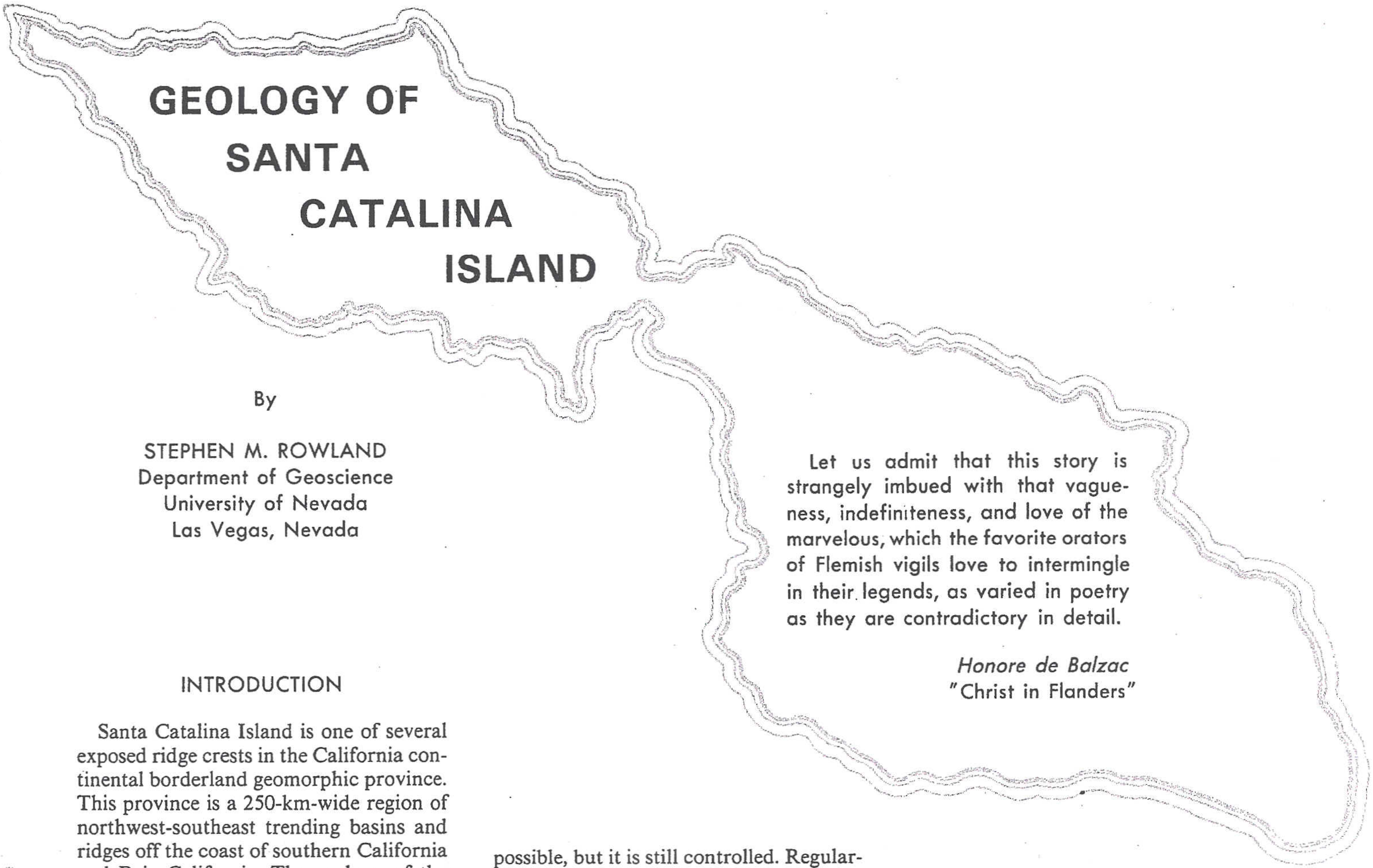

GEOLOGY OF SANTA CATALINA ISLAND

By

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> Let us admit that this story is strangely imbued with that vagueness, indefiniteness, and love of the marvelous, which the favorite orators of Flemish vigils love to intermingle in their legends, as varied in poetry as they are contradictory in detail.
>
> *Honore de Balzac*
> "Christ in Flanders"

INTRODUCTION

Santa Catalina Island is one of several exposed ridge crests in the California continental borderland geomorphic province. This province is a 250-km-wide region of northwest-southeast trending basins and ridges off the coast of southern California and Baja California. The geology of the continental borderland is complex, and because it is mostly under water, it has been the last major province in California to receive detailed study. Recent work on Santa Catalina and throughout the continental borderland has resulted in a much improved picture of this region's geologic history.

Simply stated, the geology of Santa Catalina consists of a Mesozoic metamorphic basement complex intruded and overlain by Miocene igneous rocks. A few scattered deposits of Tertiary sedimentary rocks are also present (Figure 1). The basic geologic relationships, if not the exact ages, have been known since 1897 when the first geologic map of the island was published (Smith, 1897). Until very recently, however, it was not known how these rocks fit into the geologic evolution of western North America.

Prior to 1975, it was difficult to casually examine the rocks on Santa Catalina because most of the island was privately owned by the Wrigley (chewing-gum) family. In 1975, however, 86 percent of the island was transferred to a non-profit foundation called the Santa Catalina Island Conservancy. Los Angeles County has a 50-year easement on most of this land. Access to the island's interior is now possible, but it is still controlled. Regularly scheduled bus tours depart from Avalon, and arrangements for geologic field trips or research can be made through the Santa Catalina Island Conservancy, P.O. Box 2739, Avalon, California 90704.

CATALINA SCHIST AND THE FARALLON-NORTH AMERICAN SUBDUCTION ZONE

Distribution

The Catalina Schist, a Mesozoic metamorphic complex, occupies most of the northwestern half of the island (Figure 1). Catalina Schist crops out on land in only two places—Santa Catalina Island and in a small area on the Palos Verdes Peninsula. Samples of Catalina Schist have been dredged from several localities within the continental borderland (Howell and Vedder, 1981), however, and it is thought to form the basement complex of much of the inner borderland (see Crouch, 1979, Figure 1).

Relationship with the Franciscan Complex

Catalina Schist lithologies are similar to those of the Franciscan Complex, and the Catalina Schist has generally been considered to be a southward extension of the Franciscan (Woodford, 1924). Potassium-argon dating of Catalina amphibolite and blueschist has yielded ages of 95-109 million years (uppermost Lower Cretaceous) (Suppe and Armstrong, 1972), which falls within the Upper Jurassic through Eocene age for the Franciscan of the Coast Ranges. The Catalina Schist is not "typical" Franciscan, however, because the blueschists of the Catalina Schist terrane are more thoroughly recrystallized than most Franciscan blueschists (Platt, 1975). Also, it has been shown that Catalina blueschists probably experienced relatively higher temperatures and/or relatively lower pressures (that is, a lower P/T ratio) than those of Coast Range Franciscan (Sorenson, 1984a, b).

Lithology

The Catalina Schist comprises three metamorphic grades (Table 1). These are blueschist, greenschist, and amphibolite, all of which are derived from mafic igneous rocks and sedimentary rocks (Platt, 1975; Sorensen, 1984a, 1984b). The greenschist and amphibolite facies rocks

