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Late Cenozoic Sedimentation and Tectonics, Western Salton Trough, California

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Introduction

Cenozoic sedimentary and volcanic rocks exposed in the canyon walls and badlands along the western margin of the Salton Trough provide the most complete, best exposed, and most accessible stratigraphic record of the northern Gulf of California. These Cenozoic rocks have been the topic of many past studies [e.g., Woodring, 1932; Tarbet and Holman, 1944] (Figure 1); no doubt the complex stratigraphy, unusual paleontologic assemblages, and importance to the history of the Gulf of California have contributed to the long interest in this area.

These rocks have also been the subject of past field trips [e.g., Robinson and Threet, 1974; Crowell and Sylvester, 1979], as well as a favorite field trip site for colleges and universities. However, most visitors are offered only the exposures in Split Mountain Gorge and those along Fish Creek Wash. This trip includes stops that are some distance from the main travel path. The participant is, thus, given the opportunity to appreciate the complex facies relationships that characterize the upper Cenozoic fill of the Salton Trough.

The 6.5-km-thick upper Cenozoic rock record has a long and controversial history of stratigraphic nomenclature (Figure 1). The intent here is not to review nor propose new nomenclature, but instead to stress depositional facies relationships and interpretation; nomenclature is kept to a minimum. Particular emphasis is placed on the implication of the sedimentary, as well as volcanic, record for tectonic activity in the Trough, and how this constrains the evolution of the Gulf of California, of which the Salton Trough is its northern tectonic extension (Figure 2).

In this guidebook, and during the field trip itself, Dennis Kerr has taken responsibility for description and interpretation of the lower nonmarine part of the Cenozoic section (Figure 1). The marine and deltaic deposits (Figure 1) covered on days 2 and part of 3 have been the responsibility of Susan Kidwell, based on her own work and that of research collaborator Charles Winker [1987].

In Geological Excursions in Southern California and Mexico (M.J. Walawender & B.B. Hanan, eds.). Guidebook 1991 Annual Meeting Geological Society of America, San Diego, California, p. 397-416b (1991).

Geologic Setting

The Salton Trough straddles the transform boundary of the North American and Pacific Plates. The shallow crustal expression of this boundary is a system of right-lateral faults collectively called the San Andreas fault system; 300 km of right-lateral offset has been documented for the San Andreas system since Late Miocene time (Figure 2) [c.f., review in Crowell and Sylvester, 1979]. The 3 main fault zones of the San Andreas fault system form clear tectonic boundaries within the Salton Trough (Figure 2). The northwest trending San Andreas fault zone bounds the eastern margin of the Trough. The northwest trending, right-lateral San Jacinto and Elsinore fault zones pass through the Salton Trough in right-stepping, en-echelon arrangement (Figure 2). The Elsinore fault zone bounds the western margin of the Trough with 40 km of offset, whereas, the San Jacinto fault zone, with 30 km of offset, courses through the middle of the Salton Trough and has highly variable vertical separation across its many fault segments.

From geophysical surveys, and location of geothermal and recent volcanic centers, two north-oriented spreading centers have been identified (Figure 2) [Fuis and Kohler, 1984]: one extending from the south part of the Salton Sea to under Brawley, and the other under Cerro Prieto, 20km south of the international border. Each spreading center is connected by transform faults that occur along trend with the en-echilon fault zones of the San Andreas system.

In addition to the right-lateral faults discussed above, a number of other structures are developed along the western Salton Trough. Perhaps the most pronounced are expressed geomorphically by tall escarpments, and by the juxtaposition of crystalline basement rocks against upper Cenozoic sedimentary rocks. Such great vertical separation is found along segments of northwest strike-slip faults (e.g., Elsinore fault zone, stop 3-1), along north-northwest- to north-trending faults, and along the northeast trending faults flanking the southeast sides of the Vallecito and Fish Creek Mountains (stops 1-6 and 3-1). Folds with west-northwest to east-southeast plunging anticlinal axes are present in much of the Quaternary and

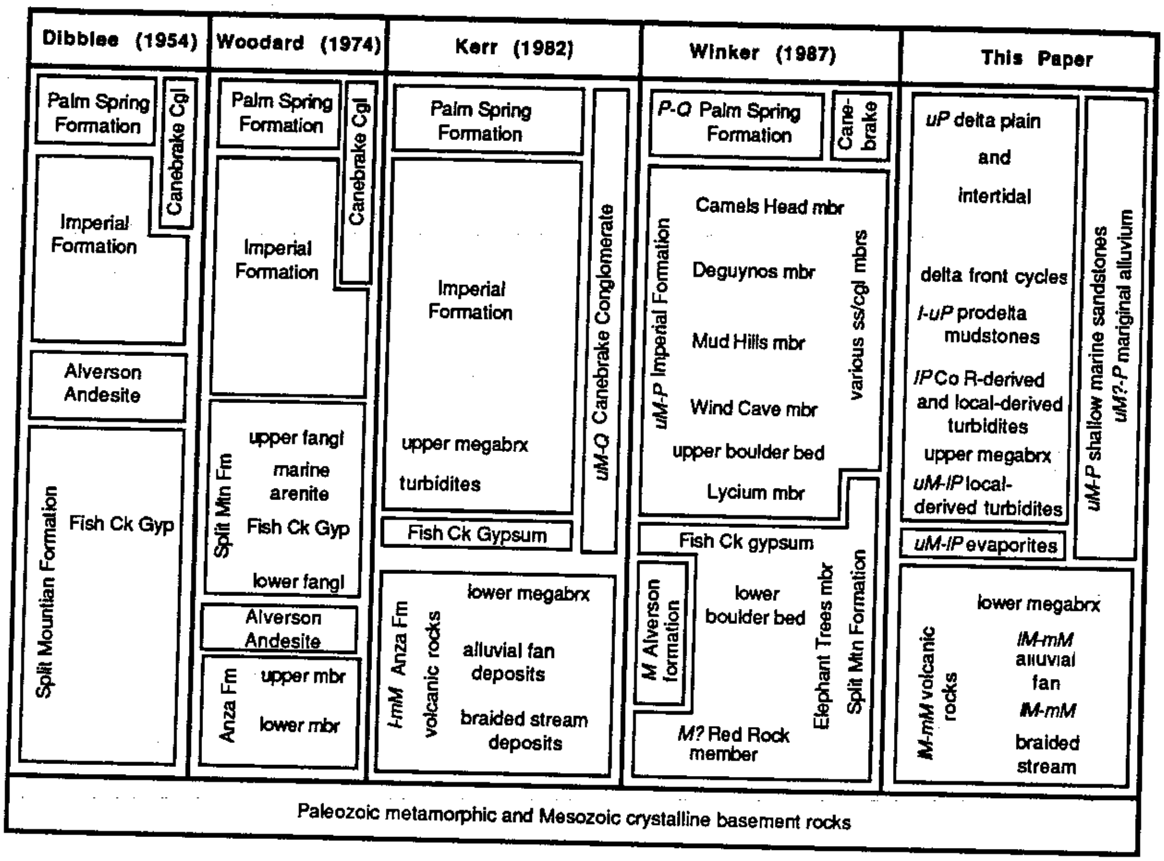

Fig. 1. Partial synonymy of informal and formal (capitalized) stratigraphic nomenclature for the late Cenozoic of the western Salton Trough, California. For a more complete synonymy see Winker [1987].

some Pliocene rocks. Such axial configurations are compatible with the shear strain of the San Andreas system; however, some folds involving older Cenozoic rocks have axes oriented to the northwest-southeast (e.g., Split Mountain anticline, Figure 3). Either compressional stress orientation has changed with time or parts of the western Salton Trough have undergone rotation since Miocene time; paleomagnetic studies offer evidence that rotation up to at least 35 degrees in a clockwise direction has occurred since the late Pleistocene [Johnson et al., 1983], and perhaps greater clockwise rotation since the Miocene [Mace, 1981].

Basement rocks, not visited directly during this trip but seen as detrital material in Cenozoic conglomerates, are predominantly Cretaceous batholithic rocks and metamorphosed Paleozoic sedimentary rocks. Batholithic rocks are mostly of tonalite composition, although composition can vary locally. Spotted tonalite, composed of plagioclase-quartz-sphene "spots" in a biotite, plagioclase and quartz matrix, are particularly common to the Vallecito Mountains. Marble and biotite-quartz gneiss are particularly common in the basement complex of the Coyote Mountains and in a fault-bounded block in the northern extreme of the Fish Creek Mountains.

The early Cenozoic history of the southern California Peninsular Ranges has been interpreted as a time with mature erosional topography development [Minch, 1979]. This paleotopography is characterized by broad pediment surfaces with local protrutions of basement rock. Coarse gravels of extraregional (derived from Sonora, Mexico; Figure 2) [Abbott and Smith, 1978] rhyolite and metasedimentary clasts were transported westward through deep valleys incised into these mature surfaces. Such paleotopography is preserved along the western Salton Trough [c.f., geologic map of Kerr, 1982]. To the east and west of Split Mountain the sub-upper-Cenozoic section nonconformity has low relief; at Split Mountain, however, Miocene rocks rest with high-angle buttress nonconformity against basement rock. The base of the Miocene section, here, includes an extraregional clast population strongly diluted with detritus from the local basement complex. Such diluted clast populations and high-angle nonconformities are characteristic of deposits that are regarded as reoccupied fill of early Cenozoic incised valleys [Abbott et al., 1983].

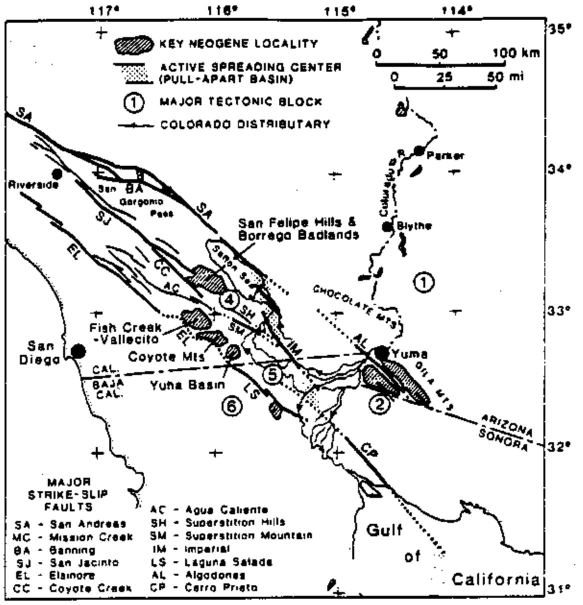

Figure 2. Location of the Fish Creek-Vallecito area (days 1 and 2) and the Coyote Mountains (day 3). Relationship of field trip area to San Andreas fault system, northern Gulf of California, Colorado River and delta, and other Neogene localities is shown.

LOWER TO MIDDLE MIOCENE ROCKS

Braided Stream Deposits

Lower to Middle Miocene braided stream deposits (Figures 1 and 4) crop out in the core of the Split Mountain anticline (Figure 3; Stop 1-2b), and the south flank of the Fish Creek Mountains. Lesser areas of outcrop are found in the Coyote Mountains (Stop 3-1) and at Superstition Mountain [Kerr, 1982]. Conglomerates and coarse-grained sandstones of the braided stream deposits rest nonconformably on crystalline basement rock throughout the western margin of the Salton Trough. They are overlain in turn either by Lower to Middle Miocene volcanic rocks or Miocene alluvial fan deposits. Locally, braided stream deposits are interstratified with alluvial fan (Stop 1-2b) or volcanic lithologies. In addition, these strata also include volcanic clasts derived from Miocene volcanic rocks (Figure 1) [Woodard, 1974; Gastil et al., 1979]. Thus, the braided stream deposits are, at least in part, the lateral equivalent to the volcanic rocks that are dated to be Early to Middle Miocene in age [Ruisaard, 1979; Mace, 1981].

Large-scale lenses, each containing thinning-upward stratification, are conspicuous [Kerr, 1984]. Maximum lens thickness is 6m at Split Mountain and 1m in the southern Fish Creek Mountains. Upper fill of one lens merges laterally with that of an adjacent lens. Where lens are defined by erosional contacts, the width to depth ratio is 28:1 at Split Mountain and 70:1 in the southern Fish Creek Mountains. Thus, braided stream channel-fill deposits are narrower and deeper at Split Mountain than in the southern Fish Creek Mountains.

