Extensional tectonics, Cretaceous Andes, northern Chile (27°S)

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ABSTRACT

In the Andes of northern Chile, the Sierra Fraga-Puquios region (27°S) exposes a complete record of superposed deformation that affected this part of the orogen during the Mesozoic and Cenozoic. A major extensional event, which probably occurred between the Aptian and Cenomanian(?), generated a suite of structures remarkably similar to those observed in the extensional terranes of western North America. Four allochthons involving Paleozoic and Mesozoic strata are bounded by low-angle normal faults that place younger rocks over older, omitting as much as several kilometers of stratigraphic section. In one area, an extensional "chaos" is composed of domino and boudined blocks of Neocomian limestone floating in a matrix of cataclastically deformed volcanics. Domino orientation, boudin asymmetry, sheath folds(?), and mesoscopic sense-of-shear indicators identify two senses of movement on the detachments. The first and less important was top-to-the-northwest and the second major event was top-to-the-northeast. The parautochthonous, upper Paleozoic basement core of the extensional terrane differs from the metamorphic core complexes in that it is not highly metamorphosed or ductilely deformed. We attribute this difference to the lack of a prior crustal thickening event in the Andes and to the position of the Sierra Fraga-Puquios at the margin of the central Chile aborted marginal basin. The extensional events occurred during a global episode of rapid spreading, which was accompanied along the Andean margin by a substantial increase in magmatism.

INTRODUCTION

The Central Andes have been constructed during the subduction of oceanic crust beneath the margin of South America from the Jurassic until present. Cenozoic horizontal shortening is interpreted to be responsible for the morphologic edifice that we see today (Isacks, 1988; Mpodozis and Ramos, 1990). The role of horizontal extension during the building of the Central Andes, however, has long been a focus of debate. Recent minor normal faulting has been recognized in numerous places (Dalmayrac and Molnar, 1981; Sébrier and others, 1985; Allmendinger and others, 1989), but the earlier history of the orogen presents a far more likely candidate for significant extension. Cretaceous extensional tectonics have long been inferred for the Andean margin, but this interpretation has previously been based on indirect evidence such as paleogeography, tectonostratigraphic assemblages, and the presence of ophiolites (for example, Dalziel, 1981; Mpodozis and Ramos, 1990; Flint and others, 1993). In general, well-documented Andean structural systems, displaying the magnitude and style of extension comparable to that described in the extended terranes of other orogens, have not been described.

We present new data from a region in north-central Chile, east of the city of Copiapó (Fig. 1), which has preserved one of the most complete records of Mesozoic and Cenozoic deformation, including an exceptional record of Cretaceous extension. Although extensional structures may have existed originally along much of the Andean margin, elsewhere they have been obscured or obliterated by superimposed Late Cretaceous to Tertiary compressional deformation and volcanic and sedimentary deposits. Our work is the first to document the structural geometry and kinematics of extensional deformation within and at the margin of the mid-Cretaceous Andean arc. The geometry of these extensional structures is strikingly similar to that described for detachment terranes in the western United States. The tectonic history leading up to extension is quite different however; the western United States experienced a crustal thickening event prior to extension, whereas no such event preceded extension in this part of the Andes.

MESOZOIC TECTONIC SETTING OF THE CENTRAL ANDES

The "basement" upon which Mesozoic strata were deposited is the result of a complex Paleozoic history, characterized by the collision of diverse terranes (Ramos and others, 1986; Mpodozis and Ramos, 1990) and a major crustal melting and rifting event during the Permo-Triassic (Charrier, 1979; Kay and others, 1989; Jaillard and others, 1990). The products of these events are the oldest rocks in this part of the Andes.

The present subduction system along the western margin of the South American continent began in the Early-Middle Jurassic, coeval with the breakup of Pangea-Gondwana. The deformation, magmatism, and metamorphism related to continuous subduction from Jurassic to Holocene constitute the "Andean Orogeny" (Dalziel, 1986; Mpodozis and Ramos, 1990). Shortly after the beginning of Andean subduction, "aborted" marginal basins were formed during the Cretaceous along the western margin of South America. Large volumes of volcanic rocks were erupted between the Albian and Cenomanian in the Andes of Perú and central Chile during an intense episode of magmatism (Atherton and Webb, 1989; Mpodozis and Ramos, 1990; Soler, 1991). The formation of these basins has long been inferred to be a product of extension of the continental margin, although until the present study, the structures that produced the extension have never been observed in detail. The basins are referred to as "aborted" because, except in the northern Andes of Colombia and in Tierra del Fuego (Bourgeois and others, 1987; Dalziel, 1981), complete rupture of the continental crust and production of new oceanic crust was never achieved (Levi and Aguirre, 1981; Atherton and others, 1983; Åberg and others, 1984; Soler and Bonhomme, 1990; Aguirre, 1991).

In central Perú, the Casma-Huarmey marginal basin formed in the Aptian after a period of relative magmatic quiescence during the Neocomian (Cobbing, 1985; Soler and Bonhomme, 1990; Soler, 1991). It reached its maximum development in the Albian with the submarine accumulation of as much as 9,000 m of andesite, andesitic basalt, dacite, and volcaniclastic rock (Myers, 1974; Jaillard, 1987). The aborted marginal basin of

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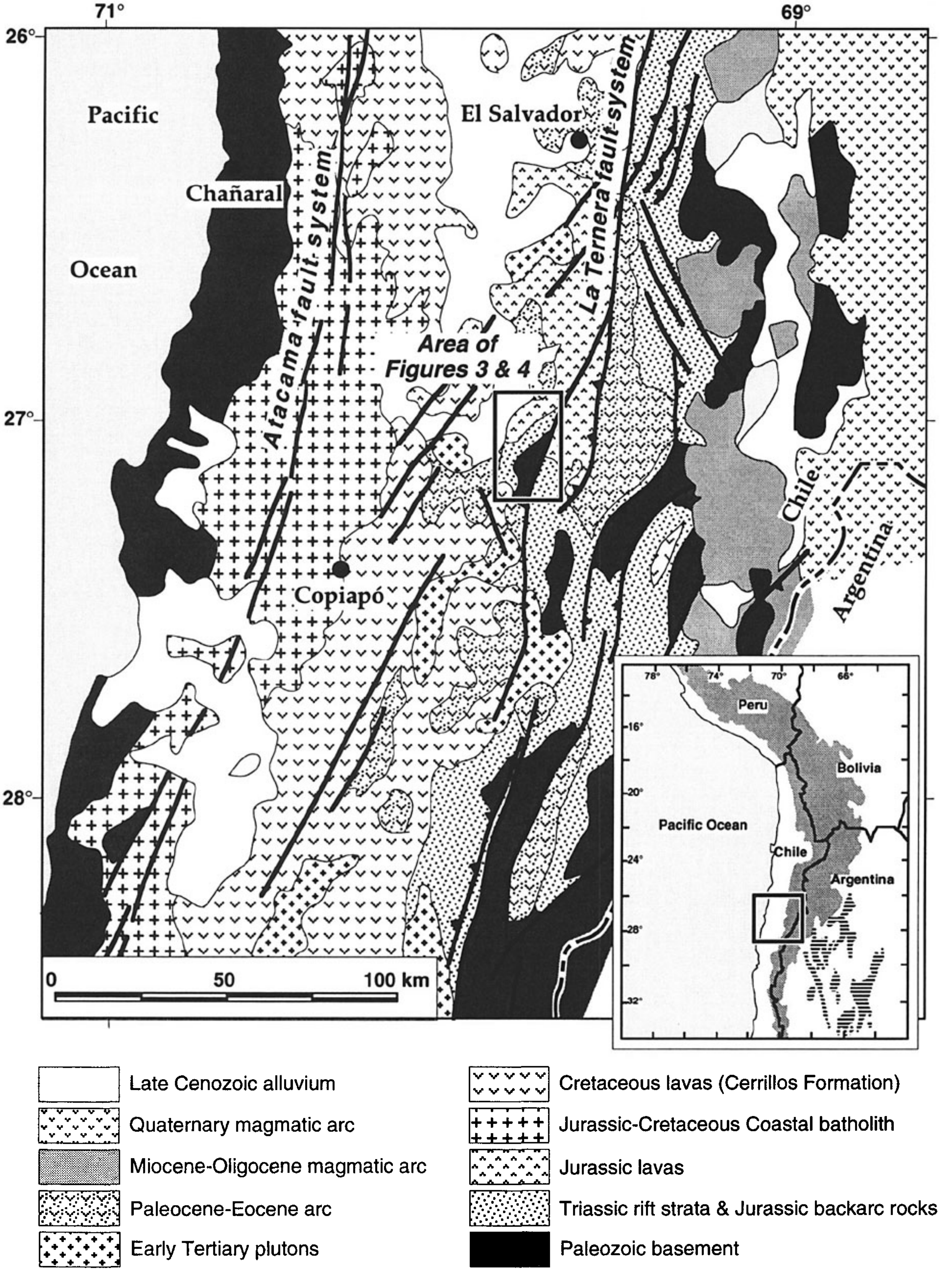


Figure 1. Generalized geologic map of the Copiapó region, northern Chile. Inset map shows location with respect to the western margin of South America. Box shows area of study, depicted in Figures 3 and 4.

central Chile extends for >1,000 km, between 27°S (Copiapó area) and 34°S (south of Santiago). In the Santiago area, volcanic rocks of Neocomian to Cenomanian age attain thicknesses of 10 km, including a few thin intercalations of Neocomian limestones (Thomas, 1958; Aguirre, 1960; Munizaga and Vicente, 1982; Ramos and others, 1991). North of La Serena (30°S), limestone levels become more common, and in the Copiapó region, extensive outcrops are present (the Chañarcillo Group), indicating a relative lull in magmatism in the northern part of the marginal basin at that time. During the Aptian-Albian, an intense magmatic episode occurred in the Coastal Cordillera west of Santiago (Thomas, 1958; Levi and Aguirre, 1981; Åberg and others, 1984) and as far east as the Argentine Principal Cordillera (Aguirre, 1960; Mpodozis and Ramos, 1990; Ramos and others, 1991). Similar Cretaceous volcanic rocks occur in discontinuous exposures as far north as La Serena and Copiapó (Aguirre and Egert, 1965; Segerstrom, 1968; Rivano and Sepúlveda, 1991). In the Copiapó area, several kilometers of andesite, conglomerate, pyroclastic breccia, and tuff of the Cerrillos Formation (Segerstrom, 1968) probably accumulated during this time. Our study area in the Sierra Fraga-Puquios region is located at the extreme northern end of the central Chile marginal basin, at the eastern border of the band of outcrops of the Cerrillos Formation. Farther east, volcanic rocks of mid-Cretaceous age are much reduced in importance (Mercado, 1982).

