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Miocene to Recent structural development of an extensional accommodation zone, northeastern Baja California, Mexico

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Abstract—The Gulf of California Extensional Province in northeastern Baja California contains a major structural transition from a northern domain of widely spaced basins and ranges to a southern domain of closely spaced, NNW-striking high-angle faults. In the northern domain, the western boundary of the province (the Main Gulf Escarpment) is a single listric normal fault, the San Pedro Mártir fault; in the southern domain it is a 5 km wide zone of numerous E-dipping high-angle normal faults. The western half of this structural transition, studied here, does not occur by a single 'transfer fault' but rather by: (1) transfer of displacement from the San Pedro Mártir fault onto multiple fault zones in the footwall, without intervening cross-faults; and (2) increased southward disruption of the hanging wall by WNW-striking strike-slip faults (oblique to the extension direction) and NNW-striking normal faults and extension fractures. This structural transition involves both the hanging wall and the footwall of the escarpment. The lack of a discrete transfer structure is attributed either to insufficient extension (<10%) or to a gradual change in geometry of the basal detachment.

INTRODUCTION

WITHIN a region of continental extension, the style and scale of extensional structures, the direction of upper-plate transport and regional tilt directions may vary. Boundaries between regions with different fault styles, extension directions or amounts of extension have been referred to as "zones of compensation" (Anderson 1973), "transfer faults", "hinge zones", "accommodation zones" and "accommodation faults" (see discussions of terminology by Gibbs 1984 and Bosworth 1985). Although these boundaries represent a continuum of structures, two end-member classes have been identified (Lister *et al.* 1986a): structures which cut and displace major detachment systems, with or without a change in polarity of the basal detachment fault; and structures accommodating differential motion between blocks within a single extensional allochthon, which are truncated by the major detachment systems. More detailed subclasses of these structures have been proposed by Şengör (1987). Either type of accommodation zone may be expressed at the surface by single, through-going faults (e.g. the Garlock fault—Davis & Burchfiel 1973); short, interconnected fault segments (within the Lake Mead shear zone—Anderson 1973); short, unconnected fault segments ("relay systems"—Larsen 1988); fault-bounded, interbasinal basement highs (Reynolds & Rosendahl 1984); or regions of very little deformation (Stewart 1980). Accommodation zones may be either oblique or parallel to the regional extension direction (Bosworth 1986, Lister *et al.* 1986b). In many areas the details of structures within these zones are not well understood.

Here we describe a field study of part of an accommodation zone, within the Gulf of California Extensional Province in northeastern Baja California, Mexico. The study area lies at the southern end of an extensional basin and at the western edge of the extensional province, in a region where the structural style within the extensional province differs markedly from north to south. North of the study area, widely spaced, large-displacement normal faults bound 10-km scale coherent structural blocks in a basin-and-range physiography. South of the study area, normal faults with smaller throw are spaced about 1 km apart across the exposed width of the extensional province; no major basins and ranges are present. We mapped the western half of this boundary zone at a scale of 1:20,000 (Stock submitted) to examine the details of this north-to-south structural transition. In this region, good three-dimensional exposures, resulting from ~1000 m of fault-related and erosional topographic relief, provide excellent structural constraints. Only about 10% extension has occurred in this area, so the observed structural pattern may exemplify the initial development of accommodation zones in more highly extended regions elsewhere.

GEOLOGIC SETTING OF THE GULF OF CALIFORNIA EXTENSIONAL PROVINCE IN NORTHEASTERN BAJA CALIFORNIA

The eastern side of the Baja California peninsula lies within the Gulf Extensional Province (Gastil *et al.* 1975, Stock & Hodges 1989) adjacent to the Gulf of California (Fig. 1, inset). The western boundary of the province, the Main Gulf Escarpment, separates the relatively unextended central portion of the Baja California penin-

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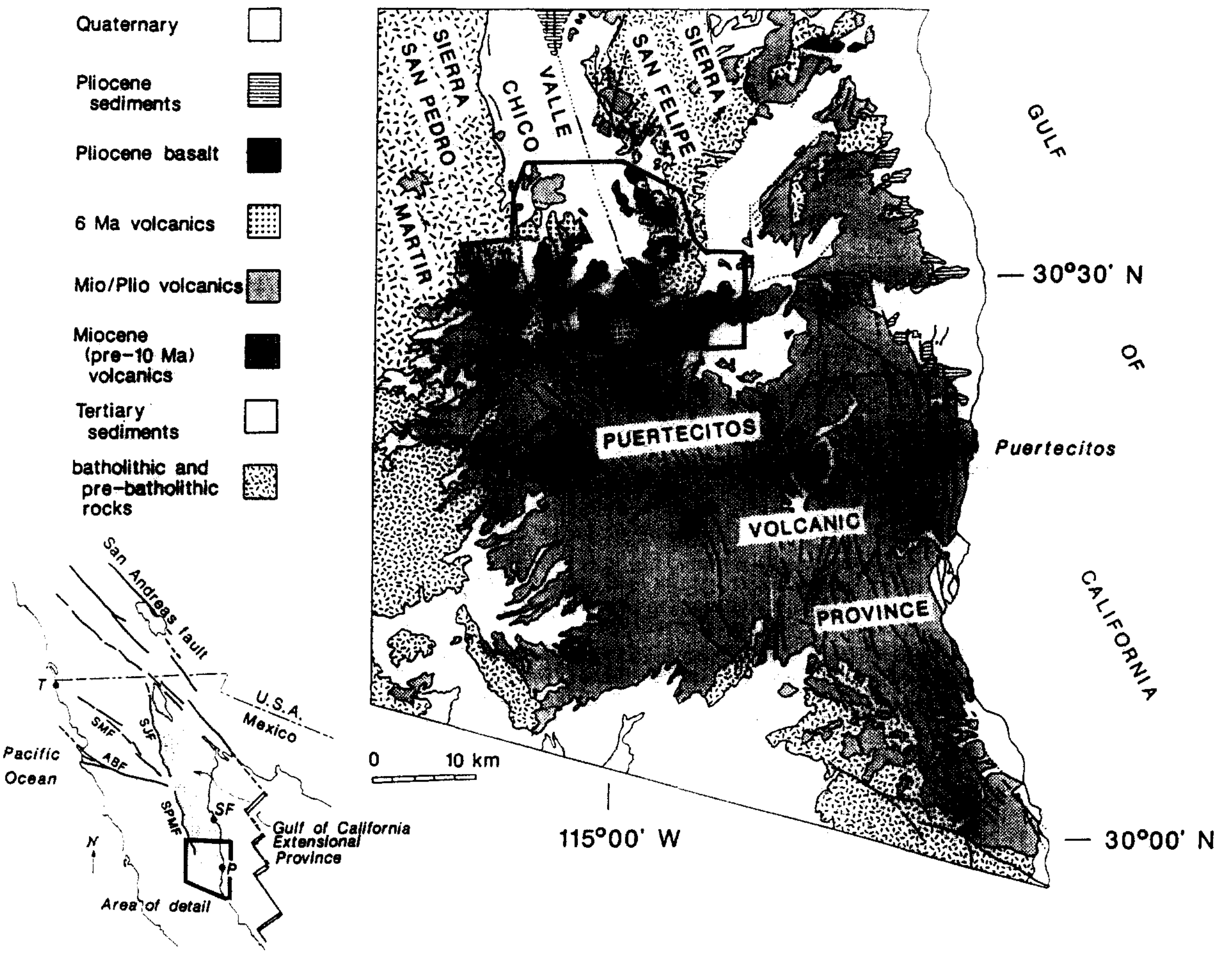

Fig. 1. Geologic map of Valle Chico and the Puertecitos Volcanic Province, generalized from the reconnaissance map of Gastil *et al.* (1971) and the 1:20,000 mapping of this study. Area of this study, shown in more detail in Fig. 3, is outlined. Inset shows the San Andreas fault system, spreading centers in the northern Gulf of California, the Gulf Extensional Province (shaded) and major faults of northeastern Baja California: SJF = Sierra Juárez fault; SMF = San Miguel fault; ABF = Agua Blanca fault; SPMF = San Pedro Mártir fault. Cities (inset): SF = San Felipe; P = Puertecitos, T = Tijuana. The western edge of the extensional province, along the Sierra Juárez and San Pedro Mártir faults, is the Main Gulf Escarpment. Differences in fault density within and outside of the area of this study reflect differences in the scale of mapping.

sula from low-lying basins and ranges near the Gulf coast. At its northern end, the Gulf Extensional Province merges with, or is truncated by, strike-slip structures of the San Andreas fault system in southern California.

