DETAILED STRUCTURAL ANALYSIS OF DETACHMENT FAULTING NEAR COLOSSAL CAVE, SOUTHERN RINCON MOUNTAINS, PIMA COUNTY, ARIZONA

by

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STATEMENT BY AUTHOR

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GEORGE HERBERT DAVIS
Professor of Geosciences

Date

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ABSTRACT

The Colossal Cave detachment terrane is located on the southern flanks of the Rincon Mountains in southeastern Arizona. Detailed geometric and kinematic analysis of a 2 square km area has revealed three structural domains defined by southwest vergent, low angle detachment faults. One of these, the Catalina Fault, is deformed into southwest plunging folds. Finite strain for detachment deformation is given by subhorizontal maximum stretching oriented east-northeast, subhorizontal intermediate shortening oriented north-northwest, and vertical maximum shortening. Total Middle Tertiary detachment translation of the Colossal Cave terrane is estimated to be 30 km.

Within one of the detachment domains are low angle faults with northeast vergence, which are interpreted as Laramide thrust faults. Thrust deformation now exposed in the detachment terrane actually occurred far to the northeast of the Colossal Cave area, and was later dissected and transported southwestward to its present location.

CHAPTER 1

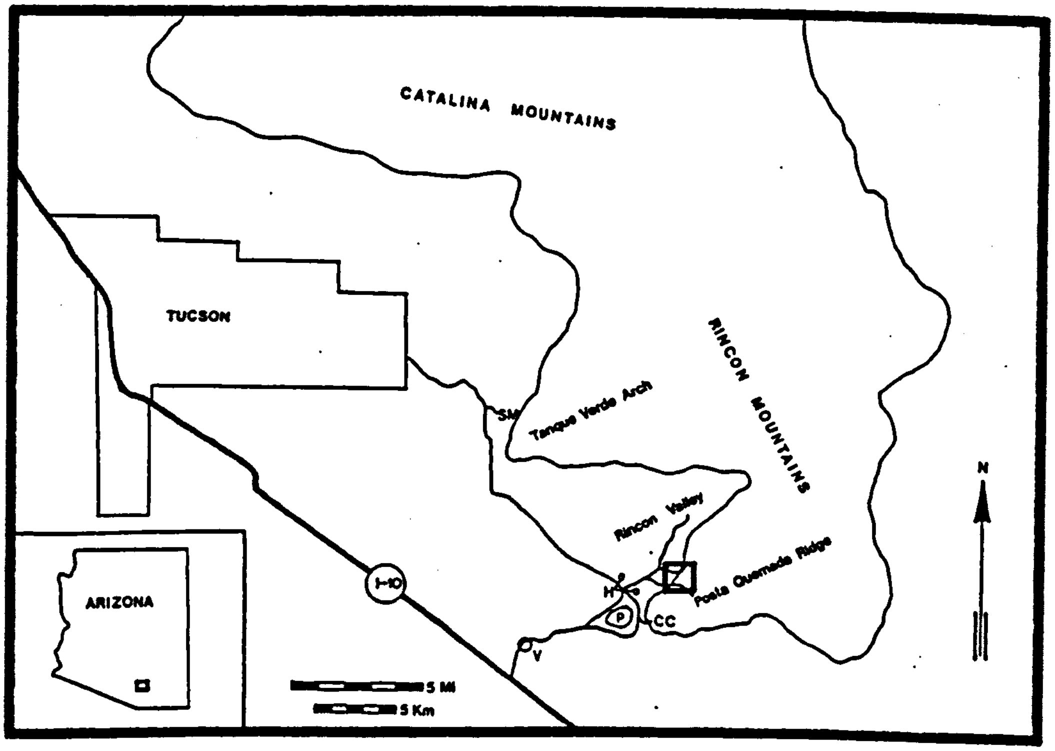
INTRODUCTION

Colossal Cave is located in the southern flanks of the Rincon Mountains of southeastern Arizona (Figure 1). The low hills surrounding the cave comprise a highly faulted assemblage of a wide variety of rocks representing the entire geologic column of southeastern Arizona. This fault assemblage of relatively unmetamorphosed rocks structurally overlies a high grade, mylonitic gneiss. The Catalina Fault, a major low angle, southwest dipping detachment fault, separates the gneiss and the faulted cover rocks.

History of Investigation

The low angle faults in the Colossal Cave region were first recognized by Darton (1925), who interpreted them to be thrusts. Moore et al. (1941), Acker (1958), and Pashley (1966) all concurred with the thrust fault interpretation and related the faulting to Laramide deformation. Acker (1958) studied the siliceous breccias in the area in some detail and concluded they represented a fault zone phenomenon. Pashley (1966) dealt with the entire Catalina Fault, exposed for more than 35 km along the mountain front.

Figure 1. Study area location map, mapped area in heavy outline. -- Location Abbreviations: V, Vail; CC, Colossal Cave; P, Pistol Hill; SM, Saguaro National Monument East; H, Low Hills.


CATALINA MOUNTAINS
TUCSON
RINCON MOUNTAINS
Tanque Verde Arch
SM
Rincon Valley
Posta Quemada Ridge
H
P
CC
V
I-10
ARIZONA
5 Mi
5 Km
N

Arnold (1971) and Davis (1975) concluded that faulting was largely normal slip, and related to gravity-induced deformation. Their conclusions were based on fold asymmetries and fault offsets. Timing was suggested to be Middle Tertiary.

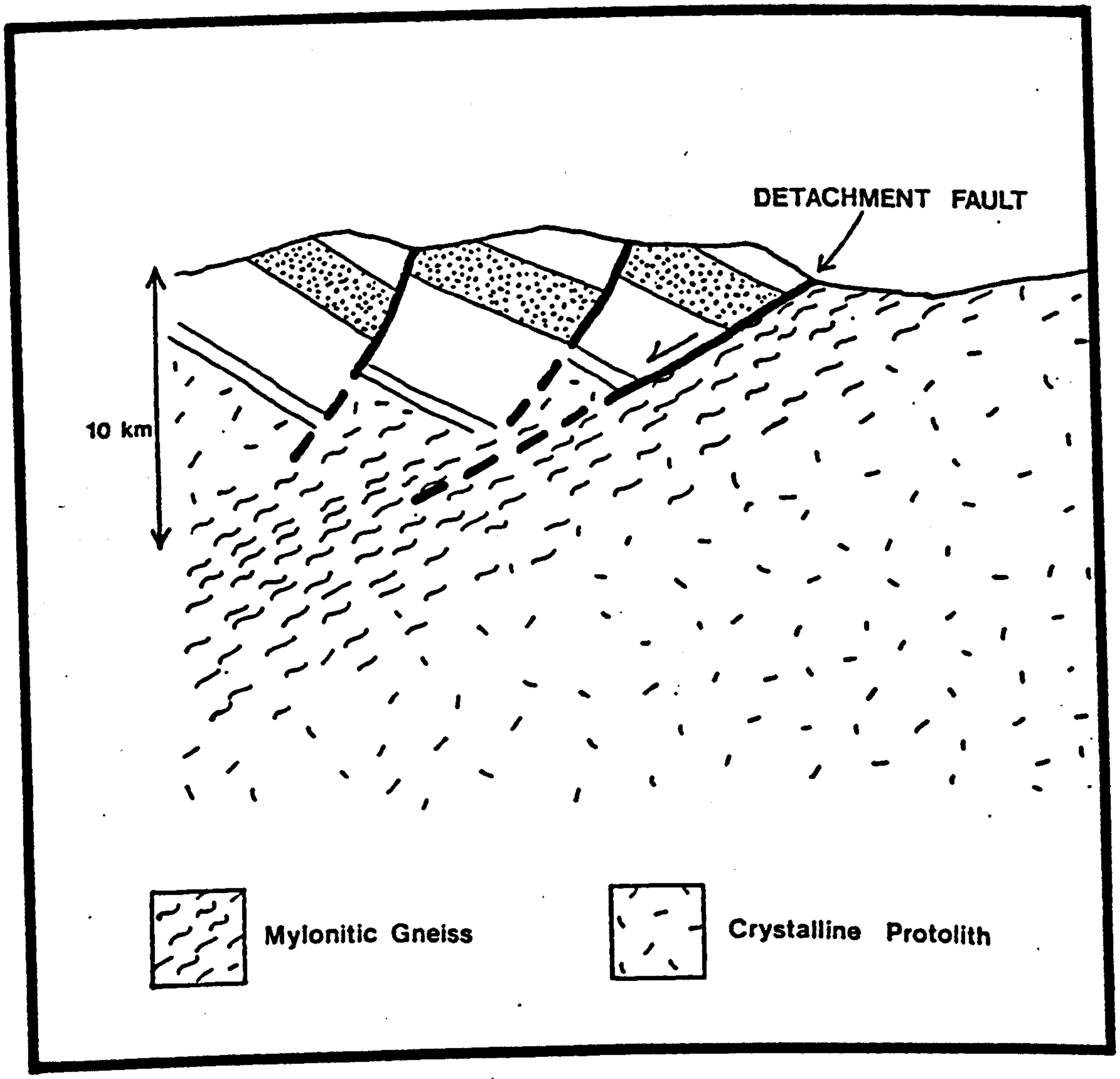
Drewes (1973, 1977) integrated both thrusting and normal faulting. He suggested both occurred along the reactivated Catalina Fault, but that normal faulting accommodated only a few kilometers of slip. Thrust displacement was interpreted to be on the order of tens of kilometers, and is largely responsible for the deformation seen in the southern Rincon Mountains.

Davis and Coney (1979) included the Rincon Mountains, along with the adjacent Catalina Mountains, in their compilation of metamorphic core complexes, and related both the faulting and mylonitic gneisses to normal sense simple shear along a broad zone. Ductile mylonitization, operating at depth, accommodated the same displacement as did detachment faulting, further up dip along the shear zone (Figure 2). Davis (1980, 1981) has further refined and quantified these concepts in the context of the Rincon and Catalina Mountains.

Statement of Problem

Major controversy exists among workers in the southern Rincon Mountains. Various kinematic interpretations have been suggested for the sense of major displacements on the Catalina Fault and other faults, the relative magnitudes of those displacements, the role of reactivation or fault surfaces, and whether the fault system

Figure 2. Schematic cross section of core complex shear zone detachment fault.


DETACHMENT FAULT
10 km
Mylonitic Gneiss
Crystalline Protolith

represents essentially extensional or compressional strain. Tectonic analyses often attribute northeast-southwest compressional strain and thrust faulting to the Cretaceous Laramide Orogeny, while extensional strain and detachment faulting is often related to Middle Tertiary metamorphic core complex-related deformation.

The major purpose of this study is to address these questions via evidence revealed in the detachment fault zone and the overlying, allocthonous cover rocks. Conclusions reached are then integrated into regional hypotheses including all of the southern Rincon Mountains and the adjacent Johnny Lyon Hills.

Study Area

Detailed mapping of a 2 km^2 area astride the Catalina Fault has revealed a complex stacking of tabular, fault-bound bodies (Figure 3). An oblique view of the proposed model is provided by Figure 4. Three basic domains are present (Figure 5), each reflecting distinctly different styles of faulting, deformation, metamorphism and alteration. Within the context of this study, detachment fault refers to a low angle normal fault and detachment refers to the allocthonous body of rock in the hanging wall. Lowest in the structural stacking is the mylonitic gneiss, which is here interpreted to be para-autochthonous. The gneiss is capped by the Catalina Fault zone, a variably thick horizon of brecciated material below the Catalina Fault proper. Above the Catalina Fault is the lower detachment, with complex internal faulting and cross-cutting fault

Figure 3. Geologic map and cross sections. -- Circled locations: 1, Loco Wash; 2, Bolsa Hill; 3 BB Ridge; 4, Bowl.

