G. C. DUNNE

1st ANNUAL FALL FIELD FROLIC

October, 1983

A field guide to eastern California

by George Dunne

FIELD TRIP OUTLINE
1st ANNUAL ALL-DEPARTMENT FALL FIELD FROLIC

by GEORGE DUNNE
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The following outline provides geologic background material for our 3-day field trip through the Basin-and Range province of eastern California. In addition to this guide, there should be in each vehicle at least one copy of each of the three following California Division of Mines and Geology 1:250,000-scale geologic maps: Los Angeles, Trona, and Death Valley (1977 edition). If walkie-talkies are available, I shall provide a running commentary concerning geologic features at which we will not have time to stop. We do not have a collecting permit for Death Valley National Monument, so please do not glom onto specimens there.

FIELD TRIP OVERVIEW

DAY 1: Northridge to Stovepipe Wells (Death Valley) major geologic features, in the order seen*

a) late Cenozoic stratigraphy and structure of the Transverse Ranges
b) San Andreas fault zone
c) the Mojave "terrane"

L.A.Sheet ↑
Trona Sheet ↓

d) Garlock Fault
e) Cantil Valley "transtensional graben"
f) Red Rock Canyon (Ricardo Formation of Miocene age)
g) southern Sierra Nevada pediment
h) Robber's Roast "inselbergs"
i) Indian Wells Valley
j) Coso Range
k) pluvial Owens River, Little Lake gap

Rest stop in Rose Valley; discussion of regional geologic setting

Trona Sheet ↑
Death Valley Sheet ↓

l) Coso Formation
m) Owens Lake
n) 1872 fault scarps at Lone Pine (stop, and examine on foot)
o) Mesozoic plutons and Independence dike swarm of southern Inyo Mountains
p) structural geology of southern Inyo Mountains (stop, and arm-wave)
q) structural geology of Darwin and Talc City Hills
r) Father Crowley Overlook (stop, feast eyes and arm-wave)

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[1] *The location of all lettered points after point 'c' of the first day may be found on figure 1.

s) Panamint Valley
t) Panamint Range; Nova Formation, Tucki Mountain
u) Death Valley

- END OF FIRST DAY (WHEEW!) -

1

DAY 2: Tour of Death Valley area (listed itinerary subject to change, depending on road conditions)

a) Kit Fox Hills, Furnace Creek fault zone
b) Funeral Range 'core complex' (stop, examine high-grade metamorphic rocks and/or basal detachment fault
c) Titus Canyon loop (**spectacular!**)
d) Furnace Creek fault zone (again)
e) Visitors Center at Furnace Creek (brief stop)
f) Black Mountains frontal fault zone and turtleback structures (one or two stops)

↑ Death Valley Sheet
↓ Trona Sheet

g) Shoreline Butte, Confidence Hills
h) Amargosa 'chaos complex' (if time permits)
i) return to campground via same route, with one or two stops, as time permits

- END OF SECOND DAY -

DAY 3: Return to Los Angeles via Panamint, Searles, and Cantil Valleys (start in Death Valley sheet)

a) Tucki Mountain detachment fault in Mosaic Canyon
b) Nova Formation in Emigrant Canyon
c) Skidoo pluton (muscovite-biotite granite of Cretaceous age)
d) Aguereberry Point (Stop for view; **WOW!**)
e) Stretch-pebble conglomerate (stop)
f) Wildrose graben
g) Panamint Valley (Stop, arm-wave)
h) Ash Hill fault zone

Death Valley Sheet
Trona Sheet

i) Slate Range Pass (view stop, if time permits)
j) Searles Valley and Dry Lake (tufa towers)
k) Sierra Nevada batholith, Independence dike swarm
l) Rand Schist
m) Garlock 'Formation' and 'The Black Hole' of the Southern Sierra Nevada
n) return to Los Angeles via California Rt. 14

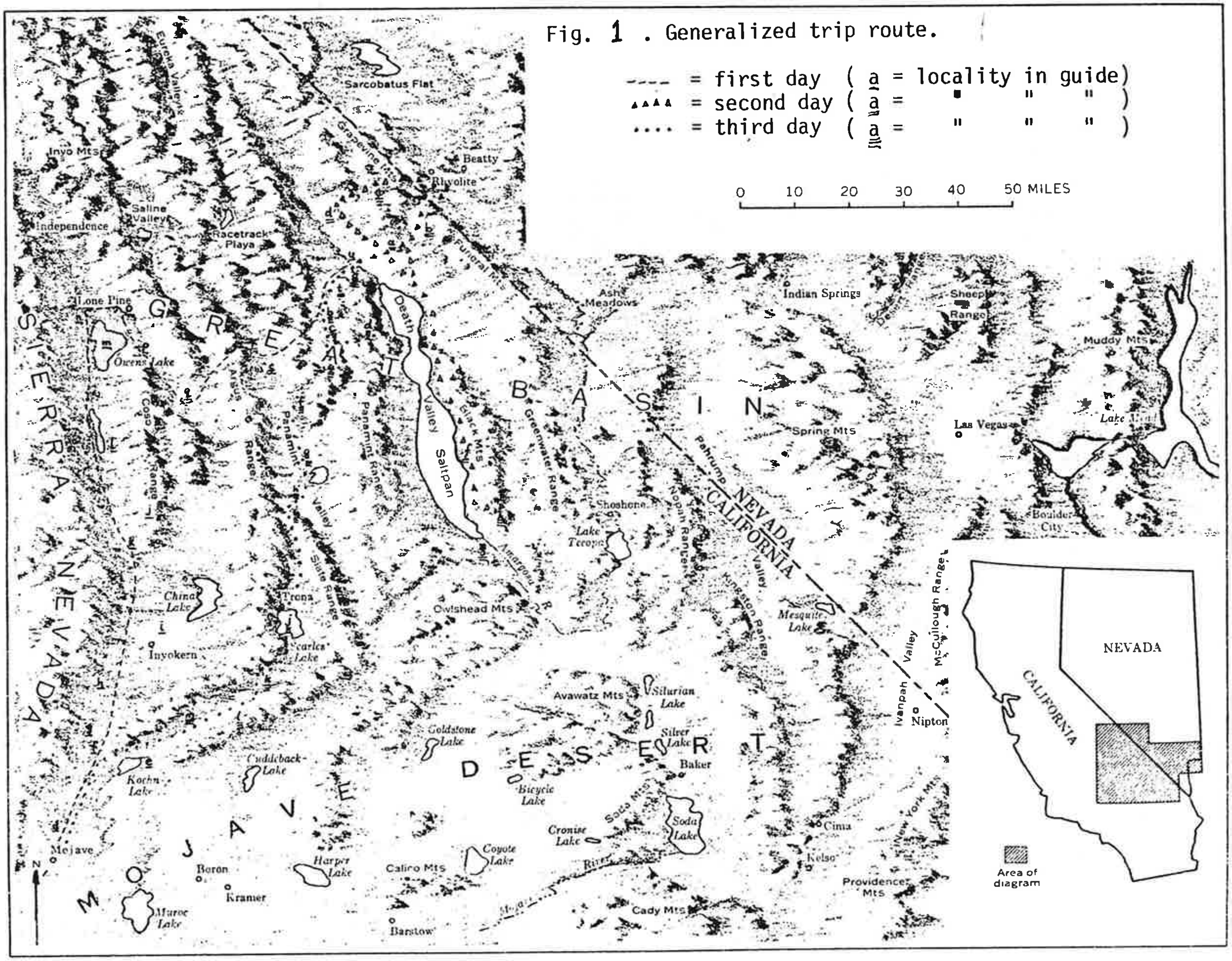

Fig. 1 . Generalized trip route.

---- = first day (a = locality in guide)

▲▲▲▲ = second day (a = " " ")

.... = third day (a = " " ")

COMMENTARY, FIRST DAY

The east-west-trending San Fernando Valley and the bounding ranges (Santa Susana and San Gabriel Mountains to the north, and the Santa Monica Mountains to the south) have come into existence within the past few million years as a result of generally north-south compression caused by movement of the San Andreas fault around its "big bend". As the San Fernando earthquake of 1971 reminded us, these mountains and valleys are still being formed. We live in an active mountain-forming tectonic setting.

Moving north along the 405 freeway, we encounter roadcuts through the Mission Hills that expose steeply inclined and faulted exposures of late Miocene marine shale and Pliocene marine and non-marine sandstone and shale. This region lay beneath marine waters until Late Pliocene time, about 3 million years ago.

About 3 miles north of the Mission Hills we enter the Santa Susana-San Gabriel Mountains. Steeply inclined and strongly deformed strata of the Saugus and Pico Formations which range in age from Pliocene to Early Pleistocene. A few miles along Highway 14, we pass the Placerita oilfield. Before reaching the next road summit we cross the hidden trace of the San Gabriel fault which is interpreted to be a major ancestral strand of the San Andreas fault system.

In another few miles we drop down into the Soledad basin in which is exposed the terrestrial Mint Canyon Formation. At and a few miles beyond Sand Canyon Road, note the striking angular unconformities between tilted Miocene strata and subhorizontal Pleistocene gravels that are exposed in the freeway roadcuts. At Aqua Dulce Road, the coarse conglomerates lie near the base of the Mint Canyon Formation. To the north this conglomerate horizon is progressively replaced by sandstone and shale, whereas to the south this conglomerate becomes even coarser. This distribution of rock types suggests a southern source for this part of the Mint Canyon Formation. This interpretation is supported by the observation that the clasts are of distinctive metamorphic and igneous rock types (especially anorthosite) that are only exposed in the San Gabriel Mountains to the south.