In the Late Cretaceous, a profound reorganization of the orogen occurred, resulting in the collapse and closure of the back-arc basins all along the Andean margin from Colombia to Tierra del Fuego. This change has been related to the opening of the South Atlantic and the initiation of the westward drift of the South American plate (Dalziel, 1986; Bourgeois and others, 1987; Mpodozis and Ramos, 1990). The Cordillera Darwin has been interpreted as a "core complex" resulting from the closure of a marginal basin in Tierra del Fuego (Dalziel and Brown, 1989). During the Tertiary, various changes in the velocity and direction of plate convergence coincide with deformational events within the Andes (for example, Pardo Casas and Molnar, 1987).

In northern Chile (north of 27°S), the Andean magmatic arcs have migrated eastward, from the position of the Jurassic arc along the *present* coast of Chile to the Quaternary magmatic arc located along the international border between Argentina and Chile (Fig. 1). The position of the Mesozoic and early Tertiary magmatic arcs anomalously close to the present-day trench has been interpreted by numerous authors as evidence of subsequent "tectonic erosion" of the western margin of South America (Rutland, 1970; Ziegler and others, 1981); this interpretation also explains the absence of older accretionary prisms or fore-arc basins along the margin.

GEOLOGY OF THE SIERRA FRAGA-PUQUIOS

Regional Setting

The extensional structures that constitute the focus of this report crop out in the Sierra Fraga-Puquios area, ~60 km northeast of the city of Copiapó. The Copiapó region, between 26°S and 28°S (Fig. 1), is located on the western slope of the Andes in the present region of the change from flat to steep subduction of the Nazca Plate (Jordan and others, 1983; Isacks, 1988). To the west of the Sierra Fraga-Puquios region, the coastal zone is dominated by the composite Jurassic-Cretaceous batholith, which represents the initial phases of Andean subduction. The batholith intrudes an older basement formed by a late Paleozoic accretionary wedge and Permian to Triassic intrusions (Mercado, 1978; Berg and Bauman, 1985; Bell, 1987; Naranjo and Puig, 1984). The Atacama fault, a structural discontinuity in the Coastal Cordillera of northern Chile active since the Late Jurassic, crosses the batholith along its axis (Scheuber and Adriessen, 1990; Brown, 1991a, 1991b). During the Jurassic and Cretaceous, the fault experienced ductile, mylonitic deformation and left-lateral shear as it cut the axis of the coeval magmatic arc (Naranjo and others, 1984; Hervé, 1987; Scheuber and Adriessen, 1990). Recently, studies of movement indicators in concert with $^{40}Ar/^{39}Ar$ dating of the various generations of mylonites near Chañaral suggest that, between 130 and 125 Ma, a change occurred from normal displacement under amphibolite facies conditions to left-lateral slip at greenschist facies of metamorphism (Brown and others, 1991a, 1991b).

East of the batholith, a thick cover of Cretaceous volcanic rocks, the Cerillos Formation, and Neocomian limestone crop out. These are covered unconformably, or intruded, by lavas, ignimbrites, and associated plutons of Paleocene and Eocene age (Segerstrom, 1968; Mortimer, 1973; Zentilli, 1974; Rivera and Mpodozis, 1991). Farther east, a system of strike-slip faults, known locally as the La Ternera part of the Domeyeko fault system (Maksaev, 1990), marks the eastern border of the extensional terrane described here. These faults, which have a strike length of 800 km, have been interpreted as Eocene-Oligocene in age because many of northern Chile's most famous Oligocene porphyry copper deposits (Chuquicamata, La Escondida, Quebrada Blanca, etc.) are localized along them.

Stratigraphic Sequence

The stratigraphic sequence of the Sierra Fraga-Puquios (Fig. 2), which rests in tectonic contact on the late Paleozoic igneous and metamorphic basement core of the range, begins in the upper Carboniferous and continues into the Cretaceous. These units occur in four extensional allochthons; their distribution is shown in Figure 3. Rapid facies changes in these continental and shallow marine, volcanic and sedimentary sequences prevent all but the most general descriptions of the stratigraphic sequence. These rocks are overlain unconformably by Paleocene lavas and tuffs, which provide the upper age limit for the major extensional deformation.

Parautochthonous Basement. The basement core of the Sierra del Fraga is composed of granitoids and low-grade metamorphic rocks, overlain by a silicic and volcaniclastic sedimentary sequence. The main outcrop of the basement is composed of Paleozoic coarse-grained, leucocratic granites and, in lesser proportion, tonalites and amphibole- and biotite-bearing granodiorites. Pervasive alteration prevents reliable geochronologic studies of these igneous rocks; in general, similar rocks of the Atacama region (to which this area belongs) consistently yield Carboniferous to Permian ages using both K/Ar and Rb/Sr methods (Farrar and others, 1970; Zentilli, 1974; Brook and others, 1986). In a narrow belt (500 by 200 m) east of and tectonically beneath the intrusive rocks, calcareous, muscovitic, and actinolitic schists are present. Farther east in the Sierra Fraga and in horses of the La Ternera strike-slip fault system (Fig. 3), the same intrusive rocks are covered by quartziferous rhyolites and acidic pyroclastic rocks (the "Pantanoso Formation" of Sepúlveda and Naranjo, 1982; Mercado, 1982). With the exception of the metamorphic rocks, which are unknown elsewhere in the region, the leucocratic granites and rhyolites in the basement of the Sierra Fraga are similar to the late Paleozoic basement throughout northern Chile.

Permo-Carboniferous. The structurally lowest allochthon is composed of rocks of

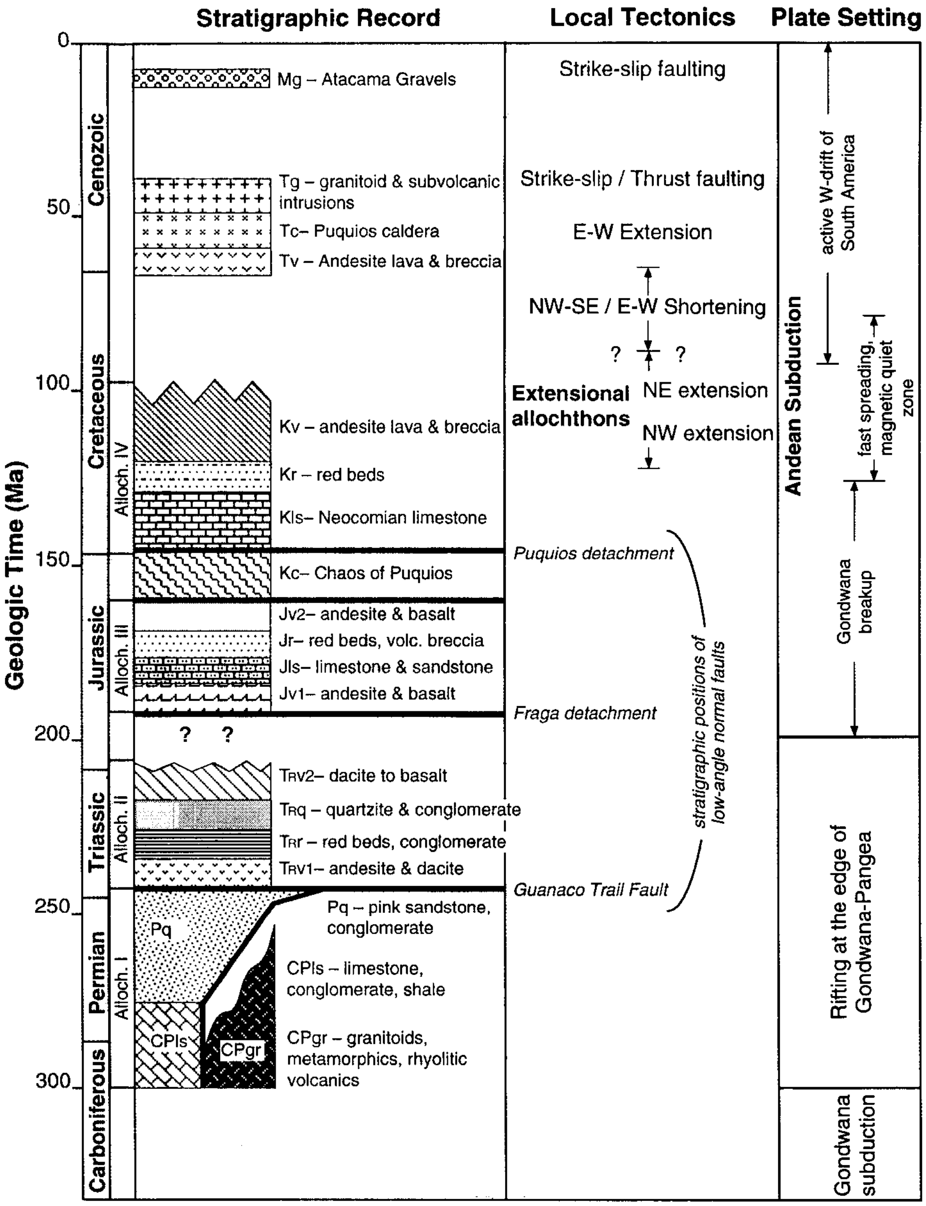


Figure 2. Tectonostratigraphic diagram showing the stratigraphic section of the Sierra Fraga-Puquios in the context of the regional structural evolution and the plate margin history of western South America. Patterns are the same as used in Figure 3.

Pennsylvanian and Permian(?) age. The stratigraphic sequence, from base to top, includes 40–50 m of black shale, about 200 m of gray bioclastic limestone, and at the top, an interfingering sequence of limestone, yellow sandstone, and conglomerate composed of clasts of rhyolite and leucocratic granite (Fig. 2). The well-preserved fauna in the limestone, which includes *Kochinoproductus peruvianus d'Orbigny* (von Hillebrandt and Davidson, 1979; Sepúlveda and Naranjo, 1982), permits a correlation with Pennsylvanian–Lower Permian limestones and interbedded rhyolites in the Antofagasta region ~500 km farther north (Niemeyer and others, 1985; Britkreutz and others, 1988), the closest known limestones of the same age.