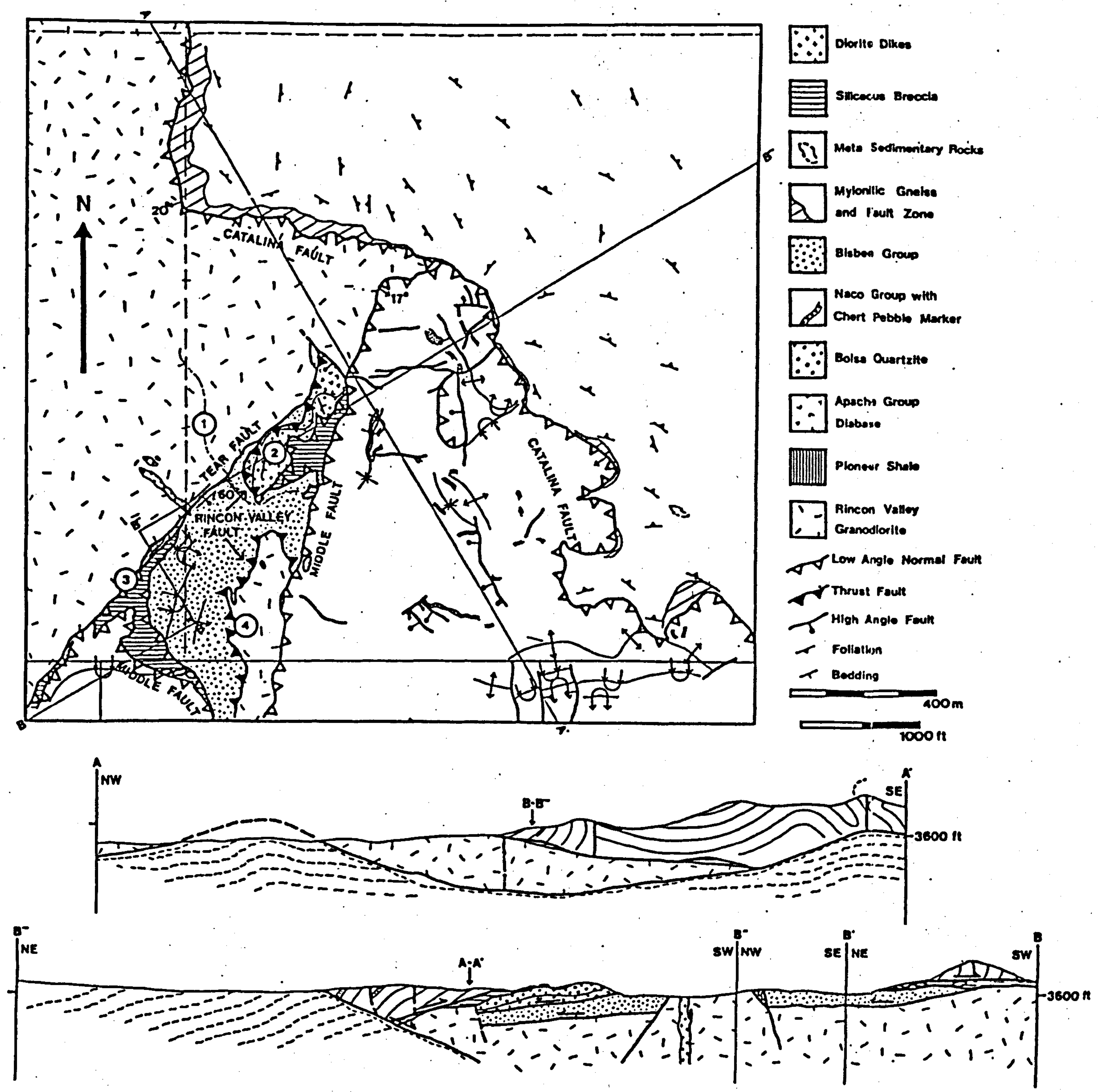

Diorite Dikes
Siliceous Breccia
Meta Sedimentary Rocks
Mylonitic Gneiss and Fault Zone
Bisbee Group
Naco Group with Chert Pebble Marker
Bolsa Quartzite
Apache Group Diabase
Pioneer Shale
Rincon Valley Granodiorite
Low Angle Normal Fault
Thrust Fault
High Angle Fault
Foliation
Bedding
400 m
1000 ft
N
CATALINA FAULT
TEAR FAULT
RINCON VALLEY FAULT
MIDDLE FAULT
A
NW
SE
A'
B-B"
3600 ft
B"
NE
SW
NW
SE
B
A-A'

Figure 4. Oblique block diagrams of map area and subsurface, looking southeast.

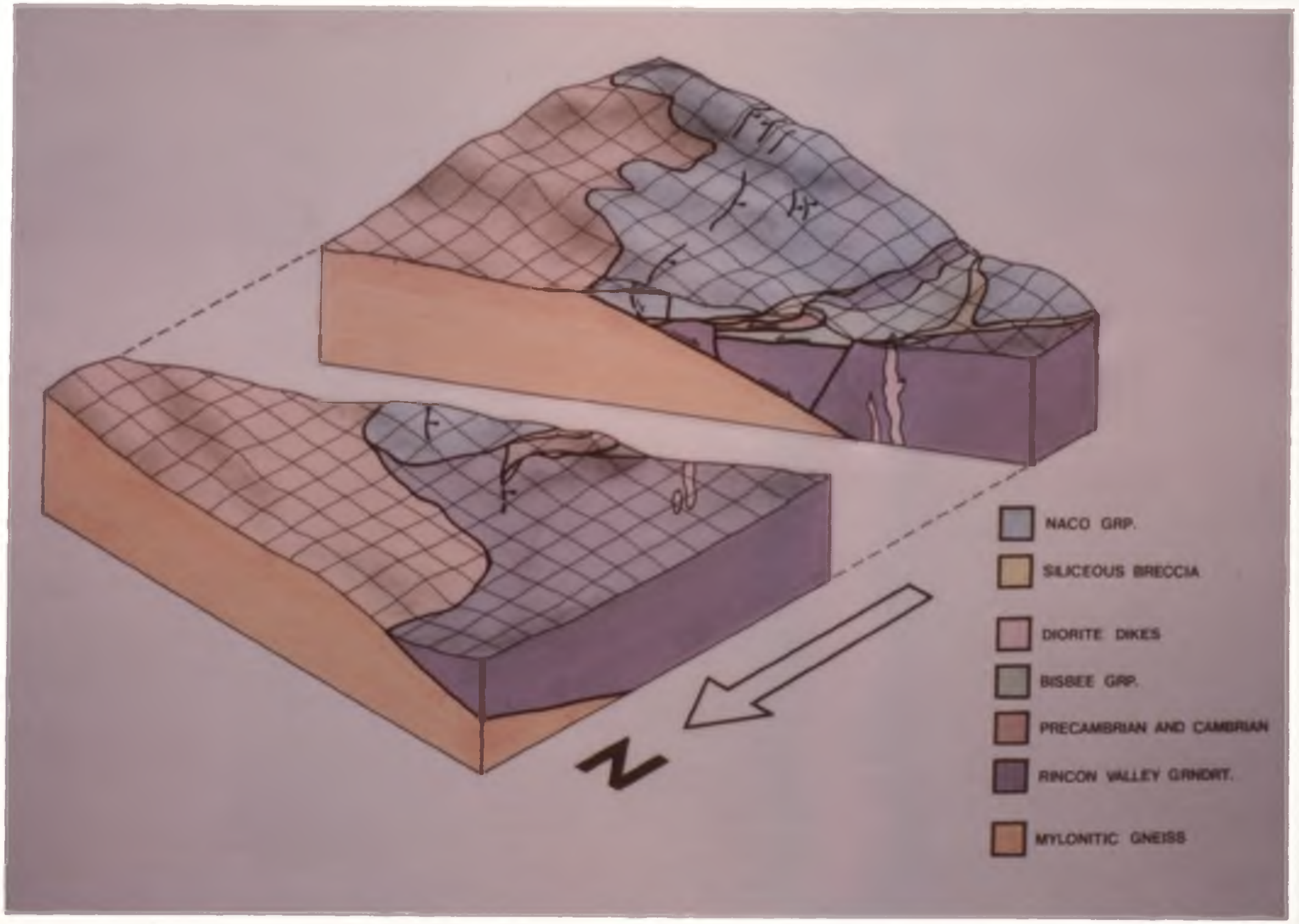
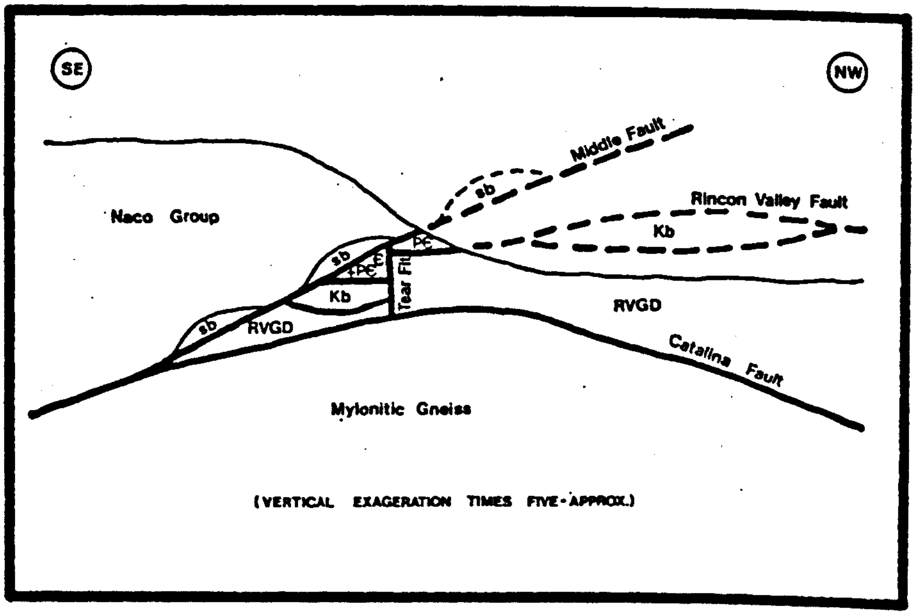

N
NACO GRP.
SILICEOUS BRECCIA
DIORITE DIKES
BISBEE GRP.
PRECAMBRIAN AND CAMBRIAN
RINCON VALLEY GRNDRT.
MYLONITIC GNEISS

Figure 5. Schematic cross section of structural stacking.


SE
NW
Middle Fault
sb
Rincon Valley Fault
Kb
Naco Group
sb
PC
Kb
Tear Flt
sb
RVGD
RVGD
Catalina Fault
Mylonitic Gneiss
(VERTICAL EXAGERATION TIMES FIVE-APPROX.)

relationships. The highest domain is the upper detachment, with simpler internal structure. The Middle Fault separates the two detachments and is associated with silicic alteration and brecciation.

The wide variety of lithologies and metamorphic grades implies assembly, by faulting, of rocks with very different histories. Cross-cutting faults suggest a complex sequence of displacements; reactivation of some structures is likely. Kinematic analysis supports interpretations of normal slip on major faults. However, the exact opposite sense of vergence is revealed by some structures within the lower detachment. It is likely that components of an earlier deformation episode have been disturbed and isolated by the later detachment system.

CHAPTER 2

LITHOLOGIC DISTRIBUTIONS

As shown in Figure 5, a structural stacking of both detachment domains and lithologic units is present. Each domain contains distinct lithologic assemblages. Within the map area no rock unit is exposed in more than one domain. The autochthon is composed of mylonitic gneisses and minor amounts of meta-sedimentary rocks. The lower detachment contains the widest variety of lithologies, including Precambrian crystalline rocks, Precambrian, Cambrian and Cretaceous sediments, and Tertiary dikes. The upper detachment is entirely composed of Upper Paleozoic clastic and carbonate rocks. Several fault zones contain distinct tectonic lithologies directly related to deformation and alteration along fault planes.