Just beyond Aqua Dulce turnoff, we enter exposures of the Vasques Formation that is composed of terrestrial sedimentary and volcanic rock.

Approximately 0.5 mi beyond Soledad Canyon exit we pass through exposures of the Lowe granodiorite, a 230 million year old intrusive widely exposed in the San Gabriel Mountains.

Between the Angeles Forest Road and the Lamont Odet Vista Point we pass through several roadcuts. The first four expose volcanic rock of Oligocene age, whereas the last exposes Precambrian crystalline rock that is approximately 1.5 billion years old.

Passing the vista point, we can see the San Andreas fault zone, a major portion of which underlies the broad, southeast-trending valley that passes beneath the freeway just before Avenue S offramp. Palmdale Reservoir lies within the fault zone. The last major earthquake here was in 1857 and produced about 20 ft of right slip. Crossing the fault valley and approaching the road cut through the ridge beyond, we can see a 5 to 10-ft high scarp along the south side of the ridge. This is a scarp created by the 1857 event. The wildly contorted beds in the roadcut beyond are part of the Anaverde Formation of Pliocene age.

Between the San Andreas and Garlock fault we cross a broad relatively flat expanse of the western Mojave Desert. The pre-Cenozoic bedrock of this structural block may be exotic to North America.

About 4 mi beyond the Kern County Line we pass over the Rosamond Hills. Here are exposed Mesozoic granitoids overlain by the Tropico Group of middle Tertiary age, composed of volcanic and sedimentary strata. The Tropico group is host to rich deposits of borate minerals to the east near Boron, and to gold and silver deposits along and to the west of the freeway. The several isolated hills between here and Mojave are supported by volcanic and sub-volcanic rocks of the Tropico Group. Note the numerous mines developed to exploit the gold and silver deposit from the late 1800's to World War II.

From Mojave to Red Rock Canyon our route runs approximately parallel to the Garlock Fault which is at the base of the southern Sierra Nevada to the northwest. Look for beheaded alluvial fans caused by this left-flip fault.

As we pass Phillips Road on the right, we gain a good view of the Cantil Valley to the northeast. It lies between the El Paso Mountains to the north and the Rand Mountains to the south. The valley is a complex structural graben lying between the Garlock fault to the north (south base of El Paso Mountains) and a parallel left-slip fault on the south side of the valley.

Entering Red Rock Canyon, the first mile of roadcuts expose granitoids of Mesozoic age. Beyond these are spectacular castellated exposures of the Ricardo Formation of Miocene age. This formation is about 7,000 ft thick and was deposited in fluvial and lacustrine environments. Petrified wood and numerous kinds of vertebrate fossils (horses, camels, rhinos, saber-toothed cats, etc.) have been found in these sandstone, siltstone, conglomerate and tuff beds. About 2 mi north of the Red Rock Parking Lot we see a black basalt flow which is at the top of the lower part of the Ricardo Formation.

As we pass Abbott Drive (to the left), look over your left shoulder to see a well-developed, gently inclined erosion surface beveled across inclined beds of the Ricardo Formation. This surface is a "pediment", and it is clear that this one has been uplifted (relative to baselevel) and is now being eroded.

From Robber's Roast Cafe (on the left) we can see at 11:00 isolated knobs of granitoid bedrock sticking up from the alluvial fans. These are "inselbergs", or erosional remnants of the mountain front that has retreated westward.

Beyond Isabella Lake Road (Highway 178) we gain a good view of Indian Wells Valley and the Coso Range. For the remainder of the day we shall be in classic Basin and Range country, and a more extensive geologic commentary is provided.

BASIN AND RANGE PROVINCE OF EASTERN CALIFORNIA - AN OVERVIEW

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Stratigraphy

All of eastern California as far north as Mono Lake is inferred, on the basis of geochemical data, to be underlain by Precambrian continental basement approximately 1.7 billion years old. Exposures of this basement are present on the west flank of the Panamint Range, in the Black Mountains, and in smaller scattered exposures farther southeast.

Resting unconformably upon this basement in the Panamint Range and southeastward are strata of the Pahrump Group (Crystal Spring, Beck Spring and Kingston Peak Formations) of late Precambrian age. These formations were deposited in fault-bounded basins interpreted by some to have been aulacogens developed during one or two early rifting events that created a passive (Atlantic type) continental margin in western North America. The older two formations are at least 1.2 billion years old, whereas the Kingston Peak Formation, notable for its basalt flows and glacial diamictite, was probably deposited some time during the interval 700-800 million years ago.

Resting unconformably upon Pahrump Group rocks in some areas and upon older metamorphic basement where the Pahrump is absent are latest Precambrian (650-600 million years) and Paleozoic miogeoclinal strata of the Cordilleran geosyncline. These strata form a NW-thickening wedge extending from the outer margin of the stable platform near Las Vegas to the White Mountains (Fig.2.). This northwesterly thickening was accomplished by thickening of Paleozoic