A thick sequence of pink conglomerate and coarse-grained sandstone crops out southeast of the Sierra Fraga in a broad area that spans both sides of the Quebrada Paipote (Fig. 2). Large-scale cross-beds, mud cracks, and paleochannels indicate deposition of these rocks in a semi-arid environment (Bell and Suárez, 1991). Except for one small, poorly exposed area, the pink conglomerate and sandstone are everywhere separated from the Paleozoic limestones by a northeast-striking thrust fault (Fig. 3). We infer that the two units are probably part of the same extensional allochthon because both occur structurally beneath the allochthon bearing the continuous Triassic section. In previous regional studies, the pink clastic sequence was assigned to the Triassic (Segerstrom, 1968; Sepúlveda and Naranjo, 1982). The total lack of fossil material and the similarity in clast composition to the sandstones and conglomerates that overlie the limestone, however, indicate that the pink sandstone and conglomerate beds were continuous with that Pennsylvanian–Lower Permian sequence (Mpodozis and Davidson, 1979). Like the basement, the pink sandstone and conglomerate are pervasively intruded by at least three phases of dikes.

Triassic. The overlying allochthon is composed entirely of Triassic strata (the La Ternera Formation of Brüggen, 1950), which crop out in a northeast-striking band along the southeast flank of the Sierra Fraga; it constitutes one of the least-disrupted stratigraphic sequences in the area. Outcrops also occur east of the La Ternera fault system. Both areas display a broadly similar sequence (from base upward): (1) as much as 400 m of andesite and dacite lava and breccia, (2) 300 m of red sandstone and shale, (3) 900 m of quartz pebble conglomerate and arkosic sandstone with intercalations of shale and minor coal seams with abundant plant remains (*Dicroidium* flora) attributed to the Upper Triassic (Brüggen, 1950; Segerstrom, 1968; Sepúlveda and Naranjo, 1982), and (4) an upper volcanic unit with very variable thickness and composition. To the southwest of Sierra Fraga, the upper volcanic horizon is 400 m thick and is composed of pyroclastic breccias and felsic tuffs, whereas east of the La Ternera fault system, it is no more than 100 m thick and is predominantly andesite and basalt lava. The La Ternera Formation is representative of rift basin fill found throughout Chile and Argentina during the Triassic (Charrier, 1979; Ramos and Kay, 1991).

Jurassic. Jurassic strata make up the third allochthon, which occurs along the crest and western flank of the Sierra Fraga (Fig. 3). This sequence also can be divided into four units (from base to top): (1) 200 m of interbedded marine limestone and andesitic amygdaloidal lava and breccia; (2) 300 m of yellowish limestone and sandstone with Bajocian ammonites (*Pseudotoites*, *Sonninia*; Davidson and others, 1976; Sepúlveda and Naranjo, 1982); (3) 400 m of finely stratified

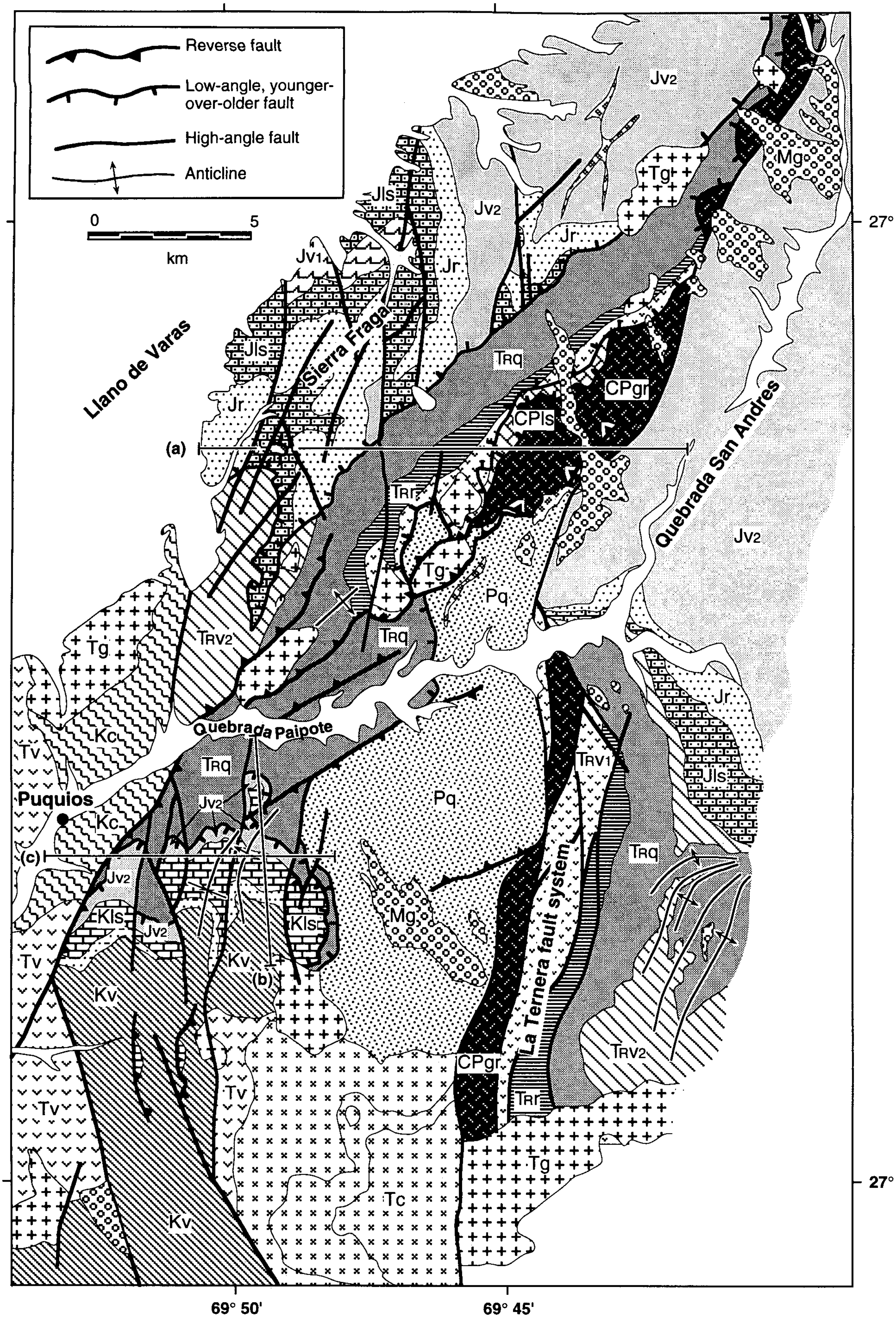

Reverse fault
Low-angle, younger-over-older fault
High-angle fault
Anticline
0
5
km
27°
27° 15'
69° 50'
69° 45'
Llano de Varas
Sierra Fraga
Quebrada San Andres
Quebrada Paipote
Puquios
La Ternera fault system
(a)
(b)
(c)
Jv2
Jv1
Jls
Jr
Tg
TRq
CPgr
CPls
TRr
Pq
Mg
TRv1
TRv2
Kc
Kls
Kv
Tv
Tc

Figure 3. Geologic map of the Sierra Fraga-Puquios. For key, see the tectonostratigraphic diagram in Figure 2. Lines labeled (a), (b), and (c) show the locations of the cross sections in Figure 5.

red sandstone, which grades laterally to the southwest into thick volcaniclastic breccias and andesitic lavas; and (4) more than 2,000 m of massive andesite and basalt lavas, which form the peak of Sierra Fraga. East of the La Ternera fault system, the Jurassic sequence rests depositionally on the Triassic La Ternera Formation; there, the lowest unit described above is missing and the yellow limestone includes fauna ranging in age from Sinemurian to Bajocian (Mpodozis and Davidson, 1979; Sepúlveda and Naranjo, 1982). Davidson and others (1976) and Sepúlveda and Naranjo (1982) interpret the Jurassic sequence of the region as back-arc basin strata deposited immediately after the beginning of Andean subduction in the Early Jurassic.

Cretaceous. Cretaceous strata occur only in the structurally highest allochthon located south of the Quebrada Paipote (Fig. 3). The base of the sequence is composed of ~200 m of Jura-Cretaceous andesite and basaltic andesite lava. Bioclastic and oolitic limestone, 200 m thick, overlie the volcanics and form some of the most spectacular cliffs and exposures in the region. The limestones contain a late Valanginian to Barremian ammonite fauna (*Crioceras*, *Olcostephanus*, etc.; Mpodozis and Davidson, 1979; Sepúlveda and Naranjo, 1982) and probably represent a marine transgression during a period of reduced volcanic activity. Overlying the Neocomian limestones are a 50-m-thick red volcaniclastic sandstone bed and then much more than 1,000 m of massive andesite (Fig. 2). The Cretaceous andesite grades westward into the thick sequence of volcanic and sedimentary strata of the Cerrillos Formation (Segerstrom, 1968; Zentilli, 1974; Sepúlveda and Naranjo, 1982).

Structural Geometry of Extensional Detachments

Because of outstanding exposure, more than 2,000 m of vertical relief, and a broad range of rock units, the Fraga-Puquios region provides a relatively complete and largely decipherable record of deformational events from the Cretaceous through the late Cenozoic. The low-angle faults that are the focus of this paper were previously interpreted as thrust faults (Godoy and Davidson, 1976; Mpodozis and Davidson, 1979). First, we describe the structure of the low-angle-fault–bounded allochthons (Fig. 4), and then we justify our new interpretation of an extensional origin.

Allochthon I. The structurally lowest allochthon rests with marked angular discordance directly on the parautochthonous basement. Bedding in the Permian limestone dips steeply (60°E to overturned and westward-dipping) and lies nearly perpendicular to the low-angle (~20°W-dip) fault that separates it from the basement (Fig. 5a). The limestone lacks any evidence of massive recrystallization indicative of thermal metamorphism, and fossils are well preserved to within a few meters of the contact, indicating that the boundary between limestone and basement is not intrusive. The fault zone is characterized by 5 to 10 m of cataclasite on the top of the granitoids of the basement and locally abundant calcite veining in the limestone. The fault surface is exposed at just one locality; striae on the surface there show that, despite the current northwest dip of the fault, the axis of movement was southwest-northeast (Fig. 6a). The Permian strata of the upper plate are nearly isoclinally folded about a northeast-trending hinge although the underlying fault surface is planar. The fold has the same orientation as folds in Puquios Chaos, described below, which also have hinges parallel to the slip of the allochthons. Mafic dikes, presently undated, crosscut the fault surface, the allochthon, and the basement parautochthon.