Kerr [1982; 1984] interpreted these Miocene rocks as the deposits of a broad, braid plain draining westward off the backtipped half graben developed in the southern Fish Creek Mountains area. This drainage connected with a graben-axis-parallel system, which drained northward, at Split Mountain. The axial drainage system received sediment from the southern Fish Creek Mountains (e.g., Lower to Middle Miocene volcanic clasts), reworked early Cenozoic valley-filling gravels, and crystalline basement rock via adjacent alluvial fan systems. Although of only limited exposure, the deposits at Superstition Mountain and Coyote Mountains appear to be compatible with axial drainage systems.

Winker [1987] regarded the braided stream deposits (name of this report; c.f., Figure 1) as the filling of an integrated drainage system incised into the crystalline basement. The extraregional clasts found in this valley fill are similar to the Eocene Ballena (San Diego area, and Vallecito Mountains) and Table Mountain (Jacumba area) Gravels. Because the lower age of these valley filling deposits is unconstrained, these deposits could be as old as the Eocene gravels.

Alluvial Fan Deposits

Red to reddish-brown alluvial fan deposits are the oldest strata exposed in Split Mountain Gorge itself, and comprise about 180 m of section (Figures 3 and 4). Alluvial fan deposits crop out from the faulted eastern front of the Vallecito Mountains (4 km west of Split Mountain) to about 2.5 km southeast of Split Mountain Gorge where they lie in high-angle buttress nonconformity with crystalline basement rocks (Figure 3) [Kerr, 1982]. In the Split Mountain area, these deposits consist of monomictic matrix- or framework-supported boulder conglomerates that are interstratified with pebbly coarse sandstones with detritus clearly derived from the local crystalline terrane. At the mouth of Split Mountain Gorge (Figure 3), as well as other localities (e.g., Superstition Mountain and Volcanic Hills) [Fourt, 1979; Ruisaard, 1979; Kerr, 1982], the alluvial fan deposits also contain clasts derived from Miocene volcanic rocks. Alluvial fan deposits also occur interstratified with Miocene volcanic rocks in the Volcanic Hills, Superstition Mountain, and extreme northwestern Coyote Mountains. Thus, as also seen with braided stream deposits, the alluvial fan deposits are approximately coeval with the Lower to Middle Miocene volcanic rocks [Kerr, 1982, 1984].

The alluvial fan deposits at Split Mountain have been divided into three subfacies based on stratification and relative proportion of channel-fill, debris flow and sheetflood strata [Kerr, 1984]. Each subfacies is related

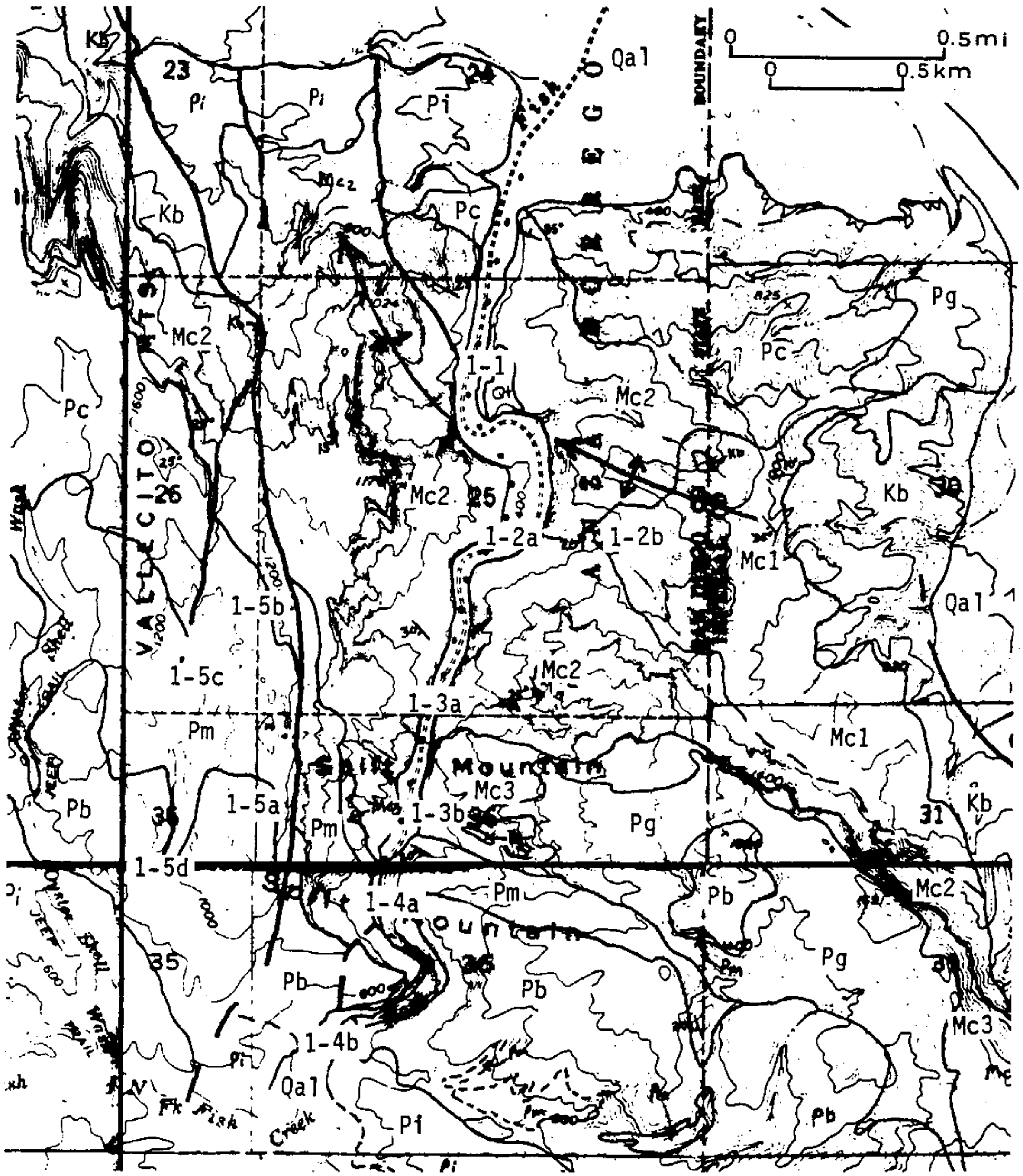

Figure 3. Geologic map of the Split Mountain area showing day 1 field trip stops (hyphenated numbers). Kb = crystalline basement rock; Mc1 = Lower to Middle Miocene braided stream deposits; Mc2 = alluvial fan deposits; Mc3 = lower megabreccia; Pc = Upper Miocene to Lower Pliocene alluvial fan deposits; Pg = evaporites; Pm = marine shallow-water and turbidite sandstones; Pb = upper megabreccia; Pi = undifferentiated Pliocene marine deposits; and Qal = Quaternary alluvium and, locally, terrace deposits (see Figure 1). Geologic map from Kerr [1982].

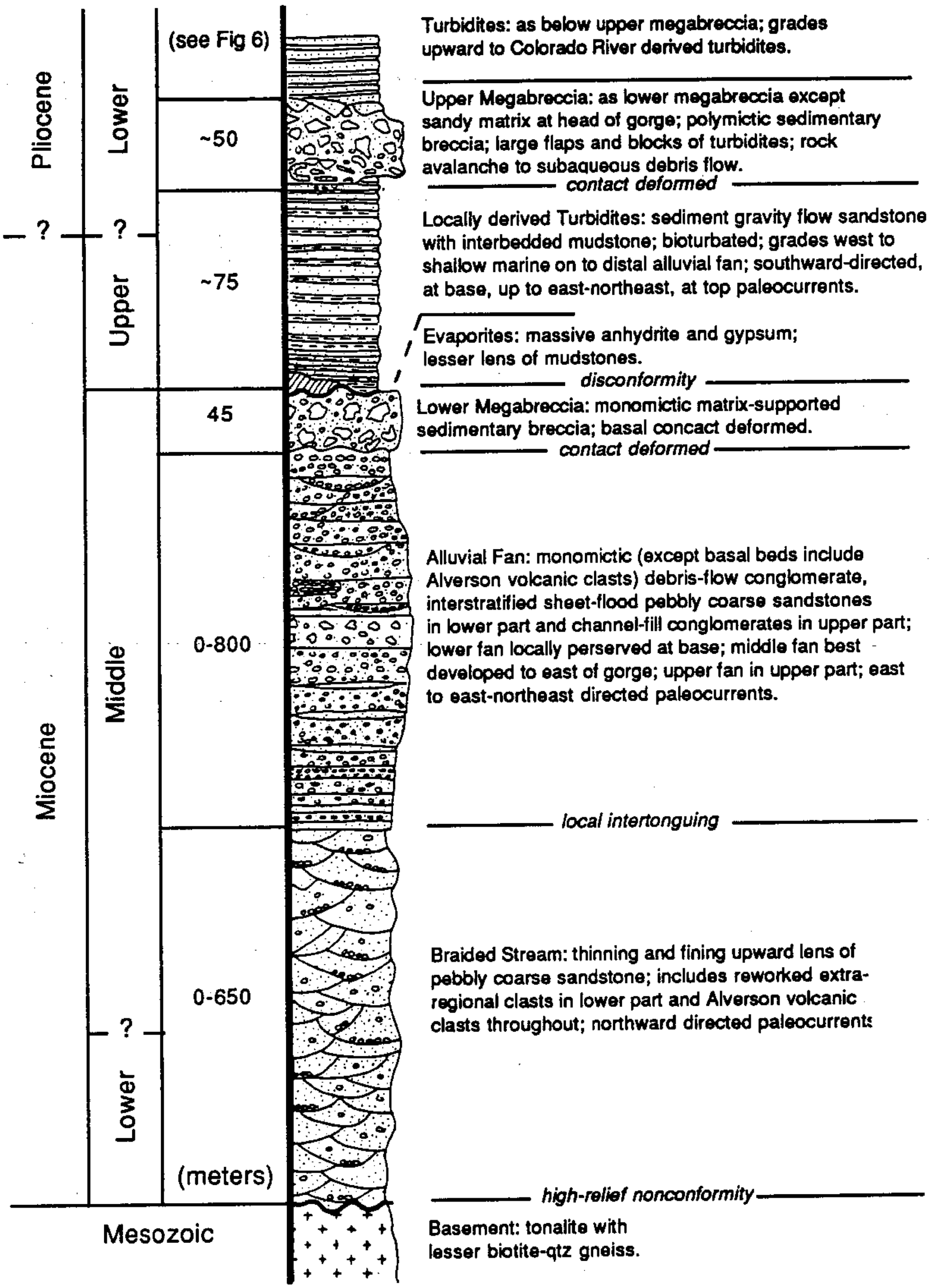

Figure 4. Generalized stratigraphic section for field trip day 1. Graphic column modified from Kerr et al. [1979].

to an inferred geomorphic location for its deposition. The upper fan (deposition occurring above the fan intersection point) is dominated by channel erosion and filling with the deposits of traction, hyperconcentrated, or debris flow processes (Stops 1-1 and 1-3a). The middle fan (deposition immediately below the intersection point) is characterized by laterally persistent, thick (up to 12 m) debris flow interstratified with thin (1 m) sheetflood sandstones (Stops 1-1 and 1-2b). The lower fan (the most distal fringe) is marked by thin (up to 1.3 m) debris flow or mudflow deposits interstratified with thin (0.5 m) sheetflood sandstones and, less commonly, with deep, narrow channel-fill conglomerates and sandstones (Stop 1-2a). The lower fan is only locally present along the contact with the underlying braided stream deposits; this may be because the braided stream axial drainage clipped the toes of the adjacent alluvial fan when the reaches were active near the fan fringe.

Lower Megabreccia (Rock Avalanche Deposit)

At Split Mountain, the lower megabreccia rests concordantly on Miocene alluvial fan deposits (Figure 3; Stop 1-3a). The lower megabreccia rests nonconformably on crystalline basement rock 2.4 km east of the Gorge. The thickness is a remarkably uniform 45 m from Split Mountain Gorge (Stop 1-3a) eastward for 3.4 km where it abruptly thickens to 180 m and in another 1.8 km terminates against crystalline basement rock. In the west wall of the Gorge, the megabreccia is sharply truncated below Upper Miocene to Lower Pliocene marine sandstones (Figure 3; Stop 1-3b).