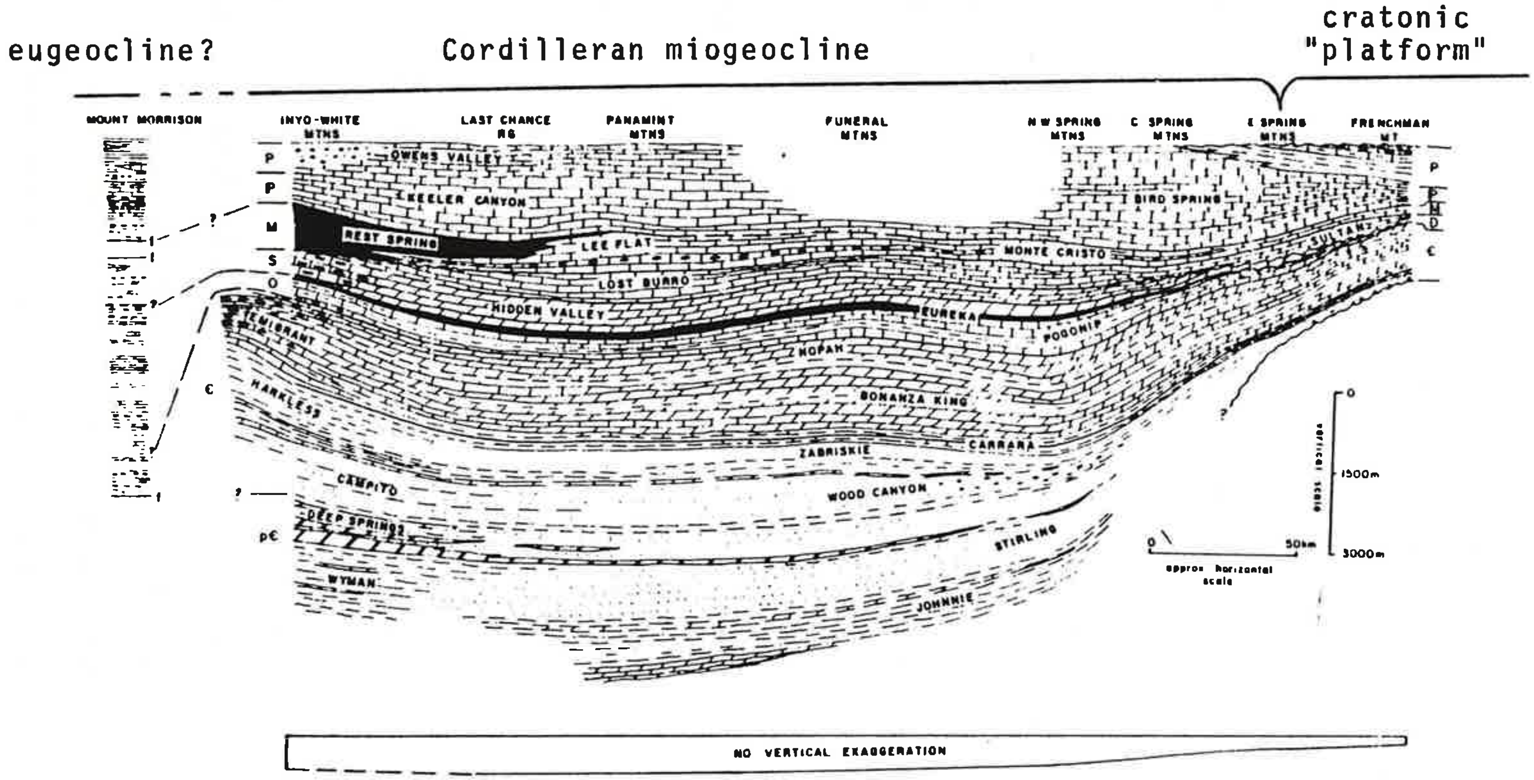


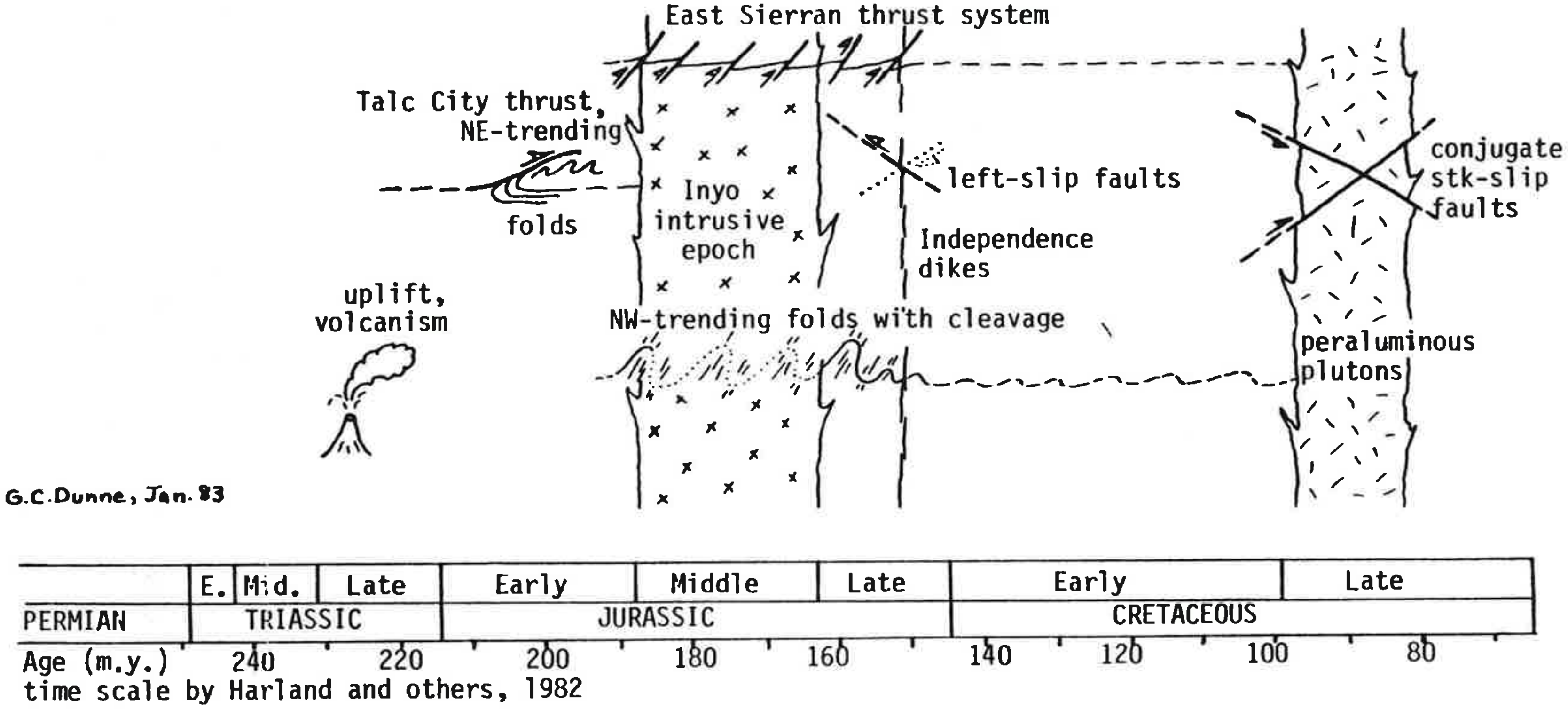
Fig. 2. Generalized stratigraphic framework of late Precambrian and Paleozoic rocks on a transect from near Las Vegas, Nevada (Frenchman Mountain), to near Mono Lake, California (Mount Morrison). No Pennsylvanian and Permian rocks crop out in the vicinity of the Funeral Mountains and are thus not shown in this section. Structural relations between the Mount Morrison rocks and thus of the Inyo-White Mountains are unknown,

units, in-filling of unconformities, and most importantly, by the appearance and northwesterly thickening of the late Precambrian basal clastic sequence. Deposition was for the most part in a tidal flat environment during late Precambrian and Early Cambrian time, and in somewhat deeper shelf environments thereafter. Major interruptions in this depositional setting occurred in mid-Paleozoic time in response to the Antler orogeny and during the Permian, possibly in response to the Sonoma orogeny. The Antler orogeny, localized along the continental margin, shed to the south and east a clastic flysch deposit (Rest Spring Shale in eastern California, Chainman Shale in Nevada and Utah) that wedges out in the vicinity of our second field stop, lapping against a major late Mississippian carbonate bank (Lee Flat Limestone). Permian tectonism, apparently extensional in nature, created pronounced ridge-basin submarine topography and an intra-Permian unconformity.

Following a brief Permo-Triassic depositional hiatus, marine waters reoccupied eastern California during Early Triassic time. Toward the end of the Early Triassic, shoaling occurred, leading to emergence. The area was overrun by alluvial fans shed from rapidly eroding, nearby source areas. Terrestrial volcanic deposits then spread across eastern California.

Structural Geology

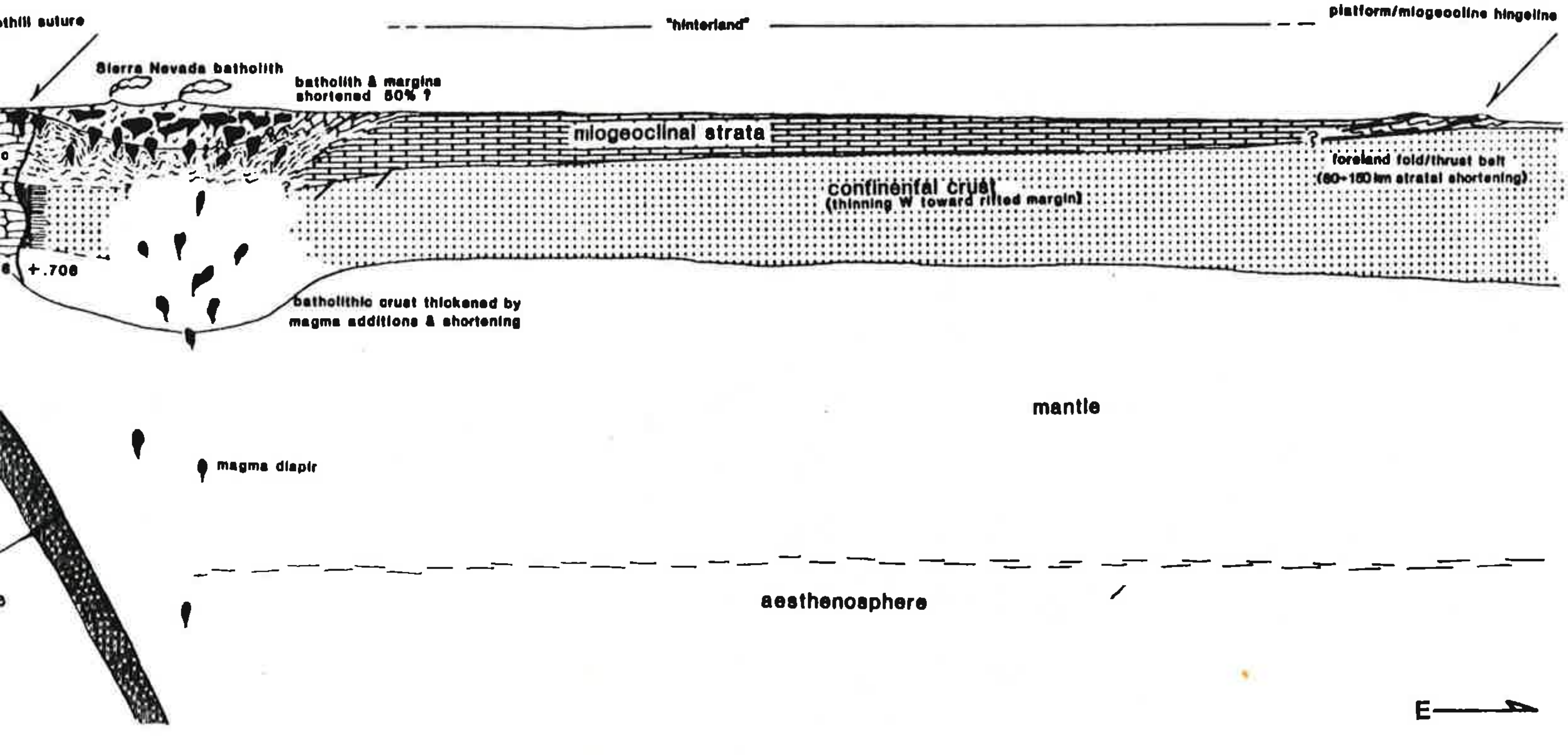
Structures resulting from two major episodes of tectonism are well displayed in eastern California. The older group of structures is dominated by east-vergent folds and thrust/reverse faults developed during several spatially superposed phases of compressional deformation that began in Middle Triassic time and continued until the mid-Cretaceous (Fig.3). During this same