Allochthon II. The next higher allochthon, composed mostly of Triassic rocks, is bounded by the Guanaco Trail fault (Figs. 4 and 5), so named because of its morphologic similarity to the Burro Trail fault in the Death Valley region (Hunt and Mabey, 1966). This fault cuts progressively down-section to the northeast; in its northeasternmost exposures, allochthon I is completely omitted and allochthon II rests directly on the basement (Fig. 4). On the Sierra Fraga side of the Quebrada Paipote, as much as several thousand meters of upper Paleozoic section in allochthon I has been cut out by the Guanaco Trail fault. Where bedding is well exposed in the lower plate, the fault cuts down-section to the east and northeast. Bedding in the Triassic section of the upper plate of the fault is essentially parallel to the fault surface and is among the least structurally disrupted in the region (Fig. 5a). Striae along the Guanaco Trail fault at several locations also indicate a southwest-northeast axis of displacement (Fig. 6b). A single observation of steps on the fault surface from an outcrop south of the Quebrada Paipote implies top-to-the-northeast movement. Although not very reliable in itself, this interpretation agrees with more complete evidence for the displacement of the overlying Cretaceous allochthon.

Allochthon III. The third allochthon occupies the crest and western flank of the Sierra de Fraga (Fig. 4) and is composed of Jurassic strata; the fault at its base is referred to here as the Fraga detachment (Fig. 7). A window into Triassic rocks beneath the detachment on the west side of the range shows that the fault has a regional dip of <20° to the northwest (Figs. 3, 4, and 5; the *apparent* dip in Fig. 5a is nearly horizontal). Allochthon III differs substantially from the other allochthons in several important respects: (1) it is broken up by numerous high-angle normal faults, most of which do not cut the detachment surface; (2) across most of Sierra Fraga, Jurassic strata in the upper plate dip to the east and are truncated against the detachment; and (3) numerous striae on the detachment surface, in combination with fault surface movement indicators (mainly fibrous vein-steps) and drag-folding of the underlying Triassic rocks in the window, record top-to-the-northwest displacement (Fig. 6c). We interpret the exposed structural geometry of allochthon III as a hanging-wall ramp across Jurassic strata over a footwall flat (or very gentle ramp) across the Triassic section.

Allochthon IV. Allochthon IV occurs only south of the Quebrada Paipote (Fig. 4) and contains Cretaceous and uppermost Jurassic rocks. The fault at its base, referred to here as the "Puquios detachment," puts this sequence directly over Triassic quartzite, omitting at least 3,500 m of uppermost Triassic and Jurassic strata (Fig. 8). The Puquios detachment is parallel to the strata in the upper plate and cuts very gently across bedding in the underlying Triassic strata (Figs. 5b and 5c). Striae oriented west-southwest–east-northeast were found at one exposure of the fault and, in combination with well-exposed domino blocks in the upper plate, suggest top-to-the-northeast movement of the allochthon (Fig. 6d). The relation of allochthons III and IV cannot be directly determined because they are nowhere in contact, but allochthons IV, II, and I all have the same direction of displacement.

Puquios Chaos. An intensely deformed unit, composed of Cretaceous limestone and Upper Jurassic volcanic rocks, is exposed on both sides of the Quebrada Paipote near the

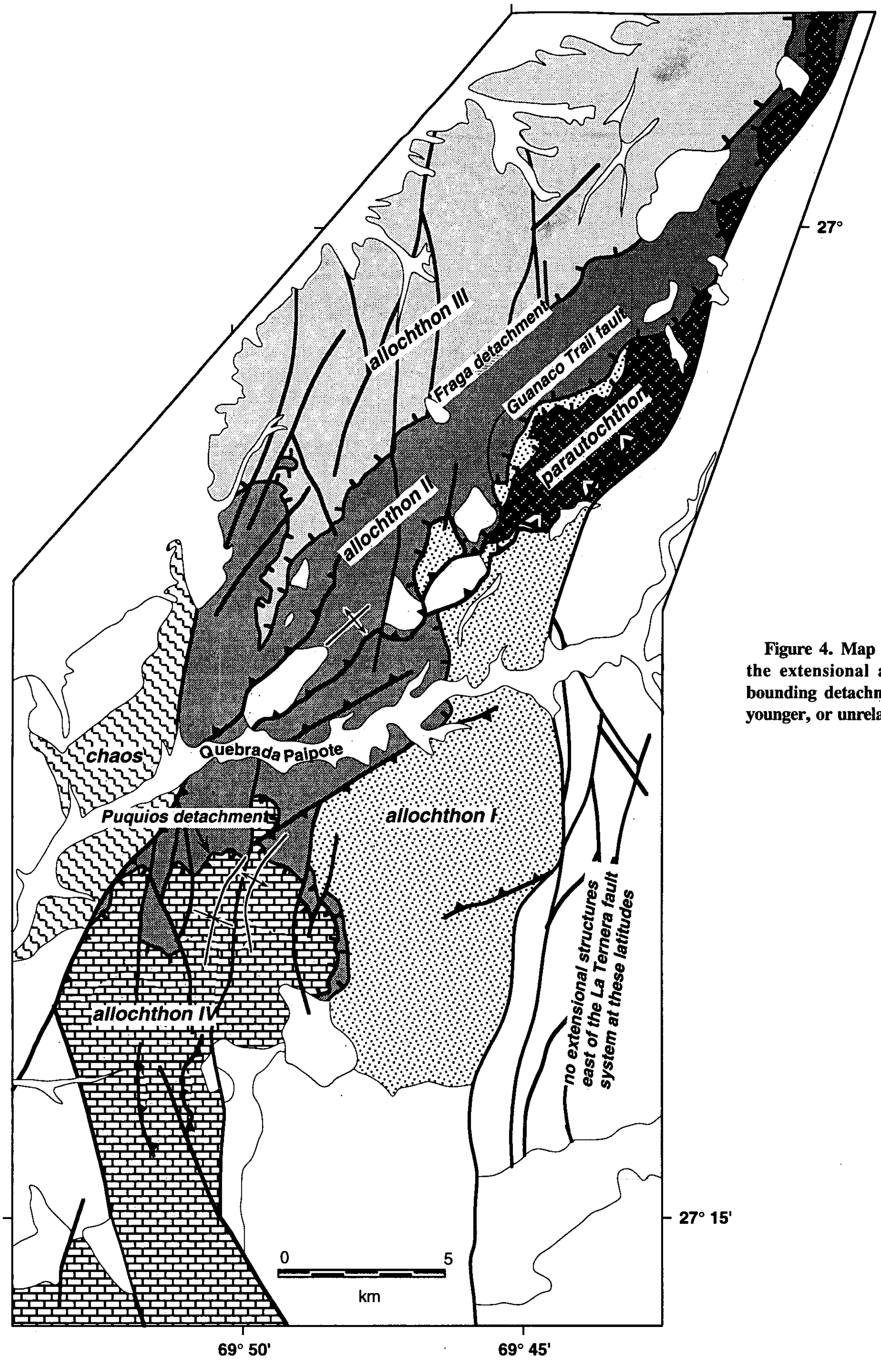


Figure 4. Map showing distribution of the extensional allochthons and their bounding detachments. White areas are younger, or unrelated, deposits.

