caused by the more pervasive and important crustal shortening manifested in the Eastern Cordillera and Subandean zone.

Normal faults trending east-west in the northern Altiplano (Mercier, 1981) indicate north-south extensional stress, subparallel to the convergent zone. That area, located near the large bend in the strike of the convergent zone, may be an area of anomalous stress orientation. Mercier (1981) reported that the extensional stress regime has been interrupted by compressive phases several times in the Neogene, but geological data seem to indicate that the net deformation has been compression (Ahlfield, 1970; Laubacher, 1978). It is also possible that the extensional deformation may be a secondary, shallow effect of uplift.

To the south, minor Quaternary normal faulting in the Puna may also be related to regional upwarping, but significant extension and large-scale rift structures (Francis and others, 1978) are not indicated by young fault geometries. Field studies show that the characteristic basin-and-range structure of the Puna is controlled largely by compressional reverse faulting rather than normal faulting (Schwab, 1970, 1972, 1973; Turner, 1964a; Turner and Mendez, 1979). In fact, the focal mechanisms of two earthquakes, events 71 and 68 (Fig. 4b) manifest possibly ongoing compression in the southern Puna.

Peru and Ecuador seismicity was discussed by Stauder (1975), Burchfiel and Davis (1976), Barazangi and Isacks (1976, 1979), and Burchfiel and others (1981). Some of the Subandean crustal events are located within the basement (Chinn, 1982), supporting the geological inference of basement-involved deformation (Koch, 1961).

Event 62 was located in the eastern part of the Subandean foreland fold-thrust belt south of Santa Cruz, Bolivia. No accurate depth was obtained for this event, but its focal mechanism indicates thrusting along a fault plane dipping at 45°.

Figures 4 and 5 show the relationships of events 70, 75, and 69 to the structure of the Eastern Cordillera, Subandean, and Santa Barbara systems of northern Argentina, spanning the change in deformational style from thin-skinned thrust belt in the north to apparent basement deformation in the transition zone. The depth (17 km) and focal mechanism of event 70 locate it near one of the major listric thrust faults inferred by Mingramm and others (1979) to form the boundary between the Eastern Cordillera and the Subandean belt (Fig. 5a). The earthquake appears to have occurred where Precambrian rocks overthrust lower Paleozoic strata. A similar relationship may hold for event 75 (depth 14 km), located slightly west of the nearest available cross section (Fig. 5b). Farther south, event 69 had nearly horizontal and vertical nodal planes, but the 26-km depth of this event and the proximity to the basement-involved structures of the Santa Barbara system (Rolleri, 1976) suggest faulting along the more nearly vertical nodal plane (Fig. 5c). For this focal mechanism, the eastern side moved relatively upward, in agreement with the history of uplift of the basement block. The earthquake would thus manifest the thick-skinned deformational style characteristic of the transition zone Santa Barbara system.

Five earthquakes exemplify the thick-skinned Pampeanas Ranges deformational style (events 20, 67, 72, 73, and 74) (Fig. 4b). Event 72 was the large (Ms = 7.3) earthquake of November 23, 1977, followed by aftershocks 73 and 74. The depths of 15 to 20 km indicate faulting in the basement. The dips of the nodal planes, all between 30° and 60°, indicate reverse faulting rather than faulting along a nearly horizontal décollement or along nearly vertical faults. These results are in good agreement with the geological evidence for uplift of basement blocks exposed in the Pampeanas Ranges by movement along reverse faults. Many of the nodal planes strike north-northwest, oblique to the northerly strike of the convergent plate boundary (and the strike of the main Cordilleras) but more nearly parallel to a common trend in the basement uplifts of the Pampeanas Ranges. This suggests that the strain pattern of the Pampeanas Ranges is partly controlled by major pre-Andean basement structures. Event 20 also displays the north-northwest trend and, with a depth of 32 km, is quite clearly located in the basement.

A large (Ms = 7.4) earthquake in 1944 destroyed the city of San Juan (31°31'S, 68°30'W), located near the boundary between the predominantly east-verging Precordillera–Frontal Cordillera system and the mainly west-verging western Pampeanas Ranges. Interpretation of the surface faulting is controversial (Richter, 1958), and the location and orientation of the causative fault is not well established. The large earthquake (Ms = 7.3) of 1977 (event 72, Fig. 4b) was located northeast of the 1944 event and is apparently associated with faulting beneath the westernmost exposure of the Pampeanas Ranges at that latitude (Algermissen and others, 1978).

Event 66 occurred near the boundary between the Precordillera and the Frontal Cordillera, in the area of inferred thin-skinned tectonics. Unfortunately, no accurate depth is available for this event, which also has a thrusting focal mechanism.

Events 71 and 68, in the southern part of the Argentine Puna, exhibit combined strike-slip and near-horizontal compressive deformation. The north-northeast and east-northeast–striking nodal planes of event 71 (15-km depth) are subparallel to the local northeast strike of the magmatic arc and western edge of the Puna. A northeast to north-northeast trend of some of the basins and ranges of the Puna (the Salar de Antofalla) is also reflected in the strike of one of the nodal planes of event 68 (11-km depth), which occurred near the Salar de Antofalla. Event 64, located along the magmatic arc in the southern segment, also exhibited horizontal compression. Its 9-km depth is one of the shallowest determined.

## COMPARISON WITH THE MESOZOIC-EARLY TERTIARY CORDILLERA OF WESTERN NORTH AMERICA

The Mesozoic and early Cenozoic cordillera of western North America has often been called an "Andean-type" margin (Hamilton, 1969; Burchfiel and Davis, 1975), because inferred eastward subduction beneath the continental margin produced a suite of tectonic provinces similar to that in South America. If the comparison is valid, then the Cordilleras of North and South America represent, respectively, deeply eroded and active examples of a single type of orogenic system.

### Foreland Basement Deformation: Laramide Province

In the western United States between 36°N and 46°N, the Laramide province is composed of large, crystalline basement uplifts, bounded by reverse or thrust faults with as much as 10 to 12 km of vertical displacement (Figs. 6 and 10). Laramide deformation occurred over a period of 30 to 40 m.y. in the Late Cretaceous and early Tertiary, approximately 1,000 to 1,500 km from the coeval active plate margin (Dickinson and Snyder, 1978; Hamilton, 1978). Although some geologists have proposed that the bounding faults steepen at depth (Sterns, 1978), deep seismic-reflection profiles crossing the Wind River and Laramie Ranges indicate that the faults have moderately low dips and suggest horizontal shortening of the entire crust (Fig. 6) (Smithson and others, 1979; Brewer and others, 1982).

The Laramide uplifts resemble the Pampeanas Ranges of western Argentina in both morphology and structure. However, the Laramide uplifts developed greater proven structural relief, occurred up to twice as far from the continental margin, and evolved over a longer time span than have the modern Pampeanas Ranges analogues.

### Foreland Thrust and Fold Belt

Thin-skinned thrusting and folding is best represented by the Canadian Rockies (Bally and others, 1966; Price and Mountjoy, 1970) and the Sevier Belt (Figs. 10 and 11) (Armstrong and Oriel, 1965; Armstrong, 1968; Royse and others, 1975). Thrusting probably began in the Middle(?) Jurassic in the west and proceeded eastward (toward the craton) into the early Eocene, spanning nearly 100 m.y. Listric thrusts sole into a basal detachment that steps downsection westward. This deformation produced 50% or more shortening of supracrustal strata without significant metamorphism or mylonite development. The shortening rate in Idaho-Wyoming was ~0.15 cm/yr.

Both the Subandean belt north of 22°S and the Precordillera between 27°S and 33°S are probably also thin-skinned thrust belts (Figs. 10 and 11). In the Subandean belt, the basal detachment is probably low in the Paleozoic section, with a minimum shortening of about 32% and a shortening rate of ~0.6 cm/yr (assuming 10 m.y. duration of deformation). Apparent thin-skinned thrusting in the Precordillera overprints complex older deformation patterns. Its deformation style may reflect older structural geometries that had no analogues in the miogeoclinal wedges of North America.