Lithologies

The oldest rocks in northeastern Baja California are Precambrian and Paleozoic marine sedimentary rocks (Gastil *et al.* 1975). These were intruded by granites and tonalites of late Cretaceous age (Silver *et al.* 1969, Silver & Chappell 1988) now exposed in the Gulf Extensional Province and in the Peninsular Ranges Batholith west of the Main Gulf Escarpment (Fig. 1). These are overlain by scattered Paleogene sedimentary rocks. Miocene to Pliocene volcanic and volcaniclastic rocks (subduction-related andesites, rhyolitic ignimbrites and late rift-related basalts) dominate the Tertiary section, attaining a thickness of 4500 m (Gastil *et al.* 1979). Upper Miocene and Pliocene marine strata, related to the early development of the Gulf of California, are present in scattered locations. Much of the extensional province is covered by recent alluvium, and many of the fault-bounded basins are still subsiding.

Western boundary of the Gulf Extensional Province

The western boundary of the Gulf Extensional Province, the Main Gulf Escarpment (Fig. 2), is controlled by two major NNW-striking, east-side-down normal faults in northeastern Baja California: the Sierra Juárez fault, to the north, and the San Pedro Mártir fault, further south (Fig. 1, inset). The arcuate trace of the San Pedro Mártir fault, and the westward steepening of the westward dips of the Miocene volcanics in its hanging wall, suggest that the fault flattens with depth (Hamilton 1971, Dokka & Merriam 1982). Normal displacement along with minor strike-slip is inferred to occur along the fault zone (Gastil *et al.* 1975). Holocene scarps up to 25 m high occur along this fault; their morphology suggests rupture within the last century, although some of the fault segments have not moved for 1000 or 3500 yr (Brown 1978). Short microseismic surveys have not

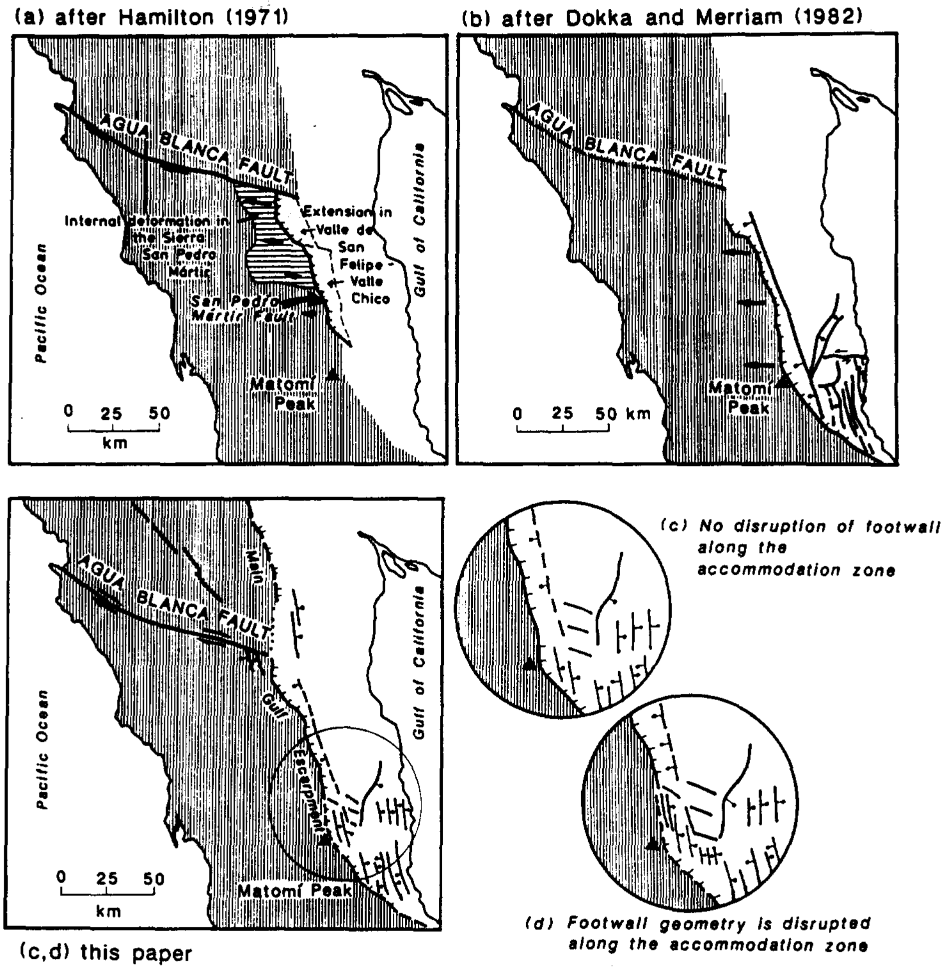

Fig. 2. Structural models of northeastern Baja California involving the San Pedro Mártir fault. In all models, the relevant faults of the Main Gulf Escarpment are hatched. The stable part of the peninsula (west of the Main Gulf Escarpment) is shaded. (a) "Pivot" model of Hamilton (1971) in which Valle Chico–Valle de San Felipe opened obliquely along the San Pedro Mártir fault, relative to a pole at the southern end of Valle Chico. (b) Model of Dokka & Merriam (1982) in which the San Pedro Mártir fault is the bounding fault for the extensional province to the east. (c) and (d) Models incorporating elements of both (a) and (b), in which motion along the Agua Blanca fault is linked to extension in the Gulf Extensional Province. In (c), the accommodation zone in the southern Valle Chico does not disrupt the geometry or amount of extension along the escarpment. In (d), the accommodation zone is related to a disruption in the geometry of the escarpment faults at depth.

detected seismic activity from the fault (Brown 1978) although an $M_B = 4.9$, $M_L = 5.5$ earthquake in 1974 apparently was located beneath the central part of the San Pedro Mártir fault, and several smaller events have occurred in northern Valle de San Felipe (Brown 1978).

Like the San Pedro Mártir fault, the Sierra Juárez fault strikes NNW, and controls an E-facing topographic escarpment in batholithic rocks, adjacent to a major depression. The Sierra Juárez fault zone is more seismically active than the San Pedro Mártir fault (Johnson *et al.* 1976, Brune *et al.* 1979), and more linear in map view.

Strike-slip faults oblique to the western boundary

Near the northern end of the San Pedro Mártir fault, two major strike-slip faults approach the escarpment from the NW: the San Miguel fault and the Agua Blanca fault. These faults might be expected to disrupt the escarpment as well as the extensional province to the east. However, neither fault can be traced into or across the faults of the escarpment (Allen *et al.* 1960, Hilinski & Rockwell 1986).

The San Miguel fault strikes about N60°W. Although its total offset is probably less than 500 m (Harvey 1986), it is very seismically active, with earthquakes of magnitude $M_L \leq 6.8$ in 1956. Composite focal mechanisms of these events indicate right-slip and south-side-down motion on a steep fault plane (Shor & Roberts 1958, Johnson *et al.* 1976).

The right-slip Agua Blanca fault strikes about N80°W. Like the San Pedro Mártir fault, it has Quaternary scarps but is nearly aseismic (Johnson *et al.* 1976). Some north-side-down displacement is indicated by the different levels of preservation of Miocene volcanic strata across the fault. Total right-slip is 5 km in Quaternary fan gravels and at least 11 km, perhaps as much as 22 km, in Cretaceous intrusive rocks (Allen *et al.* 1960). The mechanism of transfer of displacement at the eastern end of this fault is puzzling; some displacement may be transferred southward into N-striking pull-apart basins on the western side of the Sierra San Pedro Mártir (Hamilton 1971).

Basins and ranges

Valle de San Felipe–Valle Chico is one of the major composite basins of the Gulf Extensional Province. It trends NNW for 100 km, adjacent to the San Pedro Mártir fault (Figs. 2 and 3). At 31°15′ N latitude, a total normal separation of at least 5 km on the San Pedro Mártir fault is estimated from the 2.5 km height of the footwall rocks above the valley floor, and the approximate 2.5 km depth to basement in the hanging wall east of the fault suggested by gravity measurements (Slyker 1970, Gastil *et al.* 1975). Gravity anomalies within the Valle de San Felipe decrease southward, suggesting that the amount of normal separation on the San Pedro Mártir fault also decreases.