Autochthon

Rocks of the autochthon are exposed continuously across the northeastern half of the map area. Mylonites derived from granodiorite and quartz monzonite account for almost all the exposure. A single small outcrop of meta-sedimentary rocks located in the southeastern quarter of the map area is the only exception.

Mylonitic Gneiss

Within the map area, the gneiss is most often exposed as light and dark phases in intimate, lit-par-lit layering. Drewes (1977) has correlated the light phase with the Wrong Mountain Quartz Monzonite and the dark with the Continental Granodiorite. Thickness of layering is on the order of 15 to 20 cm and greater; layers vary in thickness and continuity along strike. Locally, the Wrong Mountain phase dominates.

The light colored Wrong Mountain gneiss ranges from light gray to tan to white. Foliation is commonly well developed and is defined by parallel alignment of small biotite flakes and minor amounts of muscovite, flattened laminae of quartz, and cataclastically deformed bands, boudins and augen of feldspar. A moderately developed lineation is expressed by elongate quartz and feldspar grains, as seen in the plane of foliation.

The Wrong Mountain gneiss locally grades into aplitic and pegmatitic bodies ranging in size from less than one meter to over several meters across. The smaller bodies commonly parallel the foliation. Biotite is absent but muscovite is locally abundant. Foliation development is weaker in the aplite and pegmatite bodies and in places the rock appears coarsely equigranular. Lineation is commonly absent.

The dark, Continental Granodiorite-derived gneiss ranges from gray to dark greenish gray, and from medium to coarse grained. Alignment of biotite and chlorite, along with flattened and augened feldspars, define a strong foliation. Lineation is well developed, and is expressed as elongate mineral grains and streaks.

Drewes (1977) assigned a Late Precambrian age to both the Wrong Mountain Quartz Monzonite and the Continental Granodiorite. Shakel, Silver and Damon (1977) and Silver (1978) suggest a correlation of the Wrong Mountain with Tertiary granites and gneisses. Keith et al. (1980) correlate the Wrong Mountain with the wilderness suite, which yields ages of 44 to 55 million years based on a variety of methods. Thorman and Drewes (1981) concur and support a Tertiary age for the Wrong Mountain Quartz Monzonite.

The Continental Granodiorite has been correlated with the Oracle Granite (Creasey et al. 1977; Shakel et al. 1977; Keith et al. 1980). The Oracle Granite yields well defined dates of 1400 to 1450 million years.

Meta-Sedimentary Rocks

Two lensoid masses of meta-sedimentary rocks occur within the mylonitic gneiss. Outcrops of these rocks are parallel to the mylonitic foliation, and the rocks are themselves foliated. The meta-sediments include quartzite and fine grained, quartz-feldspar gneiss.

The quartzite is a medium grained, pale blue or gray with tan streaks, and is almost entirely composed of quartz. The rock is massive but has foliation defined by color banding and alignment of small voids and blebs of lighter color. Bedding is not visible and the protolith is not readily recognizable.

The gneissic meta-sediment is a penetratively foliated, fine grained quartz-feldspar gneiss. Quartz rich bands alternate with dark brown, slightly schistose bands on the scale of a few milimeters. This gneiss has an appearance unlike that of any mylonitic gneiss, and its limited outcrop adjacent to the quartzite suggests that a sedimentary protolith is likely.

Lower Detachment

The lower detachment contains seven distinct formations, most of which are in low angle fault contact with one another. The structural stacking ranges from Rincon Valley Granodiorite on the bottom, up through Bisbee Group, Pioneer Shale and Apache Group Diabase, to Bolsa Quartzite and Abrigo Formation on the top. A set of Diorite Dikes is intruded into the other lithologies. Internal deformation is variable, and the distribution of units is complicated by cross-cutting faults. Of note is a high angle fault with probable lateral slip; this Tear Fault offsets all low angle faults internal to the lower detachment.

Rincon Valley Granodiorite

The Rincon Valley Granodiorite crops out in the western half of the map area, including the eastern part of the Bowl, and for many kilometers to the west in Rincon Valley. It occupies the lowest structural position of detachment rocks and rests on mylonitic gneiss along the Catalina Fault. In general, the Rincon Valley Granodiorite wedge thickens to both the southwest and northwest. A thin (20 meter) wedge of Rincon Valley Granodiorite is exposed in a similar structural position on Posta Quemada Ridge, two kilometers southeast along the Catalina Fault. The Granodiorite there is sandwiched between mylonitic gneiss and Paleozoic carbonates; both contacts are low angle faults.

The Rincon Valley is a medium grained, equigranular phaneritic biotite granodiorite. Hand specimens display a characteristic color array of white, pink and pale gray-green. The granodiorite is intensely fractured and jointed, and, adjacent to the Catalina Fault, the grains appear shattered and altered. However, the equigranular appearance is maintained and nowhere in the map area does the Rincon Valley Granodiorite exhibit a foliation or lineation. The granodiorite on Posta Quemade Ridge is intensely sheared and chloritized, unlike exposures in the map area. In places, chlorite comprises 25% or more of the total rock volume.

The Rincon Valley Granodiorite is assigned a Precambrian age based on K-Ar ages on hornblende (1560 ± 100 million years) and biotite (1450 ± 50 million years) from samples in the map area (Marvin et al. 1973). Keith et al. (1980) and Silver (1978) have correlated the Rincon Valley with the 1625 million year old granodiorite suite of southeastern Arizona, including the Continental Granodiorite and the Johnny Lyon Granodiorite.

Bisbee Group

An important, though anomalous, relationship is expressed by the appearance of Cretaceous Bisbee Group rocks exposed below Precambrian units on low angle faults. In essence, the Bisbee Group is present as thin, discontinuous lenses along the fault. The Bisbee is exposed throughout the central and western Bowl, although contact relationships are best seen at Bolsa Hill, where a klippe of Cambrian and Precambrian rocks is faulted above Rincon Valley Granodiorite with an interleaved slab of Bisbee Group.

The Bisbee Group rocks in the map area consist of interbedded gray and tan finely laminated shaly limestones, brown to tan well bedded and sorted arkosic sandstones, green massively bedded sandstones, and minor medium bedded medium gray massive limestones. These lithologies are very similar to those of the Amole Arkose in the Tucson Mountains 60 kilometers to the west (R. Risley, personal communication, 1982). The Amole is a Bisbee Group correlative and both are assigned an Early Cretaceous age (Hayes and Drewes 1978).

Pioneer Shale

The Pioneer Shale is one of four lithologies that rest in fault contact on Bisbee Group or Rincon Valley Granodiorite. The others are Apache Group Diabase, the Bolsa Quartzite and the Abrigo Formation. Together with the Pioneer, these rocks comprise the top of the lower detachment.

The Pioneer Shale, exposed in small outcrops on BB Ridge, consists of light tan to dark brown dense siltstone and argillite. The distinguishing feature of the Pioneer Shale is a pervasive black spotting or striping. The Pioneer Shale is a member of the Apache Group, and has been assigned a Late Proterozoic age (Gastil 1954).

Apache Group Diabase

Throughout central and southern Arizona, the Apache Group is intruded by massive sills of Diabase (Silver 1978). In the map area, the Apache Group Diabase is exposed at Bolsa Hill and on BB Ridge, where it intrudes the Pioneer Shale. At Bolsa Hill, the Diabase rests in fault contact above both Bisbee Group and Rincon Valley Granodiorite. The upper contact, where Bolsa Quartzite rests on the Diabase, appears to be an unconformity. A zone of dark maroon, argillic weathering extends for about a meter below the contact.

The Apache Group Diabase is easily recognized by the abundant, 5 mm long needle-like plagioclase crystals, in a dark green, finely crystalline matrix. The composition includes approximately 60% plagioclase, 20% chlorite, 10% biotite, 5% calcite, and 5% opaque and other, with a true diabase texture (Jackson 1970). Apache Group Diabase sills in southeastern Arizona have been dated as 1100 ± 15 my old by lead 207/206 on zircon (Silver 1978).

Bolsa Quartzite

The resistant Cambrian Bolsa Quartzite is exposed capping Bolsa Hill, where it is part of a klippe above the Bisbee Group. The base of the Bolsa Quartzite rests in nonconformable contact on the Apache Group Diabase. The lowermost several meters contain thick beds of dark maroon, argillic quartzite with rounded pebbles. The top of the formation is exposed on the east side of Bolsa Hill, along with the overlying Abrigo Formation. Total thickness of Bolsa Quartzite present is apparently 60 m.

The Bolsa Quartzite is a highly resistant, tan or gray to purplish-brown quartzite, commonly with alternating bands of light and dark colors that define bedding. The formation contains scattered horizons of quartz or quartzite conglomerate intermixed with finer material. Krieger (1968) assigned a Middle Cambrian age to the Bolsa Quartzite.

Abrigo Formation

Small outcrops of the Cambrian Abrigo Formation are exposed on the east side of Bolsa Hill. These exposures, in conformable contact above the Bolsa Quartzite, are the structurally highest portion of the lower detachment, and are in fault contact below the rocks of the upper detachment.

The Abrigo Formation is a greenish-gray to brown siltstone and mudstone, and can be recognized by abundant trace fossils and bottom marks. Locally, the Abrigo Formation exhibits a phyllitic sheen. Fossil-based ages of Middle to Late Cambrian have been reported for the Abrigo Formation (Hayes 1978).

Diorite Dikes

At the north end of BB Ridge and in the nearby Rincon Valley Granodiorite is a series of quartz diorite porphyry dikes. The dikes intrude the Bisbee Group as well as the Rincon Valley Granodiorite and display parallel alignment.

Both composition and texture are somewhat variable over the space of a few meters, but in general the dikes are dark green in color. Porphyroblasts of quartz, where present, range in size up to 10 mm and appear rounded. Plagioclase crystals are somewhat smaller and subhedral.

No age dates have been reported for these dikes in the Rincon Mountains. However, a very similar dike is exposed near the loop drive in Saguaro National Mounment, 25 km to the northwest. In the Monument, the dike intrudes mylonitic gneiss but is itself undeformed. As the age of mylonitization is assumed to postdate the intrusion of the Wrong Mountain Quartz Monzonite, 44 my ago, the dikes must be somewhat younger.

Upper Detachment

Within the map area, the upper detachment consists entirely of Upper Paleozoic Naco Group rocks. Member formations recognized in the map area include the Middle to Upper Pennsylvanian Horquilla Limestone, Upper Pennsylvanian to Lower Permian Earp Formation, and the Lower Permian Colina Limestone (Ross 1978). These formations have been intensely shuffled by faulting; commonly primary features and bedding have been obliterated. Because of these complications, and the gradational nature of the contacts, individual formations are not delineated. Instead, individual beds, especially a chert pebble marker bed belonging to the Earp Formation, were used to deduce stratigraphic positions and offsets.

Horquilla Limestone lithologies include medium to thick bedded, medium to light gray limestone, commonly with chert in localized small bodies. The limestone itself is locally slightly marbleized. Earp formation rocks include pale green to pink limey shales and mudstones, thin dark red mudstones, thin to medium bedded light gray limestones and the chert pebble conglomerate marker. Associated with the chert pebble marker is a tan to gray, fine grained limey sandstone which also occurs in the conglomerate matrix. The chert pebbles themselves are well rounded and mostly spherical, and either maroon or gray in color. Minor amounts of small limestone clasts are included. The resultant appearance is a two to three meter thick layer of large jelly beans. The conglomerate zone is succeeded by medium light gray sandy limestones, completing the Earp Formation. Dark gray, thick bedded limestones which often cap small hills are believed to belong to the Colina Limestone, and are the highest stratigraphic units exposed in the upper detachment.

Fault Zone Lithologies

The map area contains a variety of tectonically produced lithologies which are distributed along different fault planes. These include an array of chloritic breccias and microbreccias found along the Catalina Fault, intense silicic alteration and siliceous brecciation on the Middle Fault, and distinct breccias of Rincon Valley Granodiorite and Pioneer Shale.