### Hinterland

It is difficult to directly compare the hinterland of North America with that of the Andes. The ancient hinterland of North America is identified from exposure of relatively deep structural levels, on the basis of known or inferred basement involvement in thin-skinned thrusting. The foreland-hinterland boundary of the Sevier belt is probably at the Northern Wasatch and Bannock Ranges (Fig. 11) (Royse and others, 1975; Allmendinger and Jordan, 1981), whereas farther north, the boundary generally corresponds with the

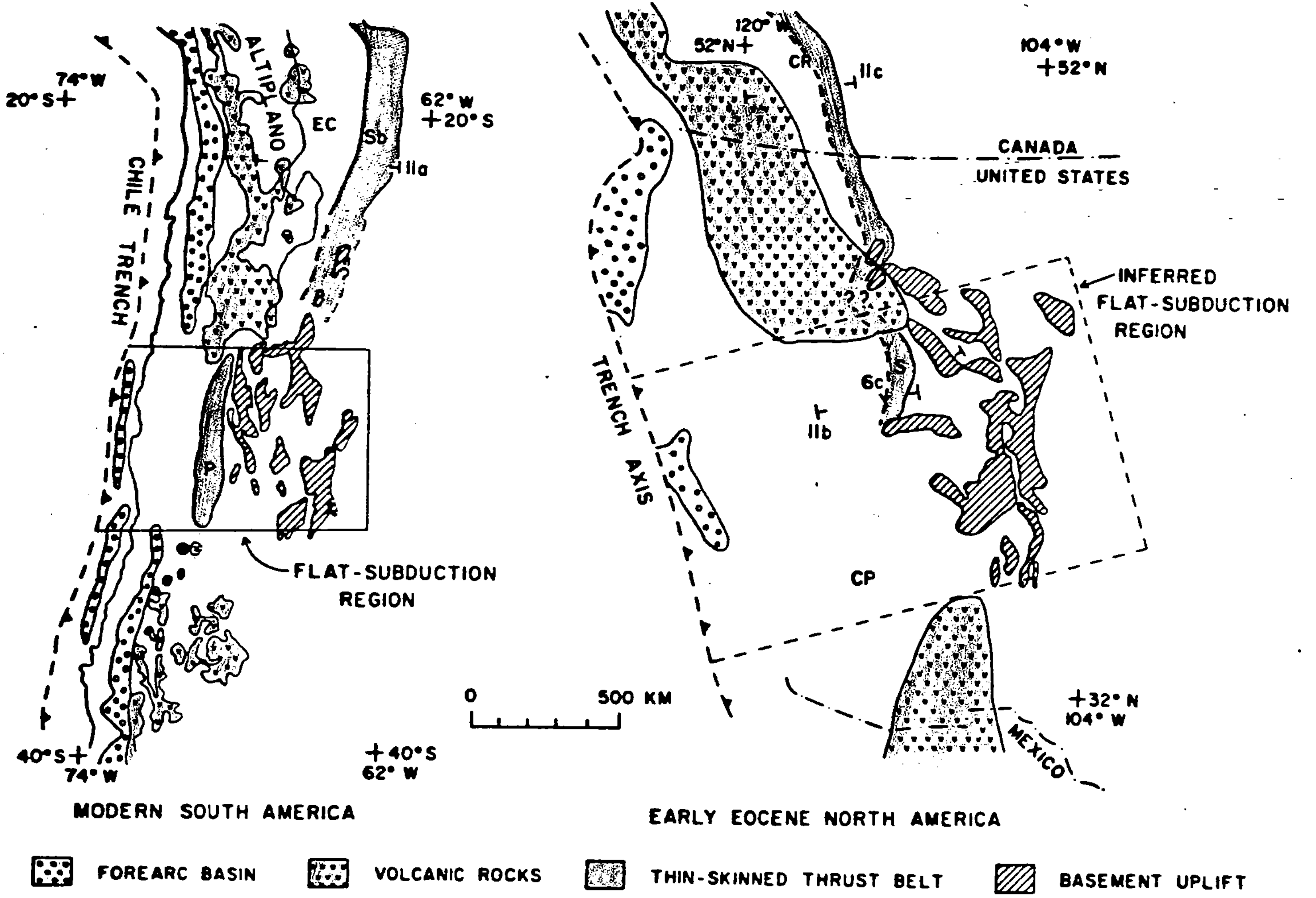

Figure 10. Comparison of Andean orogen of Bolivia, Chile, and Argentina to earliest Eocene Cordillera of western North America, at same scale. Features in North America, derived largely from Dickinson (1979), include palinspastic restoration of Basin and Range, San Andreas, Garlock, and other faults in Coast Ranges. Features in South America derived from references in text. Basement uplifts in North America are Laramide Province, and in South America are Pampeanas Ranges. Locations of cross sections of Figure 11 and of Figure 6c indicated. Key: EC, Eastern Cordillera; P, Precordillera; SB, Subandean belt; CP, Colorado Plateau; S, Sevier belt; CR, Canadian Rockies.

Rocky Mountain Trench (Price and Mountjoy, 1970; Brown, 1978; Harrison and others, 1980).

The modern Andean hinterland was deformed a few million years ago by an orogenic event that migrated toward the craton, but the hinterland is now inactive, with deep structure neither exposed nor revealed by earthquakes. The sole fault of the Subandean belt is believed to step downward to the west at the Eastern Cordillera-Subandean belt boundary, suggesting that the Eastern Cordillera and Altiplano-Puna are "hinterland."

In western North America north of 39°N, a linear belt of dynamically metamorphosed greenschist- to amphibolite-facies rocks is widely developed in the hinterland at the eastern fringes of the Mesozoic magmatic arc. The belt was probably first deformed during or just prior to Mesozoic deformation in the foreland (Fig. 11) (DeWitt, 1980; Allmendinger and Jordan, 1981). In South America, no linear metamorphic belt related to Neogene deformation is known. However, one would expect to find such a belt at depth under the eastern Altiplano-Puna.

**Magmatic Arc**

The Jurassic and Cretaceous magmatic arc was well developed along the entire length of the North American Cordillera and is presently expressed as a suite of calc-alkaline intrusives (Davis and others, 1978; Miller and Bradfish, 1980). However, in the Late Cretaceous and early Tertiary (80 to 40 m.y. B.P.), magmatism ceased in the region west of the concurrently forming Laramide uplifts (Fig. 10), and, north and south of that corridor, the axis of igneous activity swept from west to east, and then returned west (Dickinson and Snyder, 1978; Cross and Pilger, 1978). This magmatic trend has been explained as a result of shallowing in the dip of the eastward subducted slab, perhaps triggering the transition from thin-skinned to thick-skinned foreland deformation farther east (Lipman and others, 1971; Burchfiel and Davis, 1975; Coney, 1976; Dickinson and Snyder, 1978).

In Chile and Argentina, south of 33°S and north of 28°S, the volcanic zone became anomalously wide in the Miocene. In the