The Sierra San Felipe and the Sierra Santa Rosa are in the hanging wall of the San Pedro Mártir fault and form the eastern margin of Valle de San Felipe–Valle Chico. These ranges may be bounded on the east by listric or low-angle normal faults analogous to the San Pedro Mártir fault (R. G. Gastil personal communication, 1986). Thus, in a transect across the extensional province at this latitude, major E-dipping range-bounding faults are spaced 10–20 km apart.

At its southern end, Valle Chico narrows and is replaced to the south by Miocene volcanic rocks forming the Matomí Plateau. These rocks cover the Puertecitos Volcanic Province, between the escarpment and the Gulf coast (Fig. 1). In this region, the entire width of the Gulf Extensional Province is faulted into NNW-trending horsts and grabens by a series of high-angle normal faults with average spacing of 1–2 km (Dokka & Merriam 1982). Although this transition in upper-plate structural style appears broad and irregular on a regional scale, closer examination shows that it occurs over a distance of only a few kilometres in southern Valle Chico. Thus, the southern end of Valle Chico corresponds approximately to the expected position of an accommodation zone.

STRUCTURES OF THE ACCOMMODATION ZONE AS A GEOMETRIC TEST

Two kinematic models have been previously proposed relating the structures of the Valle de San Felipe–Valle Chico to structures to the northwest and south (Fig. 2). From interpretation of space photographs of the region north of the Puertecitos Volcanic Province, Hamilton (1971) suggested that extension in Valle de San Felipe–Valle Chico and normal displacement on the San Pedro Mártir fault were linked to right-slip faulting on the Agua Blanca fault, with extension decreasing southward as the San Pedro Mártir block rotated counterclockwise about a pole close to southern Valle Chico (Fig. 2a). He estimated that 4–10 km of extension had occurred across the Valle de San Felipe, related to the 5 km of post-Pliocene slip on the Agua Blanca fault (Allen *et al.* 1960), and possibly also to dilatation along strike to the north. Dokka & Merriam (1982) used aerial photographs and ground reconnaissance south of the Agua Blanca fault to show that extension in Valle Chico and in the Puertecitos Volcanic Province is kinematically related to normal faulting along the Main Gulf Escarpment. Consequently, they inferred that N–S variations in structural styles in southern Valle Chico were due to differential extension, partly accommodated by unidentified or buried transfer structures trending roughly east between the two structural domains (Fig. 2b).

Neither of these studies incorporated data from the entire region between the Agua Blanca fault and Puertecitos. However, when integrated, these studies suggest that extension in the Puertecitos Volcanic Province may be related to motion on the Agua Blanca and San Miguel faults via the San Pedro Mártir fault (Figs. 2c & d). The kinematics of this link can be constrained by the geometry of structures in the accommodation zone adjacent to the escarpment. For instance, Valle de San Felipe–Valle Chico might be an oblique strike-slip or 'pull-apart' basin (Burchfiel & Stewart 1966) controlled by right-slip motion on the Agua Blanca fault and oblique-normal displacement on the San Pedro Mártir fault. In this case, the southern end of Valle Chico should contain a strike-slip boundary parallel to the Agua Blanca and/or San Miguel faults, and normal displacement on the escarpment should decrease south of the accommodation zone. The accommodation zone would then constitute a fundamental boundary within the extensional province, disrupting the detachment surface of the San Pedro Mártir fault (Fig. 2d). Alternatively, structures within the accommodation zone might accommodate only local differences in amount of extension, and might not be parallel to the Agua Blanca–San Miguel faults or to the overall extension direction. In this case, the change in structural style across this accommodation zone would not reflect the presence of a major boundary within the extensional province, or a disruption of the escarpment (Fig. 2c). The direction, style, and amount of extension within the accommodation zone and along the adjacent escarpment thus provide a geometric test of the significance of this structural transition within the extensional province.

LITHOLOGIES AND FAULT DOMAINS OF THE ACCOMMODATION ZONE

Southern Valle Chico contains granitic to gabbroic batholithic rocks, prebatholithic metasediments, and Miocene volcanics and sediments. The Miocene and Pliocene rocks were classed into five groups (Fig. 3), and subdivided into 25 separate units, on the basis of mapping and K–Ar dating (Stock 1988, in press). The lowest group, Group 1, comprises unstratified volcanic rocks, ranging in age from 20 to 15 Ma. Group 2 comprises up

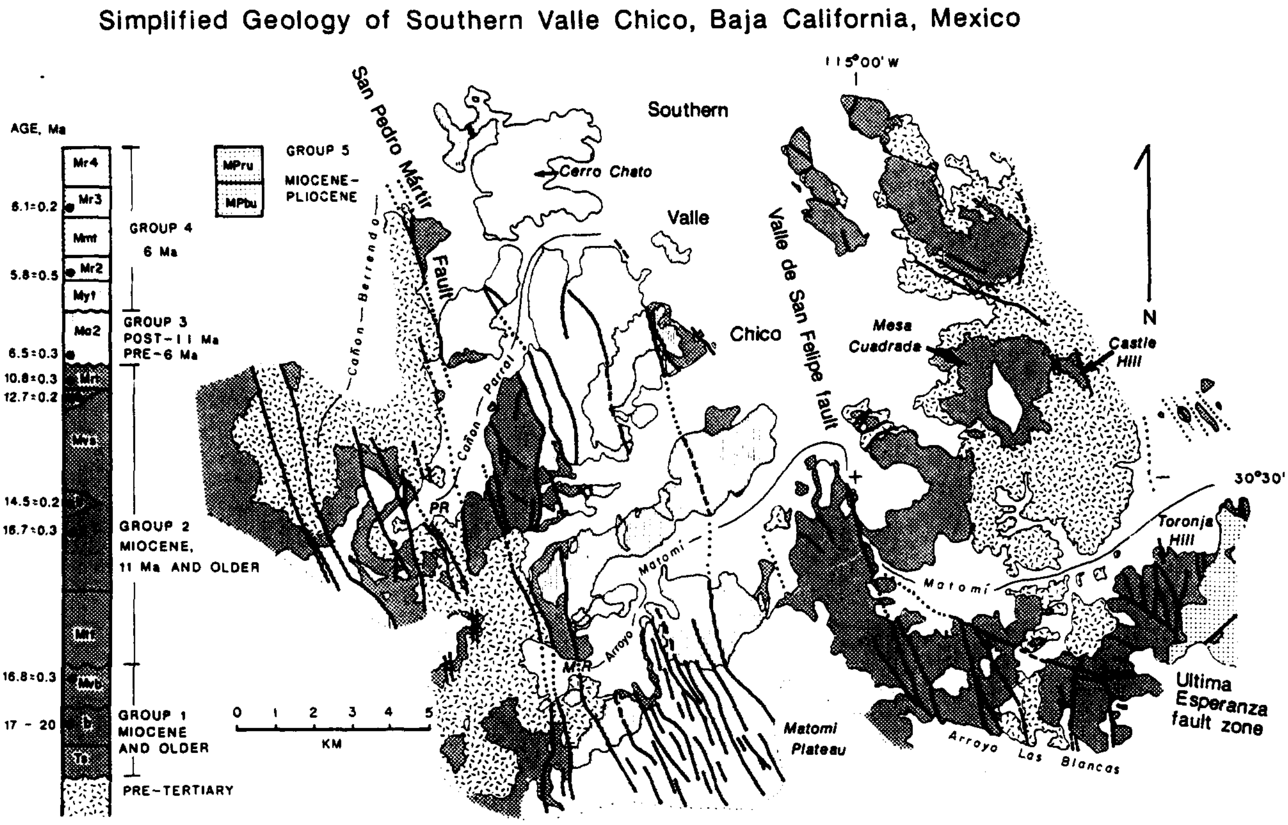

Fig. 3. Principal geographic features and generalized geology of the study area. MR = Rancho Matomí; PR = Parral Ranch. Stratigraphy and K–Ar ages after Stock (1988, in press), with 'b' = basalt. Quaternary rocks not shown.

to 350 m of tuffs and sediments ranging in age from 16.75 to 10.85 Ma. Group 3 comprises unstratified volcanic flows and breccias, younger than 11 and older than 6 Ma, on the basis of stratigraphic relations and one 6.47 Ma K–Ar whole rock date. Group 4, up to 370 m thick, is mainly tuff, all about 6 Ma in age. Groups 2 and 4 probably were deposited over the entire map area; Groups 1 and 3 are of more local extent. Basal strata of Groups 2 and 4 pinch out against surfaces with topographic relief, and contain no major angular unconformities. Therefore, we infer that these strata were deposited horizontally, and that their present attitudes reflect post-depositional tectonism.