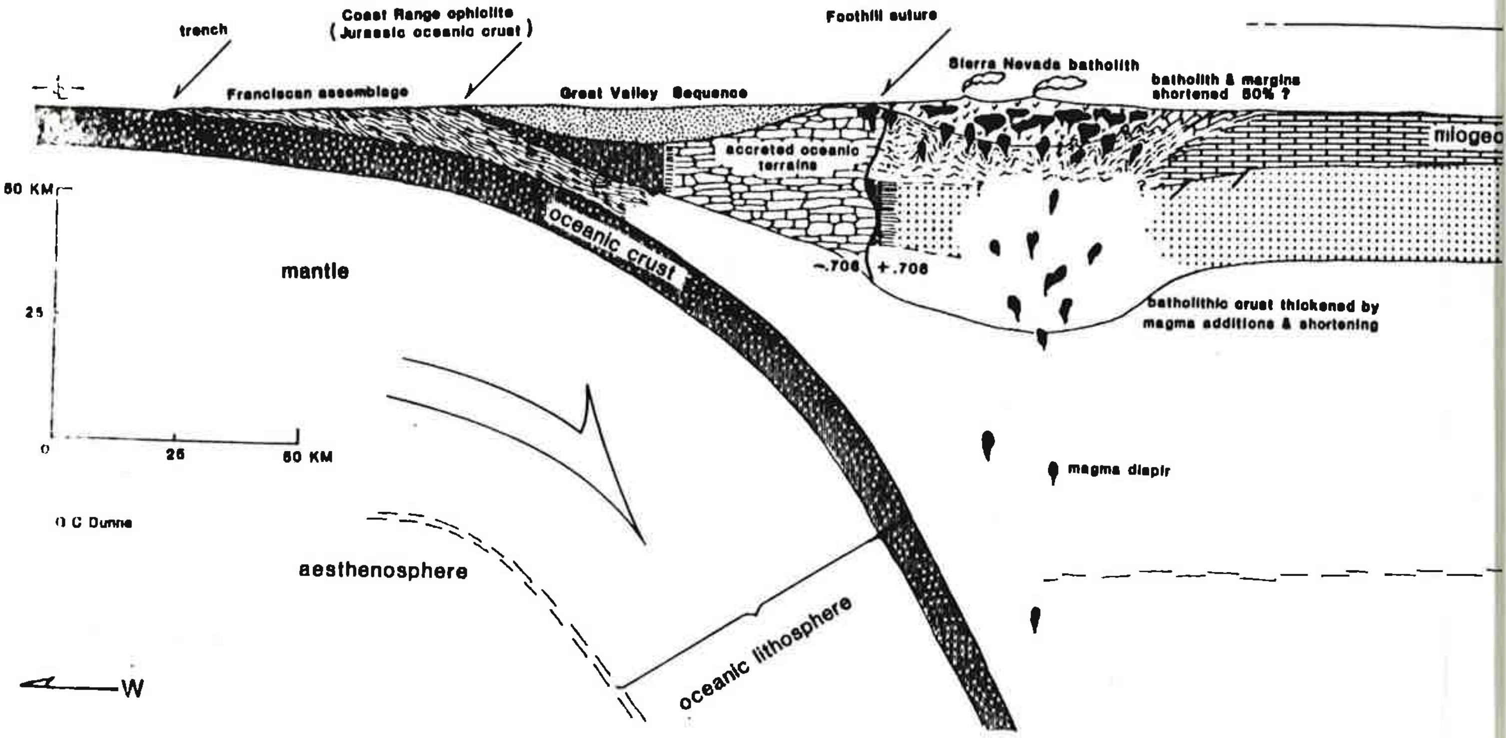
G.C.Dunne, Jan. 83

time scale by Harland and others, 1982

Figure 3 Schematic time-event diagram depicting major igneous and deformational events in eastern California during the Mesozoic.



horst graben
topography. Major
ed during this interval are
in Saline Valley.



faulting that gave rise to the present spectacular topography. Major accumulations of predominantly basaltic lava extruded during this interval are exposed in the Coso Range, the Darwin Plateau, and in Saline Valley.

interval, the Sierra Nevada batholith was emplaced, and numerous outlying plutons invade pre-Mesozoic country rock in ranges east of Owens Valley. Both compressional deformation and plutonism are genetically linked to an east-dipping subduction zone that operated west of the Sierra Nevada throughout much of Mesozoic time.

Cutting these older compressional structures is a younger group of structures developed during extensional (Basin-and-Range) tectonism in late Cenozoic time (Fig. 4). Northeast-, north-, and northwest-trending faults of normal-, right-normal oblique and right-strike-slip, respectively, developed in one complex and protracted phase or in two separate phases of WNW-ESE directed oblique extension (transtension) beginning at least as long ago as Early Miocene time (20 m.y. ago) and continuing today (Fig. 4). Miocene (and older) phases of this extensional tectonism developed within and behind an active volcanic-plutonic igneous arc that was generated by the last phases of east-directed subduction along the coastal California subduction zone. Manifestations of this arc are seen in the Timber Mountain and Bullfrog rhyolite centers north and west of Beatty, Nevada, and in the southern Death Valley region. About 6.1 m.y. ago (at the latitude of Death Valley), the coastal subduction zone was replaced by the San Andreas transform fault system. This plate tectonic transition seems to have been manifested in eastern California by the onset of widespread basalt and basalt-rhyolite (bimodal) volcanism and by renewed extension taking the form of horst-graben faulting that gave rise to the present spectacular topography. Major accumulations of predominantly basaltic lava extruded during this interval are exposed in the Coso Range, the Darwin Plateau, and in Saline Valley.

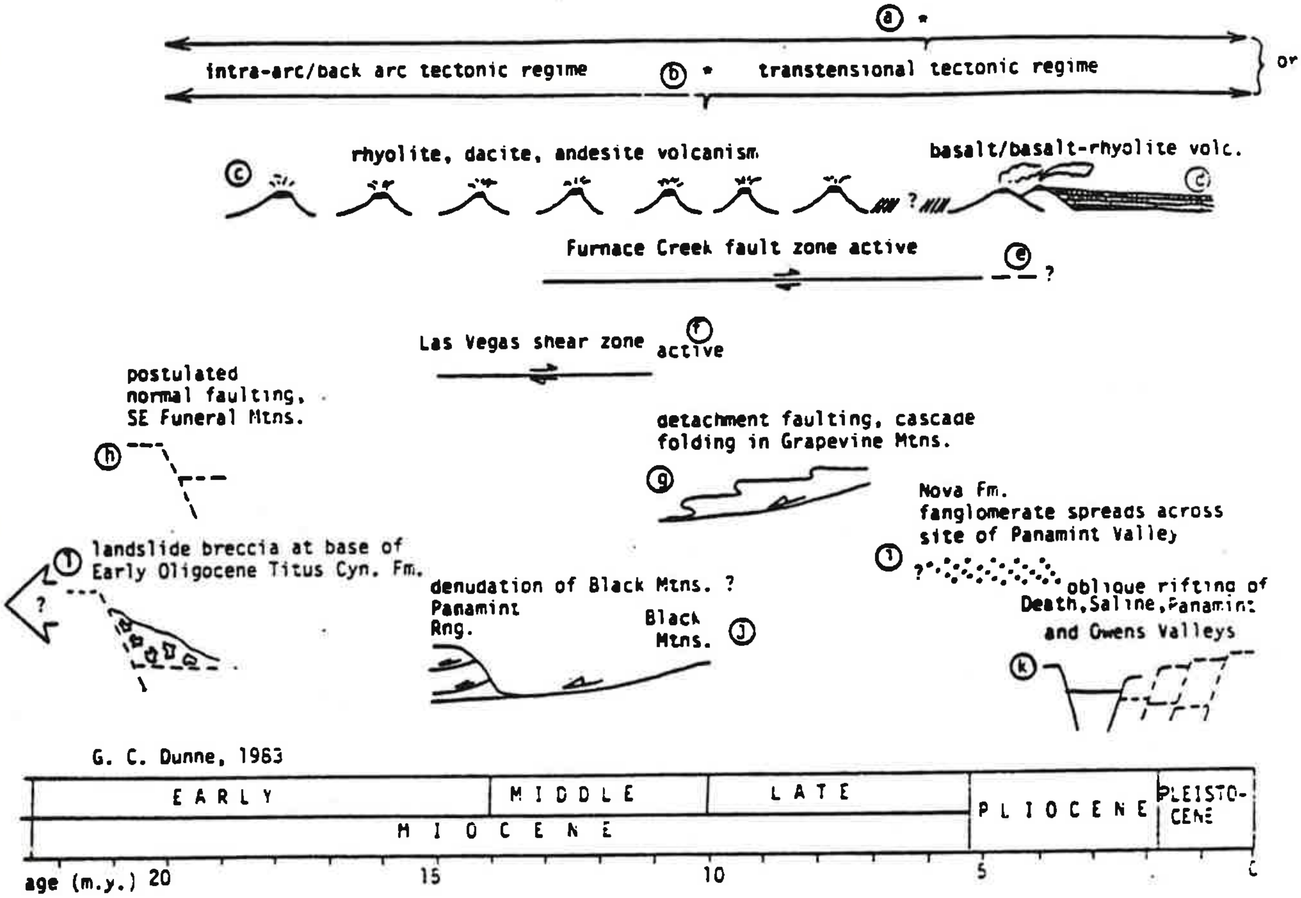


Figure 4. Schematic tectonic evolution of Death Valley and adjacent areas in eastern California during the Neogene. Symbol * represents northward migration of Mendocino triple junction past latitude of Death Valley at time indicated by position of symbol. Sources of data are as follows: a = Engebretson et. al., 1982; b = Atwater & Molnar, 1973; c = Wright et. al., 1981; Cemen et. al., 1982; Luedke & Smith, 1981; d = Larsen, 1979; Luedke & Smith, 1981; McKee, 1968; e = Drewes, 1963; Hunt & Mabey, 1966; McKee, 1968; f = Fleck, 1970; g = Reynolds, 1974; Cemen et. al., 1982; i = Hall, 1971; Larsen, 1979; j = Stewart, 1983; k = Bacon et. al., 1982; Bachman, 1979; Larsen, 1979; 1 = Reynolds, 1974; Hunt and Mabey, 1966.