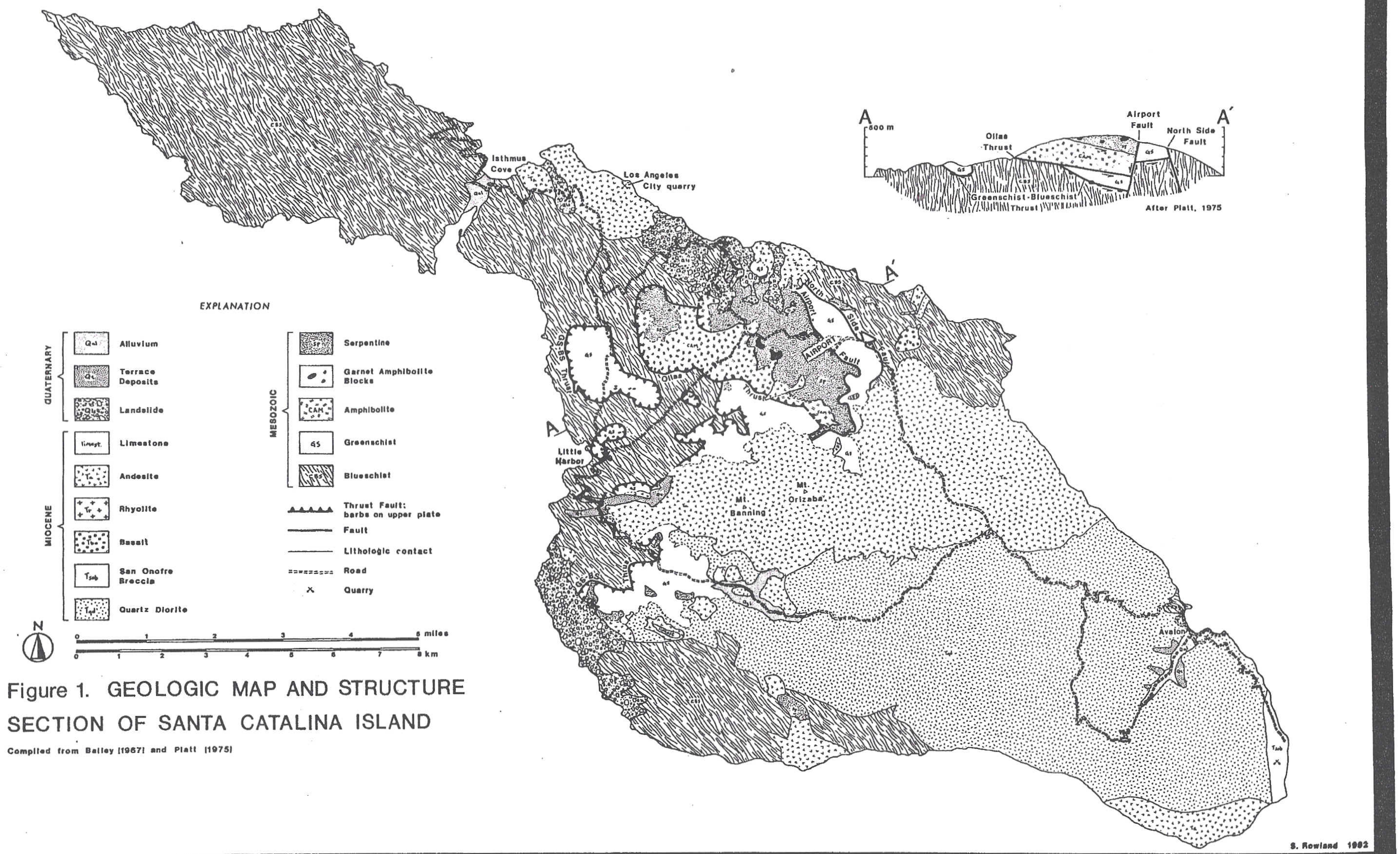


Figure 1. GEOLOGIC MAP AND STRUCTURE SECTION OF SANTA CATALINA ISLAND

Compiled from Bailey (1967) and Platt (1975)

S. Rowland 1982

Photos by Stephen M. Rowland.

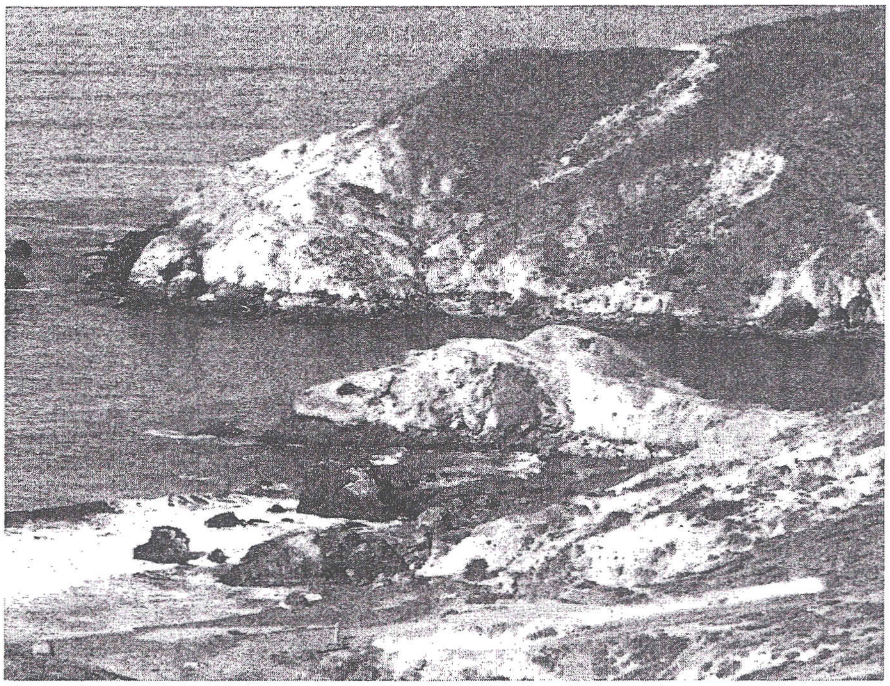


Photo 1. Blueschist mélange at Little Harbor. The geology here is confused due to landsliding. An enlargement of the right-hand-central portion of this photo is shown in Photo 2.

occur as relatively coherent tectonic blocks (Platt, 1975), while the blueschist is a mélange (Photos 1, 2, 3) (Sorensen, 1984a, 1984b).

All three metamorphic facies of the Catalina Schist are stable at a pressure of around 9 kilobars (kb), but each has a unique range of stable temperatures (Table 1). The Catalina blueschists formed under relatively low-temperature conditions (approximately 300°C), while the greenschists formed under intermediate-temperature conditions (450°C), and the amphibolites formed under much hotter conditions (580-620°C). The surprising thing is that the three facies are structurally arranged with the low-temperature blueschists on the bottom and the high-temperature amphibolites on top (Figure 1, cross section A-A')—an inverted thermal gradient. Although the three facies lie in fault contact with one another, the similar parent-rock assemblages, the common high-pressure metamorphic history, and the present structural relationships suggest that they formed in a single, zoned metamorphic complex (Platt, 1975).

Structure

Two thrust faults have been mapped in the central part of Santa Catalina (Figure 1) (Platt, 1975). The structurally lower of the two is the Greenschist-Blueschist thrust, which consistently separates blueschists below from greenschists above. Structurally above and truncating the Greenschist-Blueschist thrust is the younger Ollas thrust, which separates the amphibolites from the underlying units (Figure 1, Structure Section A-A'). Both of these thrusts are poorly exposed zones of variable width.

The Ollas thrust is a zone of sheared serpentinite, talc, and chlorite that is several meters thick (Smith, 1897; Bailey, 1941, 1967; and Platt, 1975, 1976). It is exposed in only two localities, Buffalo Springs Canyon and the west fork of Big Springs Canyon, but elsewhere it can usually be located within about 20 m (Platt, 1976, p. 76). This fault crosscuts schistosity as well as minor folds in both the lower and upper plate.

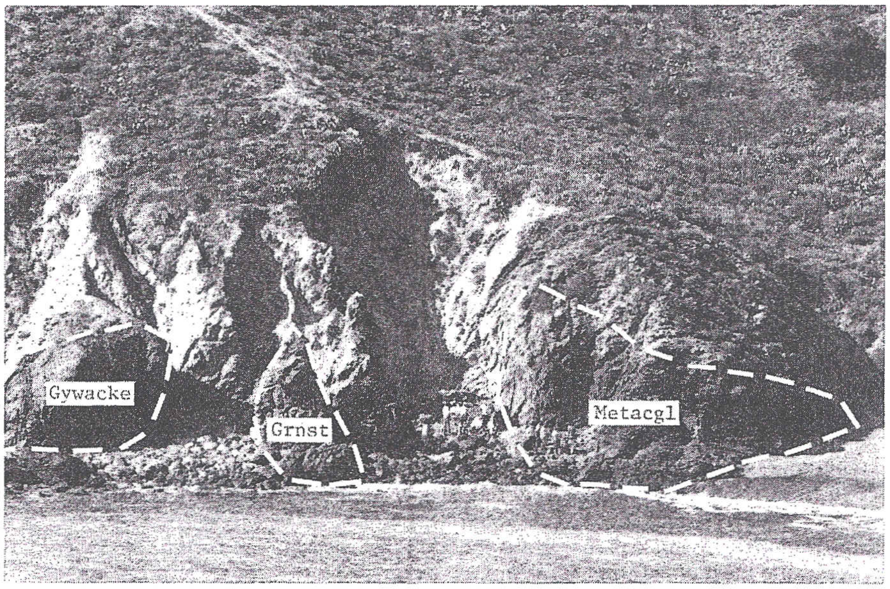


Photo 2. North shore of Little Harbor showing three discrete blocks in a mélange matrix. Note people between greenstone and metaconglomerate blocks for scale. Gywacke = graywacke, grnst = greenstone, metacgl = metaconglomerate.

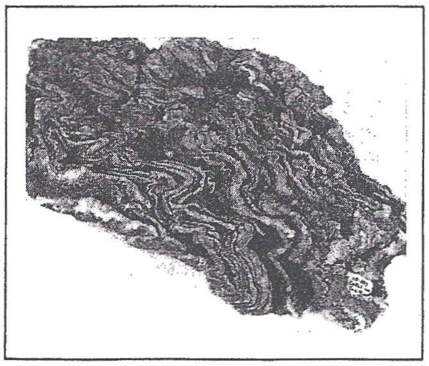


Photo 3. Blueschist-grade metachert from the Little Harbor area. Rock is approximately one foot long.

Table 1. Characteristics of the Catalina Schist on Santa Catalina Island. Compiled from Platt (1975 and 1976) and Sorensen (1984a).