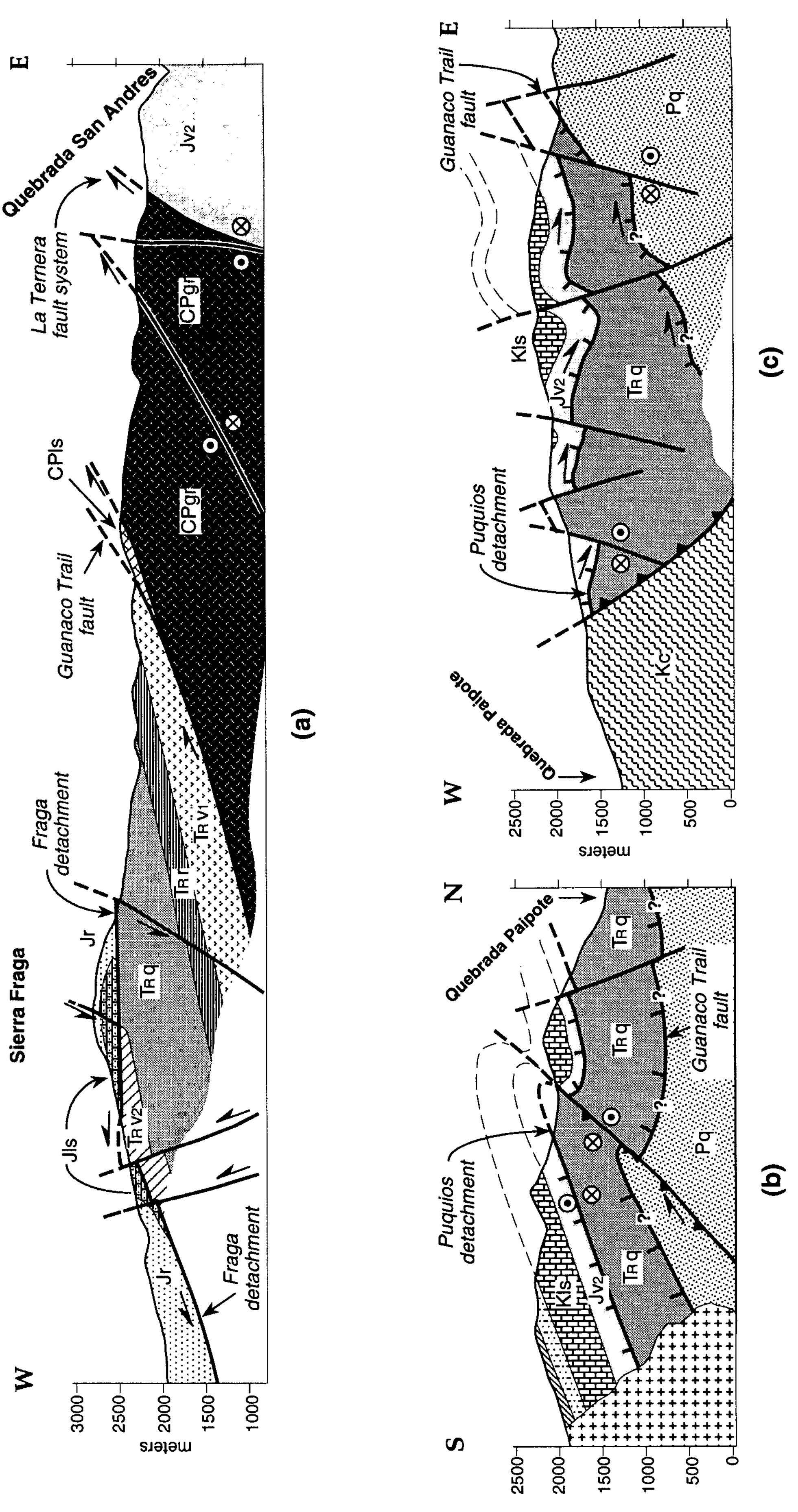
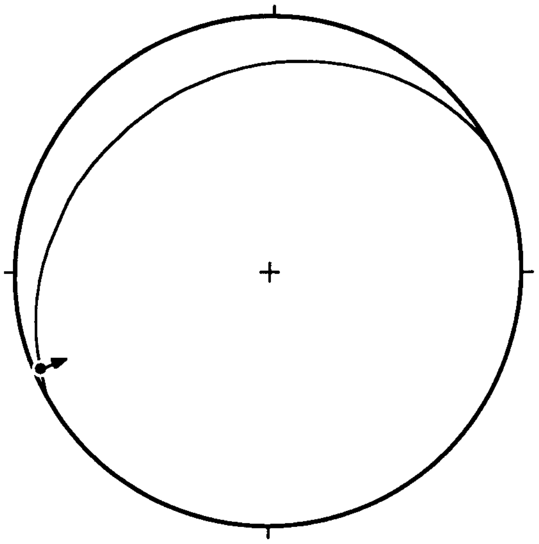
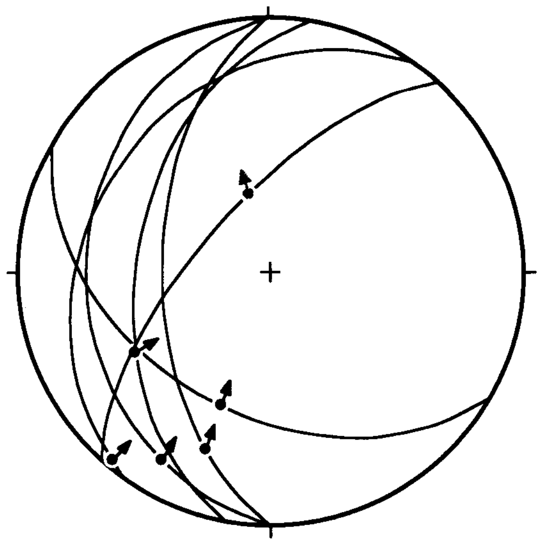


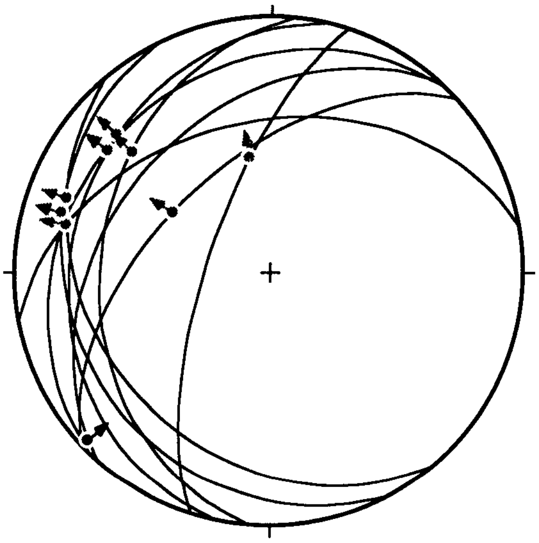
Figure 5. Generalized geologic cross sections of the Sierra Fraga-Puquios. For location see Figure 3. Symbols same as in Figure 2.



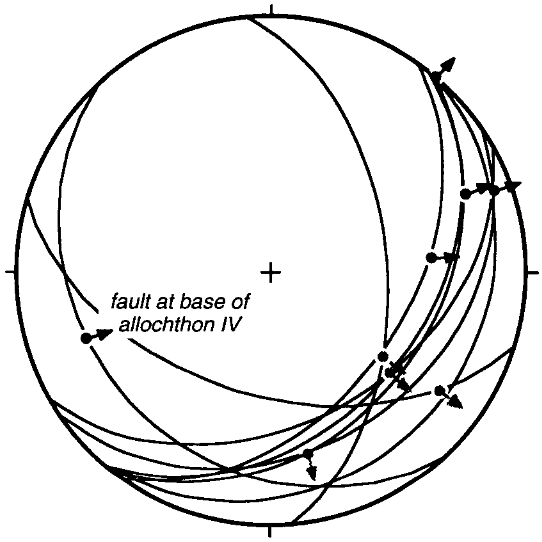
(a) Fault at base of Permian Limestone



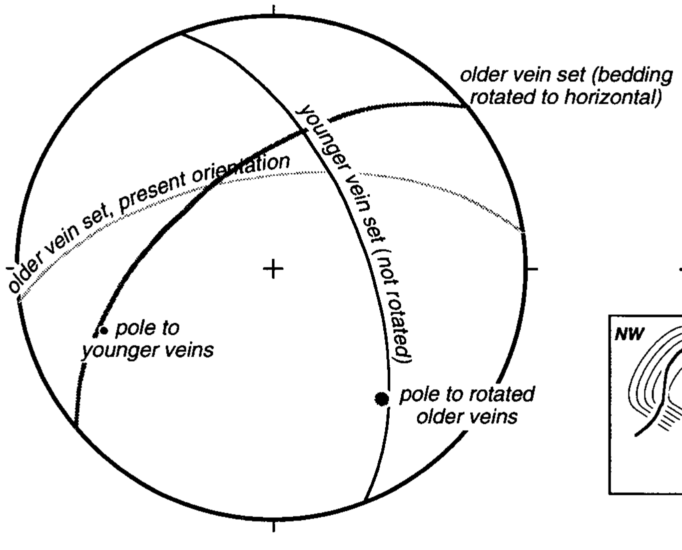
(b) Guanaco Trail Fault



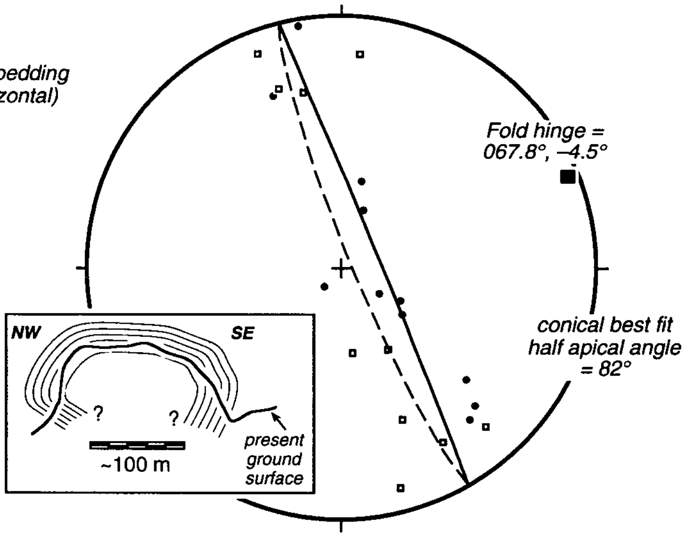
(c) Fraga Detachment Faults



(d) Puquios Chaos faults



(e) Veins Perpendicular To Bedding In Boudins At Puquios Chaos



(f) Bedding Poles In Puquios Chaos Sheath Fold

Figure 6. Structural data from the various extensional allochthons. In a–d, the great circle traces represent local fault surface orientations. The dots show slickenside or striae orientation, and the arrows show the movement of the hanging-wall block. Gray dots correspond to striae from the older extension; black dots, to the younger. In f, open boxes represent upper hemisphere poles of overturned bedding; the black dots are lower hemisphere poles of upright bedding. The dashed line is the upper hemisphere trace of the small circle cone; the solid line, the lower hemisphere trace. The inset in f shows the cross-sectional geometry of the fold. Note that it is overturned on both limbs.

ghost town of Puquios. The general character of this unit is that of boudined and dismembered limestone "floating" in a sea of volcanic rock that has retained no vestige of original stratification (Fig. 9). Close inspection of the volcanic rock shows that it has deformed by large-scale, ductile cataclastic flow around the somewhat more intact layers of limestone. Because of the extreme dismemberment, we refer to this unit as the "Puquios Chaos." Although the chaos contains rocks of the same age as those found in allochthon IV, the two structural units are everywhere separated by a northeast-striking, southeast-dipping reverse fault of probable mid-Tertiary age (Figs. 3, 4, and 5c) and the intensity of deformation in the chaos is substantially greater.

The limestone boudins in the Puquios Chaos record a large amount of information about the deformational history of the region. There are two sets of striae on faults within and around the boudins. One set, with northeast trends (Fig. 6d), occurs on the faults that bound, and are responsible for the present shape of, the boudins. The displacement across these faults is uniformly top-to-the-northeast (Fig. 9). However, a second set of low-angle normal faults with much smaller displacements within the boudins accommodated top-to-the-northwest displacement (Fig. 6d). The relative ages of the two phases of extension represented by these two fault sets are given by two sets of crosscutting veins apparent on bedding surfaces within the boudins (Fig. 6e). The pole to the younger vein set plunges gently to the southwest, generally parallel to the southwest-northeast movement direction seen in the data for allochthons I, II, and IV. The pole to the older veins in its present orientation plunges nearly due south. If the older veins are rotated by restoring bedding in the boudins to horizontal, however (that is, removing the slip on the boudin-bounding faults), then the pole to the older veins plunges southeast, subparallel to the movement direction of the Fraga detachment and allochthon III (Fig. 6e).