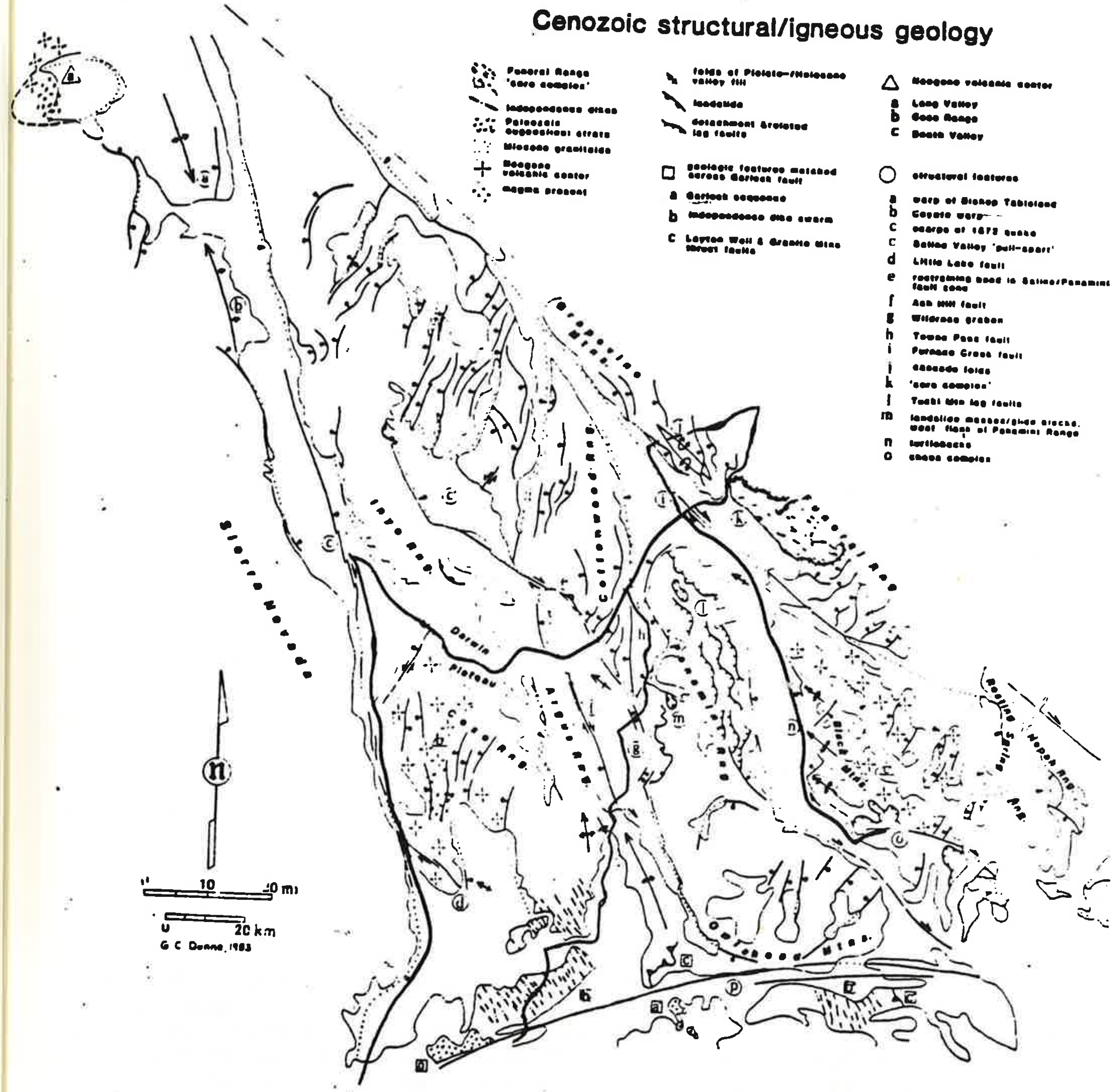


Figure 5. Principal structural and igneous features of Neogene age in eastern California. Field trip route shown by heavy line.

Total east-west extension of eastern California during late Cenozoic time is substantial. Extension along a line from the Argus Range to Pahrump Valley probably is about 100%, and in local subareas of mountain range size may be two to four times this great. Estimates of total extension across this region have in recent years yielded larger amounts as geologists have recognized the importance of gently dipping normal faults (detachment faults) exposed within ranges. The more conservative estimates made in previous decades took into account only that extension manifested by steeply dipping range-front faults and the eastward tilting of fault blocks that movement on these faults caused (Fig. 6).

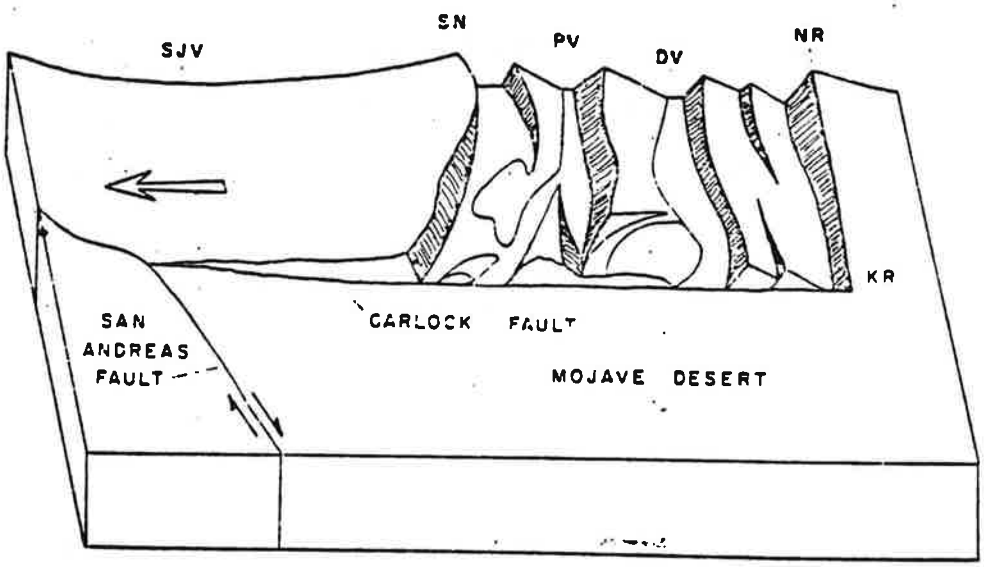


Figure 6. Northward diagrammatic view of Garlock fault, southern California, as a boundary between a northern, distended crustal block (Basin and Range province) and a southern, nondistended crustal block (Mojave Desert). Topographic relations are highly generalized and are shown only north of the Garlock fault. Geographic localities: SJV = San Joaquin Valley, SN = Sierra Nevada, PV = Panamint Valley, DV = Death Valley, NR = Nopah Range, KR = Kingston Range (after Davis and Burchfiel, 1973).

TRANSECT OF THE BASIN-AND-RANGE PROVINCE, EASTERN CALIFORNIA

Indian Wells Valley

Approaching the intersection with State Route 14, we have (on a clear day) a good view of Indian Wells Valley. It is bounded on the south by the El Paso Mountains and Spangler Hills, on the east by the Argus Range, on the north by the Coso Range, and on the west by a relatively subdued portion of the Sierra Nevada. The El Paso Mountains/Spangler Hills feature a basement complex of Mesozoic granitic rock (Sierra Nevada batholith) enclosing large roof pendants of Paleozoic strata of eugeoclinal (!) affinity. Overlying this basement are substantial thicknesses of Paleocene (Golar Formation) and Miocene (Ricardo Formation) terrestrial strata that are capped by Plio-Pleistocene basalt. Black Mountain, the dark, terraced hill at the NW corner of the El Paso Mountains, is a major volcanic edifice.

The southern end of the Argus Range, east of Indian Wells Valley, is comprised of granitic rock of the Sierra Nevada batholith. Later in the day we will have a view stop at the north end of the Argus Range. On the skyline through the low gap east of the town of Ridgecrest can be seen the double whalebacks of the Slate Range, beyond which is the southern end of Panamint Valley. Passing just south of the Slate Range is the ENE-trending Garlock fault, a left-slip fault that separates an active extensional Basin-and-Range tectonic province to the north from terrane (Mojave Desert) that experienced Basin-and-Range tectonism in Miocene time, but which now is experiencing predominantly NW-trending right shear, presumbly related to the San Andreas fault

Geophysical studies of Indian Wells Valley show it to be an irregularly shaped, fault-bounded graben. A maximum of 6500' of valley fill rests on a gently west-tilted Pliocene (?) basement surface* that lies abut 4000' below sea level. Remnants of the (presumably) same erosion surface are exposed at elevations of 7000' to 8000' in the Sierra Nevada west of Indian Wells Valley, attesting to vertical separation during Basin-and-Range tectonism of as much as 11,000' in this area, with high-standing blocks moving absolutely upward and low-standing blocks moving absolutely downward.