METAMORPHIC GRADE TEMPERATURE & PRESSURE	TEXTURE	LITHOLOGIES (Temperature- and pressure-diagnostic minerals in parentheses)	INFERRED PARENT ROCKS
Blueschist 300° C 9 kb	Melange with blocks of various lithologies in a fine-grained schistose matrix; primary textures are preserved in individual blocks	Metagraywacke (lawsonite)	Graywacke (75%)
		Metachert	Chert
		Schist and phyllite (glaucophane, lawsonite)	Well-bedded basaltic sand and conglomerate
		Greenstone (omphacite, lawsonite)	Diabase, flow breccia, pillow lava
		Eclogite blocks	Basalt
Greenschist 450° C 7-10 kb	Pervasive schistosity; primary textures largely destroyed; contains garnet-amphibolite blocks	Mafic schist (clinozoisite, epidote, ± glaucophane & crossite)	Basalt (50%)
		Gray schist (albite ± almandine garnet and biotite)	Graywacke (40%)
		FE- & Mn-rich quartz schist (± crossite & glaucophane)	Chert (10%)
Amphibolite 580-620° C 8.5-12.5 kb	Coarse-grained metamorphic texture; no primary textures preserved; contains serpentinite masses and chlorite/actinolite/talc melange and tectonic blocks of various lithologies	Green hornblende schist (zoisite)	Mafic igneous rock (dominant lithology)
		Semipelitic schist (garnet, biotite, muscovite, kyanite, zoisite)	Mudrock (volumetrically minor)
		Garnet quartzite	Chert (minor)
		Serpentinite, chlorite/actinolite/talc melange, & tectonic blocks of various lithologies	Hanging-wall peridotite with tectonically incorporated basalt and metasediment from the subducting oceanic plate

The Greenschist-Blueschist thrust is more obscure and complex than the Ollas thrust. It is a zone that is "locally up to 200 m thick, filled with tectonic blocks of amphibolite-facies rocks and serpentinite in a matrix of talc-chlorite-actinolite schist" (Platt, 1975, p. 1338). This is the same lithologic assemblage that forms the serpentinite portion of the amphibolite unit in the vicinity of the airport.

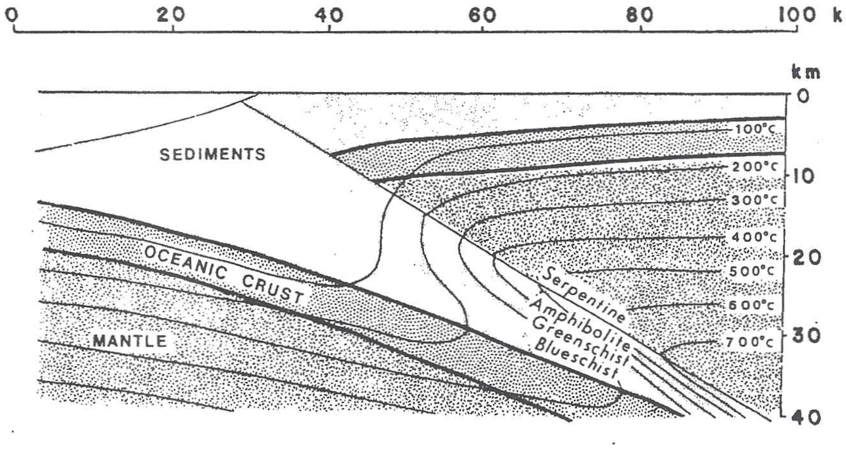
Newly Formed Subduction Complex

If the three metamorphic facies of the Catalina Schist represent separate tectonic units that formed as parts of a single, high-pressure metamorphic complex with an inverted thermal gradient, then they probably formed in a subduction zone with an overthrusting heat source (Platt, 1976) (Figure 2a). The inverted thermal gradient (see isotherms in Figure 2a) develops as the cold slab of oceanic crust slides beneath the hot, mantle peridotite of the subduction zone's hanging wall.

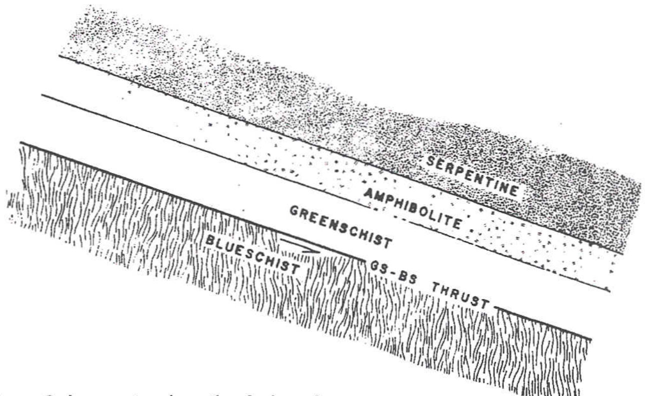
Several lines of evidence suggest that the subduction zone in which these rocks were metamorphosed was newly formed. The first is the inferred inverted thermal gradient. This phenomenon only exists during the early stages of subduction (Platt, 1975). As a subduction zone matures, insulating material accretes to the cooling hanging wall, and the inverted thermal gradient disappears. Another reason to infer a nascent subduction zone is the parent-rock composition of the three units. The amphibolite unit is mostly derived from mafic igneous rocks and lacks any graywacke-like protolith (Sorensen, 1984a, b). Graywacke, which comprises about 40 percent of the greenschist and 75 percent of the blueschist (Table 1) (Sorensen, 1984a, b), becomes an increasingly important component in each successively lower unit. Graywacke is the most common trench-fill sediment and would be expected to increase in importance as a subduction zone develops.

Detailed petrologic studies of eclogite (garnet + clinopyroxene) blocks within the Catalina amphibolite unit further support the interpretation of a newly formed subduction zone (Sorensen, 1984a, b). The eclogite blocks are interpreted to represent metamorphosed tholeiitic basalt that was transported to a depth of 35-40 km (pressure of 12 kb). The mineralogy of these blocks indicates a high temperature/pressure ratio that is diagnostic of the early stages of subduction. Many of these blocks were tectonically incorporated into the peridotite of the hanging wall of the subduction zone (Photo 4).

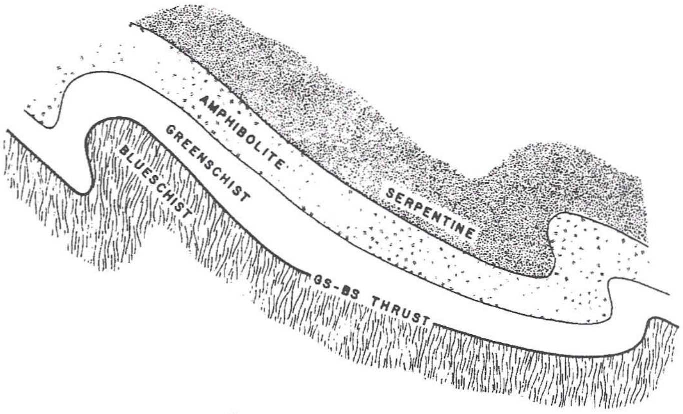
Figure 2. Structural scenario for the structural relationships observed in the Catalina Schist, central Santa Catalina Island. *Adapted from Platt, 1975.*



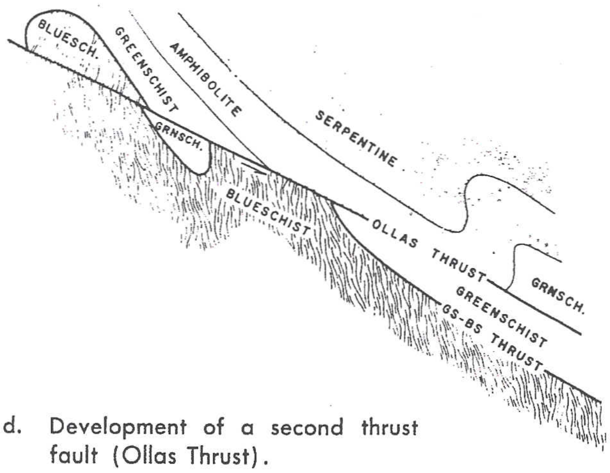
a. Idealized section through a recently initiated subduction zone, showing approximate distribution of isotherms and regions where amphibolite, greenschist and blueschist would form.



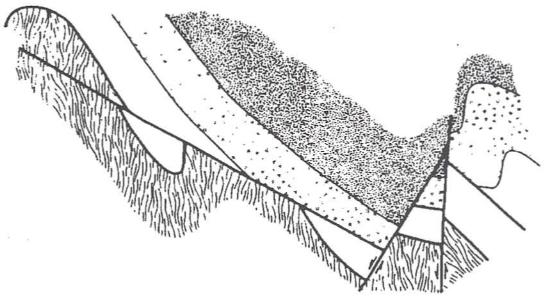
b. Schematic detail of the deep portion of a subduction zone showing a metamorphic zoning and the development of a thrust fault between the greenschist and blueschist.