Chloritic Breccias

Directly below the Catalina Fault is a variably thick zone of chloritic breccias and microbreccias, silicified breccias, and altered and brecciated mylonitic gneisses. The fault zone changes both in character and thickness along strike, but in general, the degree of brecciation increases upward.

Along the eastern portion of the Catalina Fault Naco Group carbonates of the upper detachment rest directly on the mylonitic gneiss. The intervening Catalina Fault Zone ranges in thickness from less than one meter to several meters, and in one location thickens to fifteen meters. The fault zone is characterized by weakly foliated dark green, medium grained gneiss, interleaved with a white coarse grained to pegmatitic gneiss. Foliation development is highly variable, from moderate to absent. The unfoliated white phase appears quartz monzonitic to granodioritic, but distinctly different from the Rincon Valley Granodiorite. Structurally upward the dark green phase dominates and chloritization increases. Chlorite rich zones commonly display foliation discordant to underlying mylonitic gneiss.

The northwest portion of the Catalina Fault is directly overlain by the Rincon Valley Granodiorite, and the green white gneiss is absent. Instead, the bulk of the fault zone is defined by progressively fractured and shattered mylonitic gneiss. Joint intensity, chlorite and hematite all increase upwards and relic fabrics become obliterated. The zone of brittly deformed gneisses is usually several meters thick.

Above the fractured gneiss is a variety of breccias. Most common is a chlorite breccia which appears to be a progressive form of the fractured gneiss. The chloritic breccia is fine grained, dark green, and is cut by numerous joints filled with hematite and quartz. Locally, the chloritic breccia appears silicified and lighter in color, with variable fracture intensity and occasional clast development. Elsewhere the breccia is exposed as a light gray to tan, highly silicic unit with abundant voids and cavities. Silica is present as irregular masses with interlocking needle-like growths. Drusy quartz lines some cavities.

The breccias are capped by a thin (50 cm or less) layer of microbreccia. The microbreccia is light green to gray and has a pastey appearance. An almost cryptocrystalline fracture and luster result from extreme fine grained texture. Locally, the microbreccia contains white angular clasts of altered feldspars; most are 1 cm across or smaller.

The actual Catalina Fault surface displays a mirror polish (Figure 6). The surface is undulatory on several scales, and commonly has a hematitic coating. Clasts contained in the microbreccia are truncated and polished as well.

Figure 6. Photograph of Catalina Fault surface, looking southwest (down dip).

Siliceous Breccias

Siliceous breccias are found on the east side of the Bolsa Hill and on either side of BB Ridge; all three locations are along the Middle Fault. Breccias and siliceous alteration appear to affect the base of the upper detachment, although underlying lithologies are also involved. Distribution along the Middle Fault is discontinuous and breccia bodies are likely lensodial. Maximum thickness approaches 10 meters.

Brecciated silica exists in a variety of forms, from weakly fractured and jointed to breccias with rounded or faceted clasts. Colors range from red-brown to white; clasts are usually lighter than the matrix. Polished and grooved fault surfaces are common within the breccia. Siliceous breccias often grade upward into selective siliceous replacement in the Naco Group rocks of the upper detachment. Variably affected beds of the Earp Formation, including the chert pebble conglomerate, crop out atop BB Ridge.

Two to three kilometers southwest of the map area, along Old Spanish Trail Road, are several low hills. The reddish rocks capping these hills are also siliceous breccias, but of a somewhat different type. The breccias are almost entirely composed of angular clasts of cryptocrystalline silica exhibiting banding and fine laminations defined by bands of red to pink and greenish gray. The clasts are tightly packed with little visible matrix and are randomly oriented. Some appear "bent" at their margins. These hills of breccia rest on

Rincon Valley Granodiorite in a structural position similar to that of the upper detachment.

On the east side of Bolsa Hill, the large body of siliceous breccia grades downward into a silicified Bolsa Quartzite breccia. Clasts range from 20 cm down to sand-sized, and many exhibit the purple and white banding characteristic of the Bolsa Quartzite. The matrix is identical to that of the undifferentiated siliceous breccias. A very similar breccia, but with clasts of Abrigo Formation, crops out to the south in Loco Wash.

Other Breccias

A distinctly different breccia derived from the Rincon Valley Granodiorite, and a similar one of Pioneer Shale, are exposed on the west side of Bolsa Hill and along BB Ridge in structural positions below the Precambrian and Cambrian rocks of the lower detachment. Both breccias are characterized by egg-shaped and sized clasts in a matrix of deep green, waxy fine grained silica. This waxy green matrix is very distinct and comprises up to 40% of the total volume.

CHAPTER 3

CONTACT RELATIONSHIPS

Most of the contacts within the map area are faults. The distribution and orientation of these faults reflect the overall structural assembly. Within this context, fault zone features and deformation internal to the domains relate to the same detachment system.

Two major, low angle faults serve to define the structural domains within the map area. The Catalina Fault separates detachment domains from autochthonous gneiss. The Middle Fault lies between the upper and lower detachments, and merges eastward with the Catalina Fault (Figure 5). Within the lower detachment, another low angle fault involves the Bisbee Group in a distinct style. This low angle Rincon Valley fault is in turn offset by the high angle Tear Fault. Both of these lower detachment-internal faults are truncated by the major low angle faults which bound that domain. Similarly, other structures within domains are truncated by the major faults and seem to reflect independent deformation of each domain, but in a related system.

Catalina Fault

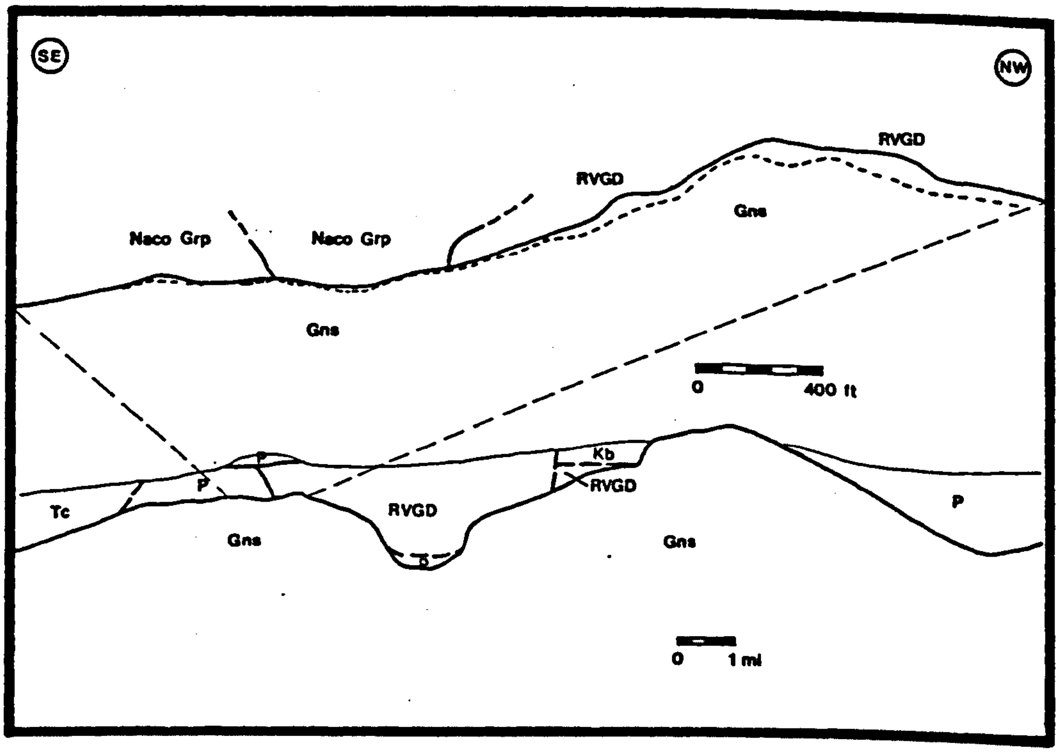
As noted by previous workers, the Catalina Fault, although in general southwest dipping, is far from planar (Pashley 1966;

Davis 1975, 1980; Drewes 1977). When seen in a down plunge view (Mackin 1950) (Figure 7) the fault defines a series of southwest plunging antiforms and synforms (Davis and Hardy 1981). The map area lies on the crest of the Posta Quemada Arch; the culmination of the arch is exposed in the northwestern corner of the map area at the pronounced bend in the Catalina Fault trace.

The portion of the fault within the map area is also quite undulatory (Figure 7). The distribution of the Catalina Fault zone breccias is related to the fault geometry. In general, the zone thickens at antiformal crests and achieves a maximum of over 30 m on and near the culmination. Intensity of brecciation is maximized and the enigmatic silicified breccia with abundant voids is concentrated near the northwest side of the culmination. This concentration of intense fault zone deformation is also present on the Tanque Verde antiform, where even higher grades of brecciation are achieved (L. DiTullio pers. com. 1982).

The chloritic breccias of the Catalina Fault zone commonly display a crude foliation, especially in the structurally highest portions of the zone. The foliation parallels the underlying fault and locally crosscuts the underlying mylonitic foliation. No systematic relationship between mylonite attitude and fault orientation was observed.

Much of the fault zone is cut by hematite and quartz filled joints, 1 to 5 mm thick. Two sets of joint orientations exist (Figure 8). The first strikes N30°W but dips steeply to the northeast,


SE
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RVGD
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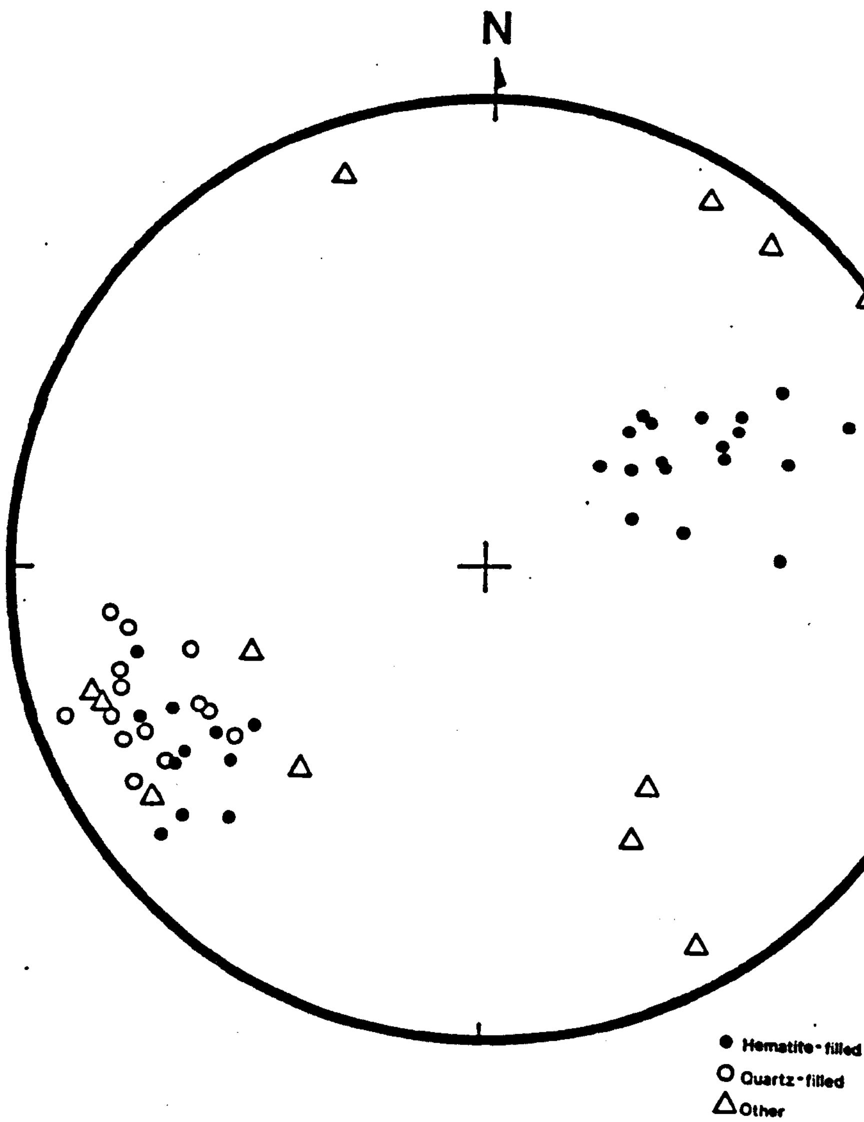
P
Gns
Gns
0
1 mi

Figure 7. Downplunge cross sections, axis of view 20°, 560°W. -- Lithologies: Gns, mylonitic gneiss; RVDG, Rincon Valley Granodiorite; Kb, Bisbee Group; P, Late Precambrian and Paleozoic Rocks; TC, Tertiary Conglomerates. Upper section shows fault zone beneath Catalina Fault, lower section after Drewes (1977).