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* A brief discussion of this Pliocene erosion surface is in order. There exists a widely held - although poorly documented - view that the Sierra Nevada and ranges immediately to the east had been beveled to a surface of low relief during late Miocene and Pliocene time. Provisionally, correlated remnants of this surface are present in the Sierra Nevada (Chagoopa surface, near Mt. Whitney) and in the Coso, Inyo, Argus, and Panamint Ranges, as well as across the Darwin Plateau. Remnants of lacustrian and fluvial deposits rest on this surface in the Coso Range (Coso Formation) and Inyo Range (Waucobi lake beds), and the earliest glacial deposits (McGee sequence, about 2 to 3 m.y. old) may rest on the same surface. Numerous basalt flows ranging in age from 4 to 5 m.y. spread across this surface. Several lines of evidence show that substantial vertical relief, and presumably the development of Basin-and-Range topography, did not begin to disrupt this surface (or at least did not become pronounced) until about 3.5 m.y.b.p. (mid-Pliocene).

Coso Range

The Coso Range is a high-standing block that separates Indian Wells Valley on the south from Owens Valley to the north. Our transect passes around a substantial part of this range. The basement of this range is granitic rock of the Sierra Nevada batholith. Forming a discontinuous veneer over this basement are abundant late Miocene to late Pleistocene volcanic rocks and a major sedimentary unit (Coso Formation) of Late Miocene to Late Pliocene age (Fig.7). About 31 km^3 of volcanic rock were extruded prior to about 2.5 m.y.b.p., being composed of basalt, rhyodacite, dacite, andesite, and rhyolite in decreasing order of abundance. Beginning about 1.2 m.y. ago, sub-equal amounts of basalt and rhyolite have been extruded, totaling about 4 km^3 in volume. Rhyolite domes formed as recently as 77,000 years ago east of Rose Valley, and basalt flows were extruded as recently as 30,000 years ago. Geophysical evidence suggests the presence of a magma body at mid-crustal depths below the rhyolite domes. Hot springs and high heat flow in the vicinity of the domes led to geothermal exploration of the area. A test well drilled in 1977 for the U. S. Navy (most of the Coso Range lies within the China Lake Naval Weapons Center) provided guidance for a second well drilled in 1981 that proved the existence of a large, commercially viable geothermal resource characterized by mixed steam and hot water at a temperature of 425^{o}F. at a depth of 5000 feet. Total generating potential for the field is estimated to be between 675,000 KW and 4,000,000 KW.

A coherent picture for effects of Basin-and-Range tectonism upon the Coso Range is provided by fault and volcanic vent patterns, recent seismic activity, and patterns of extrusion and sedimentation. Several independent studies using different kinds of data have arrived at nearly identical conclusions regarding the orientation of principal regional stresses in

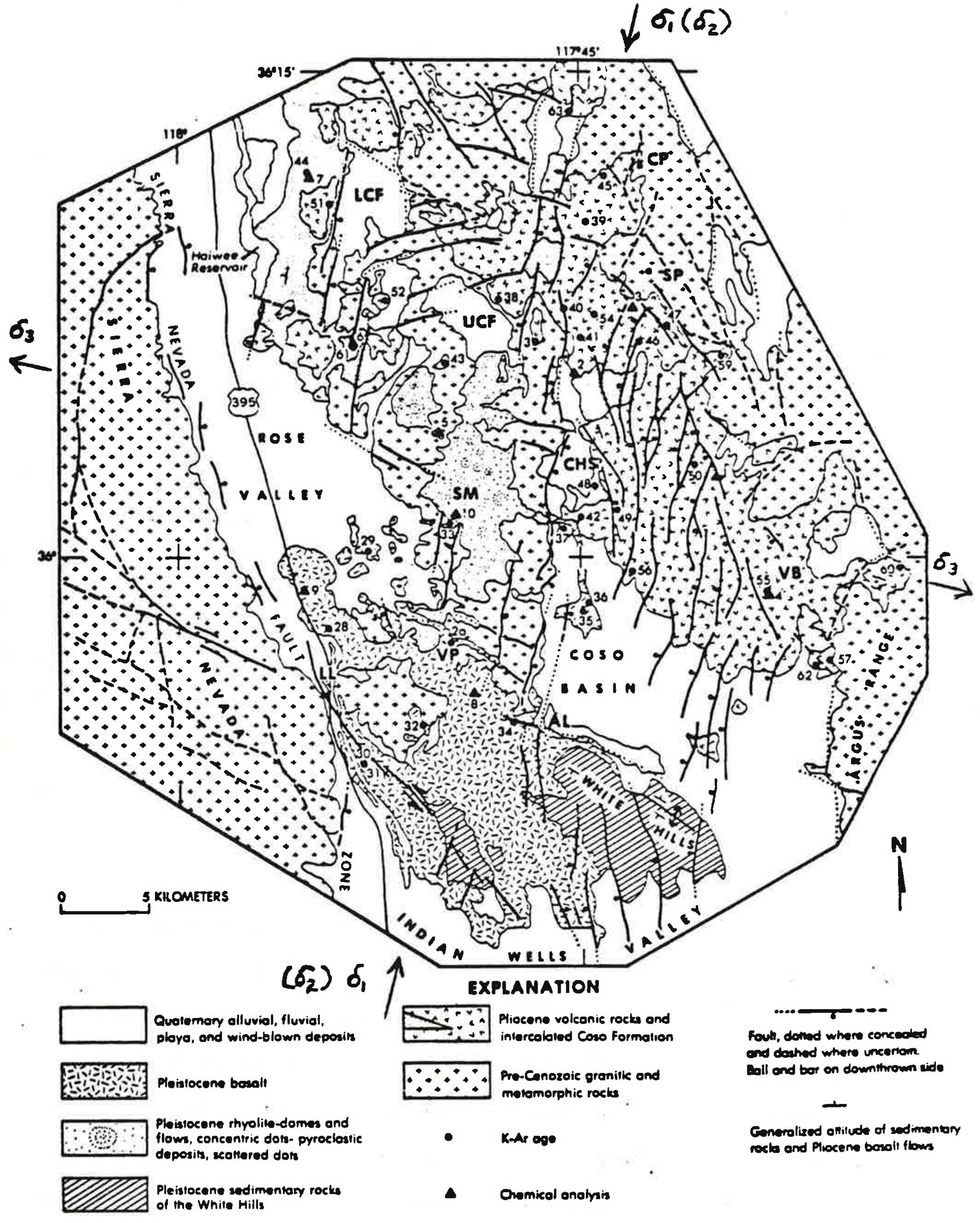


Figure 7. Geologic map of the Coso volcanic field showing inferred orientation of principal stresses giving rise to the extensional structures (after Duffield and Bacon, 1980).

eastern California for the past several million years. The averaged orientation of principal stresses has been sketched on Figure 6. First-motion studies of seismic data as well as field studies of faults have revealed that during Holocene time NW-trending faults have experienced components of right slip that are larger than their dip-slip components, whereas apparently conjugate but less abundant NE-trending faults have experienced components of left slip that are as large or larger than their dip-slip components. Finally, as might be expected from the foregoing, faults trending NNE, parallel to the regional σ_1- σ_2 stress plane, have experienced primarily dip-slip. Movements on these groups of faults have accommodated the WNW-directed tectonic extension of the Coso Range. The relative abundance of NW-striking right- and right-normal-slip faults may reflect a subsidiary tectonic influence of right shear created by the San Andreas transform system. The NW-trending Little Lake fault has experienced swarms of small earthquakes since March, 1982. First motion studies show slip to have been right lateral. These swarms continue as of this writing (January, 1983), and there is some possibility that they will prove to be foreshocks to a moderate earthquake.

The onset of extensional basin formation in this area is recorded in certain continental deposits found immediately to the east of the Sierra. Sedimentologic studies of the Coso Formation, exposures of which we will see further north, suggest that it was deposited in a tectonically quiescent lacustrian/fluvial environment during Late Miocene and Early Pliocene time, then in a terrane of pronounced relief and/or rapid erosion beginning about 3.0 m.y. ago. The switch in environments is inferred to mark the onset of substantial topographic relief caused by Basin-and-Range tectonism. Study of the Waucobi lake beds in northern Owens Valley suggests a broadly similar timing. In that area, vertical relief became pronounced during the interval 3.4 to 2.3 m.y. ago, with Owens Valley becoming a relatively down-dropped block near the end of this interval.

Two geologic phenomena of note fall readily to eye as we approach Little Lake, situated in the notch between the Sierra Nevada and the Coso Range. First, note the patchy variegated appearance of Sierran granitic rock on the west side of the highway. This is the axial portion of the Sierra Nevada fault zone, along which much of the uplift of the range has occurred. This crushed zone is almost 2 miles wide here.

The second point of interest relates to the use of this notch and one just to the east of it by the ancestral Owens River during the Pleistocene. During the most recent Ice Ages, increased rainfall as well as glacial meltwater led to the development of a series of large freshwater lakes in eastern California. Several of the largest of these were intermittently connected by rivers, forming an interconnecting chain stretching from Mono Lake (pluvial Lake Russell) to an "ultimate baselevel" in Death Valley (Fig. 7). During wetter intervals, Owens Lake in southern Owens Valley overtopped its southern margin, sending a river (ancestral Owens River) southward through the Haiwee area, across Rose Valley, and through the notches at and east of Little Lake into Indian Wells Valley. Three times basalt flows from the Coso volcanic field filled the notch near Little Lake, at least once causing a temporary lake to form in Rose Valley to the north. The first blockage occurred when the Lower Little Lake Ranch flow, originating from a vent about 1.5 miles SE of Little Lake, moved southward through the notch and spread out across the NW corner of Indian Wells Valley about 440,000 years ago. The impressive cliffs flanking the east side of the highway south of Little Lake were cut in this basalt as the ancestral Owens River finally overtopped the flow and cut a channel through it down into Indian Wells Valley. About 100,000 years ago, a second flow, that of Upper Little Lake Ranch, originated from a vent about 3 miles NE of Little Lake. It spread westward until it reached the river channel, then moved southward along the channel at least 10 miles, thoroughly blocking it. The impressive columnar basalt forming the east shore of the lake belongs to this flow. Finally, about 30,000 (±50%) years ago, after the river had again established a channel across the second flow, a third eruption, centered at the red, well-formed cinder cone (Red Hill) north of Little Lake, sent a third and final flow into the channel. This, too, was quickly breached by the river, which continued to transport significant quantities of water into China Lake in Indian Wells Valley until about 10,000 years ago.