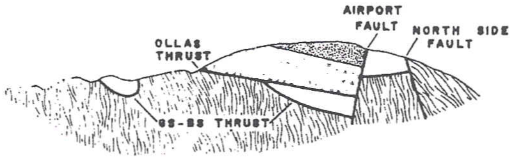
c. Folding of GS-BS Thrust and metamorphic zones.



d. Development of a second thrust fault (Ollas Thrust).



e. Normal faulting (Airport Fault and North Side Fault) caused by extension in Late Tertiary time.



f. Tilting and erosion to form structure Section A-A' of Figure 1.

For these reasons, it appears that the Catalina Schist on Santa Catalina Island represents the initiation of Mesozoic subduction in what is now the inner continental borderland.

A Structural Scenario

Figure 2b schematically portrays the zoned metamorphic complex after it became welded to the peridotite of the hanging wall. The formation of the Greenschist-Blueschist thrust was caused by continued underthrusting beneath the higher-temperature metamorphic zones. Platt (1975) estimated a minimum displacement of 9 km for the Greenschist-Blueschist thrust. The distinctly different temperatures of formation on opposite sides of this fault indicate that faulting was postmetamorphic. Tectonic blocks of serpentinite and amphibolite within the Greenschist-Blueschist fault zone may be the result of an older thrust (not shown in Figure 2) (Platt, 1975).

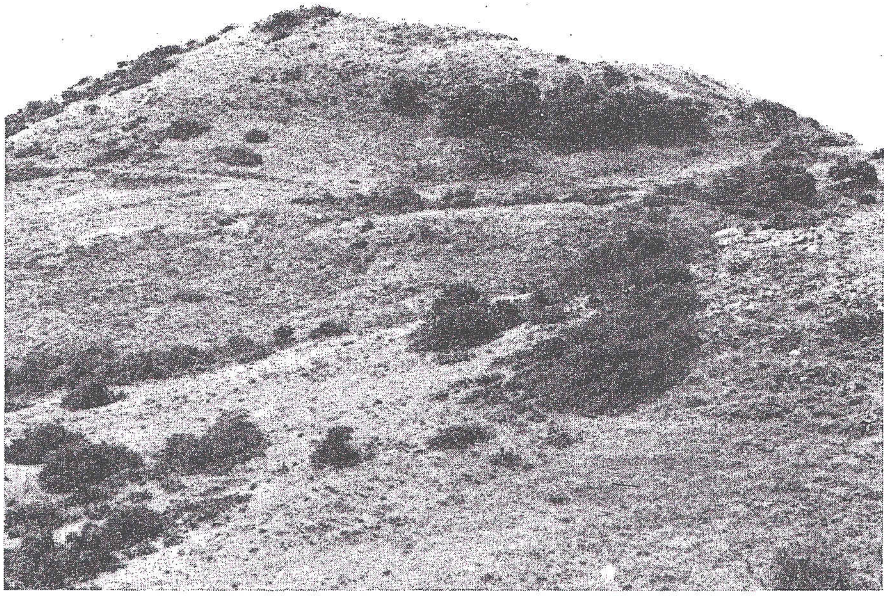


Photo 4. Serpentinite exposures northwest of the airport. The hill is capped by an eclogite that probably represents tholeiitic basalt subducted to a depth of 35-40 km and tectonically incorporated into the peridotite (now serpentinite) of the subduction zone's hanging wall.

Additional postmetamorphic underthrusting resulted in a variety of ductile and brittle responses, including folding of the entire zoned complex (Figure 2c) and displacement along the Ollas thrust (Figure 2d). Tertiary(?) normal faulting (Figure 2e), tilting, uplift, and erosion (Figure 2f) complete the scenario. Metamorphic overprinting within the Catalina blueschist facies rocks suggests that they formed at deeper structural levels (higher pressures) than did the other two units (Sorensen, 1984a and b). The blueschists, therefore, may have had a different history of uplift.

EARLY TERTIARY: STABLE FOREARC BASIN

Cretaceous (?) and Lower Tertiary Sedimentary Rocks

At East End Quarry, located at the eastern tip of the island (Photo 5), three sedimentary units are exposed (Vedder and others, 1979). The sediments were intruded by Miocene dacitic and gabbroic dikes and sills, which greatly obscure the sedimentary record. The upper part of this poorly preserved section is a Miocene breccia which some workers have assigned to the San Onofre Breccia (*Tsob*, Figure 1). Two pre-middle Miocene units occur below the Miocene breccia, neither of which has been named or studied in detail, although thin section descriptions are provided by Vedder and others (1979, Table 1).

The lower of the two pre-middle Miocene units is composed of interbedded siltstone, quartzofeldspathic sandstone, and conglomerate. Lithic fragments are of granitic, volcanic, and metamorphic origin, and they do not include detritus derived from the Catalina Schist. The age of these presumably marine sediments is not precisely known, but they resemble Upper Cretaceous sequences in the Santa Ana and Santa Monica mountains. The siltstones in this lower unit contain burrows that are similar to those that occur in Lower Cretaceous through Eocene strata elsewhere in southern California (Vedder and others, 1979).

Overlying these marine sediments is a sequence of nonmarine redbeds consisting of sandstone, pebble-cobble conglomerate, and minor mudstone. As with the underlying marine rocks, these were not derived from the Catalina Schist. These pre-middle Miocene redbeds may be correlative with the nonmarine upper Eocene to lower Miocene Sespe Formation of the Los Angeles Basin (Vedder and others, 1979).

Paleogene Paleogeography

An Eocene unit that is conspicuously absent on Santa Catalina is the Poway Conglomerate. This distinctive conglomerate, which consists of 80-90 percent porphyritic rhyolite and 10-20 percent quartzite clasts, occurs in the San Diego area and on San Miguel, San Nicolas, and Santa Rosa islands (Howell and others, 1974). This distribution, along with paleocurrent data, led Howell and others (1974) to reconstruct the middle Eocene paleogeography shown in Figure 3 (see also Howell and Link, 1979, Figure 3B). The general absence of Eocene sediments from the inner borderland (Crouch, 1979) supports the interpretation that this area was a submarine high during the Early Tertiary. The recently discovered nonmarine sediments at East End Quarry, described above, are compatible with the reconstruction shown in Figure 3, and they document a previously unknown episode of subaerial deposition in the inner borderland during the Early Tertiary.

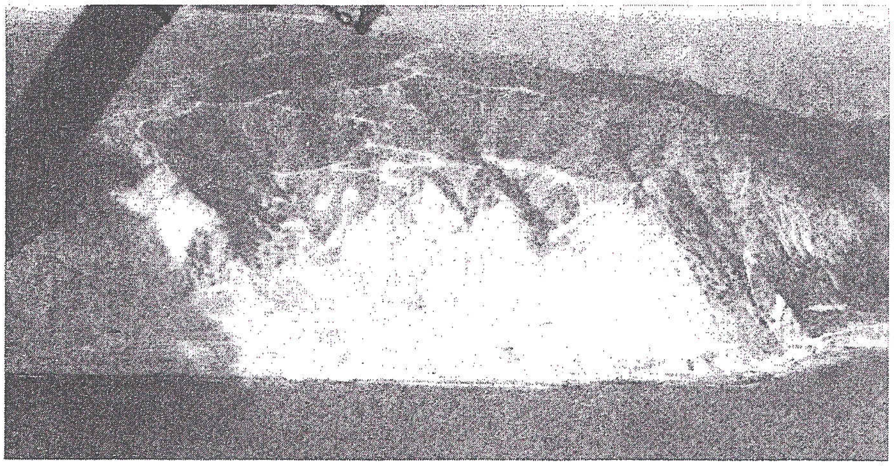


Photo 5. East End Quarry at the southeastern end of Santa Catalina Island.