Figure 8. Stereonet plot of poles to joints in the Catalina Fault zone.


N
Hematite-filled
Quartz-filled
Other

perpendicular to the fault. All of the quartz filled joints belong to this steep set.

Visible offset of markers on the Catalina Fault is not exposed in the map area, as no units in the detachment domains have recognized counterparts in the mylonitic gneiss. Sense of slip is revealed by drag folding of Naco Group limestone beds of the upper detachment in the southeastern corner of the map area. The moderately northeast dipping beds flatten out as they approach the fault, implying normal (southwest vergent) slip.

Middle Fault

The Middle Fault separates the upper and lower detachments. Within the map area, the fault attitude ranges from nearly horizontal to shallowly northeast or east dipping. The low angle nature of the Middle Fault is revealed by outcrop patterns, especially around the Bowl. The fault dips gently eastward east of the Bowl and also where the Middle Fault approaches the Catalina Fault. In the southwestern corner of the map, the trace of the Middle Fault coincides with that of the high angle Tear Fault of the lower detachment. Possible extensions of the Middle Fault beyond the map area include the shallowly southwest dipping fault between Rincon Valley Granodiorite and Upper Paleozoic rocks on Posta Quemada Ridge, and the roughly horizontal klippen of siliceous breccia above the Rincon Valley Granodiorite near Old Spanish Trail Road.

Distribution of the siliceous breccia is controlled by the Middle Fault, and perhaps by the underlying lithology. Major outcrops of siliceous breccia occur below the horizontal upper detachment on BB Ridge, and also climbing up the east side of Bolsa Hill, where the Middle Fault dips gently eastward. At both locations, the underlying lithology is a sedimentary rock belonging to the lower detachment. Markedly little siliceous breccia occurs where the upper detachment rests directly on Rincon Valley Granodirotie, at least in the map area.

Again, offset on the Middle Fault is problematic. No correlative units are exposed in the two detachment domains. Furthermore, the Middle Fault truncates all of the major structures of the lower detachment. Poorly developed flexing of Naco Group beds above the Middle Fault near the eastern Bowl suggest south vergent drag folding, but by itself is not definitive.

Rincon Valley Fault

The Rincon Valley Fault is entirely contained within the lower detachment, and separates Rincon Valley Granodiorite from overlying Precambrian and Cambrian units. It is roughly planar, and dips gently to the northeast. The irregular nature of the fault surface on a small scale is revealed in the Bowl, where outcrops of Bisbee Group and Rincon Valley Granodiorite show convoluted fault contact traces. The Bisbee Group is distributed in variably thick lenses along the fault plane; locally Precambrian lithologies rest directly on Rincon Valley Granodiorite. In northwestern Rincon Valley, roughly 5 km from the map area, a vast expanse of Bisbee Group rests in low angle fault contact atop Rincon Valley Granodiorite. Paleozoic lithologies are also present, possibly above the Bisbee Group.

Deformation within the Bisbee Group is intense. Within the map area, folding is very complex, even "turbulent" (Arnold 1971) (Figure 9). Best exposures of Bisbee Group folds are in Loco Wash. Although visually overwhelming in outcrops, the folds are systematically oriented (Figure 10). Except for a few points, all of the s-fold axes plot in the eastern half of the stereonet, while the z-folds, with two exceptions, trend northwesterly, between N60°E and S60°W. Thus the field of N to N60°E contains both s-folds and z-folds while the field of S to S60°W contains only folds without visible vergence. The best single orientation dividing the two asymmetry domains is roughly N70°E. The sense of overturning of this fold distribution is to the northeast.

Just above the folded Bisbee Group on the south side of Bolsa Hill, Apache Group Diabase is deformed into a tectonite. Foliation is defined by alternating layers of coarse white quartz and calcite and dark layers of aphanitic green material and brown iron oxides. The foliation is roughly horizontal, parallel to the Rincon Valley Fault, but without visible asymmetry.

Tear Fault

Like the Rincon Valley Fault, the Tear Fault is entirely contained within the lower detachment. The Tear Fault is a northeast

Figure 9. Composite photograph of folds in the Cretaceous Bisbee Group.

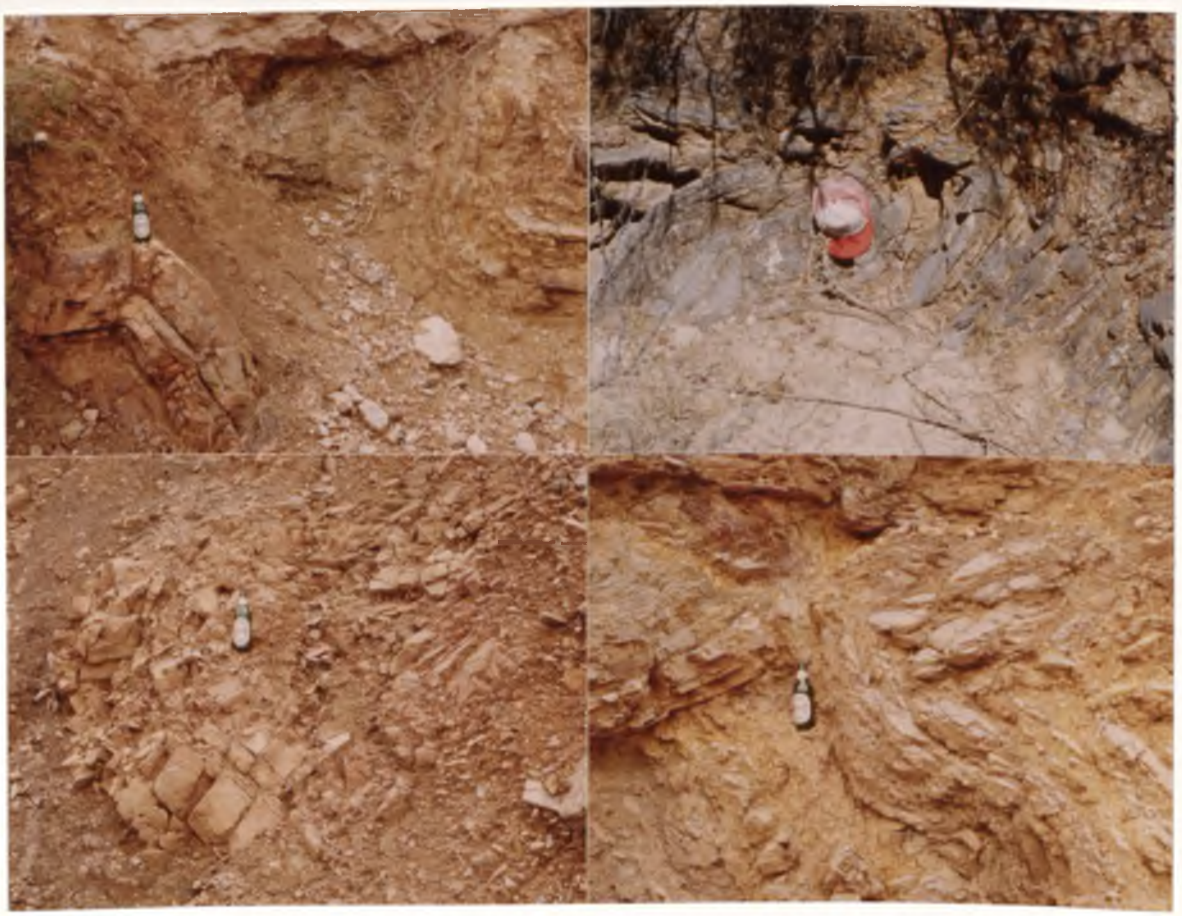
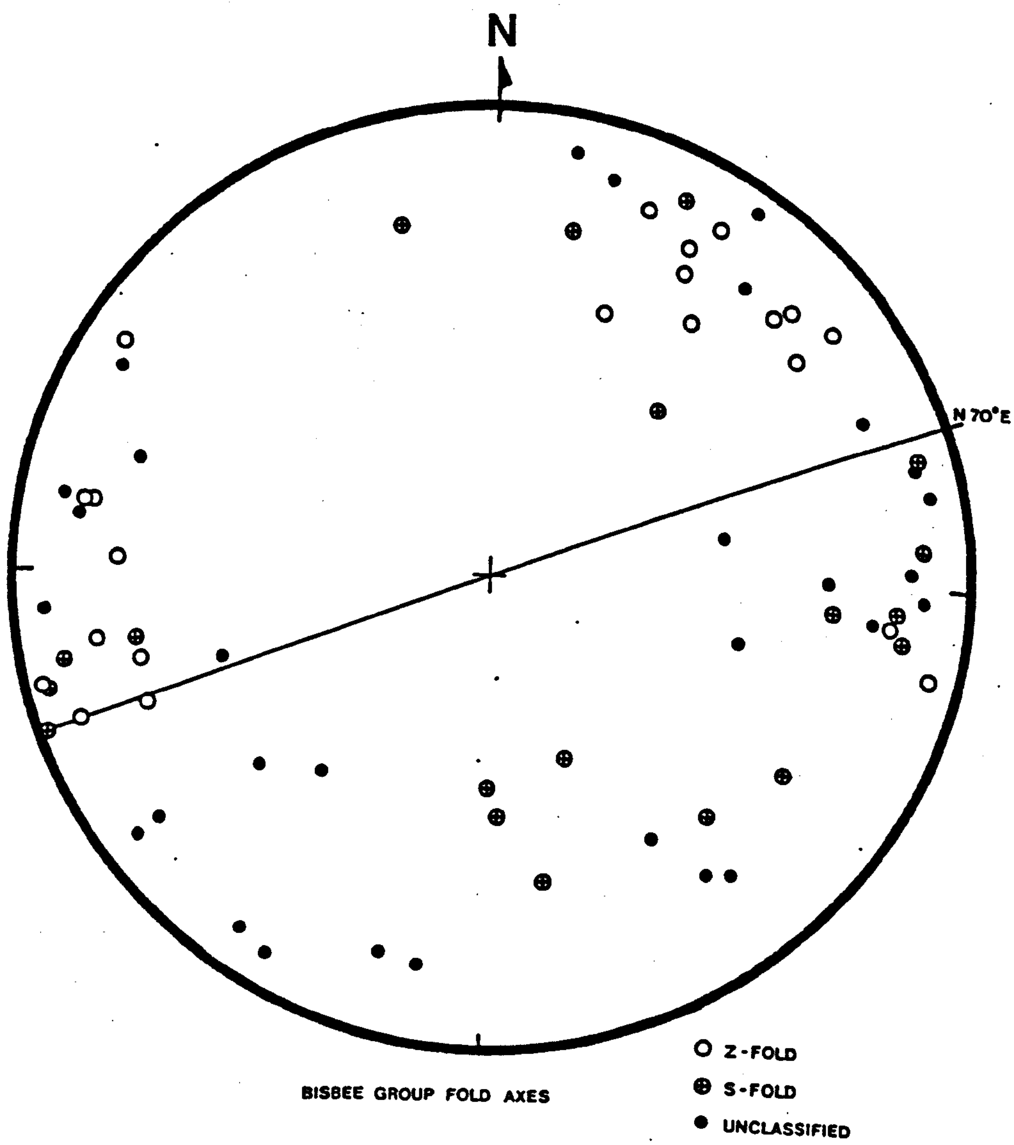


Figure 10. Stereonet plot of fold axes from the Cretaceous Bisbee Group.