A fifth group of welded tuffs and flows crops out only in the extreme southeast corner of the map area above Group 2 rocks. These Group 5 rocks may be coeval with Group 4 units, but have not been extensively studied.

Structural interpretation was based on offsets of beds within Groups 2 and 4, particularly on the thin, widespread, welded tuffs useful as marker horizons (Mr1, 11 Ma, from Group 2; Mr3 and Mr4, 6 Ma, from Group 4). An unconformity between strata of Group 2 and Group 4, previously noted by Gastil *et al.* (1975) and Dokka & Merriam (1982), demonstrates that these rocks have experienced different amounts of deformation. This unconformity is most obvious on Mesa Cuadrada where Group 4 deposits dipping 3°W pinch out against Group 2 deposits dipping 7°W. It is also visible north of Parral Ranch where fault blocks of Group 2, tilted up to 30°E, are overlain by less faulted Group 4 deposits dipping 5–10°NNE.

On the basis of faults and stratal tilts, the study area can be divided into five fault domains (Fig. 4). These are: (I) a domain of E-dipping, NNW-striking, escarpment faults; (II) a domain of principally W-dipping, NNW-striking faults, east of, and antithetic to, the escarpment; (III) the closely spaced synthetic and antithetic faults of the Matomí Plateau; (IV) a region affected by NNW- and WNW-striking faults in the SE quarter of the map area; and (V) relatively unfaulted blocks to the NE.

Escarpment fault systems (fault domain I)

The San Pedro Mártir fault does not continue into the map area as a single strand. Its southernmost Holocene scarps occur 4 km north of the northwest corner of the map area (Fig. 4), where the fault juxtaposes Miocene volcanics in the hanging wall, to the east, against batholithic rocks to the west, along a very steep range front. The fault disappears southward beneath alluvium and is replaced along strike by several parallel fault traces, labeled here the 'range front' fault system. We define the 'range front' as the eastern edge of the continuous granitic outcrops of the Sierra San Pedro Mártir (Figs. 1 and 4), although isolated small outcrops of batholithic or pre-batholithic rocks occur east of this line.

In the west-central part of the map area, the range-front fault system is the eastern edge of a 5–6 km wide zone of escarpment-related faults, with major strands spaced about 1 km apart. These faults strike N20°W and involve slightly tilted strata (<2° N or S) of Group 2,

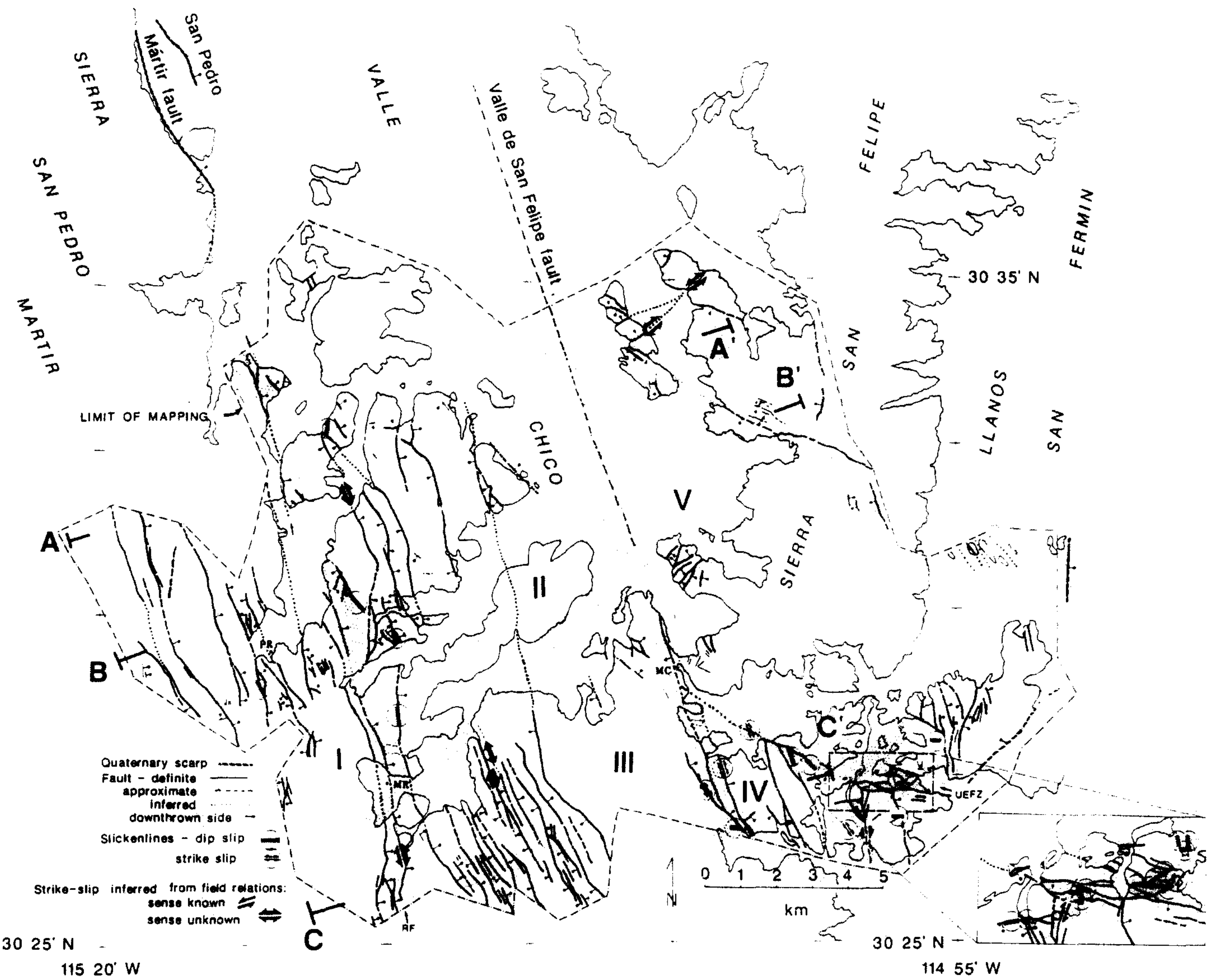

Fig. 4. Fault map of southern Valle Chico. Study area is outlined with a dash–dot line. Quaternary scarps outside the study area (San Pedro Mártir fault and the Llanos de San Fermín) were transferred from aerial photographs. Shading shows the boundaries of the fault domains I–V discussed in the text. A–A', B–B', C–C' are lines of cross-sections shown in Fig. 5. RF = range-front fault, the eastern limit of continuous exposures of batholithic rocks. Locality abbreviations: MR = Rancho Matomí; PR = Parral Ranch. Faults are shown with bar and ball on downthrown side, and heavy arrows to indicate strike-slip movement if inferred from field relations. Location and sense of all observed slickenlines are shown by symbols in circles: hachures for dip-slip, arrows for strike-slip. Valle de San Felipe fault is approximately located according to Gastil *et al.* (1971). Inset in southeast corner shows details of faults and slickenlines in the E–W-striking Ultima Esperanza fault zone (UEFZ).

andesites of Group 3 and batholithic rocks. Strata of Group 2 are generally displaced down to the east. These faults dip steeply and change dip direction along strike, locally exhibiting reverse fault geometries. This is not due to later folding or tilting of variably-dipping normal faults because the dips of marker horizons do not show tilts of the appropriate sense.

Total down-to-the-east separation across this zone is <800 m in the 11 Ma tuff (Fig. 5, sections A–A', B–B'). This is considerably less than the 5 km of normal separation inferred for the northern segment of the San Pedro Mártir fault, 70 km along strike to the north. However, the normal separation at the southern end of the San Pedro Mártir fault is not well constrained and could be about 1 km, if the southernmost Quaternary scarps are the only principal strands within the fault zone. The amount of strike-slip displacement on these faults is unknown. Slickenlines were observed on only one fault surface; their 75°S rake indicated normal displacement with a component of right-slip.