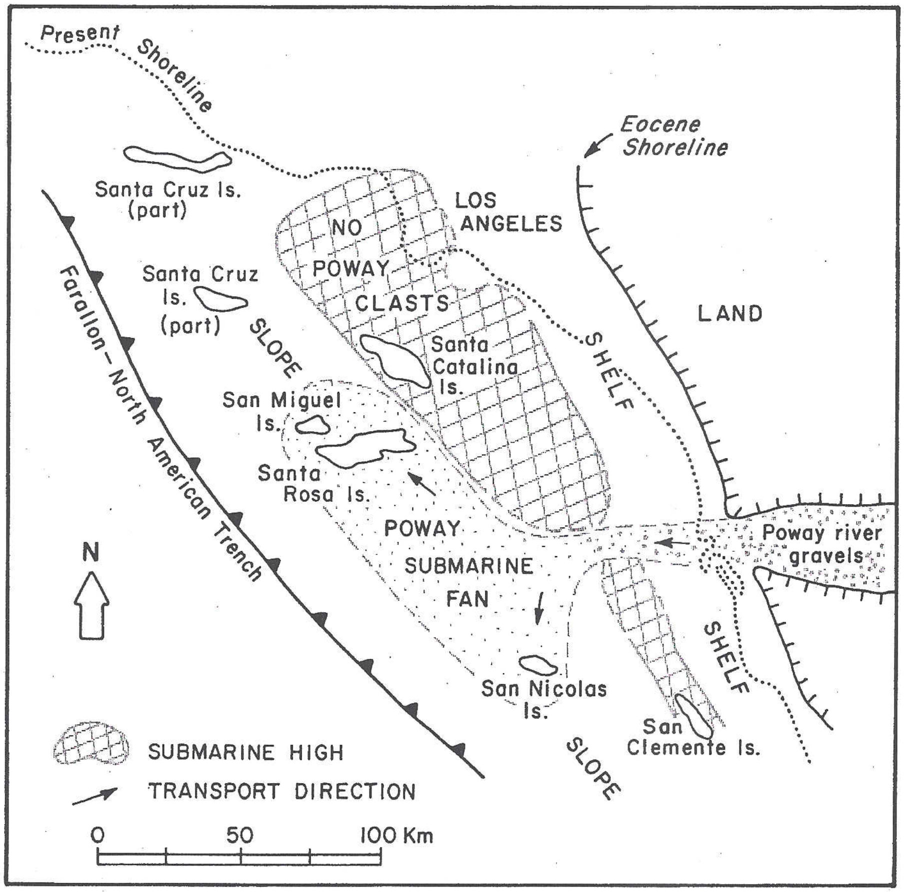


Figure 3. Reconstructed Eocene paleogeography of the continental borderland. *After Howell and others, 1974.*

The striking feature of Figure 3, in addition to the absence of known Eocene deposits in the inner borderland, is the location of San Nicolas, Santa Rosa, San Miguel, and Santa Cruz islands. In order to account for the distribution of Poway Conglomerate clasts (and age-equivalent turbidite sands on Santa Cruz Island), these islands are all placed southeast of their present positions. The borderland Poway Conglomerate occurrences are seen as remnants of a bathyal submarine fan whose submarine canyon breached the high-standing inner borderland. Howell and others (1974) used this palinspastic reconstruction to argue for 120-160 km of right-lateral, strike-slip faulting in the borderland. Their putative East Santa Cruz Basin fault system runs just to the west of Santa Catalina Island, along the edge of the cross-hatched region on Figure 3.

Figure 3 is just one of several proposed Eocene reconstructions for the borderland. Crouch (1979), for example, imagined several hundred km of post-Eocene, strike-slip faulting, rather than the 120-160 km of Howell and others (1974). Yeats and others (1974), using a slightly different definition of the Poway Conglomerate, hypothesized several "small Poway-bearing microplates" undergoing east-west spreading, with no northwest-southeast, strike-slip faulting at all. In spite of such varying models concerning the precise Early Tertiary positions of portions of the present-day borderland, there is general agreement that during the Early Tertiary this region was a broad, stable, forearc basin above the eastward subducting Farallon plate (Howell and others, 1980) (Figure 4).

EARLY AND MIDDLE MIOCENE: VOLCANIC ARCHIPELAGO

The Catalina Pluton: A Lower Miocene Quartz Diorite Stock

The oldest-known Miocene rocks on Santa Catalina are quartz diorites of the Catalina pluton, which has yielded a K-Ar date of 19 million years (early Miocene) (Forman, 1970). This pluton is exposed throughout most of the southeastern portion of the island (Figure 1). Although highly variable, most samples are porphyritic, with plagioclase (altered to kaolin and calcite) and hornblende (altered to chlorite) phenocrysts in a medium- to fine-grained groundmass (Bailey, 1967). In the southeastern exposures of the pluton, the intrusion consists of swarms of subparallel, nearly vertical dikes of variable color, composition, and texture (Vedder and others, 1979).

Even though the main intrusion evidently occurred in the early Miocene, Vedder and others (1979) suggested that this was the beginning of a 4-5 million-year-long episode of diorite-dacite intrusions that persisted into middle Miocene. They interpreted the 14-15 million-year-old dacites of the Fishermans Cove area to be late-phase extrusions from the Catalina pluton. This interpretation of long-lasting, dacite-diorite igneous activity is supported by the presence of dacite clasts in the middle(?) Miocene San Onofre Breccia at East End Quarry. This

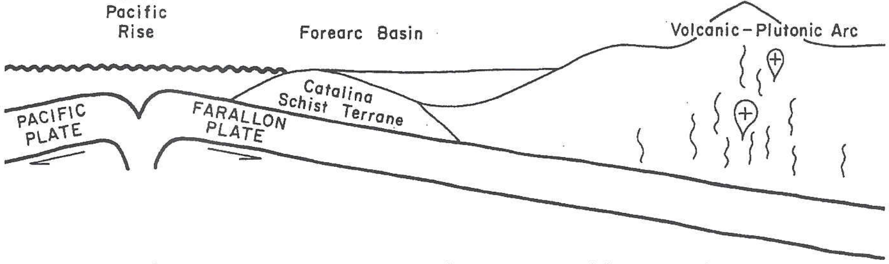


Figure 4. Schematic cross section through southern California and Nevada during the Early Tertiary. *After Dott and Batten, 1981, Figure 16.24.*

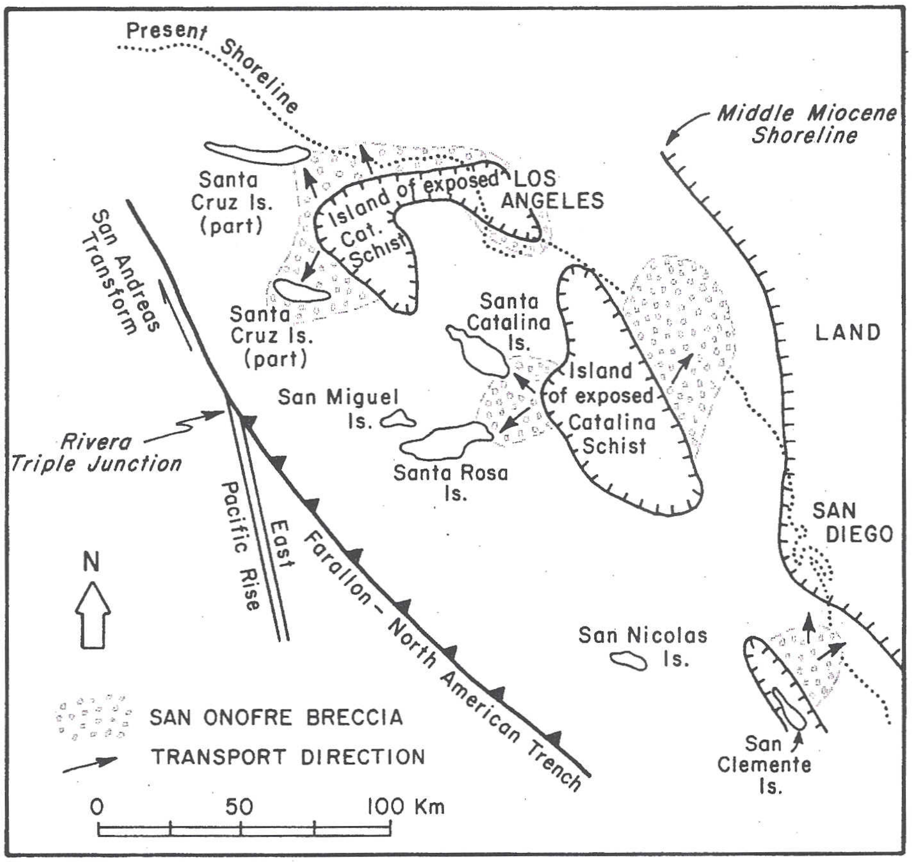


Figure 5. Reconstructed paleogeography of the borderland during deposition of the San Onofre Breccia (early and middle Miocene). Locations of islands are shown for reference; they were not islands at the time. *After Howell and others, 1974.*

breccia was intruded by dacite dikes with modal composition similar to that of the clasts (Vedder and others, 1979). Probably early Miocene dacite was eroded, redeposited, and then intruded in the middle Miocene by dacite from the same magmatic source.

San Onofre Breccia

The San Onofre Breccia is a lower and middle Miocene unit that crops out in coastal areas of southern California and northwestern Baja California, as well as on several islands in the California borderland. It characteristically contains a high percentage of glaucophane schist clasts, which are thought to be derived from the Catalina Schist terrane (Woodford, 1925; Howell and others, 1974; Stuart, 1979). Although the Catalina Schist is presently exposed above sea level only on Santa Catalina and on the Palos Verdes Peninsula, the widespread distribution of San Onofre Breccia indicates that in the early and middle Miocene, Catalina Schist exposures were much more extensive (Figure 5).