Several aspects of the lower megabreccia unit led Kerr [1984] to interpret the origin of the megabreccia as the deposit of a landslide or rock avalanche; Robinson and Threet [1974] interpreted an air-fluidized emplacement mechanism. Thickness is nearly uniform over the 5.2 km of outcrop, although the upper surface is broadly undulatory. Over large areas of outcrop, very large boulders (up to 5m in diameter; Stop 1-3) are suspended in a comminuted matrix. Locally, however, planes of finely crushed rock (clay seams) dip westward and are believed to be dislocation zones ("fault gouge") produced during emplacement [Kerr, 1984]. Where the megabreccia rests on sedimentary rock (Figure 4; Stop 1-3a), the underlying strata are highly contorted. A characteristic "jigsaw" macrofabric is especially obvious where quartz-vein fragments and host crystalline rocks can be visually reassembled (Stop 1-3a; best examples at Stop 1-5d).

Volcanic Rocks

Lower to Middle Miocene alkalic and tholeiitic basalt flows, breccias, and pyroclastics with rare basaltic andesite differentiates [Hawkins, 1970; Ruisaard, 1979; Gjerde, 1982] are widely exposed in the Coyote Mountains (Stop 3-2), Volcanic Hills, Davies Valley, Fish Creek Mountains and Superstition Mountain, and have been referred to by several nomenclatures (Figure 1). Volcanic rocks of the Jacumba area are age equivalent [Minch and Abbott, 1973]. Radiometric ages range from about 14 to 22 M.a. [Hawkins, 1970; Eberly and Stanley, 1978; Ruisaard, 1979; Mace, 1981]. Volcanic rocks rest either nonconformably on crystalline basements rocks or conformably on or intercalated with braided stream and alluvial fan deposits [Ruisaard, 1979; Kerr, 1982]. Upper Miocene and younger deposits unconformably overlie the volcanic rocks, locally with marked angular discordance (e.g., southern Fish Creek Mountains and Coyote Mountains, between Stop 3-3 and 3-4).

Secular variations in volcanic rock type and geochemistry are compatible with crustal rifting [Gjerde, 1982]. Early flows (21-16 mya) are of alkali olivine basalt composition. Later flows (16-14 mya) are of olivine tholeiitic basalt composition and include geochemical and petrographic evidence for magma interaction with continental crust.

UPPER MIOCENE TO PLEISTOCENE ROCKS

Alluvial Fan Deposits

Gray to greenish gray or dark brown alluvial fan deposits recognized by Pappajohn [1980], Kerr [1982], and Dean [1988] crop out in the Split Mountain area (Figure 3), Fish Creek Mountains, and along the faulted eastern fringe of the Vallecito Mountains. Aside from color, these alluvial fan deposits also differ from Miocene alluvial fan deposits being less indurated and containing a substantial proportion of metamorphic basement clasts locally. The basal contact is either an unconformity with local discordance with older alluvial fan deposits (Stop 1-5b), or a nonconformity, locally high-angle, with crystalline basement rock. These deposits are laterally equivalent to the Upper Miocene to Lower Pliocene evaporites and shallow marine sandstones (Stops 1-3b, 1-5a and 1-5b). Evaporites, shallow marine sandstones, and locally derived turbidites conformably overlie these alluvial fan deposits (Stops 1-3b, 1-5a, 1-5b, and 1-5c).

Processes responsible for deposition of these alluvial fan deposits include channel-fill, debris flow, and sheetflood. Upper fan subfacies is present along the faulted front of the Vallecito Mountains and San Jacinto fault zone (Stop 1-6, and underlying the unnamed ridge extending to the southeast). Lower fan subfacies equivalents to the proximal deposits are found in the Split Mountain area (Stop 1-5b). Two distinct evaporite tongues extend into these alluvial fan deposits northwest of the U. S. Gypsum mine (i.e., ne/4, ne/4, section 13, T13S, R8E; Kerr, unpub. mapping).

Winker (1987) did not make the distinction between the Lower to Middle Miocene, well indurated, red alluvial fan deposits and the Upper Miocene to Lower Pliocene, poorly to moderately indurated, gray to green alluvial fan deposits of Kerr [1982] (Kerr originally referred to the younger deposits as Pliocene continental deposits, Figure 1). Winker believed that the color criterion for distinguishing the two deposits could not be applied consistently, believing further that the difference in color represents only local diagenetic differences. In addition, he did not observe the angular discordance, as reported by Kerr [1982], within the alluvial fan deposits in the Split Mountain area, or elsewhere. Thus, Winker concluded that the division of the alluvial fan deposits was unwarranted, and that the alluvial fan deposits of the southeastern Vallecito Mountains and Split Mountain area span the time of the Miocene volcanic rocks and the Late Miocene to Early Pliocene evaporites and marine turbidites (Figure 1).

Evaporites

A thick (up to 60m) anhydrite/gypsum unit (Figure 1) crops out along the flanks of the Split Mountain syncline and, with more limited development, along the south flank of the Split Mountain anticline (Figures 1, 3, and 4). Although natural exposures are poor owing to thick development of gypcrete (a weathering product), fresh exposures can be found in the active U.S. Gypsum Company mine northeast of Split Mountain, or in exploratory pits and trenches found at many sites throughout the outcrop area.

The evaporites rest nonconformably on crystalline basement or conformably overlie transitional marine mudstones, and intertongue laterally with the alluvial fan deposits described above. The evaporites are overlain sharply by locally derived turbidites or by the upper megabreccia (Figure 3).

These nearly pure calcium sulfate deposits are of marginal marine origin, and, thus, are the first record of marine waters in the Salton Trough [Dean, 1988]. Although the age has been the subject of some dispute in the literature, microfossils retrieved from thin claystones within the evaporites date the evaporites as Late Miocene to Early Pliocene in age [Dean, 1988].

Locally Derived Turbidites

Coarse-grained, locally derived arkosic turbidites are limited to the Split Mountain and Wind Caves areas (Stops 1-4, and 2-1) as these sandstones are replaced 3.2 km to the southeast by marine mudstones [c.f., geologic map of Winker, 1987]; an outlier of similar lithology has also been noted in the southern Fish Creek Mountains [Winker, 1987]. Over a short distance (0.5 km) northwestward from the upper reach of Split Mountain Gorge, these sandstones grade laterally into shallow marine sandstones (between Stops 1-4 and 1-5a).

Winker [1987], as well as Kerr et al. [1979] and Pappajohn [1980], pointed out that the sandstones immediately underlying and overlying the upper megabreccia (Figures 1 and 4) in this area are nearly identical in character. The section below the upper megabreccia is up to 75m thick and includes structures indicating sediment-gravity-flow deposition ("turbidites"). The lower 5 to 30 m thick interval is composed of thinly interbedded silty sandstones and fine- to medium-grained arkosic sandstones with Tae, Tbe, Tbce, and Tbe turbidite sequences [c.f., Winker, 1987 for detail] (Stop 1-3). This interval has yielded a Late Miocene to Early Pliocene microfossil assemblage [Ingle, 1974; Pappajohn, 1980; Dean, 1988]. The remaining section is composed of thicker sandstone beds (up to 1m) and thin siltstone interbeds (Stop 1-4). Vertical organization of bed thickness or grain size are not obvious (contrary to an earlier statement in Kerr et al., 1979). A variety of partial Bouma sequences characterize these sandstones; Ta, Tae, and Tabe are common in medium-bedded sandstones [c.f., Winker, 1987]. The presence of largely structureless, thick-bedded sandstones, some of which contain large boulders, indicate that other sediment-gravity-flow processes (i.e., high-density turbidity currents or grain flow) likely played a role in sedimentation. Bioturbation is common to the finer grained strata and to the upper parts of many sandstone beds.

Turbidites immediately above the upper megabreccia (Figure 1) include thin to very thick beds of coarse-grained, angular, biotite-rich sandstones interbedded with gray claystones (Stops 2-1b and 2-1c). Bouma sequences are more complete, as compared to below the upper megabreccia, and include Tae, Tabe, Tace, Tbce, and Tabce [Winker, 1987]. Sole marks, such as flute casts and grooves, are well developed in this section (Stop 2-1c). Claystones yield microfossils of Early Pliocene age [Stump, 1972; Ingle, 1974], and indicate outer shelf water depths (50-150m) [Ingle, 1974; Quinn and Cronin, 1984].

Paleocurrent indicators vary through the section [Kerr et al., 1979; Pappajohn, 1980; Winker, 1987]. Below the upper megabreccia, sedimentary structures indicate an upward rotation in flow: from south-directed at the base to north-northeast-directed below, as well as above, the megabreccia [Winker, 1987]. In contrast, stratigraphically higher turbidites composed of Colorado River-derived sands have radially directed currents covering the southwest through southeast [Winker, 1987].

Shallow Marine Sandstones

To the northwest of Split Mountain Gorge, the turbidites grade laterally into or interfinger with locally derived shallow marine sandstones and conglomerates (Stop 1-5c; Figure 3). The sandstones rest conformably on Upper Miocene to Lower Pliocene alluvial fan deposits. The conglomerates rest nonconformably on the crystalline bedrock of the basin margin farther to the west.

Medium- to coarse-grained sandstones, which are of local derivation, contain a variety of structures indicating both sediment-gravity-flow and tractive deposition [Pappajohn, 1980; Winker, 1987]. Biogenic traces are abundant. Extensive bioturbation has probably destroyed much of the primary sedimentary structures and fabrics in the sandstones (Stop 1-5c).

Upper Megabreccia (Rock Avalanche and Submarine Slide Deposit)

The upper megabreccia is a very thick (up to 50 m), massive, polymictic boulder conglomerate. This unit extends from the head of Split Mountain gorge 3.5 km to the northwest and to 6.6 km to the southeast, where it is covered by alluvium in the southern Fish Creek Mountains (c.f., geologic maps of Kerr, 1982 and Winker, 1987). The upper megabreccia overlies nearly all of the units described thus far. The basal contact is highly irregular, and underlying sedimentary units are extensively contorted (Stops 1-4a and 1-4b). Large ripup flaps and blocks of the underlying turbidites are common; some flaps nearly extend to the top of the megabreccia. The upper contact is sharp at most localities; however, it is gradational to the overlying turbidites at Split Mountain (Stop 1-4b).

Unlike the lower megabreccia, the upper megabreccia has a diverse clast population that is composed of crystalline basement, schist, gneiss and marble detritus. The "jigsaw" macrofabric is clearly demonstrable owing to the diversity of clast types. The macrofabric is developed at a range of scales from the reconstruction of individual boulders (Stop 1-5d) to large domains across the outcrop (between Stops 1-4 and 1-5a). Clast size ranges up to 10 m in diameter. In the Split Mountain area, the matrix contains a higher subrounded to subangular sand fraction than the matrix to the northwest, which here is similar to the matrix of the lower megabreccia.

Kerr et al. [1979] suggested a dual mode of emplacement for the upper megabreccia. Because the upper megabreccia shares traits similar to the lower megabreccia 0.5 km northwest of Split Mountain (Stops 1-5a and 1-5b) and on northwestward to its outcrop limit, a landslide or rock avalanche origin was proposed. In the Split Mountain area, the upper megabreccia was interpreted to have been emplaced in a submarine setting, perhaps involving debris flow processes.

Colorado River-derived Turbidites

Locally derived turbidites of the Split Mountain Gorge and Fish Creek Mountains areas (Figure 5) grade upsection into turbidites that are volumetrically dominated by fine to very fine, well-sorted, subrounded and biotite-poor sandstones (Figure 6; Stop 21-) [C-suite of Winker, 1987]. These gold-weathering, quartz-rich turbidites record the initiation of the Colorado River as a major sedimentary source to the Gulf of California. The sandstones contain sparse, calcite-filled foraminifera first identified by Merriam and Bandy [1965] as Late Cretaceous species from the Mancos Shale; these forams have come to be regarded as a diagnostic indicator of Colorado sands in the Salton Trough.

The lowermost Colorado-derived turbidites (Stop 2-1) are very thick (to 8m), massive, and lenticular, and probably represent a submarine channel complex that filled the axis of the bathymetric basin. The turbidites become thinner and laterally more persistent upsection, and contain beds with Tabe, Tace, and Tabce Bouma sequences characteristic of middle to outer fan settings. This transition to low-gradient, nonchannelized fan deposition is attributed to shoaling and reduction of relief as the semi-enclosed basin was filled by the rapid influx of Colorado-derived sand [Winker, 1987]. Benthic foraminifera [Ingle, 1974], and ostracodes [Quinn and Cronin, 1984] indicate inner shelf water depths. Planktonic foraminifera [Stump, 1972] indicate an early Pliocene age.