These faults are generally difficult to identify in the granite, because of weathering, joints and the lithologic homogeneity of the granite. These faults have not been traced north beyond the map area where post-batholithic strata are absent, but they may continue north within the Sierra San Pedro Mártir, west of the recent scarps of the San Pedro Mártir fault. A few faults of similar style and orientation cut the compositional zonation of plutons at high elevations in the range further north (Gastil *et al.* 1971).

The faults west of the range front probably continue south out of the map area (Gastil *et al.* 1971). The range-front faults can be traced southward from Rancho Matomí onto the Matomí Plateau.

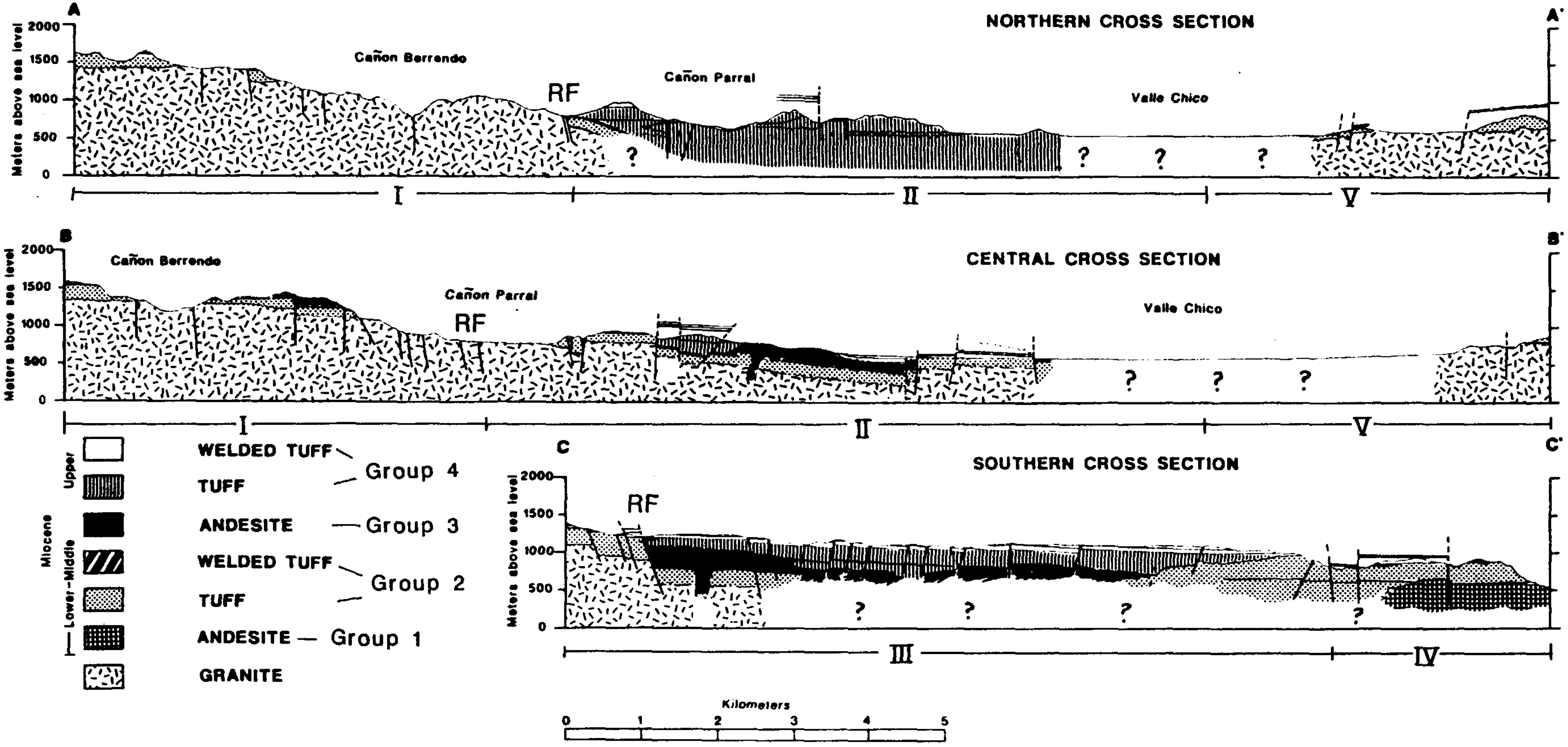

Fig. 5. Cross-sections from WSW to ENE, perpendicular to average NNW strike of faults. Locations of lines as in Fig. 4: A–A′ = northern, B–B′ = central, C–C′ = southern. RF = range-front fault zone (southward continuation of the San Pedro Mártir fault). Roman numerals I–V beneath the cross-sections correspond to the fault domains labeled in Fig. 4. Heavy lines are faults. Light lines are contacts: straight where conformable, wavy where intrusive or nonconformable on constructional or erosional topography. Points A and B are on the stable part of the peninsula. Many of the fault dips are constrained by measurements of the fault planes or by the topographic pattern of the fault trace, but others are inferred. In general, faults dip more steeply than 60°. Cross-sections have not been balanced.

Antithetic faults east of the escarpment in southern Valle Chico (fault domain II)

High-angle faults of average strike N20°W, between the range front and the southern projection of the Valle de San Felipe fault, dip east or west at angles between 60° and vertical, and cut strata of Groups 2–4. The faults with the largest offsets have down-to-the-west displacement, antithetic to the range front and escarpment faults. Spacing of major strands ranges from 0.5 to 1 km.

These faults are difficult to follow within granite, and can also be difficult to follow within andesite because of talus cover and the lack of marker horizons. Thus, the scarcity of mapped faults in andesite and granite may be more influenced by exposure than by structural style.

Of 41 fault planes measured in this area, six had striations, with rakes between 75° and 90°, indicating primarily dip-slip displacement and an ENE horizontal extension direction. The presence of occasional minor faults striking N40°W–N50°W, which may act to transfer displacements between fault systems, as well as small basins bounded by N-striking faults, suggest that the extension direction may actually be closer to E–W than WSW-ENE.

Faults of the Matomí Plateau (fault domain III)

The range front fault system continues southward onto the Matomí Plateau as two faults with a combined normal separation of at least 260 m in strata of Group 2, and 150 m in ignimbrites of Group 4 (Fig. 5, section C–C'). A 6 km wide zone east of these faults contains numerous high-angle faults of average strike N25°W, spaced at 0.2–2 km, and dipping both east and west at angles of >45°. Faults with the greatest displacements dip west, antithetic to the range-front faults, and result in eastward tilts of up to 15° in the Group 4 ignimbrites. The faults are readily traceable where they truncate drainages or juxtapose the distinctive cooling zones of Mr3 and Mr4. They do not cut the banks of old alluvium along Arroyo Matomí north of the Matomí Plateau. Sag pond limestones, collected from depressions adjacent to these faults, contained no fossils and thus could not be dated.

Faults with the greatest normal separation (>50 m) strike from N–S to N30°W and are less linear than the smaller displacement faults. Minor faults die out quickly along strike, apparently due to transfer of displacement between fault strands. The geometry of small-scale pull-apart basins on the Matomí Plateau, formed by the interaction of faults striking N18°W–N5°W and faults striking N30°W–N40°W, is consistent with primarily dip-slip displacement on faults of N to NNW strike, and oblique right-slip displacement on NW-striking faults.

Group 4 pinches out westward across the range-front faults, indicating the existence of several hundred meters of topographic relief at about 6 Ma, when Group 4 was deposited. This relief is most likely due to pre-6 Ma displacement along these faults. Some strike-slip motion may also have occurred across the easternmost range-front fault, because Mmt changes thickness abruptly across it and because there is 200 m of andesite on the eastern side of the fault, with none at the same stratigraphic level on the western side. The sense and amount of such motion cannot be tightly constrained.