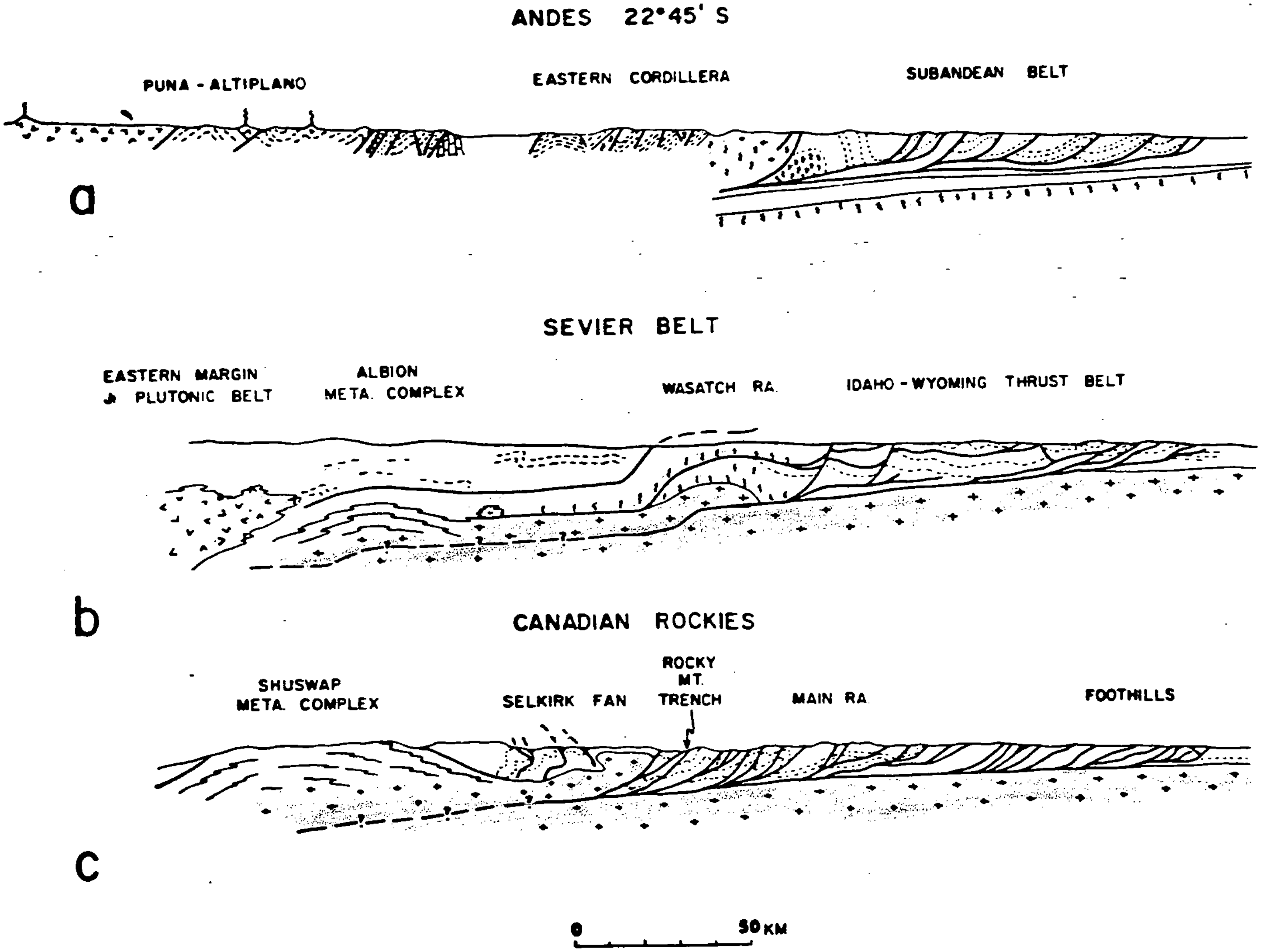

Figure 11. Comparison, at same scale, of cross sections of (a) eastern Andes in northernmost Argentina, (b) Sevier belt of Utah-Idaho-Wyoming, and (c) Canadian Rocky Mountains thrust belt. Section locations shown in Figure 10. Note similarities in width of foreland thrust belt, distance between magmatic arc and foreland, positions of metamorphic complexes, and implications for position of possible metamorphic complexes in the Andes. Compiled and simplified from Mingramm and others (1979), Turner and Mendez (1979), Turner and Mon (1979), Royse and others (1975), Allmendinger and Jordan (1981), Price and Mountjoy (1970), and Brown (1981).

intervening region, there was little volcanism during the Plio-Quaternary uplift of the Pampeanas basement blocks. The modern spatial gap in volcanism correlates with the extent of the nearly horizontal Benioff zone. Thus in the Andes and the North American Cordillera, thick-skinned foreland deformation and magmatic gaps are coincident and are inferred to be related to nearly horizontal subduction.

### Forearc Region

Forearc basins in western North America, generally represented by the Great Valley of California and related basins farther north, were best developed in the Cretaceous but persisted through the Eocene (Fig. 10) (Dickinson, 1979). The north-trending forearc basins, with volcaniclastic sediment fill, were separated from the Franciscan subduction complex to the west by an east-dipping major thrust fault (Ingersoll, 1978). Parts of the forearc region in western North America during the Mesozoic and Cenozoic were the sites of extensive accretion of island-arc fragments and exotic terranes with distant affinities (Davis and others, 1978; Coney and others, 1980).

In Chile, narrow linear basins offshore may represent poorly defined forearc basins (Schweller and Kulm, 1978). The Central (Longitudinal) Valley of Chile might also be interpreted as an incompletely filled forearc basin, although it seems to occur within continental crust ("intra-massif forearc basin" of Dickinson and Seely, 1979). In the Andes, Paleozoic accretion may have been extensive, but, in contrast with North America, there is little if any firm geologic evidence for plate-margin accretion of exotic terranes during the Mesozoic-Cenozoic Andean orogeny.

### Transition along Strike

Foreland structure in western North America changes markedly along strike between 44° N and 47° N, between the Sevier and Laramide belts to the south and the Montana Disturbed Belt and Canadian Rockies to the north (King, 1969) (Fig. 10). Transverse-trending strike-slip and oblique-slip faults occur in a region of complex structural geometry. Some details of the southern part of the transition are obscured by younger volcanic materials. Similarly, in the Andean transition zone, Pampeanas and Subandean structures apparently converge, strike-slip faulting and oroclinal flexuring may be important, and basement rock types change. Yet, Quaternary volcanoes suggest that the subducted plate dips steeply, with a geometry similar to areas north of the transition zone.

The northern portion of the North American transitional area coincides approximately with the northwest-trending dextral Lewis and Clark lineament, which apparently originated as an important boundary of the Proterozoic Belt basin and has been subsequently reactivated (Harrison and others, 1974). The southern limit of this transitional area is roughly coincident with the Cenozoic Snake River Plain volcanic belt. It is also the southern limit of a region of significant Jurassic and younger "suspect terrane" accretion (Davis and others, 1978; Coney and others, 1980). Thus, in the transition zones of both North America and the Andes, there are histories of significant cross-strike tectonism. These transition zones may primarily reflect segmentation of the upper lithospheric plate due to its pre-existing geometry, rather than the geometry of the subducted plate.

In summary, the Neogene structure of the central Andes and the Mesozoic–early Cenozoic structure of western North America are remarkably similar in scale and geometry. Furthermore, both orogens exhibit structural control by varying basin geometry along strike and structural boundaries across strike. Some of those paleogeographic elements coincide with boundaries of segments of the subducted plates. However, there are important differences in duration of tectonic events and their strain rates, as well as in accretionary histories along the two plate margins.

## DISCUSSION

### Tectonic Characteristics of Major Segments

Four cross sections summarize the tectonic comparisons and contrasts of the major segments of the Andes in relation to subducted-slab geometry (Fig. 3). The most consistent correlations between slab-dip and surface geology are (1) the correlation of flat-subduction with magmatic nulls and basement-involved foreland deformation (Figs. 3A and 3C), and (2) the association of steep-subduction with active volcanic arc segments and forearc continental basins (Figs. 3B and 3D). Other patterns of crustal deformation are of regional tectonic importance but are not equally well developed in all segments with equal slab-dip. In all four segments, the eastward extent of the Benioff zone is approximately coincident with the eastern limits of probable basement deformation of the upper plate (Fig. 3); the thin-skinned foreland fold-thrust belt of Bolivia is located well eastward of the inclined seismic zone.

Although both the Peru and Chile-Argentina flat-slabs have basement-involved deformation in the foreland, the degree of structural relief is drastically different and may depend on the duration of flat-subduction. Noble and McKee (1977) related the Pliocene expiration of the magmatic arc in Peru to the development of flat-subduction there. Available radiometric dating between 27°S and 33°S (Leveratto, 1976) indicates that the flat-slab configuration existed for 10 to 15 m.y., much longer than in Peru (and led to more extensive thick-skinned deformation of the Pampeanas Ranges). The actual magmatic history in the southern volcanic gap is a key problem for future research.

Back-arc structural distinctions between two steeply subducting segments are especially striking. Between 15°S and 23°S, the broad Altiplano–Eastern Cordillera uplift and the Subandean thin-skinned thrust belt are major features of the Andes. South of 34°30'S, over a similarly dipping subducted slab, abundant basalt at low elevations extends far east of the volcanic axis, and there is no equivalent of the Altiplano–Eastern Cordillera uplifts. Although paleogeographic differences may contribute to these striking tectonic distinctions, the marked difference in the downdip length of the Benioff zones in the two steep-subducting segments may play a key role. The Neogene volcanic fields south of 34°30'S lie far east of the Benioff zone. Whether this magmatic province is directly related to the subduction process and is analogous to the widespread magmatism of the Altiplano, or whether it is a regional intra-plate or mantle phenomenon only indirectly related to the subduction process, is unknown. An intimate relationship of the Altiplano to the subduction process is presumed because of the close correspondence of its geomorphic boundaries to the magmatic arc and to the geometry of the descending slab.

A late Cenozoic shallowing of the angle of subduction of all the segments beneath western South America might explain why the eastward limits of foreland deformation and the intermediate-depth Benioff zone correlate, and why foreland deformation is apparently almost completely Neogene in age. In fact, the 30° dip of the "steep" segments is quite gentle compared to most subduction zones (Isacks and Barazangi, 1977). Foreland deformation 700 to 800 km from the trench is associated with both flat- and steep-dipping segments of the Nazca plate, except south of 33°S. The large-scale shallowing of the subducted plate might be related to the approach of the East Pacific spreading center and the decreasing age of the subducted plate (Vlaar and Wortel, 1976; Molnar and Atwater, 1978). However, the segment with the youngest lithosphere, south of 33°S, is neither the flattest nor does it have significant foreland deformation. Subduction beneath western North America may have also shoaled during the late Mesozoic and early Cenozoic as the Pacific-Farallon spreading center approached California, thereby accounting for the analogies between the Andes and western North America.