Upsection and laterally to the southeast, the turbidites pinchout or interfinger with prodeltaic claystones.

Prodeltaic Mudstones

Colorado River derived prodeltaic deposits (Figures 1, 5, and 6) consist of (1) massive, monotonous, greenish gray slightly silty claystone, which predominates in the lower part of the sequence, and (2) rhythmically bedded, yellowish gray clayey siltstones to silty, very fine sandstones (enroute to Stops 2-2a and 2-3). Over most of the outcrop area these deposits are deeply weathered and uniform in appearance, typically with a cracked, "popcorn-ball" surface and litter of secondary selenite; underlying lithologic differences are revealed only by subtle color variations on weathered surfaces. A maximum thickness of 600-700 m in the vicinity of Fish Creek Wash was estimated from outcrop width and dip of bracketing units (sands of underlying turbidites, and coquinas of overlying delta-front; overview from Stop 2-1). The mudstones pinch out both to the northwest near the Vallecito Mountains and to the southeast along the southern flank of the Fish Creek Mountains.

The lack of fissility in the claystones may indicate extensive bioturbation and, thus, oxygenated overlying water. Discrete burrows are rare, but aragonitic deposit-feeding bivalves occur locally [Woodard, 1974; Kidwell et al., 1988]. Ostrocodes indicate inner shelf water depth [Quinn and Cronin, 1984].

Delta-Front Cycles

Prodeltaic mudstones (Figures 1, 5, and 6) are overlain by 300m of upward-coarsening cycles, typically 10-20m thick, of (1) massive gray claystone (the dark resistant "knees" on the Elephant Knees hogback), (2) yellow-gray bioturbated mudstone, siltstone, and Colorado-River-derived sandstone, locally with hints of "ribbing" suggesting rhythmites (same lithology as seen in prodeltaic deposits at Stop 2-3), and (3) in some cycles, laterally discontinuous (100's m to several km) thick

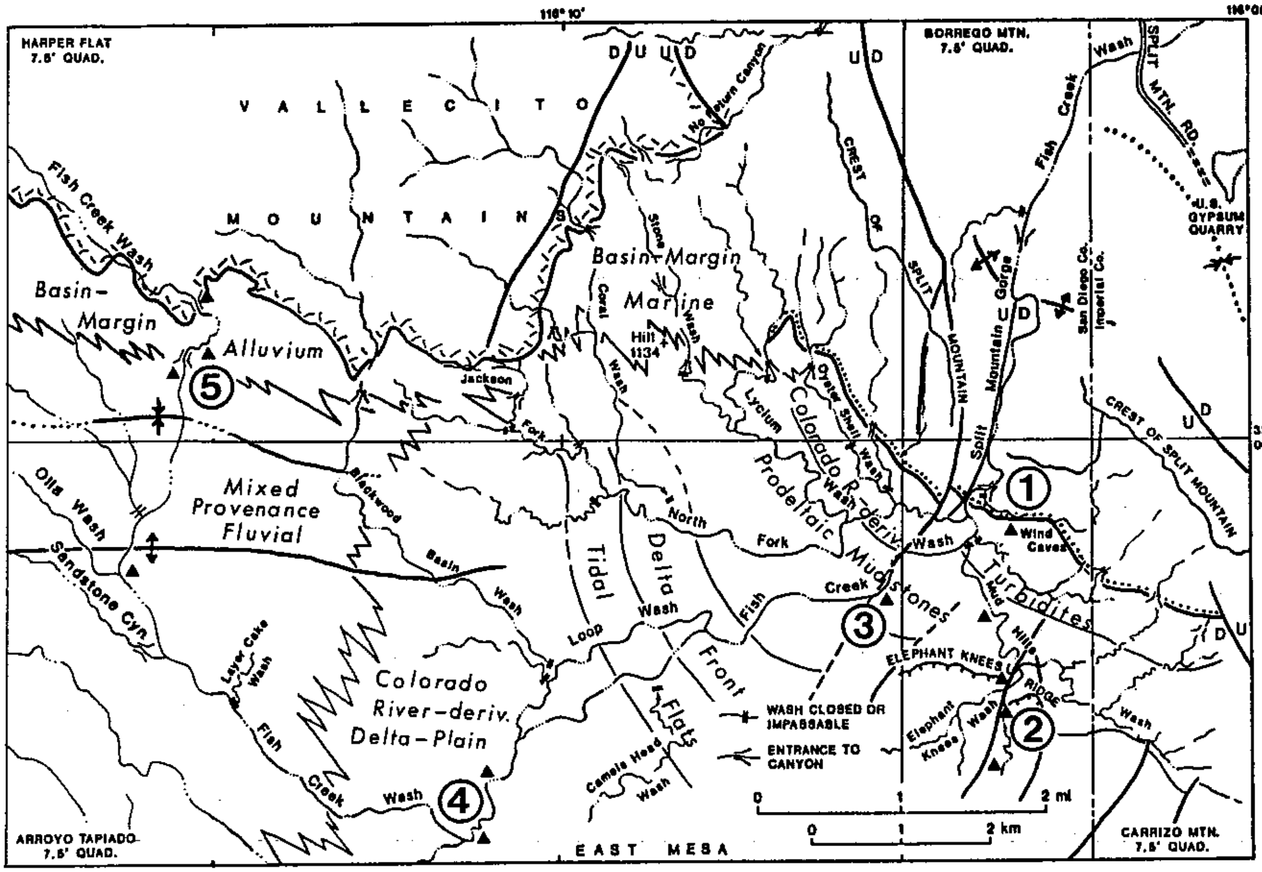

Figure 5. Index map for day 2 field trip stops (circled numbers). Map shows only major faults, and only those stratigraphic units that lie above the upper megabreccia (solid line with dots marks upper contact). Geology based on more complete map in Winker [1987].

beds of sandstone or oyster coquina. These highly resistant capping beds typically include trough cross-stratification, large-scale low- to high-angle (25 degrees) foresets (Stop 2-2a), and mud flasers. Paleocurrents measured from cross-sets show a strong southerly mode with a small secondary mode to the north, suggesting that, like the modern delta, the ancestral Colorado delta was tidally influenced [Winker, 1987; Winker and Kidwell, 1986].

Coquinas are composed of shell material in varying concentrations (shell- to matrix-supported) and states of preservation, from abraded fragments to unabraded articulated specimens. Several types of coquinas can be differentiated, all of them relatively high-energy deposits [Winker, 1987; Kidwell et al., 1988; Kidwell, 1988, 1991]. These include: (1) coalesced lenticular bodies of oyster coquina and/or channelized sandstones, such as the hogback-former of the Elephant Knees (Stops 2-2a); scale, geometry, and bi-directional paleocurrents suggest a flood-dominated subaqueous tidal ridge or giant ripple similar to those found in modern tide-dominated deltas (except for the super-abundance of shells) [e.g., Meckel, 1975). Watkins [1990] interpreted these as intertidal point-bar deposits. (2) Laterally extensive tabular coquinas (Stop 2-2b) whose tops are colonized by fully marine benthos and littered with shark's teeth, fish vertebrae, etc. suggest reworking and local redistribution of tidal-ridge sediment during marine transgression. (3) Thick (up to 10m), complexly interstratified bodies consisting of mud with life-positioned oysters, anomiid bivalves, and barnacles, "pseudo-conglomeratic" layers of serpulid worm colonies, and cross-bedded shell debris (downstream confluence of Loop and Fish Creek Washes; eastern Coyote Mountains) are dominated to greater and lesser degrees by in situ colonization. Such bodies were probably important source areas for skeletal (bioherms) material concentrated in high-energy sand bodies (types 1 and 2 above).

Intertidal to Delta Plain Deposits

Cyclic delta-front deposits grade upward into 300m of transitional sandstones and mudstones (Figure 6). These sediments form sharply dissected badlands (drive between Stops 2-3, and 2-4) that can be readily distinguished from the gray to ochre-colored hogbacks/cuestas and mounds created out of underlying delta-front and prodeltaic deposits. Transitional intertidal to delta plain deposits contain fewer and thinner sandy coquinas, more oyster/anomiid

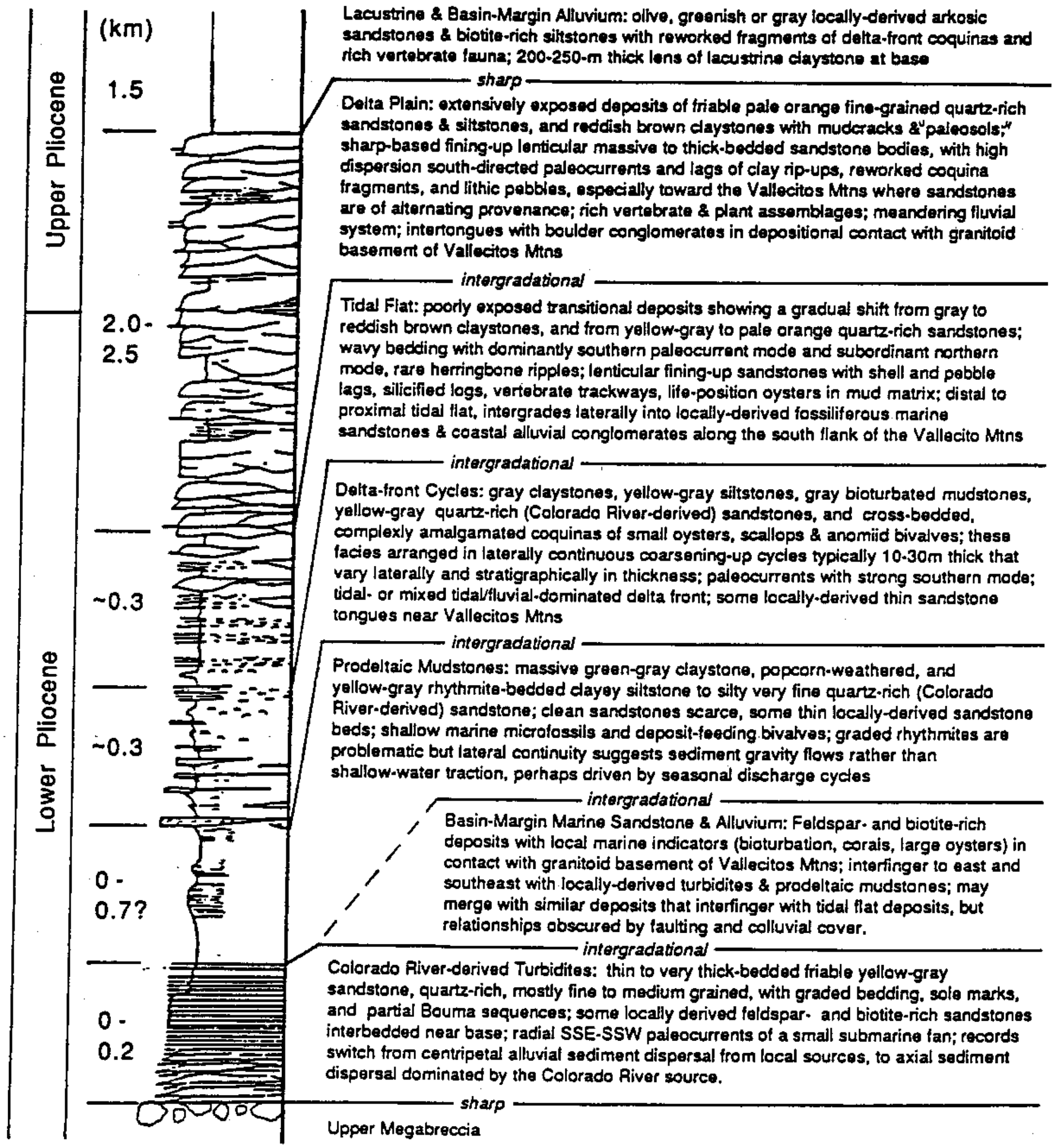

Figure 6. Generalized stratigraphic column for Pliocene deposits above the upper megabreccia (see Figure 1). Simplified from Winker [1987] detailed measured sections.

constructions with mud matrix, diminishing bioturbation, fining-up rather than coarsening-up cycles, laterally limited cycles, and increasing numbers of reddish rather than gray/olive claystones [Winker, 1987].