Fault zones south of Arroyo Matomí and east of the Matomí Plateau (fault domain IV)

Structures of the accommodation zone here separate NW-striking faults, to the south, from the unextended Mesa Cuadrada block to the north. The NNW-striking faults are spaced 0.5–2 km apart over a distance of 6 km east of the edge of the Matomí Plateau; they cut batholithic and metasedimentary rocks, Group 1 breccias, Group 2 pyroclastic rocks and thin shallowly dipping (<15°) strata of Group 4. The major faults dip east or west >70° although local small-displacement faults dip more shallowly (40–50°). Subhorizontal slickenlines on the western NNW-striking faults suggest strike-slip displacement, consistent with the minor (<50 m) vertical separation of Mr1 and Mr3 across these faults. These NNW-striking faults are shown continuing to the south on regional maps (Gastil *et al.* 1971, Dokka & Merriam 1982).

Motion on these faults is accommodated to the north by the WNW-striking Ultima Esperanza fault zone (Fig. 4). This zone contains many anastomosing fault strands with dips ranging from 35° to 90°; units within and adjacent to the fault zone dip as much as 45°. The dip separation is south-side-down along the western segment and north-side-down along the eastern segment. Slip must be only minor, as the same units occur on both sides of the fault zone, and depositional contacts of Tertiary sandstone and Miocene volcanic rocks on batholithic and prebatholithic units crop out on both sides at similar elevations. We infer that this zone has experienced strike-slip displacement, as indicated by occasional sharp lithologic contrasts across it (such as the complete truncation of basalt flows by the zone), as well as by tectonic juxtaposition of vertical slices of prebatholithic marble within the Tertiary strata. Striations indicate dip-slip displacement on many of the faults within the zone.

On the northwest, the Ultima Esperanza fault zone is inferred to end against a NNW-striking, high-angle fault in Matomí Canyon (the possible continuation of the Valle de San Felipe fault, Fig. 3). Some displacement on the Ultima Esperanza fault zone may have occurred after 6 Ma because the NNW-striking faults accommodated by the Ultima Esperanza fault zone displace Group 4 strata.

The Ultima Esperanza fault zone is 1 km wide where its eastern end is buried by old alluvium in Arroyo Las Blancas. The intersection between the range-front fault on the east side of the Sierra San Felipe and the Ultima Esperanza fault zone is not exposed. Both this range-front fault and the Ultima Esperanza fault zone may be truncated by the southwestward continuation of the NE-striking fault in the canyon on the southeast side of Toronja Hill. This latter fault may connect with a N-striking scarp in Quaternary gravels just east of the southeastern corner of the map area (Fig. 4; cf. Dokka & Merriam 1982, fig. 5).

Larger structural blocks of the Sierra San Felipe (fault domain V)

The southern part of the Sierra San Felipe comprises two relatively unfaulted structural blocks, several km wide (Mesa Cuadrada and the block to the north), separated by a WNW-striking fault zone. Dips of uppermost strata of Group 2, determined by fitting a marker horizon to a plane, are 7°W on the Mesa Cuadrada block, and 5°W on the block to the north. Marker horizons on the two blocks are nearly coplanar, indicating little motion on the intervening fault zone. Rocks of Group 4 present on Mesa Cuadrada dip only 3°W. Therefore, 4° of tilting occurred before 6 Ma and 3° of tilting after 6 Ma.

Subhorizontal remnants of Group 2 on Castle Hill, east of Mesa Cuadrada (Fig. 3) suggest very little tilt of Group 2 strata there. The transition from 7° W-dipping to horizontal orientations may be caused by a rollover anticline, with a hinge along the small N-striking normal faults between Mesa Cuadrada and Castle Hill. By analogy, the structural block to the north may also contain a rollover anticline, with its hinge along the small N-striking normal faults at the crest of the range. This cannot be confirmed because Group 2 strata are not preserved east of the crest of the range.

The fault zone between these two blocks trends WNW on the south side of the northern mesa. It comprises several vertical to SW-dipping faults across a 1 km wide zone, showing a total of at least 200 m of down-to-the south displacement of Group 2 strata against granite in the center of the fault zone. Where well exposed in gullies, individual fault strands consist of many closely-spaced splays dipping 45° or more to either north or south, bounding small fault blocks containing strata dipping 10–30°. This fault zone probably connects under the alluvium with a NW-striking fault on the next isolated hill to the WNW. This fault zone may not be active, as its topographic expression near the mesas is subdued, it appears to be deeply eroded on the east side of the Sierra San Felipe, and it does not obviously affect the shape of the range front there.

Range-front fault east of the Sierra San Felipe

No fault crops out along the eastern edge of the Sierra San Felipe, but geologic relations require a range-front fault or fault zone to be present beneath the alluvium. The difference in elevation of a Group 1 marker horizon across this zone suggests a minimum of 700 m of normal separation. This is close to the amount of normal separation on the escarpment fault system, suggesting that the range-front fault east of the Sierra San Felipe may be one of the principal structures of the extensional province. This fault zone must pass south beneath Arroyo Matomí through the southeast corner of the field area (Gastil *et al.* 1971), and may splay into smaller-displacement (<100 m) N-striking, E-dipping normal faults on Toronja Hill. In the southeast corner of the map area, the presence of Group 2 units at low elevation beneath Group 5 units suggests that the range-front fault may be partially overlain and buried by unfaulted Group 5 tuffs.

Group 2 units in isolated outcrops east of the Sierra San Felipe dip 20–40° toward the NE and are separated by NW-striking high-angle faults. These relations suggest significant small-scale extension in this area, and a very different structural pattern from the large unfaulted blocks in the southern Sierra San Felipe (structural domain V). We tentatively include this region within structural domain IV. However, if the offset on the Sierra San Felipe range-front fault is found to be comparable to that on the escarpment fault system, then this area may be a separate structural domain within another extensional allochthon, structurally higher than the rest of the map area.

EXTENSIONAL GEOMETRY

Direction of extension

Dip-slip displacement dominates the faults in the western half of the map area, based on observed slickenside striations, the anastomosing and disconnected nature of the fault segments, and the general absence of shortening structures at the ends of faults or between different strands. The N25°W strike of these faults suggests an extension direction of N65°E, similar to that indicated by the NNW alignment of post-11 Ma volcanic centers in the map area. However, observations of possible lateral offset on some N25°W faults, dip-slip displacement on N–S faults, and dip- to oblique-dip-slip displacement on N40°W faults, show that the extension direction may have varied between N50°E and E–W. These contradictions might be explained either by slip in different directions at different times on faults of similar orientation, or by partitioning of displacement between normal faults and strike-slip faults of the same strike, as has been observed along the range front of the Sierra Nevada in California (Zoback & Beanland 1986). We could not resolve any changes in slip direction with time, such as the Plio-Quaternary clockwise rotation of extension directions inferred by Angelier *et al.* (1981) for central Baja California, because of the lack of observed slickenside striations in post-11 Ma units and the lack of post-6 Ma units in the map area. Because the single generation of normal faults in this region displaces Group 2 and Group 4 units by different amounts, we infer that the extension direction did not change sufficiently to activate a new set of normal faults of a different orientation. Therefore it appears that an ENE extension direction may be reasonable for the entire duration of extension. On the larger structural blocks east of the Valle de San Felipe fault, Group 2 strata are tilted NNW, in agreement with this extension direction.

However, tilt paterns in the region are not always a reliable indication of extension direction. Elsewhere in the map area, Group 2 strata are tilted east, west and north; these directions most likely reflect local variations in the subsurface dip of the fault zone (cf. Walker *et al.* 1986), or regional tilt of the Sierra San Pedro Mártir, rather than the direction of net displacement.

The direction of extension east of the Valle de San Felipe fault is problematic because internal extension there is relatively minor, and because slickensides were only found in the southeastern part of the map area, where both steep and shallow striations are observed on faults of NNW and E–W strike, sometimes along strike in the same fault zone. This may be caused by either temporally-varying extension directions, local spatial variation in extension directions, or formation of slickenlines during minor post-kinematic readjustment of blocks. The fault patterns to the west suggest that the Sierra San Felipe is moving roughly ENE relative to the Sierra San Pedro Mártir, but internal deformation of the Sierra San Felipe may not be ENE-directed.