### Coincidence of Subducted and Overriding Plate Segments

There is a clear correspondence between seismologically defined lateral segments in the subducted plate and tectonic segments in the Andes. However, not all shallow crustal segments correlate to separate Benioff zone segments. Between about 15°S and 24°S, there is one steeply dipping segment of the subducted Nazca plate, although continuity of the volcanic axis and forearc structures suggests that it continues to 27°S or 28°S. However, east of the magmatic axis, from 15°S to 27°S, the geology defines three discrete segments. At 18°S, the coastline and structural trends change abruptly, but there is no similarly sharp coincident bend in either the Benioff zone or magmatic axis (Fig. 1). At about 23°S, the Altiplano and classical foreland thin-skinned structures on the north change to the Puna and variable foreland structures to the south in the transition zone. Yet, as is especially clear in a comparison of the Puna and Altiplano, the Neogene history of the region from 15°S to 27°S is quite uniform, and it is primarily fault geometries that differ. Therefore, the three subsegments expressed in the hinterland and foreland geology from 15°S to 27°S are probably inherited from heterogeneities of the continental plate, not from present plate interactions.

Essentially, more than one type of tectonic segmentation may operate simultaneously in a Cordilleran-type mountain belt. Forearc structures and the magmatic arc may have a strong tendency to truly reflect subducted-plate geometry, but foreland structures are probably strongly influenced by both pre-existing crustal geometry and subducted-plate geometry. To identify ancient slab segmentation and dip in an inactive orogen, one must examine the coeval transverse and longitudinal tectonic variations, rather than using one or two of the characteristic features of Figure 3, particularly if only the hinterland and foreland are preserved.

### Upper-Plate Stress Distribution

The modern crustal earthquake patterns are sufficiently similar to Plio-Pleistocene deformation trends to suggest that existing stress conditions are a continuation of those which built the modern Andes. In general, the Andean foreland and locally the magmatic arc are under east-west horizontal compression (Fig. 1). Over the steep-subducting slab from 15°S to 23°S, the 500-km-wide hinterland is aseismic, and active brittle deformation is mainly expressed as horizontal shortening in the foreland. In contrast, above the nearly horizontal-subducted Nazca plate, earthquakes indicate east-west horizontal shortening over a wide area east of the forearc region. Stress patterns in the forearc regions are more complex and possibly extensional at shallow crustal levels. In the wedge-shaped upper-plate forearc, the stresses may be substantially modified, especially at very shallow depths, by geometric effects of convergent plate coupling along the megathrust plate boundary, such as bending of the plate (Sacks and Linde, 1978; Yamashina and others, 1978). Isostatic and topographic effects of crustal thickening or mountain-building processes may also be important (Dalmayrac and Molnar, 1981).

Models of the driving forces of deformation over a steeply subducting plate must relate foreland thrusting and Altiplano-Puna uplift. The history of prolific volcanism suggests that heating and magmatism played important roles in the Altiplano-Puna evolution. Model options include (1) crustal volume increase in the Altiplano-Puna due to extensive magmatism that drove shortening at a similar horizon elsewhere (Hamilton, 1978; Smith, 1981), and (2) underthrusting of the foreland beneath a thin, upper-crustal Altiplano-Puna–Eastern Cordillera plate. To discriminate between these and other alternative models of Altiplano-Puna evolution, quantification of the variation of total upper-plate shortening along strike and across the main segment boundaries is critical. Such a model must also explain the Neogene change from compression to a neutral or slightly extensional deformation regime in the Altiplano-Puna.

### Segment Boundaries and Paleogeography

We have already emphasized that the geologic history of a region may be a profound control on its response to the modern plate geometries. But ancestral controls may also influence the geometry of the subducted plate, if rheology or lithospheric thickness of the upper plate varies along strike. Such a possibility is suggested by the coincidence of major paleogeographic boundaries in the South American plate with modern boundaries of the subducted plate. For example, the northern limit of the Pampeanas Ranges province seems to be a major transition in basement character and thickness of overlying strata (Salfity, 1980). Also, Laubacher (1978) found that the north end of the Altiplano coincides with a significant boundary in a late Paleozoic phase of deformation. In general, locating Paleozoic tectonic boundaries is hampered by inadequate compilation and understanding of complex Paleozoic geology. However, in that Paleozoic tectonic trends are somewhat oblique to the Andean trends, modern tectonic province boundaries must crosscut ancient boundaries.

Features in the subducting plate must be weighed against pre-existing discontinuities in the overriding plate as causes of segmentation of the subducted plate. The possible role of buoyancy variations in the oceanic plate in producing segmentation has been discussed by others (Pilger, 1981; Kelleher and McCann, 1976; Vlaar and Wortel, 1976). Yet the coincidence of a boundary of a flat-slab with an ancestral upper-plate discontinuity may not be strictly fortuitous. In some cases, major changes in the map-view shape of the South American plate may be the primary cause of segmentation, as, for example, where the Nazca plate subducts around the curved margin of the continental lithosphere at 15°S, forcing a geometry that favors tearing the Nazca plate. However, in other cases, the present segmentation of the Nazca plate may be the product of favorable conditions in both lithospheric plates.

In the present Andes and, by analogy, the Mesozoic and early Cenozoic western North America, the inherited three-dimensional shape and structure of the continental plate apparently played a profound role in lateral segmentation. Inherited features may have helped determine where segment boundaries in the subducted plate rmed. and quite certainly created subsegments that deformed in arying ways above longer segments of the Benioff zone. Attempts relate the modern state of stress to the driving forces generated plate interactions must first filter out the influence of these inhered controls.

## CKNOWLEDGMENTS

We thank Drs O J. Ruiz Huidobro. R. Caminos. M. Palma. nd B. Coira of Argentina's Servicio Geologico Nacional; Drs. C. ombru. N. Zilli. E Freytes. J. Robbiano. and J. Cerdan of Yaciientos Petroliferos Fiscales; Drs. J. Castano and H. Bastias of rgentina's Instituto Nacional de Prevencion Sismica; Prof. F. olponi of the Instituto Zonda (Universidad Nacional de San uan); Dr. A.R.G. Mingramm of Shell International Petroleum laatschappij; and M. Bevis. D. Chinn. and D. Sarewitz of Cornell r providing us with published and unpublished data. We espeally thank Drs. M. Barazangi. S. M. Kay. A. L. Bloom. and D. R. eely for valuable review and discussions. and P. Bulack and E. arkas for preparing the manuscript. Supported by Cornell Proram for Study of the Continents (COPSTOC). National Science oundation Grants EAR-7911876 and EAR-8025890. and the Peoleum Research fund of the American Chemical Society.

## IBLIOGRAPHY

guirre. L.. Charrier. R.. Davidson. J.. Mpodozis. A.. Rivano. S.. Thiele. R.. Tidy. E.. Vergara. M.. and Vincente. J. C.. 1974. Andean magmatism: Its paleogeographic and structural setting in the central part (30-35° S) of the southern Andes: Pacific Geology. v. 8. p. 1–38.

lfeld. F.. 1970. Zur tektonik des andinen Bolivien: Geologische Rundschau. v. 59. p. 1124–1140.

germissen. S.. Castano. J.. Langer. C.. Harding. S.. Bucknam. R.. and Uliarte. E.. 1978. A preliminary report on the western Argentina earthquake of November 23. 1977: Earthquake Notes. v. 49. p. 40.

mendinger. R. W.. and Jordan. T. E.. 1981. Mesozoic evolution. hinterland of the Sevier orogenic belt: Geology. v. 9. p. 308–313.

lmendinger. R. W.. Ramos. V. A.. and Jordan. T. E.. 1981. Paleogeographic control on the geometry of Andean foreland deformation (abs.): Geological Society of America Abstracts with Programs. v. 13. p. 395.

paricio. E. P.. 1975. Mapa geologico de la Provincia de San Juan. escala 1:750.000 (with explanation): University of San Juan. Argentina. 39 p.

rabasz. W. J.. 1971. Geological and Geophysical Studies of the Atacama Fault Zone in Northern Chile [Ph D. thesis]: Pasadena. California. California Institute of Technology. 275 p.