A lower to upper intertidal flat depositional environment is indicated from a variety of types of wavy bedding, which indicate bimodal north-south paleocurrents. Quinn and Cronin [1984] identified brackish water to intertidal ostracodes. A sporadic mixed marine/estuarine fauna of oysters, solitary corals, encrusting bryozoans, scallops, sand dollars, and gastropods have also been recognized [Woodard, 1963; Kidwell, unpub. data].

Intertidal deposits grade up in turn into a 2.0-2.5km thick interval of orange Colorado River derived suite sandstones, siltstones, and reddish claystones that are interpreted as the deposits of the ancestral Colorado delta plain [Winker , 1987] (Figure 5; Stop 2-4). Fine to very fine, massive or contorted sandstones occur in upward-fining cycles 5-10m thick. Clay rip-ups, locally derived pebble lags, load casts, and silicified logs are all present. Coalescing sand bodies are common, resulting in large aggregate sandstone thicknesses locally. Trough cross-stratification and channel paleocurrents show high dispersion but with dominant southerly mode [Winker and Kidwell, 1986]. Claystones, by contrast, make up only 20% of the delta plain deposits, by thickness; these are characterized by mudcracks, calcareous nodules, and intraclasts, "green" beds that may indicate paleosols, and thin layers of rippled siltstone or fine sandstone. Fossils include horse, camel, and turtle bones [Woodard, 1963] of Blancan age [Downs and White, 1968], and logs of laurel, cottonwood, willow, and walnut [Remeika et al., 1988], plants that dominate the banks of the lower Colorado River where in its natural state [Kniffen, 1932].

These combined features suggest a fine-grained meandering fluvial system. The sparsity of lateral accretion cross-stratification suggests that channels were more likely dominated by scour and backfilling during floods (such as the modern Colorado River) [Kniffen, 1932] than by lateral accretion. Toward the margins of the basin, fluvial deposits incorporate progressively more locally derived sediments (Figure 5; Stops 2-4 and 2-5), producing the variegated bedding of Layer Creek Wash (seen to west from Stop 2-1). These mixed-provenance deposits grade rapidly, in turn, into cobble and then boulder conglomerates that rest on crystalline basement (Stop 2-5). Magnetostratigraphy [Johnson et al., 1983] indicates that the upper fluvial part of the deltaic record is Late Pliocene in age.

Throughout the western Salton Trough, Colorado River sediments of the delta plain are overlain by predominantly locally derived Quaternary [Johnson et al., 1983] lacustrine sandstones, siltstones, and massive gray claystones [Winker, 1987].

Basin-Margin Alluvium, Rocky Shoreline, and Shallow Marine Deposits

The deposits of each phase of Pliocene Colorado Delta progradation (turbidite apron, prodeltaic muds, delta-front cycles, intertidal flats, and fluvial-lacustrine plain) interfinger laterally with coarse-grained, locally derived sandstones and conglomerates along the bedrock-margin of the basin (Figures 5 and 6), much as modern marine, deltaic, and lacustrine units interfinger with alluvium along the edges of the Gulf of California and Salton Trough today. These basin-margin facies vary in the extent to which they extend out into the Colorado River delta fill in the center of the basin [fence diagram of Winker, 1987]: they also vary in composition as a function of local bedrock from crystalline (Stop 2-5) to basaltic (Figures 7 and 8; Stops 3-2 and 3-3). The persistence of coarse-grained facies along the entire basin-margin throughout its Miocene to Pleistocene history indicates the continuing role of tectonism in maintaining fresh source areas and strong transport gradients.

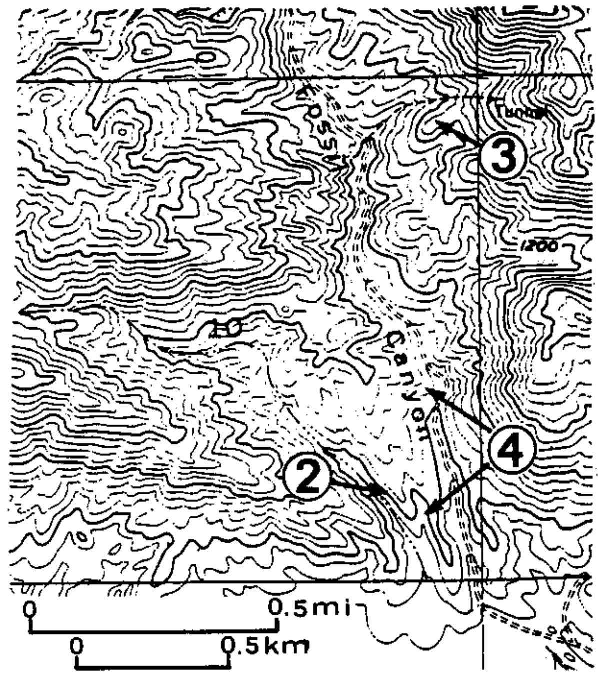

Figure 7. Index map for day 3 field trip Stops 3-2, 3-3, and 3-4 (circles marked on map with arrows; Stop 3-4 shows beginning, at north end, and ending of traverse). Area located in sec. 10, T16S, R9E (Carrizo Mountain 7.5 minute topographic quadrangle).

The topographic and bathymetric irregularity of the basin margin are particularly well-demonstrated by the marine facies that fill paleolows on the pre-marine surface and that progressively onlap the basin-margin [Kidwell, 1988; Kidwell et al., 1988]. These fossiliferous deposits are patchy and variable in matrix-type, faunal abundance, species composition, and relative age. They include: (1) bored marble [Watkins, 1990] and encrusted granite and basalt rocky shorelines and rockfalls (eastern and northern flanks of Coyote Mountains); (2) bioclastic limestones banked onto lower-gradient, sediment-starved segments of shoreline (eastern Coyote Mountains); (3) fossiliferous sands supplied by long-shore drift (Barrett Canyon on south flank Fish Creek Mountains; eastern Coyote Mountains); (4) intertidal and shallow subtidal parts of coastal alluvial fans, which provide both cobble and sand substrata for colonization (Stop 3-3); (5) coral-rich "reefs" (1-2m thick, <10m diameter mounds or 1-3m thick biostromes of rudstone/boundstone) developed on submarine bedrock highs (south flank Coyote Mountains) or at the distal toe of coastal alluvial fans (Stop 3-3); and (6) sands with minor conglomerate supplied from local granite bedrock or older non-marine fanglomerates and reworked under marine conditions (south flank Vallecitos Mountains, north flank Coyote Mountains).

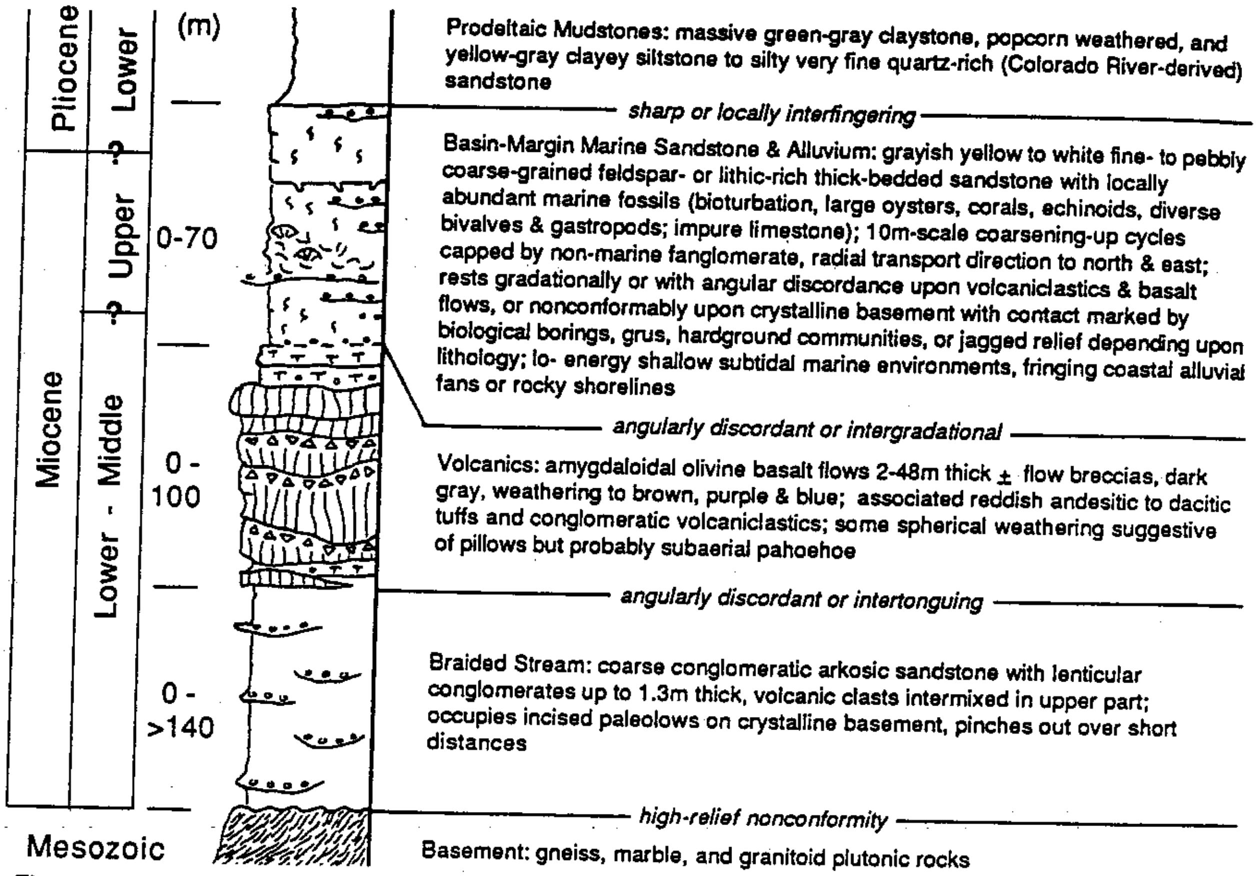

Figure 8. Schematic column for Miocene and Lower Pliocene strata exposed in the Fossil Canyon area, southern Coyote Mountains (day 3). Based on Ruisaard [1979] and Kidwell [1988, unpubl. data].

Although these marine facies are the source of most invertebrate species known from the Neogene in the Salton Trough, and are therefore an important line of evidence for the bio- and paleo-geographic evolution of the Gulf, their ages are as yet poorly known. Microfossils are rare or non-diagnostic in the sands (Ingle, pers. comm.), and a mollusk/coral-based Neogene biostratigraphy for adjacent Baja California and Sonora is still in progress [Smith, 1991, and pers. comm.]. The marine facies in the Trough are poor sediments for direct dating. However, all appear to be younger than the Miocene basalts (and therefore less than 14-22 my), and a range of ages are suggested by the progressive onlap of basin-margin facies from east to west by successively younger parts of the deltaic sequence: some basin-margin facies are overlain (and possibly interfinger with) prodeltaic deposits (south flank of Coyote Mountains), others by delta-front cycles (eastern Coyotes), and still others (western Vallecitos) by intertidal or delta-plain sediments [Winker, 1987; Kidwell et al., 1988]. Provisionally, therefore, basin-margin marine facies range in age from Late Miocene through Pliocene (Figure 1).

Tectonic Phases

Early to Middle Miocene Extension

Based on plate reconstructions along the eastern Pacific rim [Atwater, 1970; Dickinson and Snyder, 1979; c.f., review by Terres and Crowell, 1979], the westward sloping early Cenozoic pediment surfaces and incised drainage systems of the Salton Trough could have been disrupted as early as the Oligocene. The Pacific Plate contacted the North American Plate between 38 and 29 M.a., replacing a former convergent margin with a transform-ridge-trench triple junction near the present Mexico-California border. From its initial point of development, the transform-ridge-trench triple junction migrated southward along the outboard side of the present-day Baja California Peninsula reaching the latitude of northwestern Sonora, Mexico about 21 M.a. (c.f., review in Terres and Crowell, 1979). Palinspastic reconstructions of the western Salton Trough region places the Trough farther southeast (than its present position) adjacent to northwestern Sonora, Mexico (Figure 2) [Winker and Kidwell, 1986]. Initiation of extensional faulting in the Salton Trough is marked by commencement of alkalic and tholeiitic basalt volcanism at about 22 M.a. (c.f., volcanic rocks). Extension-related volcanism continued until about 14 M.a.