In the Puquios Chaos on the south side of the Quebrada Paipote, a second disrupted

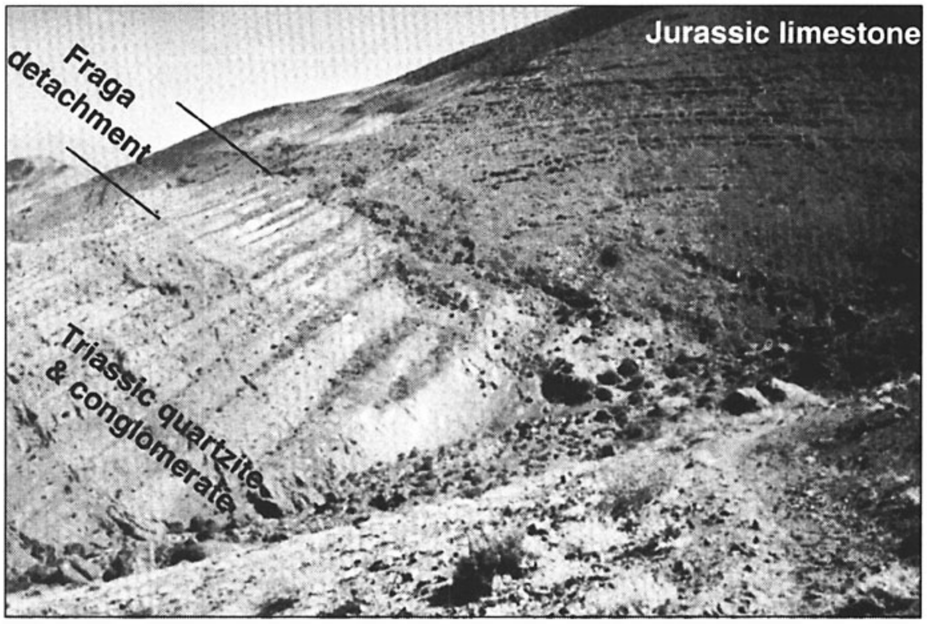


Figure 7. Photo of the Fraga detachment, looking northwest. Note hanging-wall cutoff of Jurassic strata and footwall flat in Triassic rocks.

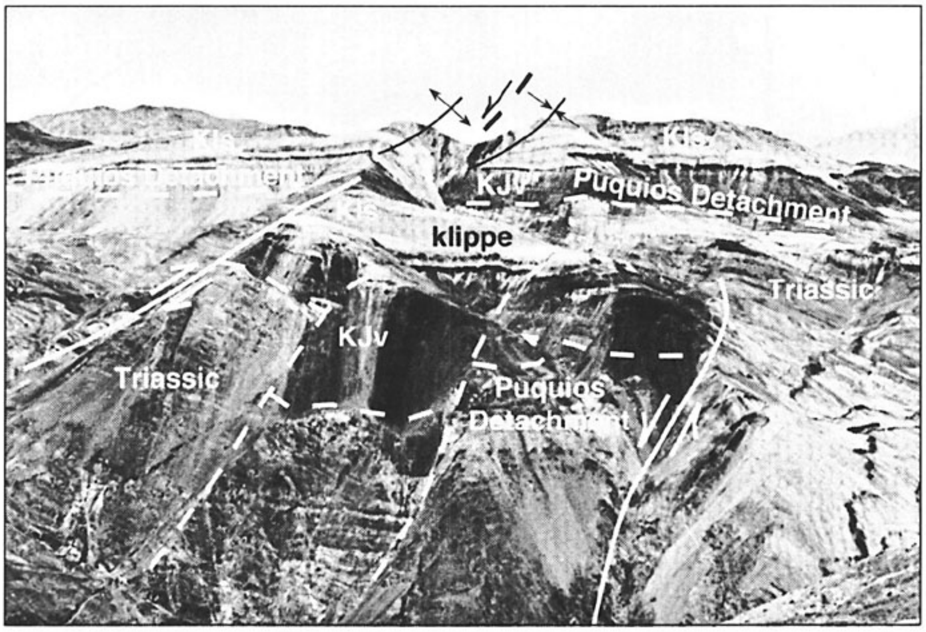


Figure 8. Photo of the Puquios detachment (horizontal dashed line) deformed by younger thrust and normal faults, looking south. More than 1,000 m of vertical relief is displayed in the photo. Letter codes as in Figure 2. The normal fault indicated on the skyline offsets an anticline-syncline pair formed at the tip of the thrust fault shown on the left (east) side of the picture. This normal fault is the same as that marked in the lower right side of the picture (the rest of the fault is behind the ridge of Kls in the foreground). The Puquios detachment is offset by the thrust fault/anticline-syncline pair, producing the down-dropped ridge of Kls.

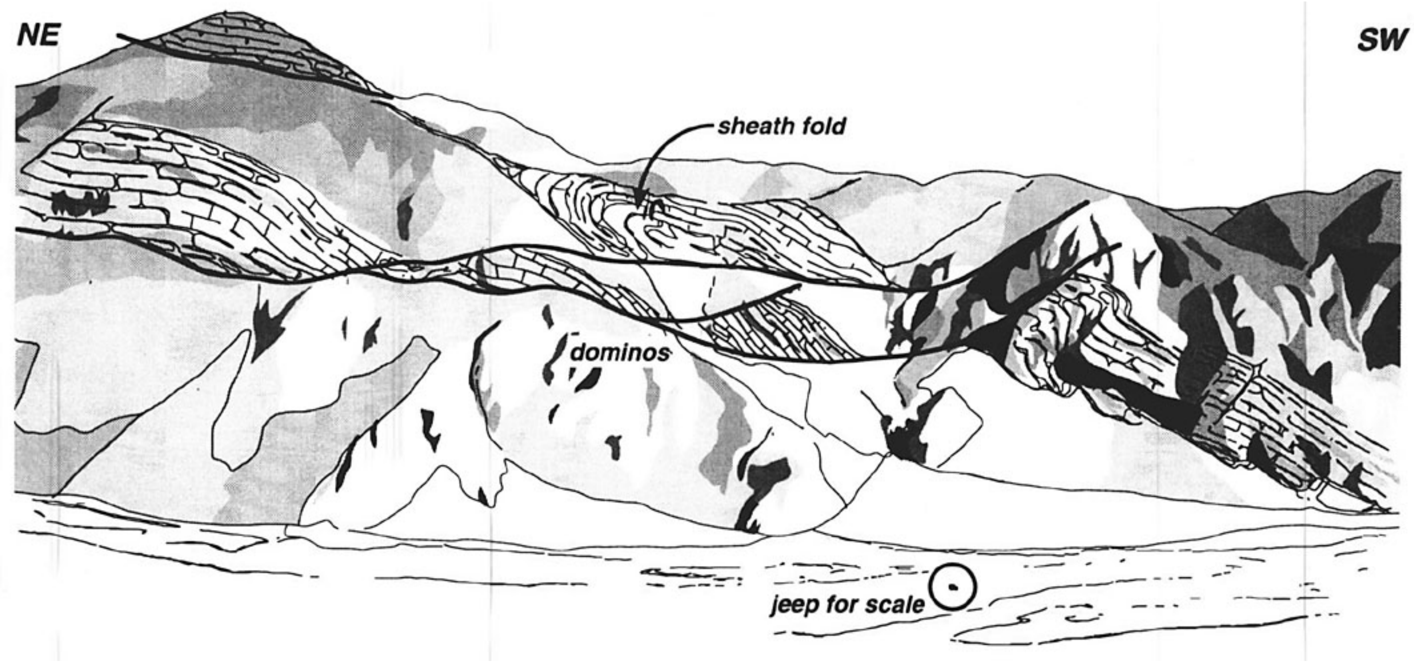


Figure 9. Sketch of a photo-mosaic, showing the disrupted Neocomian limestone blocks (line work, brick-like pattern) in a matrix of ductile cataclastic volcanic rock. Note jeep for scale.

layer of limestone displays an unusual fold with an east-northeast–trending hinge that can be traced for several hundred meters (Fig. 9). As one moves along the hinge from southwest to northeast, the closure progressively tightens. At the northeast end, both limbs are overturned; the northern limb dips as little as about 30°SE, and the southern limb has dips as low as 62°NW (Fig. 6f, inset). The bedding poles of the fold are best fit by a cone with a half apical angle of 82°, azimuth of 067.8° and a plunge of −4.5° (Fig. 6f; the negative plunge means that the cone points into the upper hemisphere), indicating that the fold is slightly noncylindrical. Marked lineations on bedding surfaces in the fold are parallel to this cone axis. The cone axis and lineations are parallel to the movement directions of allochthons I, II, and IV, and to the younger phase of movement in the boudins of the Puquios Chaos. We interpret this geometry as that of a sheath fold formed in a shear zone in which the sense of shear was roughly top-to-the-northeast.

Summary of Low-Angle Faults and Interpretation of Extensional Origin

The low-angle, fault-bounded allochthons and their associated features are the oldest structures recognized in the Sierra Fraga-Puquios. We have mapped four allochthons, three of which (I, II, and IV) probably experienced top-to-the-northeast motion and one (III) that had top-to-the-northwest transport. Although some of the faults, in their present orientation, *appear* to be thrust faults, several lines of evidence point to, or are consistent with, an extensional origin for *all* of the low-angle-fault–bounded allochthons:

1. All faults are of the younger-over-older variety, omitting variable amounts of stratigraphic section. The Guanaco Trail fault, for example, cuts down-section, but obliquely up *present* dip to the northeast, in the direction of translation. As no older deformation is recognized, this geometry cannot be ascribed to a departure from a "layer cake" stratigraphic sequence due to prior deformation. Therefore, we interpret that the present dip is due to postfaulting rotation.
2. Normal faults within allochthons III and IV are truncated by the underlying detachments. In the case of the better-exposed Puquios detachment, at least, these faults are clearly listric and sole into the basal detachment.
3. The boudins in the Puquios Chaos clearly indicate a subhorizontal orientation for the maximum principal extension axis of the finite strain ellipsoid.