At the north end of the Rose Valley, one can see an erosional notch to the NE, through which the distant Inyo Mountains can be seen. This notch, too, was cut by the ancestral Owens River. As we draw even with the notch, the headwall scarp of a large landslide within brown-weathering rock can be seen on the east wall of the notch; the body of the slide is cut by numerous bulldozer trails. The slide may have resulted from undercutting of the cliff by the ancestral Owens River.

Southern Owens Valley

The white bluffs on the east side of Haiwee (pronounced Hay-wee) Reservoir are lake-bed deposits of the Coso Formation.

Owens Valley is a classic Basin-and-Range graben, bounded by two sub-parallel normal fault zones on the west and one such zone on the east (Fig. 8). Granitic bedrock in the area of thickest valley fill lies at an elevation of -6,000 feet, whereas its counterpart on the rest of the Sierra reaches an elevation of 14,500 feet. Most, if not all, of this 20,500+ feet of relief has developed during the past 2.5 to 3.0 m. years.

As with much of the Basin-and-Range province, differential vertical movement has been accomplished not only by normal faulting, but by down-to-valley warping as well. A spectacular example of this is seen north of Big Pine where the very abrupt, normal-fault-controlled east face of the Sierra Nevada gives way to a gently curved rise, the Coyote Warp (Fig. 9). Less spectacular examples of such down-to-valley warping are seen along the margins of numerous ranges in eastern California. Dip of the Coso Formation radially away from the core of the Coso Range (Fig. 10) may be a reflection of this phenomenon.

The Inyo Mountains, Coso Range, and Darwin Plateau show no systematic tilt direction resulting from Basin-and-Range tectonism. In contrast, the Sierra Nevada tilts westward and ranges east of the Darwin Plateau tilt east or southeast. Some workers have attached considerable tectonic significance to such tilt reversals, but more recent work suggest that they may be largely a matter of chance.

As an historic aside, Owens (dry) Lake had a (wet) surface area of 100+ mi^2 and depths of up to 30 feet at the turn of the century, down from a surface area of 200+ mi^2 and depths of over 200 feet at its Pleistocene maximum. Diversion of its Owens River source water into the just-completed Los Angeles aqueduct in 1913 led to rapid desiccation of the lake.

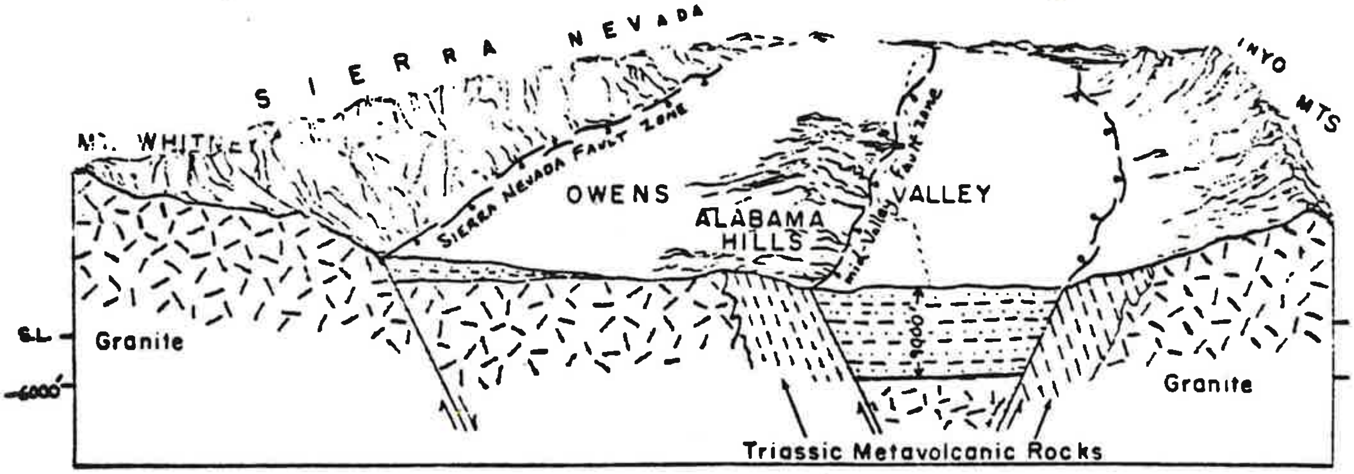


Figure 8. Diagrammatic cross section near Lone Pine. The Alabama Hills are the exposed portion of a block that has dropped midway between the crest of the Sierra and the bedrock low of Owens Valley. A subsurface fault zone on the east flank of the Alabama Hills has an escarpment that is higher than the visible Sierran escarpment to the west (after Von Huene and others, 1963).

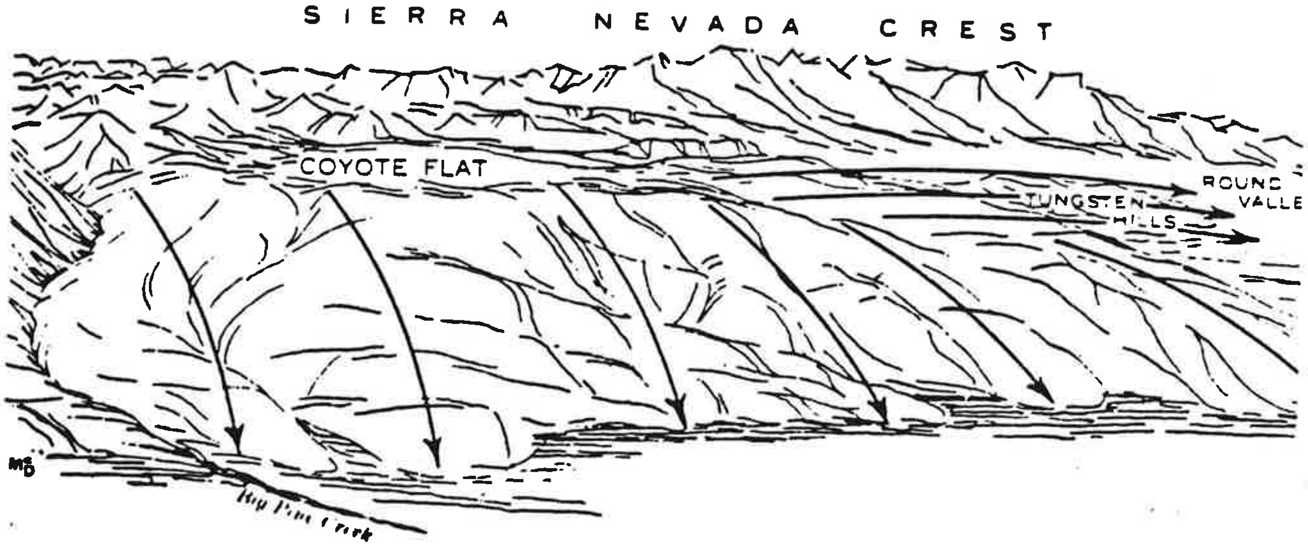


Figure 9. Sketch of the Coyote Warp, between Big Pine and Bishop, illustrating the ramp-like nature of the eastern Sierra Nevada front (after Von Huene and others, 1963).