Tectonic patterns, as inferred from Lower to Middle Miocene continental deposits, differ in the interpretations of Kerr [1982; 1984] and Winker [1987]. Kerr interpreted a series of half-graben basins bounded by northeast-trending (present orientation disregarding rotation; see below) faults (e.g., Vallecito Mountains fault; Stop 1-6). Faulted margins were the site of alluvial fan deposition. Basin-axis braided stream systems flowed northward (present orientation) and collected discharge from the faulted basin margin alluvial fans and braided-stream plains developed on the back-tipped half horsts (e.g., Fish Creek Mountains). The sediment deposited in the axial drainage included crystalline basement, *reworked* Eocene extraregional clasts, and Lower to Middle Miocene volcanic rocks. Basaltic outpours were not necessarily restricted to the faulted margins.

Alternatively, Winker [1987] interpreted the braided stream deposits as largely predating the main phase of rifting based on their stratigraphic position below alluvial fanglomerates and volcanics, and that the age of their lower boundary is not constrained to the Miocene. The presence of basalt clasts in parts of the braided stream deposits might indicate that volcanism began in the nascent Salton Trough earlier than in the immediate study area, and/or that the upper contact of the braided stream deposits is significantly diachronous, so that some clasts might be derived from laterally adjacent volcanic flows. Winker [1987] interpreted the 14-22 M.a. volcanic dates as marking the onset of continental rifting, which may have occurred along northwest-trending faults (rather than northeast-trending faults) aligned with the trend of volcanic necks south of the Fish Creek Mountains [Ruisaard, 1979]. The volcanics, their coeval fanglomerates, the lower and upper megabreccias, and the evaporites all accumulated during this earliest phase of rifting, which generated a paleotopographic low for accumulation of later sediments [Winker, 1987].

Late Miocene to Recent Transtension

The transition from extensional to transtensional tectonics is interpreted from the reorganization of the Early to Middle Miocene half-graben basin geometry during the Late Miocene [Kerr, 1982, and unpub. data]. North of the Split Mountain area, the juxtaposition of a half-horst on the north against a half-graben on the south side of the San Jacinto fault zone resulted in a steep southward deepening basin. Alluvial fan systems (Stop 1-6), and perhaps the landslide/rock avalanche of the upper megabreccia (Stop 1-4b) [Kerr et al., 1979], extended southward from the escarpment along the San Jacinto fault zone and eastward from the Vallecito Mountains fault. Evaporite pond(s) and narrow nearshore systems fringed these alluvial fans. The juxtaposition of areas of very different elevations is also inferred for Upper Miocene(?) basin margin facies in the Coyote Mountains (Stop 3-4).

Although regional evidence suggests that transtension may have begun as early as Late Miocene [Crowell, 1975], Winker and Kidwell [Winker, 1987; Winker and Kidwell, 1986, and in prep.] have found that the onset of strike-slip tectonism in the western Salton Trough is difficult to date precisely, in part because it possibly built up gradually. The Trough began with Early to Middle Miocene rifting, which disrupted pre-existing regional drainage; extensional subsidence led eventually to marine transgression of a high-relief topography that began with "deep-basin, shallow-water" evaporites. The first fully marine deposits (Late Miocene) were diverse and laterally variable; shallow-water fringes were associated with alluvial fans, fan deltas, and rocky shorelines, whereas deeper-marine fan fringes were dominated by high-density turbidity currents on high-gradient slopes (Stops 1-4a, 1-5c, 2-1b, 3-3, and 3-4). The initiation of the Colorado River as a major sediment supplier to the Trough in the Early Pliocene (~5 M.a.) caused a major change in sedimentation patterns, introducing large volumes of clay, silt, and fine sand which rapidly overwhelmed coarse-grained locally derived sediment and displaced full-marine conditions farther to the south. The first Colorado River-derived sediments filled local paleolows with submarine fan deposits (Stop 2-1c) but were soon succeeded by much thicker and more widespread progradational deltaic deposits (Stops 2-2 to 2-4). This change in sediment source coincided with a dramatic increase in sedimentation rates and subsidence [Johnson et al., 1983], which may have been either rift or transtensional in origin and which accommodated ~3.5 km of Pliocene deltaic sediments and 1.5 km of Pliocene-Quaternary nonmarine, locally derived alluvium (Figure 6). Uplift, tilting, and ~35 degrees of clockwise rotation of this fill has been constrained to the last 0.9 m.y. by Johnson et al. [1983].

During this entire period, local alluvial fans and braided streams continued to feed coarse arkosic and lithic sediment from the basin's margin, interfingering it with submarine fan (Stop 2-1), submarine deltaic (Stop 2-2), and delta-plain deposits (Stop 2-4 to 2-5). The continuity of coarse basin-margin deposits through the Neogene-Quaternary history indicates the persistence of steep-gradient, presumably fault-rejuvenated local source areas. However, Winker and Kidwell [1986] have found little unambiguous evidence for the nature of this syn-depositional faulting in the fieldtrip area itself: most exposed contacts of basin-margin deposits with basement are depositional rather than faulted in nature. The termination of Colorado River-derived sediment at 2.8 M.a., possibly by a "porpoise" structure, may be the earliest clear-cut manifestation of strike-slip sedimentation in the western Salton Trough [Winker and

Kidwell, 1986]. This conservative interpretation does not rule out a Late Miocene (~10 M.a.) to Early Pliocene (~5 M.a.) initiation of transtension in the western Trough, such as interpreted by Kerr (this paper) on the basis of a Late Miocene unconformity in the Fish Creek Mountains, or by Crowell (1975) based on regional structural evidence for the larger San Andreas system. In fact, paleocurrents from deltaic deposits indicate that the Fish Creek-Vallecito area was on the southeastern (gulfward) flank of the Colorado River delta plain (northwestern Sonora, Figure 2) at least as recently as 2.8 M.a. and at least as long ago as 4.0 M.a. [Winker and Kidwell, 1986].

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TRIP LOG

Day 1: Lower and Middle Miocene Nonmarine and Upper Miocene to Lower Miocene Marine and Nonmarine Rocks

Stop 1-1. Welcome. Trip overview. Exposed at level of canyon floor are Miocene middle alluvial fan deposits (Figures 3 and 4); exposed higher in canyon wall are upper alluvial fan deposits. Alluvial fan deposits here exhibit two different weathering characters and clast populations are seen: (1) Red to reddish brown debris flow and sheetflood deposits with generally limited surface weathering are derived from a crystalline basement source. (2) Pink alluvial fan deposits (sometimes mistaken for the braided stream deposits) with a heavy weathering patina include a Miocene volcanic source; the equivalent alluvial fan deposits are inferred to be across San Jacinto fault zone and displaced 30km to southeast at Superstition Mountain [Kerr, 1982, 1984]. Note the angular discordance between the deposits of the two alluvial fan systems.

Drive up Fish Creek wash to next bend in canyon and at confluence of tributary leading to core of Split Mountain anticline (Figure 3).

Stop 1-2a. Exposed at canyon floor are Miocene lower alluvial fan deposits. Debris-flow beds are thinner and in general carry smaller gravel clasts as compared to the middle alluvial fan deposits at Stop 1-1. Mud flow deposits and sheetflood sandstones are proportionally most common in the lower fan deposits. Note the presence of small but deep channel cut and fill complexes; at the next stop the explanation for these complexes will become obvious.

Proceed up tributary and down stratigraphic section to Miocene braided stream deposit outcrop.

Stop 1-2b. The view to the south and southwest reveals laterally continuous thicker (up to 12m) debris flow strata separated by thinner (1m) sheetflood beds of the medial fan subfacies of the Lower to Middle Miocene alluvial fan deposits. Note that the distal alluvial fan deposits are only sporadically preserved along the contact with the underlying boulder conglomerates and coarse arkosic sandstones. A view to the north illustrates the limited intertonguing of the alluvial fan and braided stream deposits.

Braided stream deposits were primarily derived from crystalline basement terranes as evident from the predominance of plutonic gravel clasts and arkosic composition of the coarse sandstones. Two other sources contributed sediment to these deposits: (1)extra-regional clasts, which are characterized by metarhyolites ("Poway" clasts), are common near the base of the section only, and are believed to be *reworked* from lower Cenozoic (Eocene) valley fills (c.f., Abbott et al., 1983). (2) Clasts similar in composition and identical in age to Miocene volcanic rocks of the area occur throughout the braided stream deposits.

Paleocurrent indicators are directed towards the north in the braided stream deposits. By contrast, indicators in the alluvial fan deposits are directed to the east-northeast. Thus, supporting the inference that the braided stream deposits represent a northward flowing axial drainage and the alluvial fan deposits a basin margin drainage sloping eastward. As observed in modern settings, axial drainage systems commonly erode the toes of marginal alluvial fan systems. Thus, in these settings it is not usually for lower alluvial fan deposits to have a low preservation potential.

Return to vehicles. Drive up Split Mountain gorge to contact of alluvial fan and lower megabreccia (Figure 3).

Stop 1-3a. Base of lower megabreccia. Note disturbed proximal alluvial fan under the undulatory basal contact of the breccia. Walk through section at canyon level noting clast size (up to 5m), "jigsaw" macrofabric representing shattering at time of deposition, and clay seams thought to represent dislocation surfaces at time of emplacement [Kerr, 1984].

Stop 1-3b. Walk short distance up eastern tributary along top contact lower megabreccia (Figure 3). Note weathering rinds on megabreccia clasts and infiltrated sediment just below the contact. Climb out of wash to north to ridgeline.

View to the northeast skyline reveals characteristically weathered outcrops of Upper Miocene to Lower Pliocene evaporites that overlie the megabreccia. Note that the evaporites pinch out westward before reaching the floor of Split Mountain Gorge (Figures 3 and 4).

Turn to west and note abrupt truncation of lower megabreccia exposed in the opposite west wall of Split Mountain gorge. The section exposed from the skyline (location of stop 1-5a and 1-5b) down to the contact with the lower megabreccia represents the rapid lateral transition of Upper Miocene to Lower Pliocene distal alluvial fan through shallow marine through turbidite apron.

Examine locally derived turbidites resting on lower megabreccia on walk back down to vehicles.

Walk or drive up canyon to sharp bend in upper part of Split Mountain Gorge.

Stop 1-4a. With little doubt, your attention will be drawn to the fault contact and associated folding between upper megabreccia and turbidites. The origin of this and similar structures to the east of Split Mountain area usually stimulates lively discussion (load structure from emplacement of upper megabreccia).

Break for lunch.

Walk up the Gorge through the turbidite section. Note sedimentary structures which collectively indicate a variety of sediment-gravity flow processes (including turbidity currents, high-density turbidity currents, and grain flows). Although not particularly common at this location, north-northeastward- and southward-oriented sediment dispersal indicators have been recorded in this part of the section.

Proceed to head of Split Mountain Gorge where these turbidites are overlain by the upper megabreccia (Figures 3 and 4).

Stop 1-4b. Note deformation at base of upper megabreccia. Also note similarities and differences in texture, macrofabric, and composition between the upper megabreccia exposed here and the lower megabreccia at Stop 1-3a. The upper megabreccia grades upward into a sandstone bed containing structures typical of deposition from turbidity currents.

Walk due west across upper megabreccia outcrop to ridgeline in extreme eastern Section 35 (skyline to west from head of Gorge) and proceed north along ridgeline (down section) to contact between megabreccia and underlying marine sandstones (Figure 3). These sparsely fossiliferous sandstones are lateral equivalents of the locally derived turbidites (Stops 1-4a) While walking across the megabreccia, note what textural or compositional changes and macrofabrics occur. The upper megabreccia at Stop 1-4b has a sandier matrix; Kerr et al. [1979] interpreted a submarine debris flow origin for the upper megabreccia there. Here, the megabreccia has a similar macrofabric as seen in the lower megabreccia (Stop 1-3a); Kerr et al. [1979] regarded the mode of emplacement as being landslide or rock avalanche.

Stop 1-5a. Look southeast and down to the floor of Split Mountain Gorge (at lunch location; Stop 1-4a) and note that the sandstones underlying the upper megabreccia in the Gorge are stratigraphically equivalent to those exposed along ridgeline between here and Stop 1-5b. Look farther to the southeast (about 6.4km) to view Lower to Middle Miocene volcanic rocks cropping out in the southern Fish Creek Mountains where they are intercalated with braided stream deposits.