Because allochthon III moved in a direction ~90° different from all of the other allochthons, a reasonable assumption is that it moved at a different time. The only relations that bear directly on the relative ages of motion are those in the Puquios Chaos, which indicate that the northwest movement was older than the northeast movement. Given the hanging-wall flat over footwall flat geometry of the Puquios detachment, we hypothesize that prior movement of allochthon III was necessary to remove the omitted strata from beneath the base of allochthon IV. This interpretation, illustrated schematically in Figure 10, would also explain why allochthons III and IV are nowhere in contact. If correct, it would suggest that the Puquios Chaos formed in the position of the thinned edge of allochthon IV, at the site of the former footwall ramp of allochthon III, and thus records both episodes of motion. In this sense, the chaos is located along a complex lateral ramp in allochthon IV. Allochthon II, the least deformed of all, probably carried the older allochthon III passively on its back, preserving most of the older structures in the latter. A few north- to north-northwest–striking normal faults do cut the Fraga detachment and may be related to movement of the younger allochthons. We do not know the relative ages of allochthons II and IV, but both have the same movement direction.

The magnitude of displacement of the extensional allochthons is difficult to estimate because of superposed structures and the

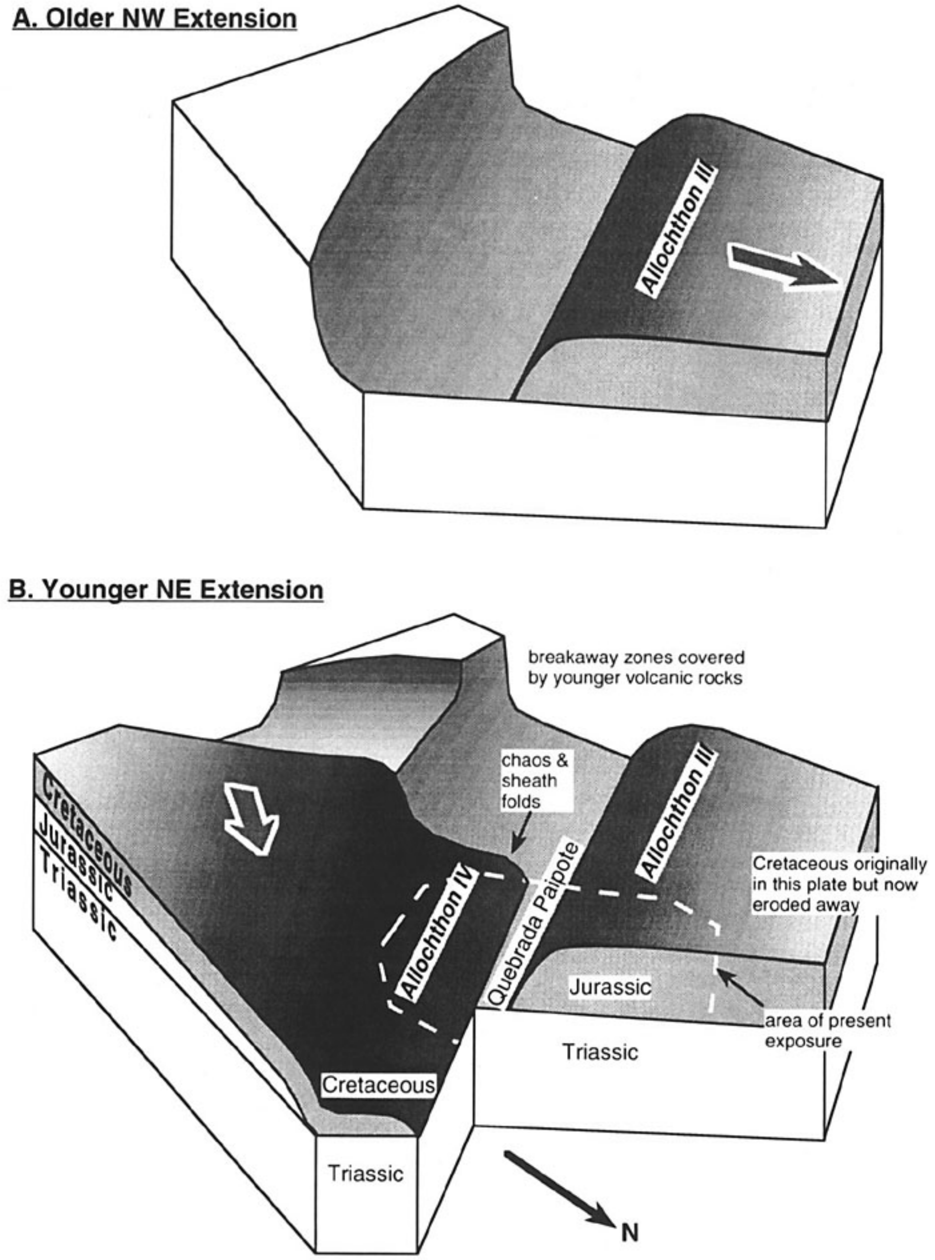


Figure 10. Schematic block diagram showing the possible evolution of allochthons III and IV. Later structures are not shown.

overall three-dimensional nature of the deformation. Furthermore, because allochthons I, II, and IV have probably been rotated, their breakaway zones should be located *down* present dip to the west or southwest; virtually all of that region is now covered by younger volcanic rocks. Nonetheless, the fact that footwall and hanging-wall stratigraphy cannot be matched anywhere along the traces of any of the detachments implies that each allochthon moved on the order of kilometers from its original position. Likewise, our interpretation of sheath folds in the chaos and perhaps in allochthon I would imply large shear strains, if correct.

Younger Structures and Relative Age Sequence

Several sets of younger structures cut the extensional allochthons described above. These are, in order from oldest to youngest, (1) northeast- and north-striking reverse faults, (2) north-striking high-angle normal faults, and (3) several episodes of strike slip and oblique thrust motion across north- to north-northeast–striking faults (Fig. 2). The relations between the first two and the extensional allochthons described previously are superbly exposed in the cliffs on the south side of the Quebrada Paipote, due east of Puquios (Figs. 5b, 5c, and 8). One of the most remarkable features of this region is a klippe of allochthon IV, located just to the north of the main exposures of the allochthon. The Puquios detachment beneath the klippe is about 150 m lower topographically than its counterpart farther south because of a northeast-striking thrust fault that offsets the detachment and dies out into a fault propagation fold along strike to the southwest (Figs. 3 and 4). The fold, well displayed in the Neocomian limestone of allochthon IV (Fig. 8), has subsequently been cut and displaced, east-side-down, by a north-striking normal fault. The klippe thus is bounded on the southeast by the thrust fault, on the northeast by the Puquios detachment, and on the west by the younger normal fault.

One of the most important structures of the area, the La Ternera fault system (Figs. 1 and 3), forms the eastern limit of the extensional structures described above. None of the extensional allochthons has been observed on the east side of this fault zone at these latitudes. Instead, in the northeastern part of the area, the Fraga detachment and the Guanaco Trail fault merge into, or are truncated by, the La Ternera fault system (Figs. 3 and 4). A compressional "pop-up" at a right-stepping bend and several minor movement indicators along the fault just north of where it crosses the Quebrada Paipote indicate that it has had significant left-lateral displacement. The anastomosing strands of the fault system, which bound lensoidal horses of Paleozoic basement rhyolites and Lower Triassic volcanic rocks to the south of Quebrada Paipote (Fig. 3), could be interpreted as a strike-slip duplex. The fault also displays some of the youngest deformation of any structure in the area: the Miocene (8–10 Ma) Atacama gravels and San Andres Ignimbrite are offset by a small amount, also in a strike-slip sense.

The La Ternera fault constitutes part of the southernmost segment of the Domeyko fault system (Maksaev, 1990), which was active during the late Eocene and Oligocene (for example, Reutter and others, 1991). Older movement, however, at least on the La Ternera segment, cannot be ruled out. Regional changes in Cretaceous facies occur across the La Ternera fault system, which therefore may have a history that predates, or coincides with, the main phase of extension. As noted above in the description of the stratigraphy, facies of the Triassic and Jurassic also are quite different across the fault, implying either substantial postdepositional offset or fault activity during the accumulation of those strata. Finally, some of the strands of the fault system are intruded by the Eocene La Ternera granite, whereas others crosscut the granite, indicating both pre- and post-pluton movement on different segments of the system.

Although detailed field relations demonstrate a clear relative sequence of structural events, it is possible that the northeast-southwest extension on low-angle normal faults, the northwest-southeast shortening on the reverse faults, and left lateral slip on the La Ternera fault system all occurred during the same protracted regional episode of deformation. These three types of faulting are kinematically coherent and could all be related to regional left-lateral strike-slip movement parallel to the plate margin.

Geochronologic Control and Timing of Deformation

The youngest rocks affected by the low-angle extensional detachments are the Neocomian limestone and the overlying sequence of red beds and andesitic lavas that form the upper part of allochthon IV. West of the Sierra Fraga near Inca de Oro, Neocomian limestones, also affected by low-angle normal faults, were intruded by tonalites and porphyries between 82 and 67 Ma (Cerro Santa Juana, Moreno, 1992), which would indicate an age of at least pre-Santonian for the extensional deformation described here. Pyroclastic breccias and lavas assigned an early Tertiary age (Venado Formation, Sepúlveda and Naranjo, 1982) overlie the Puquios Chaos with angular unconformity directly west of Puquios. The Venado Formation was intruded by granodiorites dated at ~60 Ma (Zentilli, 1974), also constraining the extensional deformation to a pre-Tertiary age. Thrust faults in the area both predate and postdate the Venado Formation. East of the Puquios caldera, two thrust faults with westward vergence place Neocomian limestone over the upper lavas of allochthon IV prior to deposition of the Venado Formation. Other, northeast-striking thrust faults cut the Venado Formation and are, in turn, cut by north-striking normal faults. To the south of Puquios, the basal detachment of allochthon IV is covered unconformably by rhyolitic ignimbrites of the Puquios caldera (53 to 58 Ma, Farrar and others, 1970; McNutt and others, 1975; Rivera and Mpodozis, 1991).

Thus, the major phase of extension probably occurred between the Aptian and the Cenomanian(?), possibly synchronous with the accumulation farther west of the great volume of andesitic lavas and pyroclastic and sedimentary rocks of the Cerillos Formation (Fig. 2). The reverse faults formed prior to 60 Ma, and we interpret them to be Late Cretaceous in age; other thrust faults are mid-Tertiary in age. The north-striking normal fault that forms the western boundary of the Puquios klippe continues farther south, where it branches into several splays. One of the splays forms the border of the Paleocene Puquios Caldera. Thus, these high-angle normal faults represent a second phase of regional extension, which accompanied the Paleocene volcanism of the Copiapó area (Rivera and Mpodozis, 1991).