Fault geometries at depth

Along the Main Gulf Escarpment north of the map area, the San Pedro Mártir fault probably flattens with depth, as suggested by Hamilton (1971) and Dokka & Merriam (1982). We infer that the escarpment fault zone within the map area is also listric at depth, despite the steep dips of the E-dipping faults in fault domain I, and the lack of rotation of strata along them. Depths and quality of exposures of the escarpment faults in southern Valle Chico are not sufficient to preclude systematic flattening of <1°/100 m, on the order of that detailed for high-angle normal faults elsewhere (e.g. Yerington, Nevada—Proffett 1977; the Hurricane fault, Utah—Hamblin 1965). The wide zone of predominantly antithetic faults in the hanging wall east of the range front could be produced as volume compensation above a listric fault (e.g. Dokka & Merriam 1982); in other areas this type of fault geometry has been observed to pass along strike into the more typically observed 'reverse drag' folds in the hanging wall of listric normal faults (Hamblin 1965). The westward tilt of the Sierra San Felipe, seen on Mesa Cuadrada and the mesa north of it, may be interpreted as evidence for a curved or planar fault beneath the entire range, and suggests that the escarpment fault zone extends east at depth at least as far as Mesa Cuadrada, although it may not be horizontal but rather still shallowly E-dipping there.

Published results of laboratory experiments, and field observations elsewhere, support the occurrence of similar fault geometries above listric faults. Laboratory experiments with layered sands indicate that for 7.5% extension, high-angle planar faults, accompanied by only minor (<10°) tilt of bedding and no visible reverse drag, may occur in the hanging wall of listric or planar basal faults (McClay & Ellis 1987). In many well-exposed and highly-extended regions, the breakaway zones in the footwall have been eroded to depth, leaving no original structures preserved and only poor constraints on the geometry of the initial breakaway zone (e.g. Dokka 1987). However, the low-angle Chemehuevi–Whipple detachment fault, at its breakaway zone in the Old Woman and Piute Mountains of southern California, probably had substantial topographic relief, no more than 2–3 km of normal separation, and high fault-bedding angles (e.g. Howard & John 1987), similar to the character of the Main Gulf Escarpment at this latitude. Hence, the structural pattern of southern Valle Chico may be analogous to that of other breakaway zones during the early stages of their development.

Amount and timing of extension

The amount of extension is best constrained south of Arroyo Matomí, where the 6 Ma tuff can be followed continuously for 10 km from the range-front fault to the Valle de San Felipe fault. Extension along a cross-section in this area (Fig. 5, section C–C′) was computed by restoration of displacement of marker horizons along high-angle faults within the upper 1–2 km of the crust, and without any assumption of a listric or planar basal detachment. This indicates about 3.5% ENE–WSW extension west of the Valle de San Felipe fault, if the fault dips shown in Fig. 5 (section C–C′) (from 60° to 90°) are correct. However, the dips of some of these faults could not be measured or inferred from the map pattern, but were assumed to be parallel to those nearby. Assuming the minimum permissible dip on these structures (60°), extension of the 6 Ma welded tuff would be 7% across this zone. Because the same fault geometries, with similar amounts of displacement, can be followed northward in the map area, we infer that extension from the range front fault to the center of the valley is similar northward *within the map area*—perhaps about 5% since 6 Ma.

The 11 Ma tuff is buried beneath much of the map area, so the total extension in it cannot be computed from surface mapping. However, because the relative tilts of the 11 Ma welded tuff and the 6 Ma welded tuff on Mesa Cuadrada suggest approximately equal amounts of tilting before and after 6 Ma, we infer that at least an equal amount of extension occurred before 6 Ma. The higher dips of the 11 Ma welded tuff beneath the 6 Ma welded tuff adjacent to the range front fault suggest that this is a minimum estimate for pre-6 Ma extension within the map area.

No evidence was found for fault displacements predating the 11 Ma welded tuff, or regional angular unconformities within pre-11 Ma (Group 2) strata. The 0–180 m variation in thickness of Group 2 in the northern half of the map area results from lithologically controlled, irregular basal topography in the granitic and pre-batholithic rocks. This range of observed thickness is similar both east and west of Valle Chico, indicating that the erosion surfaces on both sides of the present valley were at approximately the same elevation prior to about 17 Ma. Most importantly, because the thickness

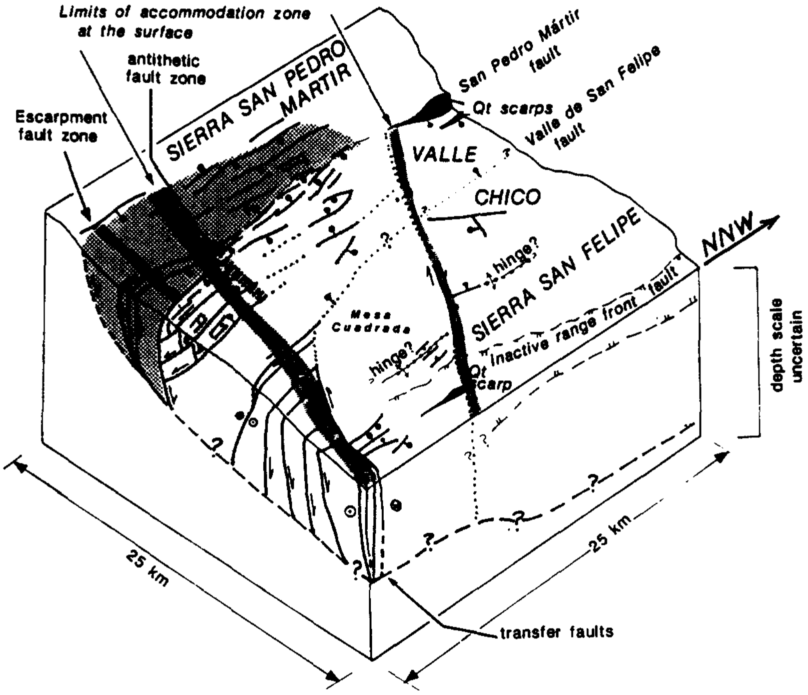

Fig. 6. Three-dimensional interpretation of structures in southern Valle Chico and their possible relationships to faults at depth. Surface geology is based on mapping (Fig. 4); subsurface relations are inferred. Black = Quaternary fault scarps. Dark shading = zone of down-to-the-east (synthetic) faults between the Main Gulf Escarpment and the range-front fault zone. Light shading = zone of down-to-the-west (antithetic) faults. These are inferred to sole into a listric detachment fault at unknown depth (see discussion in text). The change in surface expression of the normal faults is inferred to be due to a structural disruption of the detachment fault at depth; perhaps a lateral ramp such as shown here, with the north side inferred to be at greater depth in accordance with the greater width of the valley, and possibly greater amount of extension, to the north. Many other geometries are also possible. Axes labeled 'hinge' are inferred to be hinges of rollover anticlines in the hanging wall of the listric fault zone. These are inferred to have developed independently, with differences in the position and timing of rollover development accommodated by displacement on the WNW-striking fault north of Mesa Cuadrada.

of Group 2 does not vary across the faults along and west of the range-front, the escarpment faults were not topographically expressed until after 11 Ma. The only area where pre-11 Ma faulting cannot be precluded is in the center of southern Valle Chico, east of the range-front fault and beneath the alluvium, where the base of Group 2 is buried and its thickness cannot be constrained.

No Quaternary scarps were noted in the map area, but many of the NNW-striking faults may still be active, as indicated by: (1) the topographic step, vegetation line and springs associated with the range front fault closest to Rancho Matomí; (2) ephemeral lakes present in depressions along NNW-striking faults of the Matomí Plateau; (3) disruption of drainages by NNW-striking faults on the Matomí Plateau; and (4) the topographic steps visible along some of the normal faults in the andesites.

KINEMATIC INTERPRETATION OF THE ACCOMMODATION ZONE

Structures in the footwall of the escarpment

The western half of the map area, from the escarpment east to the fault in Matomí Canyon, is interpreted as a single synthetic–antithetic fault system controlled by an E-dipping escarpment fault (Fig. 6). Although normal displacement on the escarpment fault may not change along strike in this zone, the zone of escarpment faults widens southward, and the number of escarpment faults increases. The escarpment thus changes from a single well-defined fault (at the position of the southernmost Quaternary scarp) to a broad fault zone in which the transition from the hanging wall to the footwall is not well defined.