Two areas on Santa Catalina contain schist breccias that are probably part of the same erosional episode as the San Onofre Breccia. The first is at East End Quarry at the eastern end of the island (mapped as Tsob on Figure 1). Boulders of this breccia are used as riprap in Avalon Harbor, where they may easily be examined (Photo 6). Although this breccia has been correlated with the San Onofre Breccia by Woodford (1925) and Stuart (1979), the characteristic glaucophane schist clasts are conspicuously rare. The clast composition in the breccia at East End Quarry includes quartz schist, amphibolite, actinolite schist, tremolite(?) schist, talc schist, saussuritized gabbro, vein quartz, aphanitic to porphyritic siliceous metavolcanic rocks, porphyritic basalt, and feldspathic sandstone (Vedder and others, 1979).

Because of the presence of large (up to 30 cm), angular, disoriented clasts and the occurrence of some lenses that are nearly monolithologic, a nearby source area is suggested. Additional evidence that this breccia was locally derived is the presence of dacite clasts, which become increasingly abundant upsection.

Because of the absence of glaucophane clasts and the presence of volcanic clasts in the East End Quarry breccia, Vedder and others (1979) suggested that assigning these rocks to the San Onofre Breccia obscures important lithologic differences; they more closely resemble portions of the Blanca Formation on Santa Cruz Island.

The second occurrence of schist breccia on Santa Catalina is in the Fishermans Cove area (immediately to the right of the word "Isthmus" on Figure 1). As at East End Quarry, the volcanic clasts become more abundant upsection (Figure 6). Unlike the East End Quarry breccia, however, schist clasts include abundant blueschists, as well as greenschists. These breccias were, in places, deposited directly on a middle Miocene dacite dome and on exposed Catalina Schist. They are, in turn, overlain by middle Miocene andesites. There is little doubt that they were locally derived in a high-relief setting (Vedder and others, 1979).

The Fishermans Cove breccias, being sandwiched between lower middle Miocene volcanic rocks, are, therefore, lower middle (Luisian) Miocene in age. The

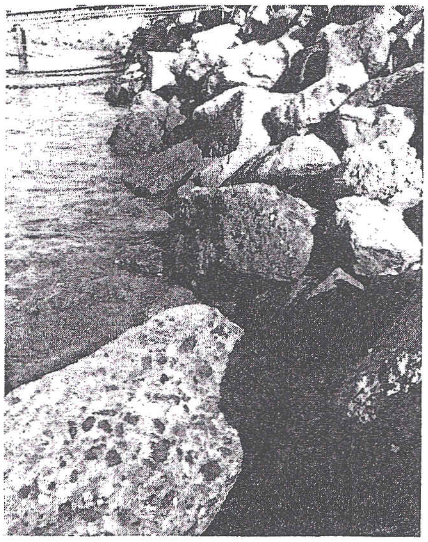


Photo 6. Boulders of San Onofre Breccia from East End Quarry used as riprap in Avalon Harbor.

East End Quarry breccia cannot be dated as precisely. It contains probable lower Miocene dacite clasts and could be slightly older than the breccias of the Fishermans Cove area.

Middle Miocene Paleogeography

The San Onofre Breccia has been interpreted to be a series of alluvial fan and coarse-grained marine deposits that were eroded off of a Catalina Schist source area (Stuart, 1979). Present distribution and inferred transport direction of San Onofre Breccia on the southern California mainland is shown on Figure 5, along with the reconstructed occurrence of San Onofre Breccia in the borderland; however, the middle Miocene positions of present-day San Nicolas, Santa Rosa, San Miguel, and southwestern Santa Cruz islands are in dispute (as discussed in the section on Paleogene Paleogeography). Much of the inner borderland, with its Catalina Schist basement, was exposed during the deposition of the San Onofre Breccia (Stuart, 1979, Figure 15). The absence of glaucophane schist clasts in the East End Quarry breccia is puzzling, but presumably indicates that a portion of this exposed metamorphic source area was lacking in blueschist-facies rock.

Middle Miocene Volcanic and Sedimentary Rocks

Volcanic rocks, chiefly of andesitic and dacitic composition, cover approximately one-quarter of Santa Catalina Island (Figure 1, Photos 7 and 8). These rocks are the remnants of a small volcanic archipelago (Vedder and others, 1979). The exposures east of Isthmus Cove have been studied by Vedder and others (1979), and those in the central part of the island by Wood (1981). The volcanic rocks on Santa Catalina are probably all middle Miocene in age (K-Ar dates are 12-15 m.y.), apparently representing a 3-4 million-year-long episode of volcanism.

The volcanic stratigraphy for the island is shown in Figure 6. Formation names have not been assigned, and individual eruptive units have not been mapped. In the Fishermans Cove area (east of Isthmus Cove) schist-dacite breccia lenses (described above) directly overlie a 14-15 million-year-old dacite dome. Another dacite dome about two miles south-southeast of the airport forms Black Jack Peak (Wood, 1981). Both dacite domes have brecciated carapaces and are interpreted to be surface effusions of viscous lava (Vedder and others, 1979; Wood, 1981).

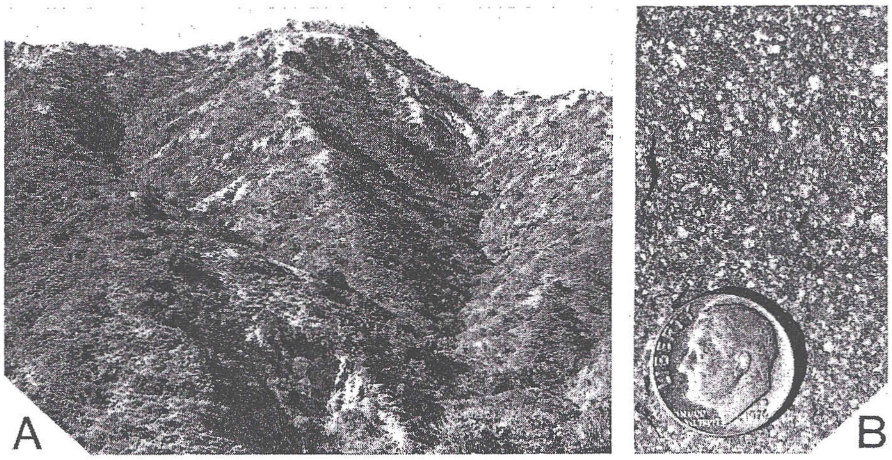


Photo 7. A. Whitleys Peak, about 3 miles northwest of Avalon (looking north). The area of the upper landslide scarp is a blocky dacite flow, the remainder of photo is andesite and basaltic andesite (Wood, 1981). B. Hand specimen of basaltic andesite from Whitleys Peak area. Phenocrysts are plagioclase (labradorite) and a three-pyroxene assemblage of hypersthene, augite, and pigeonite (Wood, 1981).

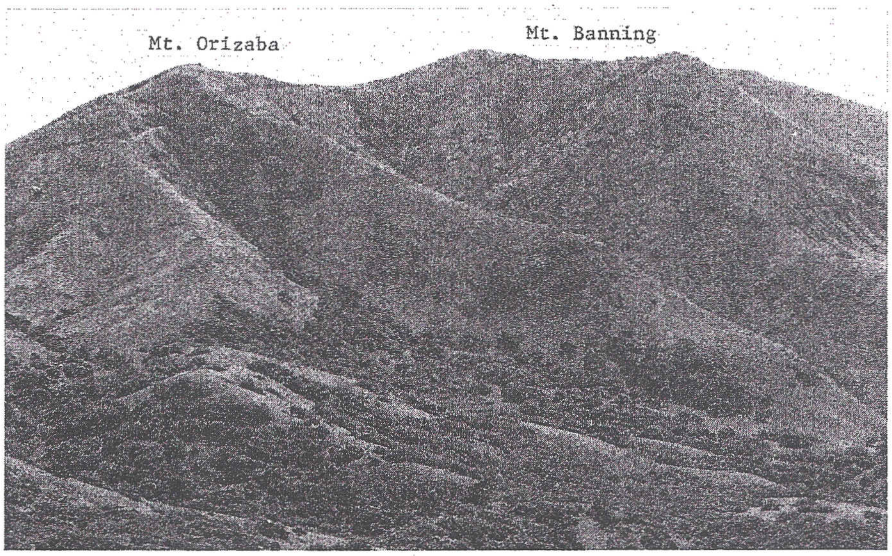


Photo 8. View southwest from airport toward Mt. Orizaba - Mt. Banning area. Most of this area is underlain by andesitic and dacitic flows. The right-hand knob of Mt. Banning is composed of fossiliferous, calcareous, volcaniclastic sandstone, which is late middle or late Miocene (Mohnian) in age and indicates a rocky, inner sublittoral environment (Vedder and others, 1979).

The remainder of the volcanic sequence, although dominated by andesite and basaltic andesite flows and flow breccias, also includes minor olivine basalt and rhyolite (Figure 1). The volcanic section in the central part of the island is over 400 meters thick (Wood, 1981).