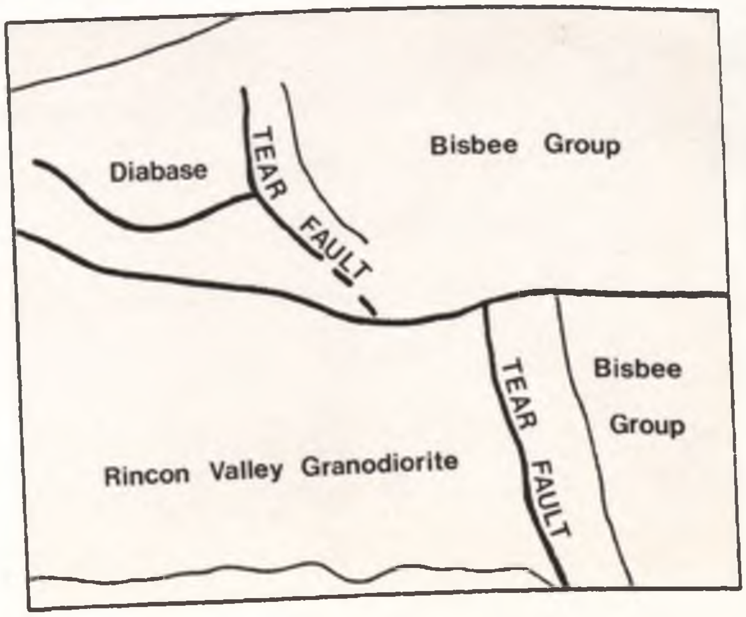
BISBEE GROUP FOLD AXES

striking, 60° southwest dipping fault exposed west of Bolsa Hill and along BB Ridge. The entire thickness of the lower detachment, including the Rincon Valley Fault, is apparently cut by the Tear Fault; the net effect has been to structurally lower the southeastern portion of the lower detachment.

Where best exposed, in Loco Wash, the Tear Fault offset relationships are complex (Figure 11). A near vertical, tabular zone of siliceous alteration, 1 to 2 m thick, defines the fault itself and separates Rincon Valley Granodiorite on the northwest side from Bisbee Group to the southeast. However, a body of Apache Group Diabase crops out in low angle fault contact above the Rincon Valley Granodiorite on the northwest side of the high angle fault; the horizontal fault below the Diabase is truncated by the Tear Fault. The tabular zone of silica, along with the adjacent Bisbee Group beds, are in turn offset by a second low angle fault. Apparent separation is upper block to the west. The unique, waxy green Rincon Valley Granodiorite breccia is found below the Diabase and along the northwest side of the Tear Fault.

To the southwest, the Tear Fault runs along BB Ridge and separates Apache Group Diabase and Pioneer Shale from Rincon Valley Granodiorite. Again, the Rincon Valley Granodiorite breccia is present along the fault trace. Further southwest, the waxy green breccia derived from the Pioneer Shale crops out along the fault trace, just before the upper detachment overlies the trace of the Tear Fault.

Figure 11. Photograph of fault relationships at the Tear Fault exposure in Loco Wash (looking northeast).


Diabase
TEAR FAULT
Bisbee Group
TEAR FAULT
Bisbee Group
Rincon Valley Granodiorite

North of Bolsa Hill, the Tear Fault is truncated by a northwest striking, southwest side down normal fault. Any further northeast extension of the Tear Fault was not visible, and may lie under the upper detachment.

Of note is the relationship between the Tear Fault and the Diorite Dike set. At the northern end of BB Ridge, the longest of the dikes crosscuts the Tear Fault and is exposed on both sides. Lateral offset of the dike, if any, is minimal.

Deformation within Detachment Domains

A variety of structures are exposed within the different domains. To further understand the process of fault assembly, it is necessary to integrate these structures with each other and with the major faults. Some features, such as normal faults, are present in all domains. Others, such as tension gashes and dikes, are restricted to one of the domains, but still are consistent with the detachment system as a whole. Finally, the mylonitic gneisses exhibit intriguing characteristics, some of which are unique within the Rincon Mountains.

Normal faults are present in all domains on a variety of scales. The largest can be traced for over 200 meters and have minimum separation of 10 m or more. Several of these large normal faults are responsible for the repetition of units, especially marker beds, in the upper detachment. More common are small faults with a meter or less separation, visible in many outcrops. Both the upper detachment and the mylonitic gneisses are penetratively cut by small faults.

Listric normal faults are exposed in Loco Wash in both the Bisbee Group of the lower detachment and the Naco Group of the upper detachment. These listric faults display definitive curvature and rotation of hanging wall blocks.

Despite the variety of sizes and styles, the normal faults exhibit remarkable similarity in orientation. Figure 12 shows measured orientations of small faults in all of these domains. All strike northwest to north and dip to the southwest. The large normal faults, as shown in figure 3, strike northwest to north-northwest and also dip southwestward. The overwhelming majority of all normal faults seen in the map area are southwest side down.

Naco Group carbonate beds of the upper detachment locally exhibit en echelon sets of tension gashes. One set has an average strike of N32°W with gashes oriented N65°W, inclined to the right. A second set averages N63°W with gashes inclined to the left at N31°W (Figure 13). The bisector of the obtuse angle between the sets is N45°E. Both sets are present in some outcrops and locally the limestones are penetratively cleaved by near vertical, northeast striking dissolution surfaces.

The Naco Group beds are also pervasively offset by dozens of small vertical, northeast striking faults. Many of these faults have extremely short exposures along strike (2-3 m or less) and often display enigmatic offset patterns. Finding left lateral and right lateral separation on the same fault is not uncommon. These faults

Figure 12. Stereonet plot of poles to normal faults.

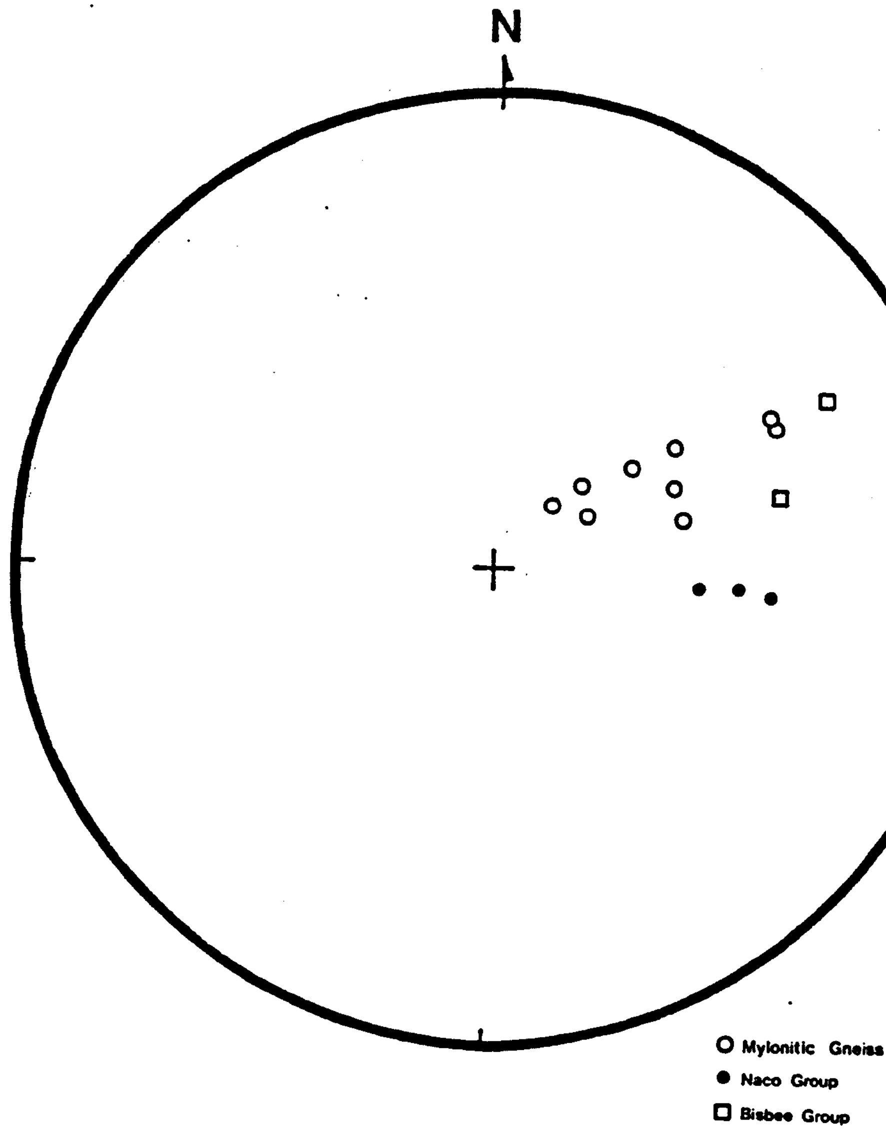
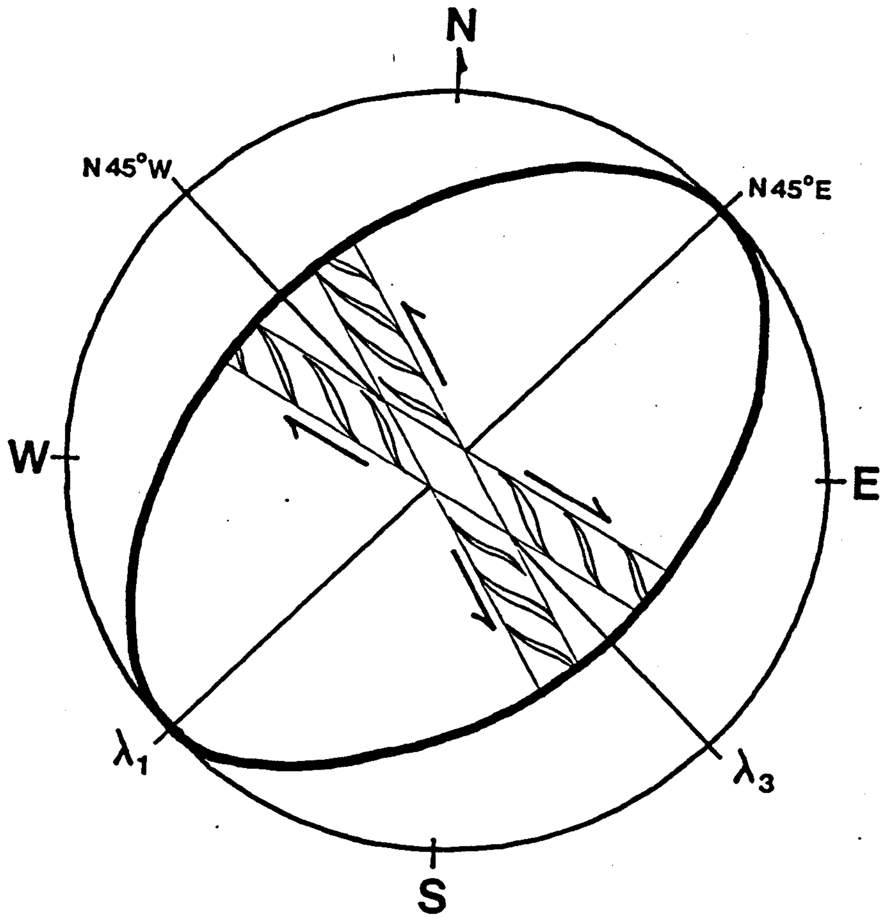

N
Mylonitic Gneiss
Naco Group
Bisbee Group

Figure 13. Schematic diagram of Naco Group tension gashes and strain relationship.