Pan from east to north. The evaporite deposits pinch out before reaching the Gorge (c.f., Stop 1-3b) on the south limb of the Split Mountain anticline (Figures 3 and 4). They thin to a narrow tongue between the younger alluvial fan deposits and Pliocene marine mudstones on the north flank of the anticline just west of the mouth to the gorge. 3.2km to the northeast, mine workings of the U.S. Gypsum Company can be seen. 4.8km to the north, the evaporites extend as two discrete tongues into the younger proximal alluvial fan deposits (Kerr, unpub. geologic mapping) that crop out along the north flank of the syncline and form the low ridge between the Split Mountain area and the Split Mountain Road.

Walk along ridgeline descending in elevation and stratigraphic units (Figure 3). Observe evidence for deposition in marine waters shallower than the equivalent turbidite section examined at Stop 1-4a. Proceed to first outcrop of alluvial fan deposits, noting transition enroute.

Stop 1-5b. Note the similarities and differences of these distal alluvial fan deposits of Upper Miocene to Lower Pliocene age to that of the Lower to Middle Miocene age alluvial fan deposits at Stops 1-1 and 1-2a. Kerr [1982; 1984] made a distinction between the gray and dark brown alluvial fan deposits exposed here, as well as at Stop 1-6, and the red, better indurated alluvial fan deposits exposed at Stops 1-1, 1-2a, and 1-3a. Near this location, 10 degrees discordance in strike was recorded between these two alluvial fan deposits; in the southern Fish Creek Mountains up to 20 degrees discordance in dip was recorded across the contact of Lower and Middle Miocene rocks and Pliocene rocks [c.f., Kerr, 1982 geologic map]. Winker [1987] did not make such a distinction, and included all alluvial fan deposits in one unit. Whereas, Kerr [1982], as well as Pappajohn, [1980] and Dean, [1988], placed an unconformity between the Lower to Middle Miocene rocks and the Upper Miocene to Lower Pliocene rocks. Walk a short distance down section and locate the contact between the two alluvial fan deposits (Figure 3).

Walk southwest down the dipslope of distal alluvial fan deposits (Figure 3). Note lentils of primary gypsum, which are thought to be equivalents to the evaporites noted earlier. Continue to the floor of the north-south trending tributary of Oyster Shell Wash (Figure 3).

Stop 1-5c. The polished outcrop surfaces along this wash bring out a number of physical and biogenic structures that taken together support the interpretation of shallow marine origin for these sandstones and siltstones. Attention given to the contact with the overlying upper megabreccia provides a stratigraphic reference for comparison with the deeper marine section exposed in the Gorge (Stop 1-4a).

Walk down the tributary, which progressively crosses higher in the stratigraphic succession. Continue into upper megabreccia until the dry waterfall is reached (Figure 3); enroute note texture, macrofabrics, and internal deformation features.

Stop 1-5d. Outstanding examples of "jigsaw" macrofabric are exposed in this part of the upper megabreccia. Note the similarities in texture, macrofabrics and internal deformation of the upper megabreccia here and lower megabreccia visited earlier (Stop 1-3a), suggesting that the two had similar origins as landslides or rock avalanches. However, recall the character of the upper megabreccia at the head of Split Mountain Gorge (Stop 1-4b); the sandy texture of the matrix there and association with turbidites together suggest that the upper megabreccia at the Gorge was deposited in a submarine setting Kerr et al. [1979].

Climb out of tributary and proceed overland to vehicles parked in Oyster Shell Wash (Figure 3).

Drive down Oyster Shell Wash turning down (left) North Fork Fish Creek Wash (Figure 3). Join the main fork Fish Creek Wash, turn left, and retrace route down

Fish Creek Wash through Split Mountain Gorge (Figure 3). At paved road, Split Mountain Road, turn left to Ocotillo Wells. If time permits, turn into Elephant Tree nature area and continue to end of jeep track.

Stop 1-6. This optional stop (located in ne/4, sw/4 section 1, T13S, R8E) provides an opportunity to view Upper Miocene to Lower Pliocene alluvial fan deposits (based on intertonguing relationship with the biostratigraphically dated evaporites; c.f., Dean 1988) along modern stream cuts. These gray boulder conglomerates are regarded as the proximal deposits to the distal alluvial fan deposits at Stop 1-5b. About 2.4 km to the west, the northeast-trending Vallecito Mountains fault juxtaposes Neogene and Quaternary deposits against crystalline basement rock.

Day 2: Pliocene Marine, Deltaic and Basin-Margin Rocks

Drive up Fish Creek Wash and continue through Split Mountain Gorge (Figures 3 and 5). Stop about 0.25 mi beyond head of Gorge (stop 1-4b). Find trail head to Wind Caves where terrace gravels contact the upper megabreccia. Walk up trail through scree derived from the upper megabreccia. Find a good vantage point just short of the Wind Caves.

Stop 2-1a. The panorama from west to south to east offers an overview of the largely Pliocene marine, deltaic and marginal nonmarine deposits that dominate the late Cenozoic record of the Salton Trough, constituting 6 km of section (Figures 5 and 6). The low-angle, morning light brings out the color contrast of sandstones derived from local basement sources from those derived from the ancestral Colorado River. Petrographic analysis of these rocks indicates two provenances: (1) feldspar- and biotite-rich sandstones derived from local bedrock sources, and which are pink to gray, and (2) lithologically more homogeneous quartz-rich sediments derived from the ancestral Colorado River. Looking east and south over the badlands in the fore- to middle-ground, you can see the yellow and grayish green prodeltaic mudstones and hog-backed delta-front sediments of the ancestral Colorado River; notice the knobby Elephant Knees hogback, the destination of Stop 2-2 (Figure 5). The Coyote Mountains on the southern horizon mark the far-side of this tectonic block (Day 3). Panning toward the west up Fish Creek Wash and into the distance, you will see pinkish tidal flat and delta-plain sediments, which interfinger laterally toward the Vallecito Mountains (right) with dark-colored locally derived sediments.

Walk along trail to the Wind Caves.

Stop 2-1b. Examine turbiditic sandstones that rest on top of the upper megabreccia. These locally derived sandstones are similar in provenance and sedimentary structures to those below the megabreccia (Stop 1-4a), but are coarser grained and include clasts of similar provinance as that of the upper megabreccia.

Walk downslope (upsection) back toward Fish Creek Wash.

Stop 2-1c. Note change to yellow-weathering quartz-rich turbiditic sandstones. Overturned blocks at wash level provide outstanding examples of sole marks and other south-directed paleocurrent indicators. The change to Colorado River-derived sediments coincides with a switch from centripetal to axial sediment dispersion (dominantly southern)[Winker, 1987], and with a dramatic increase in sediment accumulation rates [Johnson et al., 1983].

Proceed about ~0.25 mi. up Fish Creek Wash to the mouth of Mudhills Wash (blocked to vehicular traffic; natural history signpost) and regroup (Figure 5).

Stop 2-2a. Walk up Mudhills Wash (meanders in a south-southeast direction) for ~1 mi., examining cut-bank exposures of prodeltaic mudstones along the way. In the first cut-bank you will see some intercalated mica-rich fine-grained sandstones with ripple lamination, load casts, micaceous burrow-fills, and molds of aragonitic bivalves. Stop a little farther up the wash when you have a good vantage point of the Elephant Knees, and note cyclicity in the color and erosional resistance of the mudstones.

Stop 2-2b. Turn up a small drainage that cuts through the east end of the Elephant Knees (Figure 5) and examine the large-scale cross-sets in the sandstone and its capping oyster-coquina. Major foreset surfaces dip southward as do most other paleocurrent indicators, although a few intrasets indicate flow to the north. When traced laterally, it becomes clear that these cycle-capping sandstones and coquinas are broadly lenticular and laterally amalgamated. The oysters (*Dendostrea vesperina*) are disarticulated and primarily allochthonous, although some articulated, in-situ specimens are present in top-sets. These deposits are probably meso- to macrotidal ridges of giant ripples of entirely subaqueous origin.

Stop 2-2c. Proceed up the left fork of this wash through a narrow cut with a high sandstone wall on the left (east). This provides a internal view of one of these delta-front sandstone bodies, laterally equivalent (but fault-offset) from the oyster coquina of the Elephant Knees. Note quartz-rich lithology and large-scale bedding features.

Stop 2-2d. Proceed farther up this wash to the ridge of the next coquina-capped hog-back; you will walk through several mudstone-cycles along the way. Notice rhythmite-bedded siltstone and fine sandstone under the coquina, and the complex internal stratigraphy and dense-packing within the coquina itself. Climb up onto the dipslope of the coquina, and notice its tabular geometry. Sharks teeth, small estuarine corals, barnacles, and bivalves in addition to *Dendostrea* suggest marine transgressive reworking of older delta-front coquinas. Views across strike show the repetitive nature of the delta-front deposits, with cycles consisting of prodeltaic mudstone and rhythmites that coarsen upward into sandstone and/or coquina. Views along structural strike reveal the lateral continuity of individual cycles and the lenticularity of the coquina/sandstone caps.

Retrace steps back to vehicles (Figure 5).

Drive ~ 0.75 mi up Fish Creek Wash to first large cutbank on left (east) side (Figure 5).

Stop 2-3. Break for Lunch. This is a spectacular exposure of proximal prodeltaic deposits. The corrugated surface reflects differential weathering of thinly interbedded, upward-coarsening couplets (to 30 cm thick) of clayey siltstone and very fine sandstone. Although graded and faintly laminated, these beds are not classic turbidites. Their lateral continuity, however, suggests gravity-driven deposition rather than shallow-water traction, and perhaps was driven by seasonal changes in sediment supply.

Drive about 3.25 mi up Fish Creek Wash (Figure 5) to narrow cut and radical bend to the southeast. Along the way we will drive upsection out of the prodeltaic mudstones (rounded badlands) and through the delta-front cycles (hogbacks capped by rusty-weathering coquinas or thin sandstones) and tidal flat deposits (variegated red and gray sharply dissected low badlands). The tidal flat deposits grade upsection into delta-plain sandstones and mudstones that are exclusively reddish.

Optional route: drive through Loop Wash (Figure 5) to examine prodeltaic rhythmites with discrete burrows, delta-front oyster-anomiid bivalve bioherm with circumrotary serpulid colonies (both near downstream confluence with Fish Creek Wash), and better exposed tidal flat deposits (near upstream confluence).

Stop 2-4. 2 to 2.5 km of delta-plain sediments are exposed in this part of the Salton Trough (figures 5 and 6). Sandstones are fining-up channel-fill deposits with antidunes, contorted bedding, claystone rip-ups, and mudcracks, and are distributed in varying proportions among overbank deposits of red claystone with interbedded siltstone and sandstone. By a combination of walking or driving, examine the variety of channel and overbank features between here and the signed turnoff for Arroyo Diablo.

Continue driving up Fish Creek Wash. Over the next 5 mi, the wash cuts approximately along strike toward the Vallecitos Mountains (Figure 5), and you will notice how the pinkish quartz-rich sandstones of the Colorado River delta-plain are interbedded with and are eventually replaced by dark gray sandstones derived from crystalline basement. Optional stops can be made enroute to examine details; exposures near the mouth of Olla Wash (signpost) are particularly good.

Proceed up Fish Creek Wash to the mouth of a small gorge through conglomerate rocks (figure 5).

Stop 2-5. Proximal basin-margin conglomerates seen here are lateral equivalents of the Pliocene delta-plain deposits exposed over the last 2 mi. Typical crystalline basement rocks are also exposed in canyon walls. Note the dramatic grain size changes over short distances away from basement.

Caution: Although a good jeep trail continues west from this point and eventually connects with County Route S2, traffic is strictly one-way to the east because of the large Pinyon Canyon drop-off.

Turn around and retrace route down Fish Creek Wash (Figure 5).

Day 3: Lower and Middle Miocene Nonmarine and Volcanic Rocks and Miocene(?) and Pliocene Basin Margin Rocks

Drive west on Highway 78 and turn south on County Route S2. Proceed ~37 mi. to Badlands Overlook.

Stop 3-1. The large area of badlands between this point and Split Mountain are formed almost entirely of deposits of the ancestral (Pliocene) Colorado River delta, particularly delta-plain deposits (figure 5). Faults can be seen along the north flank of the Coyote Mountains.