rmstrong. F. C.. and Oriel. S. S.. 1965. Tectonic development of Idaho-Wyoming thrust belt: American Association of Petroleum Geologists Bulletin. v. 49. p 1847–1866.

rmstrong. R. L.. 1968. Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin. v. 79. p. 429–458.

ubouin. J.. Borrello. A. V.. Cecioni. G.. Charrier. R.. Chotin. P.. Frutos. J.. Thiele. R.. and Vicente. J.-C.. 1973. Esquisse paleogeographique et structurale des Andes meridionales: Revue de Geographic Physique et de Geologie Dynamique. v. 15. no. 1-2. p. 11–72.

udebaud. E.. Capdevila. R.. Dalmayrac. B.. Debelmas. J.. Laubacher. G.. Lefevre. C.. Marocco. R.. Martinez. C.. Mattauer. M.. Megard. F.. Paredes. J.. and Tomasi. P.. 1973. Les traits geologiques essentiels des Andes Centrales (Perou-Bolivie): Revue de Geographie Physique et de Geologie Dynamique (2). v. 15. p. 73–114.

aker. M.C.W.. and Francis. P. W.. 1978. Upper Cenozoic volcanism in the central Andes ages and volumes: Earth and Planetary Science Letters. v. 41. p. 175–187.

aldis. B.A.J.. Gorrono. A.. Ploszkiewicz. J. V.. Sarudiansky. R. M.. 1976. Geotectonica de la Cordillera Oriental. Sierras Subandinas y comarcas adyacentes: Actas del Sexto Congreso Geologico Argentino. v. 1. p. 3–22.

Bally. A. W.. Gordy. P. L.. and Stewart. G. A.. 1966. Structure. seismic data. and orogenic evolution of the southern Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology. v. 14. p. 337–381.

Barazangi. M.. and Isacks. B L.. 1976. Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America: Geology. v. 4. p. 686–692.

—— 1979. Subduction of the Nazca plate beneath Peru: Evidence from spatial distribution of earthquakes: Geophysical Journal of the Royal Astronomical Society. v. 57. p 537–555.

Bellido. E.. Girard. D.. and Paredes. J.. 1972. Mapa metalogenico del Peru: Lima. Servicio de Geologia y Mineria.

Bettini. F. H.. 1980. Nuevos conceptos tectonicos del centro y borde occidental de la cuenca Cuyana: Asociacion Geologica Argentina. Revista. v. 35. p. 579–581.

Brewer. J. A.. Smithson. S. B.. Oliver. J. E.. Kaufman. S.. and Brown. L. D.. 1980. The Laramide orogeny: Evidence from COCORP deep crustal seismic profiles in the Wind River mountains. Wyoming: Tectonophysics. v. 62. p. 165–189.

Brewer. J. A.. Allmendinger. R. W.. Brown. L. D.. Oliver. J. E.. and Kaufman. S.. 1982. COCORP profiling across the northern Rocky Mountain front. in southern Wyoming. Part I: Laramide structure: Geological Society of America Bulletin. v. 93. p. 1242–1252.

Brown. R. L.. 1978. Structural evolution of the southeast Canadian Cordillera: A new hypothesis: Tectonophysics. v. 48. p. 133–151.

—— 1981. Metamorphic complex of SE Canadian cordillera and relationship to foreland thrusting. *in* McClay. K. R.. and Price. N. J.. eds.. Thrust and nappe tectonics: Geological Society of London Special Publication. v. 9. p. 463–473.

Burchfiel. B. C.. and Davis. G. A.. 1975. Nature and controls of cordilleran orogenesis. western United States. extensions of an earlier synthesis: American Journal of Science. v. 275-a. p. 363–396.

—— 1976. Compression and crustal shortening in Andean-type orogenesis: Nature. v. 260. p. 693–694.

Burchfiel. B. C.. Molnar. P.. and Suares. G.. 1981. Possible thin-skin tectonics in the eastern Andes of Bolivia and Peru (abs.): EOS (American Geophysical Union Transactions). v. 62. p. 1047.

Caminos. R.. 1979a. Cordillera Frontal. *in* Segundo Simposio de Geologia Regional Argentina: Cordoba. Academia Nacional de Ciencias. v. 1. p. 397–454.

—— 1979b. Sierras Pampeanas noroccidentales. Salta. Tucuman. Catamarca. La Rioja y San Juan. *in* Segundo Simposio de Geologia Regional Argentina: Cordoba. Academia Nacional de Ciencias. v. 1. p. 225–292.

Carte Geologique de l'Amerique du Sud. 1:5.000.000. 1964. Commission de la carte geologique du Monde.

Case. J. E.. and Keefer. W. R.. 1966. Regional gravity survey. Wind River Basin. Wyoming: U.S. Geological Survey Professional Paper. v. 550-C. p. C120–C128.

Charrier. R.. and Munizaga. F.. 1979. Edades K-Ar de volcanitas Cenozoicas del sector cordillerano del rio Cachapoal. Chile (34° 15′ de latitud sur): Revista Geologica de Chile. v. 7. p. 41–51.

Chase. C. G.. 1978. Plate kinematics: the Americas. east Africa. and the rest of the world: Earth and Planetary Science Letters. v. 37. p. 355–368.

Chinn. D.. 1982. Accurate source depths and focal mechanisms of shallow earthquakes in western South America and in the New Hebrides Island Arc [Ph.D. thesis]: Ithaca. New York. Cornell University.

Chong. D. G.. 1977. Contribution to the knowledge of the Domeyko Range in the Andes of northern Chile: Geologische Rundschau. v. 66. p. 374–403.

Clark. A. H.. Farrar. E.. Caelles. J. C.. Haynes. S. J.. Lortie. R. B.. McBride. S. L.. Quirt. G. S.. Robertson. R.C.R.. and Zentilli. M.. 1976. Longitudinal variations in the metallogenic evolution of the central Andes: A progressive report: Geological Association of Canada Special Paper no. 14. p. 23–58.

Cobbing. E. J.. 1972. Tectonic elements of Peru and the evolution of the Andes: International Geological Congress. 24. Montreal. Canada. Section 3. p. 306–315.

Cobbing. E. J.. Ozard. J. M.. and Snelling. N. J.. 1977. Reconnaissance geochronology of the crystalline basement rocks of the

Coastal Cordillera of southern Peru: Geological Society of America Bulletin, v. 88, p. 241–246.

Coira, B., Davidson, J., Mpodozis, C., and Ramos, V., 1982, Tectonic and magmatic evolution of the Andes of northern Argentina and Chile, *in* Linares, E., and Cordani, U. G., eds., Magmatic Evolution of the Andes Earth-Science Reviews (in press).

Coney, P. J., 1976, Plate tectonics and the Laramide orogeny: New Mexico Geological Society Special Publication, no. 6, p. 5–10.

Coney, P. J., Jones, D. L., and Monger, J.W.H., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329–333.

Criado Roque, P., and Ibanez, G., 1979, Provincia geologica Sanrafaelino-Pampeana, *in* Segundo Simposio de Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, v. 1, p. 837–869.

Criado Roque, P., Mombru, C. A., and Ramos, V. A., 1981, Estructura e interpretacion tectonica, *in* Relatorio, geologia y recursos naturales de la provincia de San Juan: Octavo Congreso Geologico Argentino, p. 155–192.

Cross, T. A., and Pilger, R. H., 1978, Constraints on absolute motion and plate interaction inferred from Cenozoic igneous activity in the western United States: American Journal of Science, v. 278, p. 865–902.

Dalmayrac, B., 1974, Un example de tectonique vivante: Les failles subactuelles du pied de la Cordillere Blanche (Peru): Cahiers ORSTOM, Series Geologie, v. 6, p. 19–27.

——— 1978, Geologie de la Cordillere orientale de la region de Huanuco: Sa place dans une transversale des Andes du Perou central (9°S a 10°30'S): Geologie des Andes Peruviennes: Paris, Travaux et documents de l'ORSTOM, no. 93, 161 p.

Dalmayrac, B., and Molnar, P., 1981, Parallel thrust and normal faulting in Peru and constraints on the state of stress: Earth and Planetary Science Letters, v. 55, p. 473–481.

Dalmayrac, B., Laubacher, G., and Marocco, R., 1980a, Caracteres generaux de l'evolution geologique des Andes Peruviennes, Geologie des Andes Peruviennes: Paris, Travaux et documents de l'ORSTOM, No. 122, 501 p.

Dalmayrac, B., Laubacher, G., Marocco, R., Martinez, C., Tomasi, P., 1980b, La chaine hercynienne d'amerique du sud, structure et evolution d'un orogene intracratonique: Geologische Rundschau, v. 69, p. 1–21.