A variety of middle Miocene sedimentary rocks occur within the volcanic sequence (Figure 6). In the Fishermans Cove area, these are volcaniclastic breccias (Photo 9), tuffaceous shales and claystones that locally occur in beds up to 20 meters thick. Fossils in the shales and

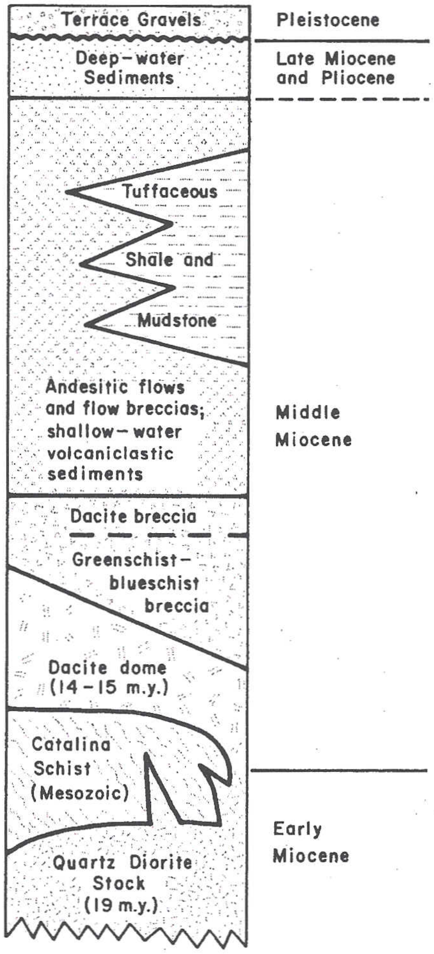


Figure 6. Generalized stratigraphic column of the Cenozoic rocks exposed in the central part of Santa Catalina Island. No scale implied and highly schematic. *After Howell and others, 1979, Figure 2.*

Photo 9. Middle Miocene volcaniclastic sediments in Fishermans Cove.

claystones include diatoms, foraminifera, smelt and herring scales, and a variety of molluscs. All of these fossils are middle Miocene, which corroborates the middle Miocene K-Ar dates of the volcanic rocks. Furthermore, the fossils indicate sublittoral (continental shelf) environments with water depths no greater than 200 meters and in some cases probably shallower than 30 meters (Vedder and others, 1979).

Coarser-grained, volcaniclastic sediments occur in association with andesites on Mt. Banning (Photo 8) and in the region southeast of Little Harbor (Figure 1). One outcrop 2 miles south-southwest of Mt. Banning is limy sandstone (shown as "limestone" on Figure 1). These coarser sediments are locally very fossiliferous, with sea urchin spines, ostracodes, foraminifera, bryozoa, barnacles, brachiopods, snails, and clams (Vedder and others, 1979). These fossils are also middle Miocene in age and indicate shallow, inner-shelf, locally rocky environments.

Middle Miocene Plate Tectonic Setting

The middle Miocene volcanic rocks on Santa Catalina are typical of those in the southern California borderland. Nearly continuous submarine volcanic exposures occur all the way to Patton Ridge near the western edge of the borderland. There have been two plate tectonic interpretations of these rocks (Vedder and others, 1981; Wood, 1981). The first is that they represent an island-arc sequence produced by partial melting of the subducting Farallon plate. Alternatively, it has been suggested that this middle Miocene volcanic pulse was caused by partial melting of the upper mantle related to the proximity of the East Pacific Rise (Hawkins, 1970).

The volcanic rocks in the central part of the island cannot be unambiguously classified as either calc-alkalic or tholeiitic (Wood, 1981). The basalts and basaltic andesites have tholeiitic characteristics, while the andesites and dacites indicate a calc-alkalic series. This ambiguity is most compatible with an island arc interpretation because island arcs often begin erupting tholeiitic magma and conclude with calc-alkalic magma. This phenomenon is not typical of mid-ocean ridge volcanism. Also the abundance of hypersthene andesite, which makes up about 35 percent of the volcanic rocks, is very typical of island arcs. However, other petrographic and geochemical aspects (low K_2O and moderately high TiO_2 compositions) are not typical of arc settings and lend support to the interpretation that these rocks were derived from undifferentiated mantle material.

Based on the geology and tectonics of the entire southern California borderland there are three arguments against the island-arc interpretation (Vedder and others, 1981). The first is that middle-Miocene, intermediate-composition volcanic rocks are too widespread in the borderland to have been derived from a subduction zone. Secondly, some of these rocks (on Patton Ridge) are within 20 km of the ancestral Farallon-North American trench—anomalously close for an island arc. And last, the youngest oceanic crust off the southern California borderland is approximately 17 million years old (uppermost lower Miocene). Thus, it appears that most of the volcanic rocks in the southern California borderland formed after sea-floor spreading and subduction off the coast of southern California had already ceased. In rejecting the island-arc interpretation, Vedder and others (1981) invoked the proximity of the ancestral East Pacific Rise as the volcanic source.

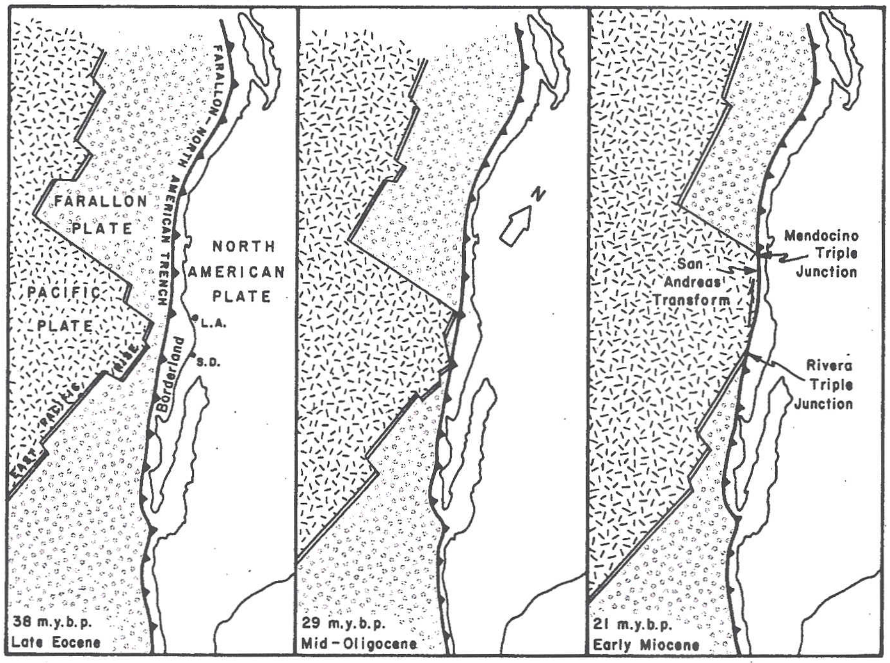


Figure 7. Plate interactions for three Tertiary intervals. Schematic diagram showing the relative positions of the North American, Farallon, and Pacific plates from late Eocene to early Miocene time. The first contact between the East Pacific Rise and the Farallon-North American trench was made about 29 million years ago (mid-Oligocene), and it occurred off the coast of southern California (Dickinson, 1979). It was at this point that subduction began to cease and the San Andreas transform (the offshore precursor of the San Andreas fault) was created. This transform lengthened southward and northward, at the expense of the East Pacific Rise, as the North American plate drifted westward *After Crouch, 1981.*

The first contact between the East Pacific Rise and the Farallon-North American trench occurred about 29 million years ago (mid-Oligocene) off the coast of southern California (Figure 7) (Dickinson, 1979). At this point subduction ceased and the San Andreas transform (the offshore precursor of the San Andreas fault) was created. This transform lengthened southward and northward, at the expense of the East Pacific Rise, as the North American plate drifted westward. Because of the oblique angle between the East Pacific Rise and the North American plate, the Rivera triple junction traveled southward through late Oligocene and Miocene time presumably accompanied by a wave of volcanism (Figure 7).

If the borderland's mid-Miocenc volcanic archipelago was produced by the proximity of the East Pacific Rise then these rocks were erupted at a more southerly latitude than present-day Santa Catalina Island. When the San Andreas transform shifted inland to form the San Andreas fault, in the late Miocene or early Pliocene, the Santa Catalina block was transferred from the North American to the Pacific plate and began a northward journey. During the following 5-6 million years, up to the present time, this block has probably traveled approximately 250 km northward as part of the Pacific plate (Wood, 1981). In the middle Miocene, therefore, it was located at the latitude of northern Baja California, where the southward migrating Rivera triple junction did not arrive until about 15 million years ago.

LATE MIOCENE TO THE PRESENT: VERTICAL AND WRENCH-FAULT TECTONICS OF THE BORDERLAND

Upper Miocene and Pliocene Sediments

Beneath the Quaternary terrace deposits on a ridge about 1 km southeast of Little Harbor are thin beds of tuffaceous sandstone and siltstone that have yielded upper Miocene and Pliocene fossils. Benthic foraminifers in the upper Miocene beds indicate a water depth of approximately 500-1,000 meters (mid-bathyal), and the Pliocene benthic foraminifers indicate lower bathyal to abyssal depths (1,000 m to more than 2,500 m) (Vedder and others, 1979).