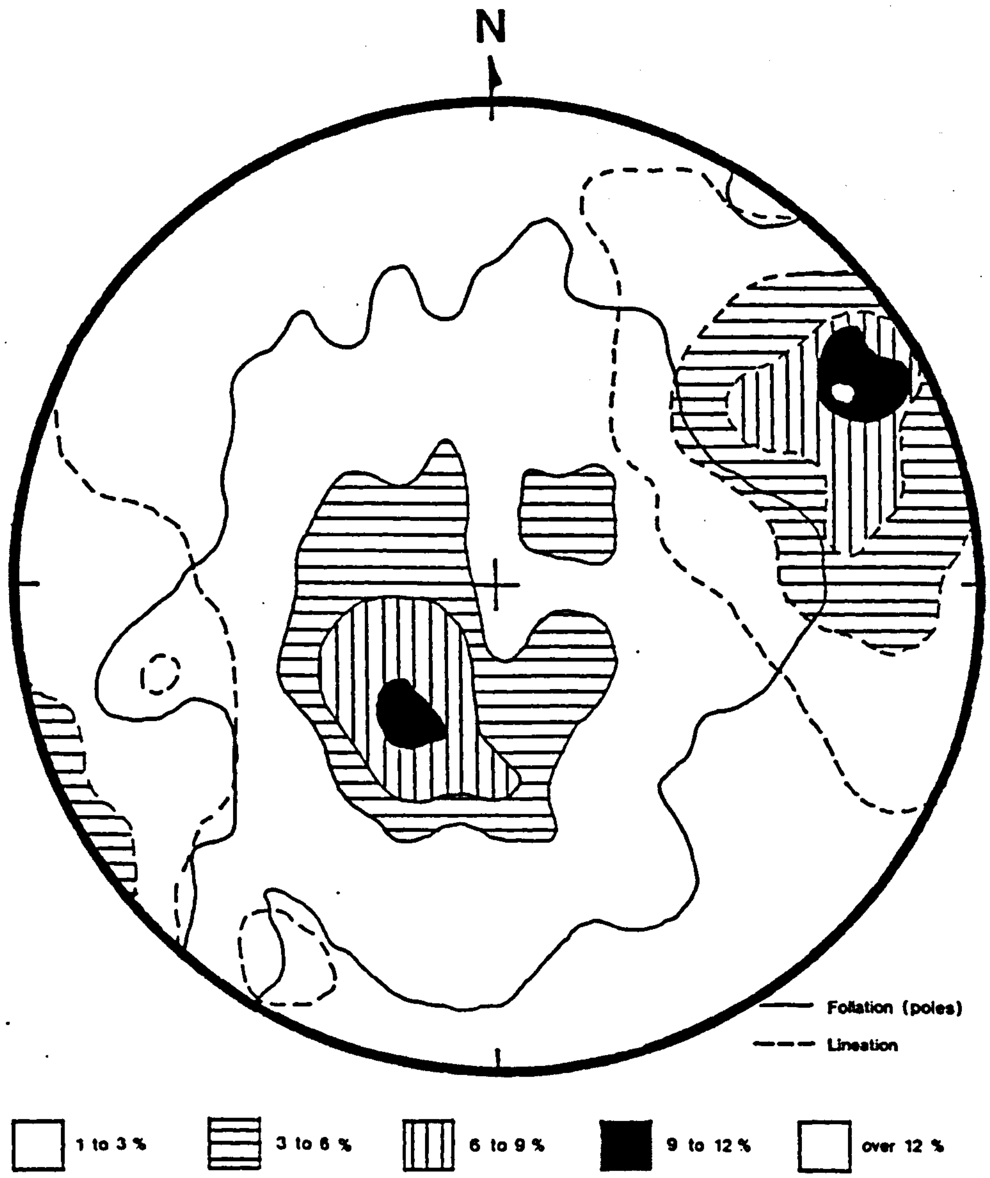

N
N 45°W
N 45°E
W
E
λ1
λ3
S

are parallel to the dissolution planes and may have some kinematic relationship.

A feature similar to the tension gash sets is found in the lower detachment in the form of a set of Diroite Dikes. The average strike of the dikes is N45°W, and they are believed to be vertical. Near the largest dike, the Rincon Valley Granodiorite is intensely veined by a set of N45°W striking, vertical quartz veins. The veins affect an area only a few meters across, but exhibit remarkable parallel alignment. Individual veins are up to 3 cm thick, but thinner ones are more common. Measurements of positive dilation in a horizontal direction of N45°E range from 20 to 100% within this zone.

Although perhaps not directly related to detachment faulting, certain features in the mylonitic gneiss are intriguing, especially in the context of the Rincon Mountains as a whole. The vast majority of gneiss outcrops in the Rincon Mountains dip to the southwest (Davis 1975, 1980; Drewes 1977). However, the dominant orientation of gneiss in the map area, and for a short distance beyond, is northeast dipping (Figure 14). Further, internal variation of dip magnitude and direction is expressed as horizontal northwest trending folds within the map area. Interlimb angles may be as low as 100°. These folds cannot readily be traced along their axial directions, but a southwest-northwest traverse always encounters some sort of variation in foliation orientation.

Figure 14. Contoured stereonet plot of lineation and poles to foliation, mylonitic gneiss.


N
Foliation (poles)
Lineation
1 to 3 %
3 to 6 %
6 to 9 %
9 to 12 %
over 12 %

A second fold set is also visible. These folds trend northeast and are best exposed in northwest striking cliff faces, where the lit-par-lit layering is commonly folded into a series of gentle, upright antiforms and synforms. Both orientation and style are reminiscent of the undulations of the Catalina Fault surface.

CHAPTER 4

FAULT KINEMATICS

The Colossal Cave detachment terrane is a product of fault assembly. The complex stacking present was achieved through superimposed, continued low angle faulting. Both northeast and southwest vergent structures are present, suggesting the super-position of thrust and normal slip deformation. Thrust fault features have been isolated, and perhaps in some cases reactivated, by crosscutting detachment faults; the detachment system itself is an integration of major low angle faults and domain-internal extensional structures.

Thrust Faulting

Deformation along the Rincon Valley Fault, within the lower detachment, is associated with thrust faulting. Within the context of southwest vergent detachment faulting, both the geometry and style of thrust deformation are distinct. Fold vergence in the smeared-out bodies of Bisbee Group is undeniably east-northeast, and the dominant fault relationship is older on younger. That the Rincon Valley Fault is now horizontal may be a result of detachment deformation; listric rotations most probably tilted an originally gently or moderately southwest dipping thrust fault into a horizontal position. Deformation within the fault zone is also distinct. The extreme nature of

Bisbee Group folds, along with the tectonite derived from the Apache Group Diabase, represent a decidedly ductile style of deformation, unlike the breccias associated with the detachment faults. Scatter of the Bisbee Group fold axes is probably due to differential rotations by faulting or folding of parts of the lower detachment during later detachment deformation.

The Tear Fault is likely another component of thrust deformation. Crosscutting relationships suggest that it is, at least in part, older than detachment structures. Although the sense of displacement is not revealed by exposures in the map area, relative downdropping of the Rincon Valley Fault on the southeast side suggests left-lateral slip on the Tear Fault.

As the features representative of thrust deformation are entirely contained within the lower detachment, estimations of offset are impossible. Bolsa Quartzite is widely exposed 3 km to the southwest, but the degree of shuffling by detachment faulting is unknown. That the Tear Fault had to accomodate enough slip to eliminate the Bisbee Group on the northwest side is not much help; distribution of the Bisbee Group is discontinuous.

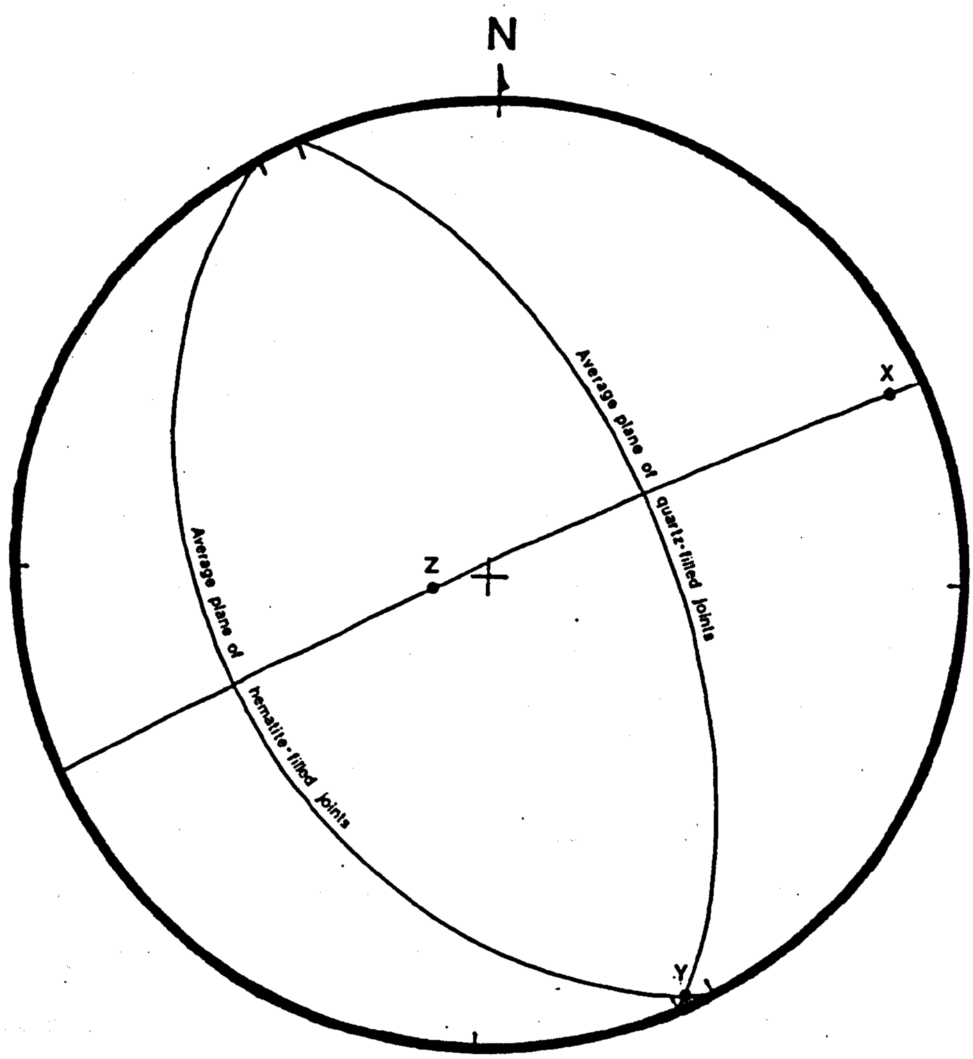
Detachment Deformation

The majority of features seen in the study area, and more importantly, the basic structural framework of the area, are a result of deformation within a detachment fault system. The southwest vergent detachment system is responsible for the assembly of diverse components as well as isolation of thrust fault features within the lower detachment.

Both the Catalina Fault and the Middle Fault display evidence for southwest vergence in the form of drag folding. Further support for southwest slip on the Catalina Fault comes from the hematite and quartz filled joints in the fault zone breccias (Figure 8). Two interpretations are possible. The first assumes that the quartz filled joints, all perpendicular to the Catalina Fault, represent positive dilation, while the other joints are, more accurately, small, mostly synthetic faults. Thus deformation in the fault zone is dominantly extensional, with the direction of maximum elongation oriented S60°W. The second interpretation considers the bisector of the acute angle between the two dominant joint sets (Figure 15). If this bisector is assumed to represent minimum elongation (Ramsay 1967), the resulting strain elipse is defined by X oriented 10°, N60°E, Y oriented 0°, S30°E, and Z oriented 80°, S60°W. Again, this strain field represents down dip extension, with a maximum elongation of S60°W. These two interpretations are mutually compatible.