Dalziel, I.W.D., and Elliot, D. H., 1982, West Antarctica: Problem child of Gondwanaland: Tectonics, v. 1, p. 3–19.

Dalziel, I.W.D., de Wit, M. J., and Palmer, K. F., 1974, A fossil marginal basin in the Southern Andes: Nature, v. 250, p. 291–294.

D'Angelo, E. P., and Aguirre, L.B.L., 1969, Relacion entre estructura y volcanismo Cuaternario Andino en Chile: *in* Maldonado-Koerdell, M., ed., Simposio Panamericano del Manto Superior: Instituto de Geofisica, Mexico, p. 39–46.

Davis, G. A., Monger, J.W.H., and Burchfiel, B. C., 1978, Mesozoic construction of the cordilleran "collage," central British Columbia to central California, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic Paleogeography of the Western United States, Pacific Coast Paleogeography Symposium, 2, Los Angeles, California: Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 1–32.

Dewey, J. F., and Bird, J. M., 1970, Mountain belts and the new global tectonics: Journal of Geophysical Research, v. 75, p. 2625–2647.

Dewey, J. W., and Spence, W., 1979, Seismic gaps and source zones of recent large earthquakes in coastal Peru: Pure and Applied Geophysics (PAGEOPH), v. 117, p. 1148–1171.

DeWitt, E., 1980, Comment on Geologic development of the cordilleran metamorphic core complexes: Geology, v. 8, p. 6–7.

Dickinson, W. R., 1979, Cenozoic plate tectonic setting of the cordilleran region in the United States, *in* Armentrout, J. M., Cole M. R., and TerBest, H., Jr., eds., Cenozoic Paleogeography of the Western United States, Pacific Coast Paleogeography Symposium, 3, Los Angeles, California: Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 1–13.

Dickinson, W. R., and Seely, D. R., 1979, Structure and stratigraphy of forearc regions: American Association of Petroleum Geologists Bulletin, v. 63, p. 2–31.

Dickinson, W. R., and Snyder, W. S., 1978, Laramide folding associated with basement block faulting in the western United States: Plate tectonics of the Laramide orogeny, *in* Matthews, V., III, ed., Geological Society of America Memoir 151, p. 355–366.

Flores, M. A., 1979, Cuenca de San Luis, *in* Segundo Simposio de Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, v. 1, p. 745–770.

Francis, P. W., Hammill, M., Kretzschmar, G. A., and Thorpe, R. S., 1978, The Cerro Galan caldera, northwest Argentina, and its tectonic setting: Nature, v. 274, p. 749–751.

Fuller, C. R., director, 1968, Mapa geologico de Chile, escala 1:1,000,000: Instituto de Investigaciones Geologicas, Chile.

Furque, G., and Cuerda, A. J., 1979, Precordillera de la Rioja, San Juan y Mendoza, *in* Segundo Simposio de Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, v. 1, p. 455–522.

Gonzalez Bonorino, F., 1950, Geologic cross section of the Cordillera de Los Andes at about parallel 33°L.S. (Argentina-Chile): Geological Society of America Bulletin, v. 61, p. 17–26.

——— 1972, Descripcion geologica de la Hoja 13C, Fiambala: Buenos Aires, Direccion Nacional de Geologia y Mineria Boletin, v. 127, 74 p.

Gonzalez Diaz, E. I., 1978, Estratigrafia del Cuartario, *in* Relatorio, Geologia y Recursos Naturales del Neuquen: Septimo Congreso Geologico Argentino, p. 85–97.

Gordillo, C. E., and Lencinas, A. N., 1979, Sierras Pampeanas de Cordoba y San Luis, *in* Segundo Simposio de Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, v. 1, p. 577–650.

Gutenberg, B., and Richter, C. F., 1954, Seismicity of the Earth and associated phenomena: Princeton, New Jersey, Princeton University Press, 310 p.

Ham, C. K., and Herrera, L. J., Jr., 1963, Role of Subandean fault system in tectonics of eastern Peru and Ecuador, *in* Childs, O. E., and Beebe, R. N., eds., Backbone of the Americas: American Association of Petroleum Geologists Memoir, v. 2, p. 47–61.

Hamilton, W., 1969, The volcanic central Andes—A modern model for the Cretaceous batholiths and tectonics of western North America: Oregon Department of Geology and Mineral Industries Bulletin, v. 65, p. 175–184.

——— 1978, Mesozoic tectonics of the western United States, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic Paleogeography of the Western United States, Pacific Coast Paleogeography Symposium, 2, Los Angeles, California: Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 33–70.

Harrington, H. J., 1956, Argentina, *in* Jenks, W. F., ed., Handbook of South American geology, Geological Society of America Memoir 65, p. 131–165.

Harrison, J. E., Griggs, A. B., and Wells, J. D., 1974, Tectonic features of the Precambrian Belt basin and their influence on post-Belt structures: U.S. Geological Survey Professional Paper 866, 15 p.

Harrison, J. E., Kleinkopf, M. D., and Wells, J. D., 1980, Phanerozoic thrusting in Proterozoic belt rocks, northwestern United States: Geology, v. 8, p. 407–411.

Hasegawa, A., and Sacks, I. S., 1981, Subduction of the Nazca plate beneath Peru as determined from seismic observations: Journal of Geophysical Research, v. 86, p. 4971–4980.

Herrero-Ducloux, A., 1963, The Andes of western Argentina, *in* Childs, O. E. and Beebe, R. W., eds., Backbone of the Americas: American Association of Petroleum Geologists Memoir 2, p. 16–28.

Hollingworth, S. E., and Rutland, R.W.R., 1968, Studies of Andean uplift, part 1—post-Cretaceous evolution of the San Bartolo area, north Chile: Geological Journal, v. 6, pt. 1, p. 49–62.

Ingersoll, R. V., 1978, Paleogeography and paleotectonics of the late Mesozoic forearc basin of northern and central California, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic Paleogeography of the Western United States, Pacific Coast Paleogeography Symposium, 2, Los Angeles, California: Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 471–482.

Isacks, B., and Barazangi, M., 1977, Geometry of Benioff zones: Lateral segmentation and downwards bending of the subducted lithosphere, *in* Talwani, M., and Pitman, W., eds., Island arcs, deep sea trenches, and back-arc basins: American Geophysical Union, Ewing Series 1, p. 99–114.

James, D. E., 1971, Plate tectonic model for the evolution of the central Andes: Geological Society of America Bulletin, v. 82, p. 3325–3346.

Katz, H. R., 1971, Continental margin in Chile: Is tectonic style compressional or extensional?: American Association of Petroleum Geologists

Bulletin, v. 55, p. 1753-1758.

Kausel, E., and Lomnitz, C., 1969, Tectonics of Chile, *in* Maldonado-Koerdell, M., ed., Pan-American Symposium on the Upper Mantle, Instituto de Geofisica, Mexico, p. 47-67.

Kelleher, J., and McCann, W., 1976, Buoyant zones, great earthquakes, and unstable boundaries of subduction: Journal of Geophysical Research, v. 81, p. 4885-4896.

King, P. B., 1969, Tectonic map of North America, 1:5,000,000: U.S. Geological Survey.

Koch, E., 1961, Perfil tectonico a traves de la Cordillera Oriental y la Faja Subandina entre Tingo Maria, Pisqui Medio y Contaya: Sociedad Geologica del Peru, Segundo Congreso Nacional de Geologia, v. 36, p. 131-138.

Kussmaul, S., Hormann, P. K., Ploskonka, E., and Subieta, T., 1977, Volcanism and structure of southwestern Bolivia: Journal of Volcanology and Geothermal Research, v. 2, p. 73-111.

Laubacher, G., 1978, Geologie de la Cordillere Orientale et de l'Altiplano au nord et nord-ouest du lac Titicaca: Geologie des Andes Peruviennes: Paris Travaux et Documents de l'ORSTOM, no. 95, 217 p.

Leveratto, M. A., 1976, Edad de intrusivos Cenozoicos en la Precordillera de San Juan y su implicancia estratigrafica: Asociacion Geologica Argentina Revista, v. 31, p. 53-58.

Lipman, P. W., Prostka, H. J., and Christiansen, R. L., 1971, Evolving subduction zones in the western United States as inferred from igneous rocks: Science, v. 175, p. 821-825.

Lohmann, H. H., 1970, Outline of tectonic history of Bolivian Andes: American Association of Petroleum Geologists Bulletin, v. 54, no. 5, p. 735-757.