These fossils document a late Miocene-Pliocene subsidence of the Santa Catalina structural block from near sea level to a depth of at least 1,000 meters, and perhaps twice that depth. This episode of subsidence was followed by one of uplift and subaerial exposure in the Pliocene or Pleistocene. During this Late Tertiary cycle of roller-coaster tectonics, the Santa Catalina block experienced vertical elevation changes at rates as high as one meter per thousand years (Howell and others, 1980).

Wrench Faulting and Clockwise Rotation

The initiation of vertical tectonics throughout the borderland in Late Tertiary time signaled the transition from a stable forearc basin to an unstable continental borderland. With the origin of the San Andreas transform (Figure 7), the western edge of the North American plate began to experience wrench faulting. A series of northwest-southeast-trending dextral faults divided the region into structural blocks. Northwestward lateral translation of these fault blocks within the incipient borderland resulted in the formation of lens-shaped ridges and rhomboid-shaped "pull-apart" basins (Howell and others, 1980).

As a result of the Pacific-North American right-lateral shear couple, many structural blocks within the borderland and western Transverse Ranges have undergone clockwise rotations of about 70° to 80° (Luyendyk and others, 1980). Santa Catalina has apparently rotated at least 60°. These rotations probably began in mid-Oligocene time, with the initiation of the San Andreas transform, and ended in late Miocene time, when right-lateral faulting was largely transferred onshore to the present San Andreas fault (Luyendyk and others, 1980; Dickinson, 1981).

Pleistocene Terraces

Santa Catalina lies midway between two areas in which Pleistocene terraces are spectacularly developed—the Palos Verdes Peninsula to the north and San Clemente Island to the south. In contrast to these neighboring borderland ridge crests, Santa Catalina is conspicuously impoverished with regard to marine terraces. This phenomenon was first noticed by Lawson (1893) who interpreted it as a "diastrophic anomaly," in which "Santa Catalina has not been subjected to the uplift which has affected the two prominent insular masses (San Clemente Island and the Palos Verdes Peninsula)." In a geology textbook published in 1931, the San Clemente-Santa Catalina-Palos Verdes distribution of marine terraces was described as follows: "Perhaps the most striking example of simultaneous opposite movements observable in neighboring portions of the earth's crust is furnished by the coast of southern California....Midway between...two rising sections of the crust, and less than twenty-five miles distant from either, is the island of Santa Catalina, which has been sinking beneath the waves, and apparently at a similarly rapid rate (Hobbs, 1931, p. 256-257)."

The diastrophic anomaly explanation was ultimately debunked by Smith (1933), who had published the first geologic map of Santa Catalina (Smith, 1897). He described a variety of geomorphic features on Santa Catalina—benches on ridges ("notched salients"), leveled summits, and an elevated embayment at Little Harbor—that together record successive episodes of marine planation and pulses of uplift. Smith explained the relatively poor development of these features as a product of hard rocks and a mature pre-Pleistocene topography. He concluded that "instead of differentiation there has been a remarkable uniformity in the general later Pleistocene movements of all the southern California islands and the neighboring mainland coast as well (Smith, 1933, p. 136)." Although there is no question about the general truth of Smith's interpretations, a recent review of the occurrences and elevations of emergent terraces in the southern California borderland clearly demonstrates that the rates of uplift have not been uniform (Vedder and Howell, 1980, Figure 9).

The most noteworthy Pleistocene feature preserved on Santa Catalina is the Little Harbor embayment. All of the ridges within a radius of about a mile from Little Harbor have flat crests. These ridges typically have a 200-300 foot cliff at their seaward ends, and they gradually rise to an elevation of about 700 feet over a distance of about 1 ¼ miles. One of these ridges, southwest of Little Harbor, is capped by terrace deposits (sandstone and conglomerate) up to a few meters thick (Figure 1). These flat-crested ridges define the former floor of the Little Harbor embayment (Smith, 1933).

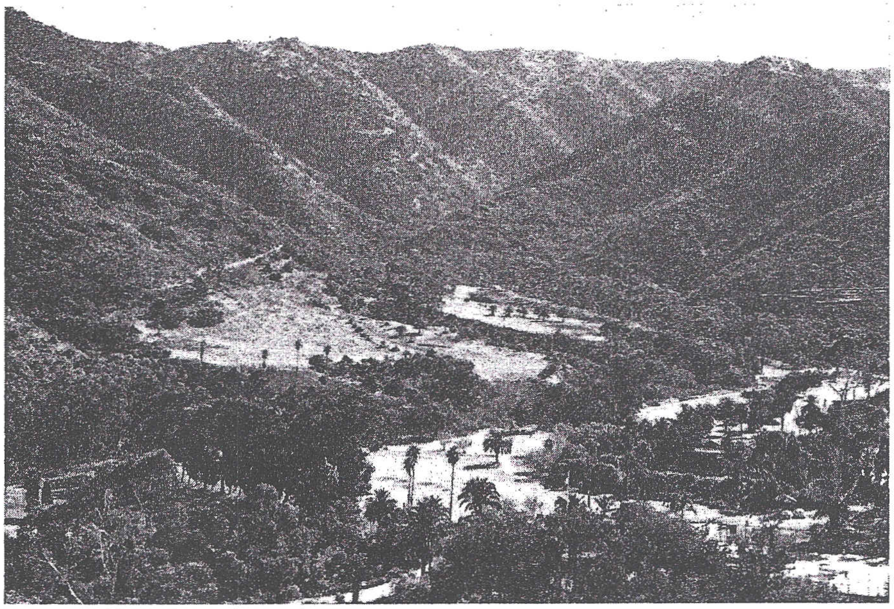


Photo 10. Dissected Pleistocene constructional terrace beneath a golf course in Avalon Canyon.

Dissected terrace deposits also occur southwest of Avalon in Avalon Canyon (Figure 1, Photo 10). This is a constructional terrace which probably formed when Avalon Canyon was flooded by the sea, before the island was tectonically lifted to its present level. The precise timing and magnitude of Quaternary uplift on Santa Catalina are not known and may be impossible to determine. There is no evidence that the Santa Cruz - Catalina Ridge was ever emergent enough for Santa Catalina to be subaerially connected to any other currently existing island or to the mainland.

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I thank Sorena Sorenson and Jack Vedder for helpful discussion. Any oversimplification of the interpretations of other workers is of course my responsibility. I thank John Klenke, Laura Deanne, and Gene Smith for their helpful comments on an early draft of the manuscript. And I thank Barney Pipkin for his encouragement and for generously flying me over Santa Catalina to take photographs.

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LETTER TO THE EDITOR

INVITATION TO GEOLOGISTS

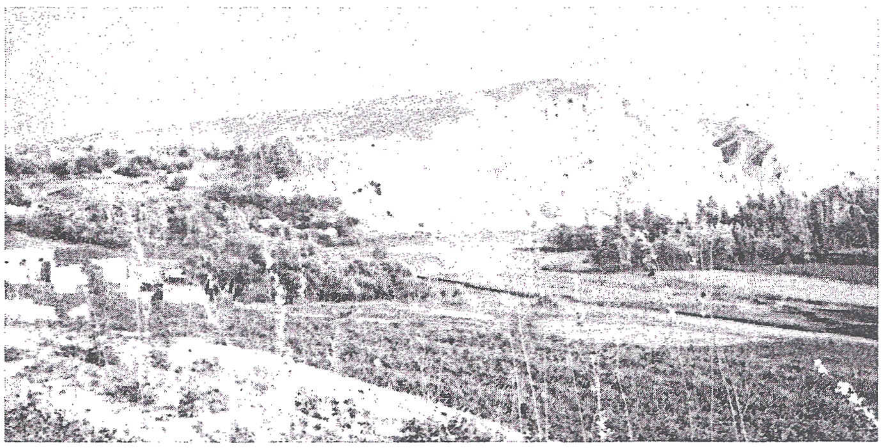
A wish from a Chinese geologist taking advantage of the visit of Mary C. Woods to Xinjiang, China with the American geology delegation. As a geologist in Xinjiang, I ask permission to extend a friendly and cordial regard through CALIFORNIA GEOLOGY to the geologists in California and in the United States and also a heartfelt wish that a friendly exchange of information be carried out effectively between us.

There is a striking resemblance between the natural landscapes, climate, landforms, and geological features of Xinjiang Uygur Autonomous Region and those of California. I have a firm belief that through friendly exchange programs we will bring about mutual benefit and future progress in our geological science.

Besides this, in Xinjiang there are many other spectacular and attractive geological and geomorphic forms in the region such as the Heavenly Lake, a well-known glacier fossil lake, the Flaming mountain as described in Chinese Legend, the unusual mountains and glaciers, and the beautiful gems and jades. You are heartily welcomed to come to Xinjiang for geological research and exchange purposes.

Professor Wang Gong Gue
Geology Department,
Xinjiang Engineering Institute
Urumqi, PRC

Xinjiang-Shanghai Geological
Travel Office



Turpan Depression, Xinjiang Uygur Autonomous Region, People's Republic of China.