Structures within the detachment domains are consistent with these strain field orientations. Normal faults within all domains display markedly similar orientations (Figures 3 and 12). Separation is almost always southwest side down, synthetic to the major faults. The direction of maximum elongation for the faults is taken to be at right angles to their strikes, and thus varies from about N45°E to N70°E.

Figure 15. Stereonet of strain field deduced from joints in the Catalina Fault Zone.


N
X
Z
Y
Average plane of quartz-filled joints
Average plane of hematite-filled joints

The value of lambda for normal faulting in the upper detachment is 1.1 to 1.2, based on offset of the chert pebble marker.

The tension gash sets within the Naco Group carbonates of the upper detachment tell a very complete strain story. Each set of en echelon gashes has a sense of shear deduced from internal asymmetry (Figure 13); the slightly sigmoidal gashes are inclined opposite to the sense of shear (Ramsay 1967). The bisector of the acute angle between the gash sets defines the direction of minimum elongation and is oriented N45°W. Maximum elongation is thus oriented N45°E, roughly at right angles to the individual tension gashes. The northeast striking dissolution planes are also consistent with this strain field. It is possible that the northeast striking faults within the Naco Group relate to the same strain field and can be interpreted as either mega-dissolution planes or faults isolating different dissolution domains.

Northwest-southeast shortening is implied by the undulatory southwest plunging folds in both the mylonitic gneiss and along the Catalina Fault. Values of lambda calculated from the gneiss average .89, a horizontal shortening of 6%, while lambda for the Catalina Fault within the map area is also .89 and for the southern Rincon Mountains is .80, equivalent to 11% shortening. (Lambda values for the fault surface are based on the down plunge cross sections shown in Figure 7). Thus even though the Catalina Fault may never have been a planar surface, at least part of its undulatory nature is probably due to folding caused by northwest-southeast shortening. This shortening still represents the intermediate strain direction, as maximum elongation remained northeast-southwest and minimum elongation, with probably much higher values of shortening, remained vertical. Pashley (1966) interpreted the folds in the Catalina Fault to reflect maximum shortening oriented northwest-southeast.

Strain orientations within the lower detachment are further revealed by the Diorite Dike set. Both the dikes and the adjacent quartz veining, have a horizontal positive dilation of N45°E, which is taken to be the direction of maximum elongation. The intermediate and minimum directions can only be constrained to a vertical plane striking N45°W.

Thus the strain ellipse derived from detachment structures is defined by the axis of maximum elongation lying east-northeast-west-southwest, maximum shortening vertical, and the intermediate strain direction, which is also a shortening direction, trending north-northwest.

CHAPTER 5

HISTORY OF FAULTING

The complex geometry of fault-bound bodies present in the study area suggests a sequence of fault displacements; the distinct styles and kinematics displayed by the faults relate to the condition and the mechanisms involved. That the final assembly contains distinctly different lithologies and metamorphic grades is a reflection of very different histories for the different domains. Assembly within a single system is implied by consistent geometric and kinematic relationships throughout the area. Regional orogenic events are represented by various structures; at least two events are recognizable in the rocks of the map area.

The earliest faulting in the area is represented by northeast thrusting on the Rincon Valley Fault, which sandwiched Cretaceous rocks between Precambrian units. The original geometry is engimatic. Although the Bisbee Group may have been in part depositional on the Rincon Valley Granodiorite, no evidence for this was seen. Some kind of structural relief is implied by the need to have Rincon Valley Granodiorite higher than Apache Group and Cambrian units prior to thrusting. This relief may relate to earlier orogenic events and to the pre-thrust distribution of the Bisbee Group (Titley 1976; Bilodeau 1978).

Lateral separation on the Tear Fault postdates at least some of the displacement on the Rincon Valley Fault, but is probably part of the same event. The Tear Fault is a likely place for reactivation during later deformation.

The orogenic event represented by thrusting in the map area is the Laramide orogeny (Davis 1979; Drewes 1981). The Laramide is represented in southeastern Arizona by northeast-southwest compression producing thrust and reverse faulting and folding which often involves the Bisbee Group. Different styles of Laramide deformation have been proposed, but the basic context of northeast-southwest shortening is consistent with the study area results.

Study of the detachment system reveals a sequence of faulting and other deformation which remains somewhat vague. Within the map area, relationships suggest the Catalina Fault is younger than the Middle Fault, and that internal deformation of the domains predates both. However, it is more likely that all the faults are to some extent contemporaneous, and operated together over some period of time. In the context of Middle Tertiary core complex deformation (Davis 1980; 1981) the detachment faulting is coeval with mylonization of crystalline rocks, but at different positions along a low angle shear zone. Thus, continued faulting on the Catalina system has juxtaposed rocks that were once being deformed simultaneously, but in different structural positions and with different results (Figure 2). The continued northeast-southwest extension throughout the operation of the system is reflected in the faults, dikes and other features which affect all the domains. Northwest-southeast shortening, perhaps of a progressive or late stage nature, is revealed by folding of the mylonitic gneisses and detachment fault surfaces, and by tension gash sets and dissolution planes in the Naco Group. The youngest deformation likely occurred on the Catalina Fault, with only minor, synthetic deformation within the domains.

CHAPTER 6

REGIONAL IMPLICATIONS

During the course of this study, an effort was made to integrate field data and ideas based on the map area with the regional geology. Two important regional implications have emerged; both relate to detachment deformation. One is a suggested estimate of total detachment offset, and the other relates to the anomalous orientations of the mylonitic foliation in the map area.

The search for a tectonic source for the Colossal Cave detachment terrane is a difficult one. Within southeastern Arizona, the Late Precambrian and Paleozic lithologic sequences are monotonously similar from place to place. More variability is displayed by the crystalline rocks of the Precambrian basement which underlies the sedimentary sequence. The different ages and lithologies of basement rocks make them a valuable tool in regional correlation.

In a simplified view, the Colossal Cave detachment terrane consists of a northeast dipping stack of Precambrian through Paleozoic rocks in depositional contact above the Precambrian Rincon Valley Granodiorite. Good exposures of the basal unconformity exist on the south side of Pistol Hill. The Rincon Valley Granodiorite is reported elsewhere only in the Happy Valley region to the northeast (Drewes 1974). However, several workers have correlated the Rincon Valley

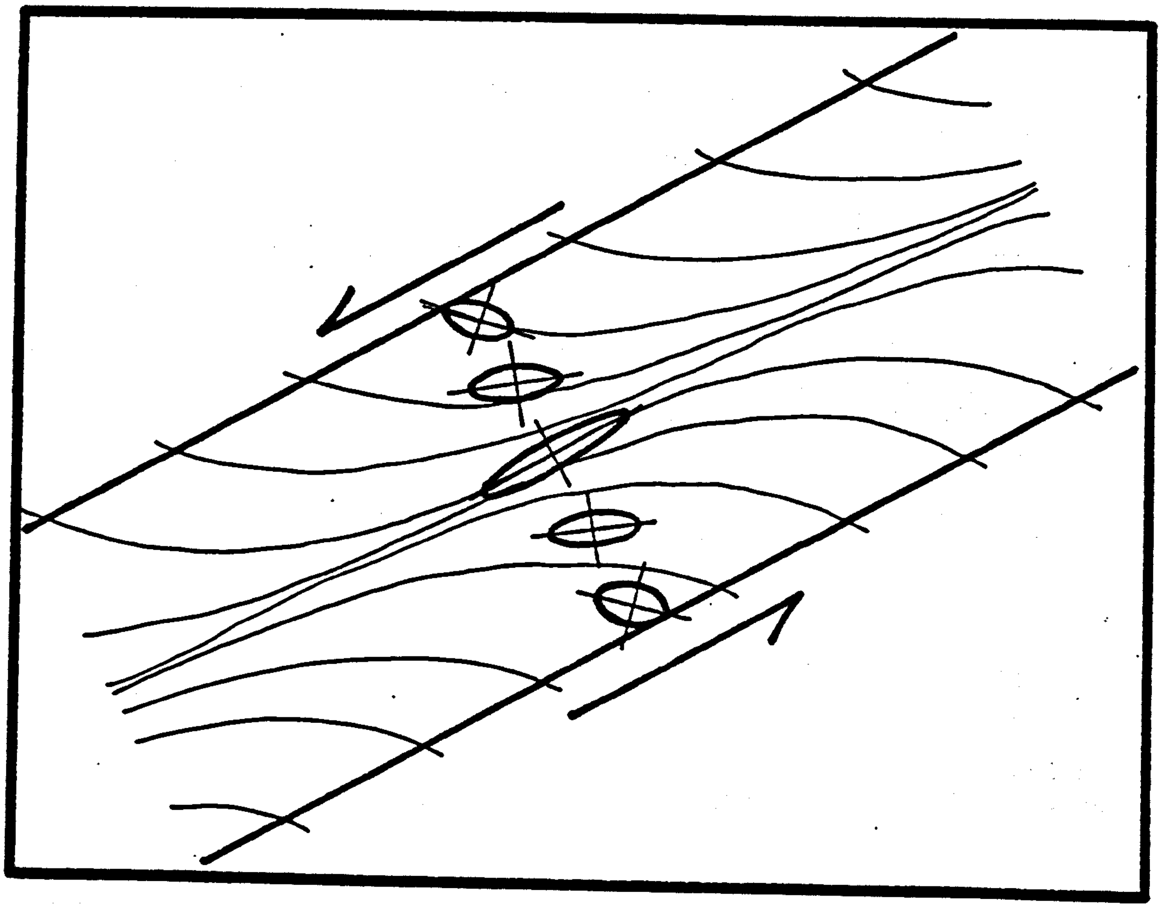
Granodiorite with the Johnny Lyon Granodiorite exposed in the Johnny Lyon Hills (Silver 1978; Keith et al. 1980). Both the Rincon Valley Granodiorite in Happy Valley and the Johnny Lyon Granodiorite in the Johnny Lyon Hills are associated with the Precambrian and Paleozoic rocks contained in the Colossal Cave detachment.

Thus if a tectonic source is sought for the Colossal Cave terrane in an east-northeast direction, similar rocks are encountered first in Happy Valley and then in the Johnny Lyon Hills. The rocks in Happy Valley are also similar to the Colossal Cave terrane in that they are allochthonous (Drewes 1974; Lingrey 1982) and are here interpreted to relate to detachment deformation on a continuation of the Catalina Fault system. In contrast, the assemblage in the Johnny Lyon Hills is autochthonous. If first the Happy Valley allochthons and then the Colossal Cave terrane are backed up against the Johnny Lyon Hills, a total offset of roughly 30 km is suggested for the Colossal Cave rocks. Remnants of the autochthon are strung out between the two locations, represented by the allochthons in Happy Valley.

An additional implication of the detachment deformation is that the Laramide deformation now present in the southern Rincons was actually produced much nearer to the Johnny Lyon Hills region where thrust faults are presently exposed. During detachment faulting, thrust features were distributed between two locations, and perhaps, in the subsurface, even farther to the southwest.

Ramsay and Graham (1970) present an analysis of distribution of strain across a shear zone (Figure 16). Maximum strain is achieved in the center of the zone, and decreases toward the boundaries. A foliation within the center would parallel the zone, while foliation toward the boundaries would be oblique, and ultimately inclined at 45° to the boundaries. Thus a gently southwest dipping shear zone would display, from boundary to boundary, foliation first dipping northeast then horizontal, then southwest, horizontal again, and finally northeast. It has been suggested (Davis 1983) that the dominantly southwest dipping foliation in the southwestern Rincon Mountains represents the central portion of the shear zone, while northeast dipping foliation common along the crest of the range to the northeast represents the base of the zone. In the same context, the northeast dipping foliation present in the map area can be interpreted as the top of the zone, consistent with the structurally high position of the area (Figure 7). Total exposed thickness of the shear zone is calculated to be 3.5 km.

Figure 16. Schematic diagram of strain variation and foliation orientation across a shear zone.



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