This structural transition cannot be confined to the upper plate because of its expression in footwall (escarpment) faults. We infer that this change is gradual, rather than a discrete structural break in the footwall, because no transfer structures are known to exist in the footwall at, or south of, the southernmost Quaternary scarp, and because changes in the hanging wall geometry are also gradual, as discussed below.

Structures in the hanging wall of the escarpment, close to the escarpment

The zone of antithetic faults east of the escarpment develops progressively southward without an abrupt northern boundary (Fig. 4). Antithetic faults in the hanging wall of the escarpment increase in importance to the south, as do the minor synthetic faults between them. This structural transition occurs without the formation of identifiable cross faults, and no discrete hanging wall transfer structures intersect the escarpment within this domain. The anastomosing and disconnected nature of many of the faults is more analogous to a network of dilatational cracks which decrease in both spacing and offset as they increase in number southward. However, these cracks do not increase in density at all scales: throughout the map area, basal contacts of the welded tuff marker horizons are coherent at small scales. Pervasive microfaulting as recognized in some other extended areas (e.g. Scott in press) is generally absent in the map area.

No lithologic control of this change in geometry is apparent, because similar units (including the well-exposed marker horizons) are exposed to the north and to the south. Minor differences in mapped fault density between the stratified (Groups 2 and 4) and unstratified (Group 3) units may be attributed to the lack of marker horizons within Group 3, but this does not explain the changes in structural patterns within the stratified units. Although undetected lithologic differences at depth cannot be ruled out, we prefer a structural explanation for this geometry, as follows.

This structural transition may be one variety of the "extensional relay systems" described by Larsen (1988) as zones of unconnected normal faults which accommodate differential displacement on a basal detachment fault, and which are connected by ductile strain and microfaulting rather than by discrete transfer faults. The faults present in the hanging wall adjacent to the escarpment would then reflect the gradual change in geometry of the detachment at depth, inferred from the geometry of footwall faults discussed above. In extensional relay systems, cross-faults are expected to develop in the hanging wall as extension continues. The lack of cross-structures in southern Valle Chico may indicate that here, more than 10% extension is required for the development of cross-faults.

Our mapping of Cerro Chato suggests that it is not cut by any major WNW-striking faults, although minor NNW-striking faults were observed. Thus, if the WNW-striking fault north of Mesa Cuadrada (Fig. 4) or the NE-striking faults further north in the Sierra San Felipe (Fig. 1) extend beneath alluvium to the escarpment, they must intersect it at or north of the southern end of the Quaternary scarp. The morphology of the valley floor, and aerial photographs of the region, show no evidence for Quaternary rupture along these trends, but would not preclude earlier motion. If these faults intersect the San Pedro Mártir fault in the subsurface, they might act as conservative or non-conservative barriers to rupture propagation (Bruhn *et al.* 1987), offering a structural explanation for the position of the termination of the Quaternary scarp. This kinematic model would require the Valle de San Felipe fault to be discontinuous in southern Valle Chico, but as the Quaternary trace of this fault is entirely inferred, this is certainly possible.

Structures in the hanging wall of the escarpment, further east

The southern end of the Sierra San Felipe is less extended and structurally more coherent than regions closer to the escarpment. Our preferred interpretation of this area, consistent with the field evidence, is that the WNW-striking faults are oblique transfer faults, accommodating differential extension caused by the NNW- to N-striking normal faults and extension fractures. Additional differential extension may be caused by synchronous development of independent rollover anticlines on Mesa Cuadrada and the block north of it, resulting in different geometries and hinge positions (Fig. 6). The direction of displacement along the WNW-striking faults is unclear, but the amount of displacement is certainly small (less than 1 km strike-slip and less than several hundred meters dip-slip). As discussed above, the total lengthening in southern Valle Chico is probably no more than 1 or 2 km, so large displacements would not be expected on these faults. Because of the continuity of the Sierra San Felipe east of southern Valle Chico (Fig. 3), and the consistent westward tilts of hanging wall units, the WNW-striking fault north of Mesa Cuadrada is probably not a major break in upper plate structure. The Ultima Esperanza fault zone seems to be a more important break, as the structural character of the upper plate changes completely across it.

Structures east of the southern Sierra San Felipe are separated from it by a buried and presumed inactive range-front fault, inferred to be an E-dipping normal fault (Figs. 3 and 4). The geometry of the accommodation zone as it continues eastward across this fault system has not been studied. The accommodation zone may be offset to the north or south or have a different structural expression, from the structures described here.

DISCUSSION AND CONCLUSIONS

Our study reveals several interesting features of a transition along strike from a domain of large-displacement normal faults bounding wide structural blocks, to a domain of closely-spaced, small-displacement normal faults, present in the hanging wall of the Main Gulf Escarpment. The accommodation zone of this structural transition does not merely relay differential extension in the hanging wall of the escarpment, because it affects the pattern and geometry of the footwall (escarpment) faults. The structural transition does not correlate with any known structures west of the escarpment in the unextended part of the Sierra San Pedro Mártir; hence, it must be a feature of the geometry of the basal escarpment fault itself. This structural boundary in the footwall appears to be a broad zone, occupying at least several km along strike. We speculate that there may be different amounts of extension on either side (i.e. more normal separation on the escarpment fault zone to the north than to the south). There may also be a difference in the depth of the basal detachment fault across this zone, such as is illustrated schematically in Fig. 6. However, the presence of a warp in the escarpment fault at depth, and its sense and amount of apparent offset, cannot be constrained by our data. Whatever the geometry of the escarpment fault at depth, the broad accommodation zone at the surface is oriented roughly NW (Fig. 6), oblique to the inferred direction of extension on the escarpment and range-front fault zones. If this NW trend indicates the direction of transport of the upper plate, it suggests that adjacent fault domains have extended in different directions here.

This structural transition is expressed in the hanging wall near the escarpment as a diffuse zone of unconnected and anastomosing synthetic and antithetic normal faults, lacking cross faults or other discrete transfer structures (Fig. 6). The transition from a structurally coherent hanging wall to a diffusely extending hanging wall is gradual, occupying a distance of 10 km along strike near the escarpment. There are two possible causes for the lack of discrete transfer structures here: either the amount of extension (<10%) has not been sufficient for individual "extensional relay faults" (Larsen 1988) to join into a continuous transfer structure at the surface, or else the discreteness of the structural boundary in the hanging wall is limited by the broad and gradual nature of the structural boundary in the footwall. We cannot evaluate the relative importance of these two effects without additional constraints on the geometry of the escarpment fault zone at depth. It seems likely that in other areas, the development of discrete transfer structures at the surface may depend on the total amount of extension, the breadth of the structural boundary in the footwall, and the thickness of the hanging wall. We speculate that discrete transfer structures may develop much more easily at the surface if they merely relay extension within a single extensional allochthon and do not correspond to major boundaries in the footwall of the allochthon. In this respect, the structures we describe are analogous to deformation reported along tilt-domain boundaries (another type of accommodation zone) in the Basin-and-Range province, the Gulf of Suez and the East African rift system (e.g. Bosworth 1986, Coffield & Schamel 1989, Ebinger 1989, Faulds *et al.* in press), where discrete transfer structures and throughgoing faults are equally scarce.

Widely spaced WNW-striking fault zones, further east in the hanging wall of the escarpment, are inferred to be minor transfer structures accommodating differential extension of blocks on either side. Faults such as these may decrease the normal displacement on the San Pedro Mártir fault towards its southern end, although similar faults have not been identified in the ranges further to the north and east. These zones are parallel to the inferred boundaries of individual structural basins east of the San Pedro Mártir fault, and may provide some support of an ESE direction of extension of the basin margins, parallel to the Agua Blanca fault zone. However, the zone of NNW-striking high-angle normal faults adjacent to the escarpment appears to be extending in an ENE direction, suggesting that different domains of the hanging wall are extending in different directions.

Within the map area, the escarpment fault zone is about 5 km wide and consists of numerous parallel high-angle faults, with equally distributed normal displacement totaling <1 km since 11 Ma. The 10 km wide zone of antithetic faults has experienced about 5% ENE extension since 6 Ma and probably at least 10% extension since 11 Ma. Relationships along strike to the north, as well as analogies with other areas, suggest that the escarpment may be listric at depth here. Thus, the geometry of the escarpment here is one possible configuration of breakaway zones adjacent to listric faults with small amounts of displacement, and may serve as a geometric model for the early development of some areas which are now more highly extended.

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