Lopez-Escobar, L., Frey, F. A., Vergara, M., 1976, Andesites from central-south Chile: Trace element abundances and petrogenesis, *in* Gonzales Ferran, O., ed., Symposium on Andean and Antarctic Volcanology Problems, Santiago, Chile, September 1974, Proceedings: Napoli, Italy, International Association of Volcanology and Chemistry of the Earth's Interior, Special Series, p. 725-761.

Lowrie, A., and Hey, R., 1981, Geological and geophysical variations along the western margin of Chile near lat 33° to 36°S, and their relation to Nazca plate subduction: Geological Society of America Memoir 154, p. 741-754.

Lucero M., H. N., 1979, Sierras Pampeanas del norte de Cordoba, sur de Santiago del Estero, borde oriental de Catamarca y angulo sudeste de Tucuman, *in* Segundo Simposio de Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, v. 1, p. 293-347.

Lynn, H. B., 1980, Migration and interpretation of deep crustal seismic reflection data [Ph.D. thesis]: Stanford, California, Stanford University, 159 p.

Maisonave, H. M., 1979, Descripcion geologica de la hoja 14c, Cerros Cuminchango: Buenos Aires, Servicio Geologico Nacional Boletin, v. 162, 62 p.

Marocco, R., 1978, Un segment E-W de la chaine des Andes Peruviennes: La deflexion d'Abancay: Etude geologique de la Cordillere Orientale et des hauts plateaux entre Cuzco et San Miguel, sud du Perou (12°30'S a 14°00'S): Geologie des Andes Peruviennes: Paris Travaux et documents de l'ORSTOM, no. 94, 195 p.

Martinez, C., and Tomasi, P., 1978, Carte structurale des Andes septentrionales de Bolivie a 1:1,000,000, et notice explicative no. 77: Paris, ORSTOM and Servicio Geologico de Bolivia.

Martinez, C., Tomasi, P., Dalmayrac, B., Laubacher, G., and Marocco, R., 1972, Caracteres generaux des orogenes Precambriens, Hercyniens et Andins au Perou et en Bolivie: International Geological Congress, 24th, Montreal, Canada, Section 1, p. 136-146.

Megard, F., 1978, Etude geologique des Andes du Perou central, contribution a l'etude geologique des Andes no. 1: Paris, Memoires ORSTOM No. 86, 310 p.

Megard, F., and Philip, H., 1976, Plio-Quaternary tectono-magmatic zonation and plate tectonics in the central Andes: Earth and Planetary Science Letters, v. 33, p. 231-238.

Mercier, J. L., 1981, Extensional-compressional tectonics associated with the Aegean Arc: comparison with the Andes of south Peru-north Bolivia: Philosophical Transactions of the Royal Society of London, A300, p. 337-355.

Miller, C. F., and Bradfish, L. J., 1980, An inner cordilleran belt of muscovite-bearing plutons: Geology, v. 8, p. 412-416.

Mingramm, A., and Russo, A., 1972, Sierras Subandinas y Chaco Salteno, *in* Leanza, A. F., ed., Geologia regional Argentina: Cordoba, Academia Nacional de Ciencias, p. 185-211.

Mingramm, A., Russo, A., Pozzo, A., and Cazau, L., 1979, Sierras Subandinas, *in* Segundo Simposio de Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, v. 1, p. 95-138.

Minster, J. B., and Jordan, T. H., 1978, Present-day plate motion: Journal of Geophysical Research, v. 83, p. 5331-5354.

Minster, J. B., Jordan, T. H., Molnar, P., and Haines, E., 1974, Numerical modeling of instantaneous plate tectonics: Royal Astronomical Society Geophysical Journal, v. 36, p. 541-576.

Molnar, P., and Atwater, T., 1978, Interarc spreading and cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere: Earth and Planetary Science Letters, v. 41, p. 330-340.

Mombru, C. A., and Uliana, M. A., 1979, Esquema tectosedimentario de la cuenca Mesozoica de Mendoza y Neuquen: Actas del Septimo Congreso Argentino, v. 2, p. 239-256.

Mon, R., 1972, Esquema estructural de la provincia de Tucuman, Republica Argentina: Asociacion Geologica Argentina Revista, v. 27, p. 223-228.

——— 1976a, The structure of the eastern border of the Andes in northwestern Argentina: Geologische Rundschau, v. 75, p. 211-222.

——— 1976b, La tectonica del borde oriental de los Andes en las provincias de Salta, Tucuman y Catamarca, Republica Argentina: Asociacion Geologica Argentina Revista, v. 31, p. 65-72.

Mon, R., and Urdaneta, A., 1972, Introduccion a la geologia de Tucuman, Republica Argentina: Asociacion Geologica Argentina Revista, v. 27, p. 309-329.

Mortimer, C., 1973, The Cenozoic history of the southern Atacama desert, Chile: Geological Society of London Journal, v. 129, p. 505-526.

Mortimer, C., and Saric Rendic, N., 1975, Cenozoic studies in northernmost Chile: Geologische Rundschau, v. 64, p. 395-420.

Naranjo, J. A., and Paskoff, R., 1980, Evolucion geomorfologica del desierto de Atacama entre los 26° y 33° latitud sur: Revision cronologica: Revista Geologica de Chile, no. 10, p. 85-89.

Noble, D. C., and McKee, E. H., 1977, Comment *on* Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America: Geology, v. 5, p. 576-578.

Operational Navigation Charts, 1973, Sheets ONC Q-27, ONC Q-26, ONC P-26, ONC R-23, (1:1,000,000): St. Louis, Missouri, U.S. Defense Mapping Agency Aerospace Center.

Ortiz, A., and Zambrano, J. J., 1981, La provincia geologica Precordillerana Oriental: Actas del Octavo Congreso Geologico Argentino, v. 3, p. 59-74.

Paskoff, R. P., 1977, Quaternary of Chile: The state of research: Quaternary Research, v. 8, p. 2-31.

Pennington, W. D., 1981, Subduction of the eastern Panama basin and seismotectonics of northwestern South America: Journal of Geophysical Research, v. 86, p. 10753-10770.

Pilger, R. H., Jr., 1981, Plate reconstructions, aseismic ridges, and low-angle subduction beneath the Andes: Geological Society of America Bulletin, v. 92, p. 448-456.

Price, R. A., and Mountjoy, E. W., 1970, Geologic structure of the Canadian Rocky Mountains between Bow and Athabaska Rivers—A progress report: The Geological Association of Canada Special Paper no. 6, p. 7-25.

Ramos, V. A., 1977, Basement tectonics from LANDSAT imagery in mining exploration: Geologische en Mijnbouw, v. 56, p. 243-252.

Ramos, V. A., Niemeyer, H., Skarmeta, J. and Munoz, J., 1982, Magmatic evolution of the austral Patagonian Andes, *in* Linares, E., and Cordani, U. G., eds., Magmatic Evolution of the Andes: Earth-Science Reviews (in press).

Regairaz, A. C., and Videla Leaniz, J. R., 1968, Fenomenos de la neotectonica y su influencia sobre la morfologia actual del piedemonte Mendocino: Actas del Terceras Jornadas Geologicas Argentinas, v. 2, p. 21-34.

Reyes, F. C., and Salfity, J. A., 1973, Consideraciones sobre la estratigrafia del Cretacico (subgrupo Pirgua) del noroeste Argentino: Actas del Quinto Congreso Geologico Argentino, v. 3, p. 355-385.

Richter, C. F., 1958, Elementary Seismology: San Francisco, W. H. Freeman and Company, 768 p.

Rodriquez, E. R., Cabre, R.S.J., and Mercado, A., 1976, Geometry of the Nazca Plate and its geodynamic implications, *in* Sutton, G. H., and others, eds., The geophysics of the Pacific Ocean Basin and its margin: American Geophysical Union Geophysical Monograph 19, p. 87-103.

Rolleri, E. O., 1976, Sistema de Santa Barbara, una nueva provincia geologica Argentina: Actas del Sexto Congreso Geologico Argentino, v. 1, p. 239–255.

Rolleri, E. O., and Fernandez Garrasino, C. A., 1979, Comarca septentrional de Mendoza, *in* Segundo Simposio de Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, v. 1, p. 771–810.

Roobol, M. J., Francis, P. W., Ridley, W. I., Rhodes, M., and Walker, G.P.L., 1976, Physico-chemical characters of the Andean volcanic chain between latitudes 21° and 22° south, *in* Gonzales Ferran, O., ed., Symposium on Andean and Antarctic Volcanology Problems, Santiago, Chile, September 1974, Proceedings: Napoli, Italy, International Association of Volcanology and Chemistry of the Earth's Interior, Special Series, p. 450–464.