DISCUSSION

Plate Tectonic Setting

We have documented an important phase of northeast-southwest extension, which was oblique to the Cretaceous Andean magmatic arc and presumably to the plate margin as well. Along modern plate margins such events commonly are interpreted in terms of oblique convergence. To evaluate this hypothesis for the Cretaceous Andes, we review what little is known of the Cretaceous plate evolution in the Pacific.

The direct record of Cretaceous convergence along the South American margin is gone because the oceanic plate subducted at that time has been totally consumed. Larson and Pitman (1972) named this missing plate "Phoenix" and suggested that convergence between it and the South American plate during the Neocomian was low (~2.5 cm/yr) but increased markedly to 14–18 cm/yr during the Aptian-Albian, coeval with the Cretaceous magnetic quiet zone and rapid spreading in the Atlantic. This period of rapid spreading may have been part of a global event between 120 and 80 Ma during which the velocity of oceanic crust generation worldwide increased between 50% and 75%, conceivably as a consequence of the formation of a "super plume" beneath the Cretaceous Pacific basin at about 125 Ma (Larson, 1991a, 1991b). By anomaly 32 (70 Ma), the convergence rate between the Farallon and South American plates had decreased to just 5–7 cm/yr (Pilger, 1984; Pardo Casas and Molnar, 1987; Gordon and Jurdy, 1986) and had changed to an orientation nearly parallel to the plate margin.

The type of interaction between the Phoenix and South American plates during the Early Cretaceous would have depended critically on the velocity of spreading of the Phoenix-Farallon ridge (Fig. 11), which is unknown (Duncan and Hargraves, 1984). If the velocity were slow (for example, 1–2 cm/yr), the Phoenix plate would have been displaced to the northeast with respect to South America. A fast velocity (10–15 cm/yr) would result in southeastward convergence and probably an important component of left-lateral slip along the western margin of South America. As noted above, our younger phase of extension (allochthons I, II, and IV) would be compatible with left slip along the margin; the older phase of extension would have been more compatible with right slip.

Comparison with the Extensional Terranes of the Western United States

The extensional structures of the Sierra Fraga-Puquios—low-angle normal faults, domino blocks, extensional chaos—are geometrically very similar to those observed in the extended terranes of the western United States. Those terranes in the western United States are represented by two basic end members: upper crustal stacks of extensional detachments and mid-crustal metamorphic core complexes (see review and references in Wernicke, 1992). Within this spectrum, the Sierra Fraga-Puquios region more closely resembles the unmetamorphosed extensional detachments complexes. Rather than a single master décollement, we have documented several low-angle normal faults, which lack mylonitization and significant footwall metamorphism, even in the basement core.

The map pattern of the Sierra Fraga-Puquios region resembles that observed in many core complexes. The detachments dip away from the basement core and the allochthons have moved obliquely up present dip. Such a geometry, in which extensional allochthons *apparently* moved uphill, is common in most metamorphic core complexes. We interpret that the Fraga-Puquios allochthons and bounding detachments have been rotated subsequent to their emplacement, perhaps due to isostatic uplift, or doming of basement during unloading of the footwall as interpreted in the western United States (Spencer, 1984; Wernicke, 1992).

These geometric similarities are striking, but equally intriguing is the comparison of regional tectonic setting of the western United

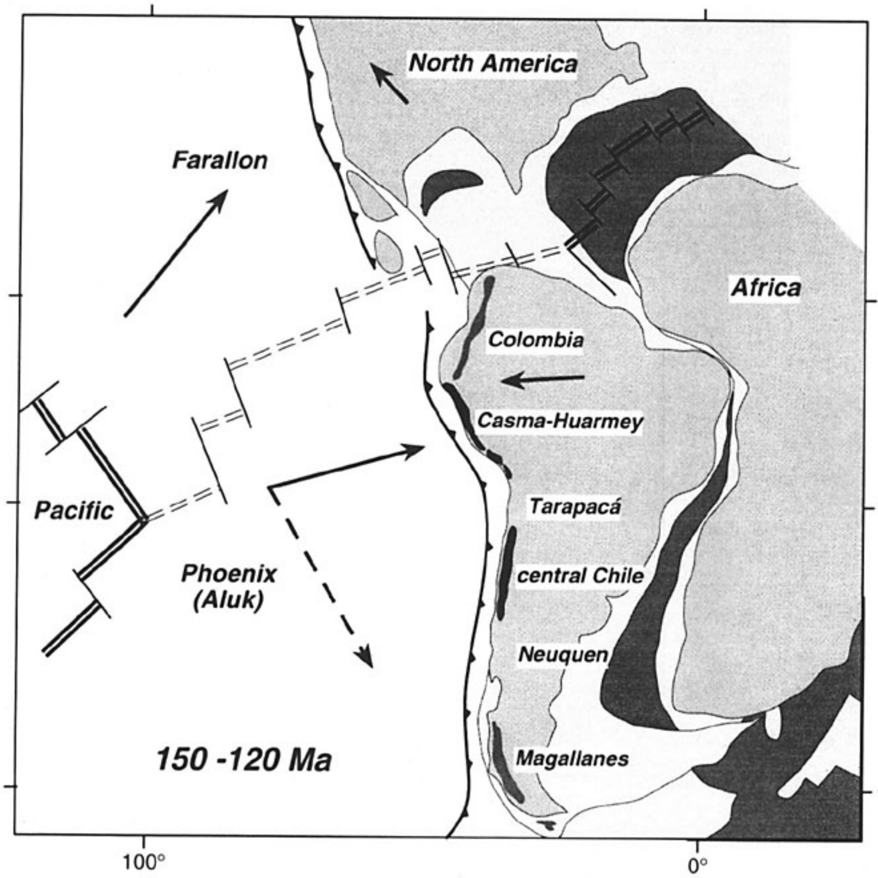


Figure 11. Reconstruction of the plates in the southeast Pacific basin at ~120 Ma, based on Duncan and Hargraves (1984) and Scotese and others (1988). This period coincides with the initiation of rapid spreading in the Pacific (Larson, 1991a). The margin of South America was characterized by a series of intra- or back-arc basins, which have been inferred to be extensional. The gray basins in Colombia (Bougois and others, 1987) and southernmost South America (Dalziel, 1981) are typical marginal basins. The black basins in Peru (Casma-Huarmey) and central Chile are aborted marginal basins on thinned continental crust. The Tarapacá and Neuquén basins are back-arc basins with dominantly sedimentary fill. The arrows represent relative displacement of the plates in a hot-spot reference frame. The direction of convergence depends on the spreading rate at the Phoenix-Farallon ridge (see text for discussion).

States and the northern Chile extensional terranes. Both regions have experienced two different directions of extension, but in the western United States the change apparently occurred as a progressive clockwise rotation through ~45° during the mid-Miocene to present (Zoback and others, 1981). The slip direction of pre–mid-Miocene detachments in the metamorphic core complexes, however, was subparallel to the modern extension direction (see review in Wernicke, 1992), and few if any individual areas display two phases of slip on detachments with ~90° difference in direction. The clockwise rotation of extension direction in the western United States has been related to the evolution of the plate boundary from subduction to a transform regime (Zoback and others, 1981). The change in extension direction in the Sierra Fraga-Puquios area is greater in magnitude, but likewise it seems reasonable that it was due to changes in plate boundary configuration, although probably only in obliquity of subduction.

The regional distribution of extensional deformation is quite different in the two areas and probably reflects patterns of associated magmatism. Cenozoic western U.S. extension occurs across a present cross-strike width of >500 km, although pre–mid-Miocene extension was somewhat more localized along an axis coinciding with the core complexes. The Paleogene subduction-related magmatic arcs of the western United States were far more laterally diffuse and of variable orientation than the Cretaceous arc of the central Andes (see review in Lipman, 1992). There is a clear spatial and temporal association of magmatism and extension in the western United States, although the exact relationship remains uncertain (Gans and others, 1989; Wernicke, 1992). Similarly, in the Sierra Fraga-Puquios area, the Cerrillos Formation coincides in time with the main phases of extension described here although the nature of the connection must be determined by additional regional study.

In the western United States, mid-Tertiary extension manifest in the core complexes and elsewhere has been interpreted as a symptom of "collapse" of continental crust thickened during a previous horizontal shortening (for example, Coney and Harms, 1984). Perhaps the most striking difference in regional tectonics is that, unlike the western United States, this part of the Andean orogen experienced no prior crustal thickening event. Thus, extensional structures like those described here may be typical of intra- or back-arc extension and may have little to do with compressional orogenesis.

Recently, much attention has been given to the rolling-hinge model of Buck (1988; see also references in Wernicke, 1992) as an explanation for the low dip of extensional detachments in the western United States. The extremely localized flexure resulting from the very thin effective elastic thickness required by the Buck model implies sharp footwall cutoffs and steep dips of strata near the detachments in the underlying allochthons. In Fraga-Puquios area, sharp footwall cutoffs are rare and are a marked exception to the more general pattern of gentle dips throughout the region. It is likely that the primary dips of the detachments were never more than 20°–30° and may have been significantly less.

Finally, although most of the preceding discussion has focused on Cenozoic extension in the western United States, there is growing evidence for Mesozoic extension as well (Wells and others, 1990; Hodges and Walker, 1992). In particular, we note that the main phase of extension at ~90 Ma documented by Wells and others (1990) is about the same age as the extension described here. This relationship may be completely coincidental or it may conceivably indicate a major event that affected the entire Pacific Ocean basin. Verification of this latter suggestion awaits the accumulation of substantially more data than are available at present.

CONCLUSIONS

The Sierra Fraga-Puquios records in great detail a sequence of structural events spanning the Cretaceous to Holocene. We have documented, for the first time, the style of extensional deformation associated with the Cretaceous marginal basins of the Central Andes and have shown that, in geometry, the structures are remarkably similar to the extended terranes of western North America. This deformation predates any significant crustal thickening in this region. The region subsequently experienced thrust faulting, high-angle normal faulting, and strike-slip deformation. Important remaining questions concern the possibility of regional strike-slip faulting coeval with the mid-Cretaceous extension, the coupling of magmatism and extension, and the relations among obliquity of subduction, extension, and strike-slip faulting.

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