Drive southeast on County Route S2. The Volcanic Hills to the south of highway are underlain by Miocene volcanic rocks [Fourt, 1979]. 11 mi. from overlook turn, north on Shell Canyon Road. At the foot of the Coyote Mountains, take the unpaved fork to north, away from the commercial gravel operation, and proceed up this jeep trail to Fossil Canyon (Figure 7), a narrow winding gorge. Along the way we will cross many slivers of the Elsinore fault zone, which juxtaposes crystalline basement and Mio-Pliocene sedimentary rocks. Park at mouth of Fossil Canyon, and walk over the divide to the west into Ocotillo Canyon, Walk up the main wash (Figure 7).

Stop 3-2. Braided stream deposits lie between crystalline basement and Middle to Upper Miocene volcanics and volcaniclastics (Figure 8). Volcanic clasts are rare in braided stream deposits at this locality, although they occur in similar deposits in the southern Fish Creek Mountains and Split Mountain area (Stop 1-2b). Winker [1987] suggested that the braided stream deposits may largely predate the volcanics, this and the consistent north-directed paleocurrents over the area also led him to suggest that the braided stream deposits may be remnants of a well-integrated, pre-rift drainage system. Kerr [1982, 1984], alternatively, regarded these deposits as the lateral equivalent of both Miocene volcanic rocks and alluvial fan deposits. Examine layering and structures in volcanic rocks.

Return to vehicles and drive up Fossil Canyon past Stop 3-4 to intersection with "Tunnel Road" (Figure 7), a steep and usually impassable jeep trail on the right. Walk up road to first bend, climb up to divide on right to gain overlook into west-draining gully to the south.

Stop 3-3. Here you see well-exposed dark gray volcanic flows overlain directly by light-colored Late Miocene(?) to Pliocene bioclastic sands and impure limestones (Figure 8). These sedimentary deposits are dominated by large (to 15 cm) marine oysters and several kinds of corals (*Solenastrea*, *Septastrea*, and *Porites*) that together form small, dispersed 1m-scale lenticular buildups of bafflestone and boundstone texture. These are embedded within arkosic sediments derived from plutonic basement to the west and not from surrounding volcanics, although a volcanic conglomerate lies mid-section.

Walk around knob to see extensive volcanic field to west. To the north you see basement and onlapping fossiliferous coarse arkosic sandstones. To the northwest is more basement and basement-derived alluvial fans (source area for Tunnel Road arkosic deposits).

Return to vehicles for lunch.

Drive down canyon through volcanic section (flows, then greenish tuffs), cross a possible angular discordance into polymictic alluvial fan deposits, and park at prominent bend at upstream end of the sandstone gorge (Figure 7).

Stop 3-4. Walk south along ridgeline on west side of canyon, following the ill-defined trail. This traverse begins with densely and richly fossiliferous limestone at wash level, and examines the lateral transition to gravelly fossiliferous sandstones and alluvial fanglomerates to the south over a distance of several hundred meters (Figures 7 sand 8). Note extensive bioturbation in most sandstones, and progressive decrease in faunal diversity and abundance to the south as conglomerate beds become thicker, coarser, and more numerous. Such transitions are characteristic of steep margins of the Pliocene basin; although some of these contacts are faulted today, the original nonconformities are usually preserved. In this instance, note that to the south no highland exists, but presumably was downdropped along the Elsinore fault. Most basin margin sandstones and alluvial fan systems along the southern flank of the Coyote Mountains indicate south-derived sediments, suggesting that the present Coyote Mountains are only a remnant of the Late Cenozoic source area. The west-derived arkosic sands and north-derived volcanic conglomerate seen at Stop 3-3 illustrate the paleotopographic complexity of the Neogene basin margin, which was a mixed shoreline of coastal alluvial fans, pocket beaches fed by longshore drift, and both steep- and low-gradient rocky stretches. However, in general, Neogene highlands were not necessarily the same as modern topography.

Return to vehicles, which have been ferried to the mouth of Fossil Canyon (Figure 7). Retrace route to County Route S2, and turn left into hamlet of Ocotillo. Join Interstate 8 and drive west to San Diego.

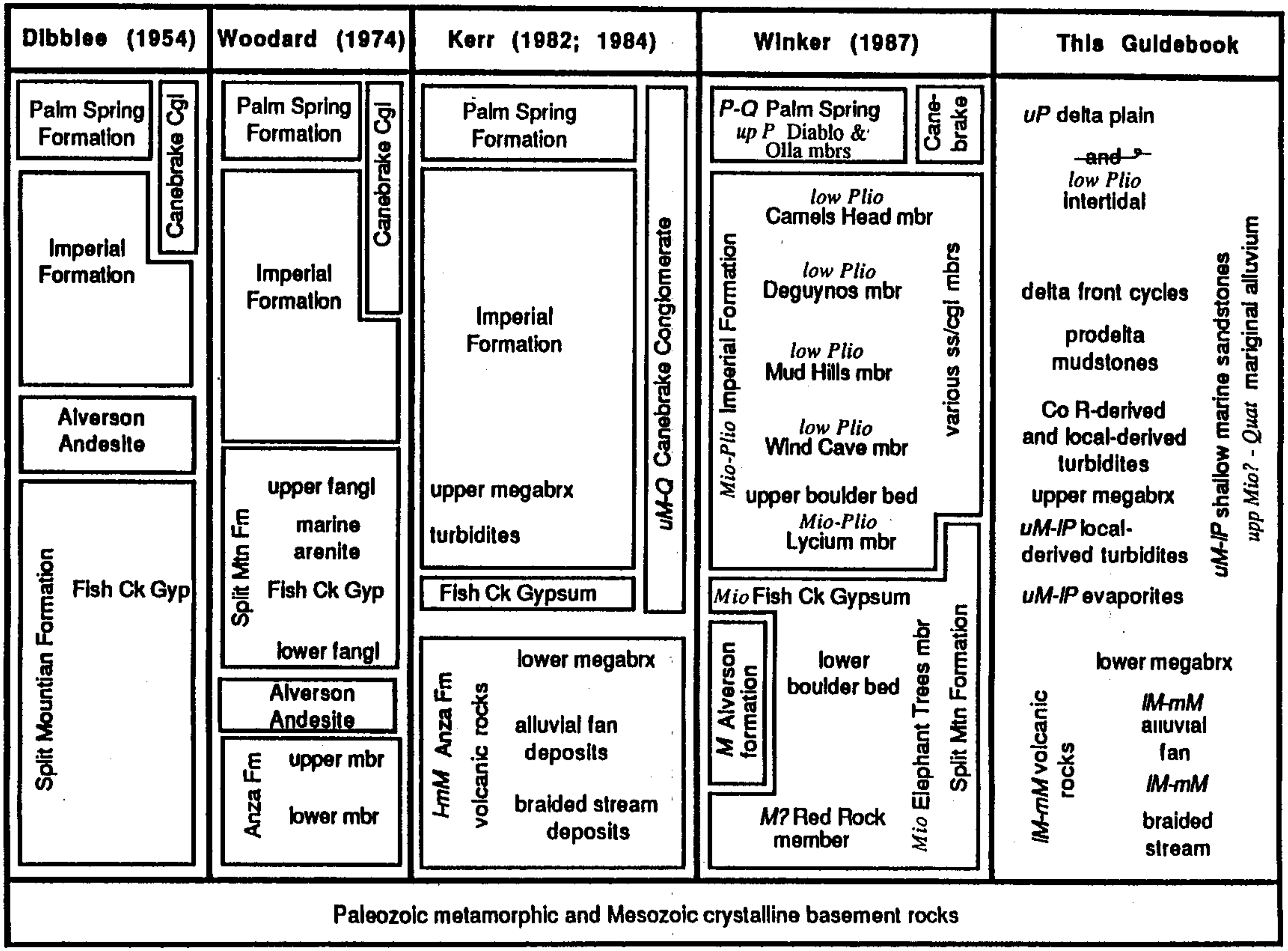

Figure 1 Note: All corrections are in the "Winker (1987)" and "This Guidebook" columns. Corrections have intentionally been printed using a different font to aid identification.

ERRATA FOR FIELDTRIP #28

Kerr, D.R., and Kidwell, S.M., Late Cenozoic Sedimentation and Tectonics, Western Salton Trough, California. *In* Geological Excursions inn Southern California and Mexico, M.J. Walawender & B.B. Hanan, eds.: *Guidebook, 1991 Annual Meeting, Geological Society of America,* p. 397-416, 1991.

Underlined words or phrases should be inserted or substituted in the text as follows:

p. 397, right column, line 6 from top: ...for the San Andreas system further north in California since Late Miocene...

p. 399, left col., line 5 under *Braided Stream Deposits:* ...in the Coyote Mountains (Stop 3-2) and ...

p. 402, left col., line 8 from top: ...debris flow deposits with ...

p. 404, right col., line 3 from top: ...these foraminifera have come to be regarded as a diagnostic indicator of Colorado River-derived sands in the Salton Trough, but are extremely rare.

p. 404, right col., line 6 under *Prodeltaic Mudstones:* ...sandstones (enroute to Stop 2-2a; Stop 2-3).
Also, last 3 lines under *Prodeltaic Mudstones*: ...[Woodard, 1974; Kidwell, 1987]. Ostracodes ...

p. 405, left col., line 4 from top: ... foresets (Stop 2-2c), and mud flasers.

p. 405, left col., line 6 in next paragraph: ...deposits [Winker, 1987; Kidwell, 1987, 1988, 1991]. These include...

p. 405, left col., next to last sentence on page: ...Meckel, 1975]. Watkins [1990a] interpreted these...
Also, last line in left column: ...tabular coquinas (Stop 2-2d) whose tops are colonized...

p. 405, right col., last sentence in first paragraph: ...Such biohermal bodies were probably important source areas for skeletal material concentrated in high-energy sand... Delete: (bioherms)

p. 407, left col., lines 9 & 10 in second paragraph: ...(Figure 5; drive between Stops 2-4 and 2-5), producing the variegated bedding of Layer Cake Wash...

p. 407, right col., line 8 from top: ... bored marble [Watkins, 1990b] ...
Also, line 10 from bottom in this column: ...sand substrata for colonization (Stops 3-3 and 3-4); ...

p. 408, left col., last sentence: ...range in age from late Middle or Late Miocene (Smith, 1991) through Pliocene...

p. 409, right col., line 9 from bottom: ...However, Winker and Kidwell [unpub.] have found little ...

p. 411, right col.: Watkins, R., ... *Palaios* ... 1990b.
Also: Winker, C.D., ...Doctor of Philosophy dissertation, University of Arizona, ...1987.

p. 412, left col., subheading: *Day 1: Lower and Middle Miocene Nonmarine and Upper Miocene to Lower Pliocene Marine and Nonmarine Rocks*

p. 412, left col., line 6 under *Stop 1-2a:* ... proportionally more common in the lower...

p. 412, right col., last sentence 2nd paragraph: ... is not unusual for lower ...

p. 414, left col.,: *Day 2: Upper Miocene(?) and Pliocene Marine, Deltaic and Basin-Margin Rocks*

p. 414, left col., line 3 under heading *Stop 2-1a* : ...deltaic and nonmarine deposits... Delete: marginal
Also, mid-paragraph under *Stop 2-1a* : (2) lithologically more homogeneous quartz-rich sediments derived from the ancestral Colorado River (yellow-weathering in subtidal facies).
Also, last sentence under *Stop 2-1a:* ...you will see pinkish Colorado River-derived tidal flat and delta-plain ....

p. 414, right col., line 10 under heading *Stop 2-2b* : ...*vespertina*) ...
Also, last sentence in same paragraph: ... macrotidal ridges or giant ripples

p. 415, right col., line 5 down from *Stop 3-2* : ...although they occur in the upper part of similar deposits ...
Also, line 8 down from *Stop 3-2:* ... the braided stream deposits may largely predate the volcanics. This and ...
Also, next to last sentence in 1st paragraph of *Stop 3-2:* ...remnants of a well-integrated, pre-rift drainage system, in contrast to the centripetal paleocurrents of stratigraphically higher, more clearly syn-rift alluvial fanglomerates and subordinate braided stream deposits.

ADDITIONS TO BIBLIOGRAPHY (page 415):

Watkins, R., Pliocene channel deposits of oyster shells in the Salton Trough region, California: *Palaeogeography, Palaeoclimatology, Palaeoecology,* v. 79, p. 249-262, 1990a.

Winker, C.D., and Kidwell, S.M., Paleocurrent evidence for lateral displacement of the Pliocene Colorado River delta by the San Andreas fault system, southeastern California: *Geology,* v. 14, p. 788-791, 1986.