Rothe, J. P., 1969, The Seismicity of the earth: Paris, France, UNESCO, 336 p.

Royse, F., Jr., Warner, M. A., and Reese, D. L., 1975, Thrust belt structural geometry and related stratigraphic problems, Wyoming–Idaho–northern Utah: Rocky Mountain Association of Geologists, 1975 Symposium, p. 41–54.

Ruiz Huidobro, O. J., 1968, Descripcion geologica de la hoja 7e, Salta: Buenos Aires, Instituto Nacional de Geologia y Mineria Boletin, v. 109, 46 p.

—— 1972, Descripcion geologica de la hoja 11e, Santa Maria: Buenos Aires, Servicio Nacional Minero Geologico Boletin, v. 134, 64 p.

—— 1975, Descripcion geologica de la hoja 12c, Laguna Helada: Buenos Aires, Servicio Geologico Nacional Boletin, v. 146, 54 p.

Russo, A., and Serraiotto, A., 1979, Contribucion al conocimiento de la estratigrafia Terciaria en el noroeste Argentino: Actas del Septimo Congreso Geologico Argentino, v. 1, p. 715–730.

Rutland, R.W.R., 1971, Andean orogeny and ocean floor spreading: Nature, v. 233, p. 252–255.

Sacks, I. S., and Linde, A. T., 1978, Shallow seismicity in subduction zones: Geophysical Research Letters, v. 5, p. 901–903.

Salfity, J. A., 1979, Paleogeologia de la cuenca del Grupo Salta (Cretacico-Eogenico) del norte de Argentina: Actas del Septimo Congreso Geologico Argentino, v. 1, p. 505–515.

—— 1980, Estratigrafia de la Formacion Lecho (Cretacico) en la cuenca Andina del norte Argentino: Universidad Nacional de Salta, Publicaciones Especiales, Tesis no. 1, 91 p.

Scholl, D. W., Christensen, M. N., Von Huene, R., and Marlow, M. S., 1970, Peru-Chile trench sediments and sea-floor spreading: Geological Society of America Bulletin, v. 81, p. 1339–1360.

Schwab, K., 1970, Ein beitrag zur jungen bruchtektonik der Argentinischen Puna und ihr verhaltnis zu den angrenzenden andenabschnitten: Geologische Rundschau, v. 59, p. 1064–1087.

—— 1972, Cenozoic volcanism in the Argentine Puna and its relationship to tectonic movements: International Geological Congress, 24th, Montreal, Canada, Section 2, p. 211–221.

—— 1973, Die stratigraphie in der Umgebung des Salar de Cauchari (N.W. Argentinien): Geotektonische Forschungen, v. 43, 166 p.

Schweller, W. J., and Kulm, L. D., 1978, Extensional rupture of oceanic crust in the Chile Trench: Marine Geology, v. 28, p. 271–291.

Schweller, W. J., Kulm, L. D., and Prince, R. A., 1981, Tectonics, structure, and sedimentary framework of the Peru-Chile trench: Geological Society of America Memoir 154, p. 323–349.

Silgado, E., 1951, The Ancash, Peru earthquake of November 10, 1946: Seismological Society of America Bulletin, v. 41, p. 83–100.

Simkin, T., Siebert, L., McClelland, L., Bridge, D., Newhall, C., and Latter, J. H., 1981, Volcanoes of the world (Smithsonian Institution): Stroudsburg, Pennsylvania, Hutchinson Ross Publishing Company, 232 p.

Smith, A. G., 1981, Subduction and coeval thrust belts, with particular reference to North America, *in* McClay, K. R., and Price, N. J., eds., Thrust and nappe tectonics: Geological Society of London Special Publication No. 9, Blackwell Scientific, p. 111–124.

Smithson, S. B., Brewer, J. A., Kaufman, S., Oliver, J. E., and Hurich, C. A., 1979, Structure of the Laramide Wind River uplift, Wyoming, from COCORP deep reflection data and from gravity data: Journal of Geophysical Research, v. 84, p. 5955–5972.

Stauder, W., 1973, Mechanism and spatial distribution of Chilean earthquakes with relation to subduction of the oceanic plate: Journal of Geophysical Research, v. 78, p. 5033–5061.

—— 1975, Subduction of the Nazca Plate under Peru as evidenced by focal mechanisms and by seismicity: Journal of Geophysical Research, v. 80, p. 1053–1064.

Sterns, D. W., 1978, Faulting and forced folding in the Rocky Mountain foreland, *in* Matthews, V., III, ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 1–37.

Stewart, J. W., Evernden, J. F., and Snelling, N. J., 1974, Age determinations from Andean Peru: A reconnaissance survey: Geological Society of America Bulletin, v. 85, p. 1107–1116.

Swift, S. A., and Carr, M. J., 1975, The segmented nature of the Chilean seismic zone: Physics of the Earth and Planetary Interiors, v. 9, p. 183–191.

Tectonic Map of South America, 1978, F.F.M. de Almeida, Coordinator, Commission for the Geological Map of the World, Departamento Nacional de Producao Mineral, Brasilia.

Thomas N., A., 1970, Beitrag zur tektonik nord Chiles: Geologische Rundschau, v. 59, p. 1013–1027.

Turner, J.C.M., 1964a, Descripcion geologica de la hoja 7c, Nevado de Cachi: Buenos Aires, Direccion Nacional de Geologia y Mineria Boletin, v. 99, 75 p.

—— 1964b, Descripcion geologica de la hoja 15c, Vinchina: Buenos Aires, Direccion Nacional de Geologia y Mineria Boletin, v. 100, 81 p.

—— 1967, Descripcion geologica de la hoja 13b, Chaschuil: Buenos Aires, Instituto Nacional de Geologia y Mineria Boletin, v. 106, 78 p.

—— 1971, Descripcion geologica de la hoja 15d, "Famatina": Buenos Aires, Direccion Nacional de Geologia y Mineria Boletin, v. 126, 96 p.

—— 1972, Cordillera Oriental, *in* Leanza, A. F., ed., Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, p. 117–142.

—— 1973, Descripcion geologica de la hoja 11d, Laguna Blanca: Buenos Aires, Direccion Nacional de Geologia y Mineria Boletin, v. 142, 70 p.

Turner, J.C.M., and Mendez, V., 1979, Puna, *in* Segundo Simposio de Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, v. 1, p. 13–56.

Turner, J.C.M., and Mon, R., 1979, Cordillera Oriental, *in* Segundo Simposio de Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, v. 1, p. 57–94.

Uliana, M. A., 1978, Estratigrafia del Terciario, *in* Relatorio, Geologia y Recursos Naturales del Neuquen: Septimo Congreso Geologica Argentina, p. 67–83.

Vasquez, J., and Gorrono, R., 1980, Limite de la faja plegada en la Republica Argentina: Asociacion Geologica Argentina Revista, v. 35, p. 582–585.

Vergara M., M., 1978, Comentario sobre la edad de las formaciones Cola de Zorro y Farellones, Chile central: Revista Geologica de Chile, v. 5, p. 59–61.

Vilela, C. R., and Garcia, J., 1978, Descripcion geologica de la hoja 9c, Amblayo: Buenos Aires, Servicio Geologico Nacional Boletin, v. 150, 64 p.

Vlaar, N. J., and Wortel, M.J.R., 1976, Lithospheric aging, instability and subduction: Tectonophysics, v. 32, p. 331–351.

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.

Yamashina, K., Shimazaki, K., and Kato, T., 1978, Aseismic belt along the frontal arc plate subduction in Japan: Journal of Physics of the Earth, v. 26, supplement, p. 447–458.

Yonekura, M., Matsuda, T., Nogami, M., and Kaizuka, S., 1979, An active fault along the western foot of the Cordillera Blanca, Peru [in Japanese]: Journal of Geography, v. 88, p. 1–19.

Yrigoyen, M. R., 1950, Algunas observaciones sobre los basaltos Cuartarios del sur de la provincia de Mendoza: Asociacion Geologica Argentina Revista, v. 5, no. 4, p. 205–226.

—— 1979, Cordillera Principal, *in* Segundo Simposio de Geologia Regional Argentina: Cordoba, Academia Nacional de Ciencias, v. 1, p. 651–694.

Zeil, W., 1979, The Andes, a geological review: Berlin, Gebruder Borntraeger, 260 p.

Manuscript Received by the Society September 14, 1981
Revised Manuscript Received April 19, 1982
Manuscript Accepted April 20, 1982
Cornell Contribution No. 721

Printed in U.S.A.