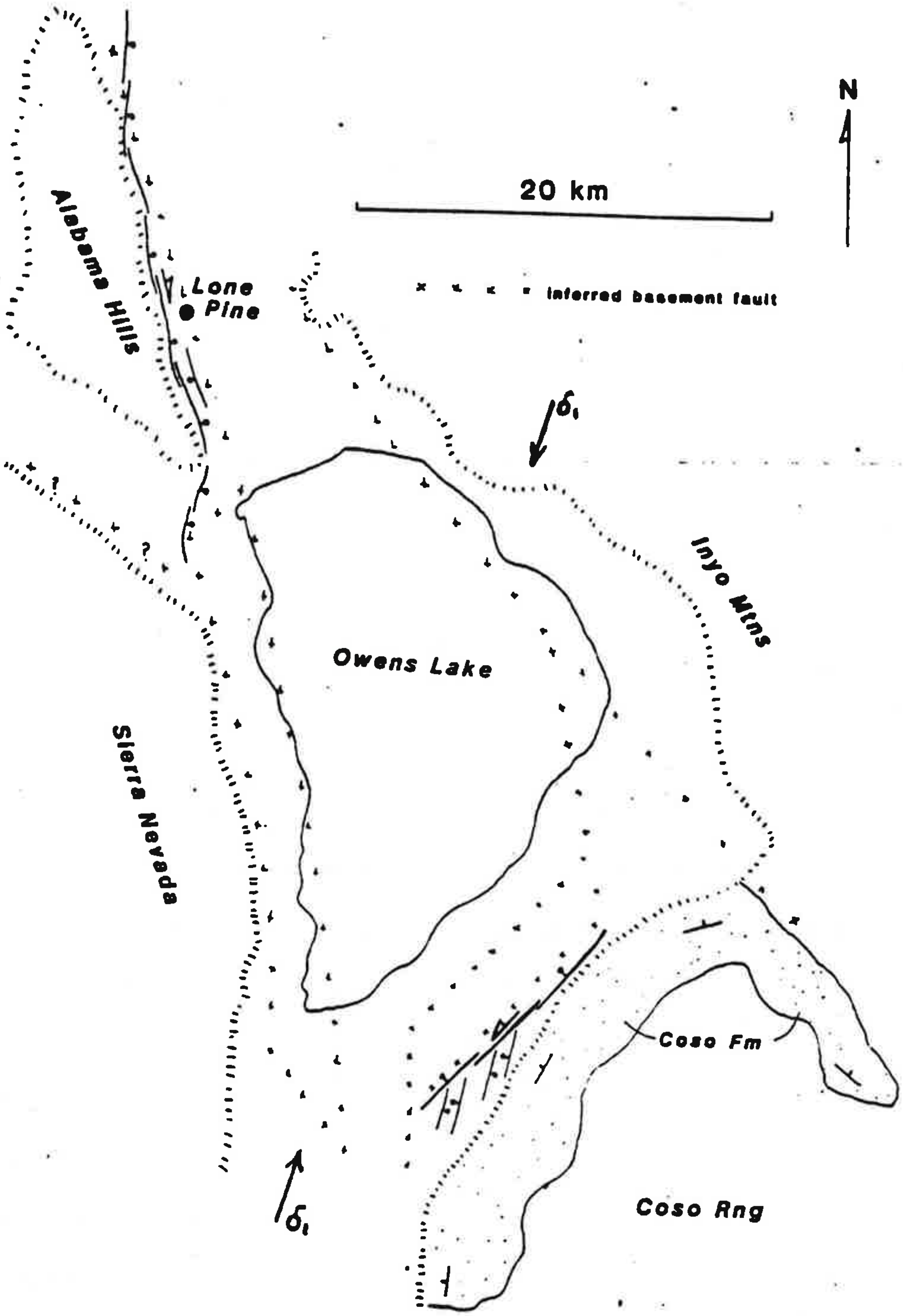


Figure 10. Sketch map of Owens Lake area showing representative Pleistocene/Holocene structures and the inferred causitive compressive stress.

The extensional neotectonics of the southern Owens Valley mimics that of the Coso Range. Conjugate right- and left-oblique-slip faults seem to be a direct response to the regional stress pattern (Fig. 10). Left slip on the NE-trending fault along the SE shore of Owens Lake is inferred from the presence of poorly developed grabens that intersect the fault at an oblique angle in a manner better exemplified by similar grabens that intersect the left-slip Garlock fault (Fig. 11). The major (M=8+) Lone Pine earthquake of 1872 caused approximately 6.5 m of right slip and 1.5 m of normal slip on the fault system fronting the Alabama Hills. Absolute downward movement of the hanging wall is suggested by rapid westward migration of the Owens River to the scarp following the earthquake.

The extensional neotectonics of Northern Owens Valley is well manifested by the structure affecting the Bishop Tuff tableland (airphoto C and accompanying fault map). The tableland was created about 0.75 m.y. ago by emplacement of a series of thick ash-flow tuffs, the upper surface of which was originally nearly flat. During Basin-and-Range deformation, this tableland has been warped into a broad S-trending anticline and cut by numerous faults that occur individually as in echelon sets, and as conjugate sets. The geometry of the latter two patterns clearly manifests generally east-west extension of the tableland.

Mesozoic Compressional Tectonism of the Inyo Mountains and Darwin Plateau

The eastern wallrock of the Sierra Nevada batholith is composed of late Precambrian through early Mesozoic strata that are now exposed in the White and Inyo Ranges, Darwin Plateau, and Argus, and Slate Ranges. These wallrock strata were affected by the multiple episodes of east-vergent compressional tectonism during the Mesozoic. Representative structures resulting from this tectonism are well exposed in the southern Inyo Mountains east of Owens Lake and in the Talc City and Darwin Hills of the Darwin Plateau (Fig. 11).

The stratigraphic record indicates that deformation began at the end of Early Triassic time (Fig. 2). The oldest recognized structures are a group of large-slip, low-dip, NE-trending imbricate thrust faults (Last Chance thrust system) and genetically related (?) NE-trending folds. Some faults of the Last Chance system (Lemoigne, Marble Canyon, Racetrack, Last Chance, and Talc City thrust faults are intruded by - and hence predate - igneous rocks at least 180 m.y. old. At several localities, these NE-trending fault and fold structures are overprinted by younger NW-trending, NE-vergent thrust and reverse faults, and by N- to NW-trending folds with well-developed axial cleavage. Although first recognized in smaller subareas and given local names, the NW-trending thrust and reverse faults are here interpreted to form a colinear group called the East Sierran thrust system that can be recognized from the White Mountains to the Mojave Desert. Faults of this system are characterized by moderate dip (45°-60° SW), modest slip (a total of a few to perhaps several km at any one transect across the system), and by a strikingly uniform slip direction averaging N75°E., manifested both by elongation lineations and by asymmetric folds found in partially to thoroughly transposed rock adjacent to the faults. Two cross sections transecting the fold/thrust belt on the west slope of the southern Inyo Range are provided in Figure 15, and a "big picture" cross section depicting the East Sierran and Last Chance thrust systems as they may exist in the vicinity of the Darwin Plateau is given in Figure 12.

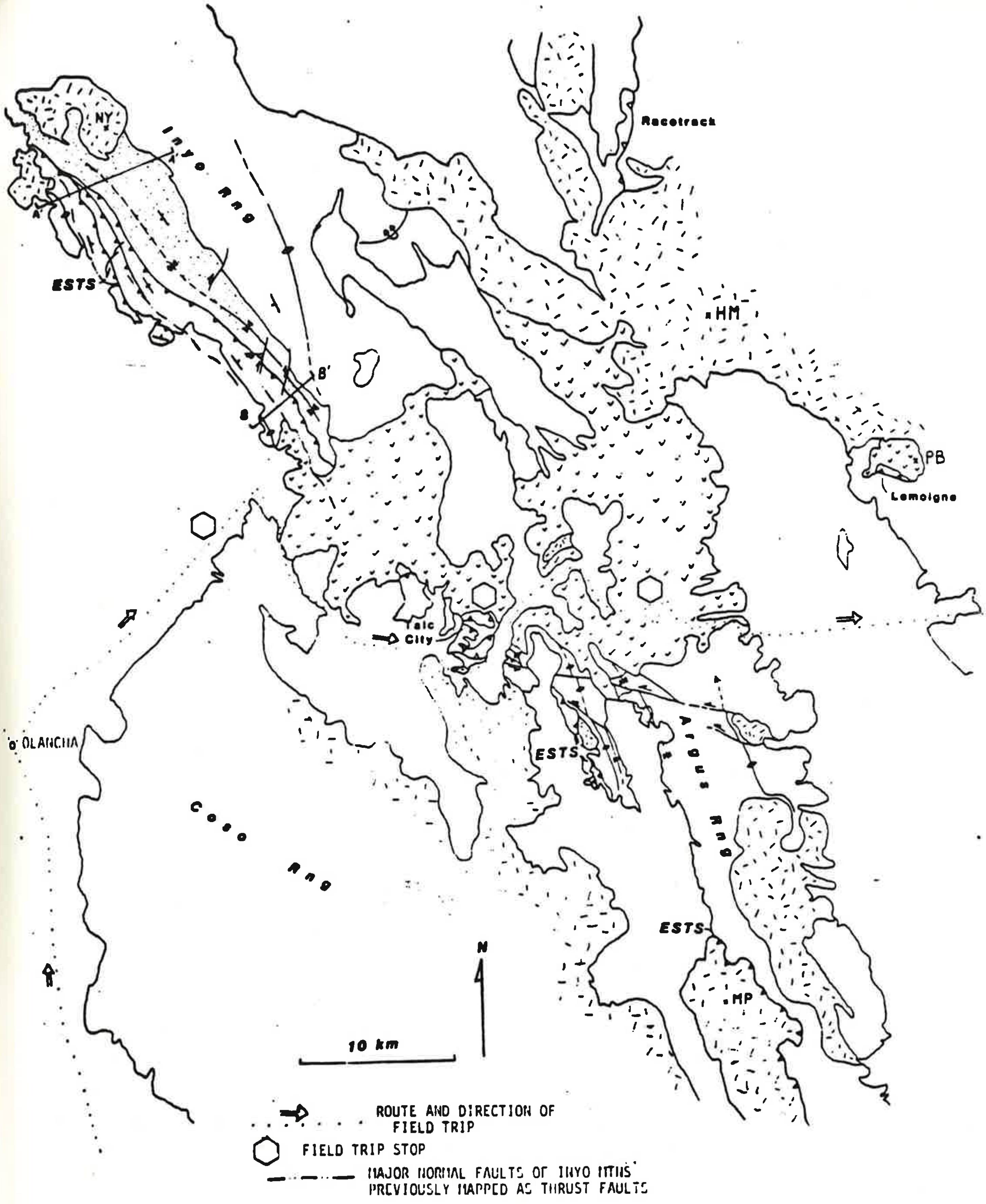


Figure 11. Principal compressional structures of Mesozoic age in the southern Inyo Range, Darwin area, Argus Range and Panamint Range. Prominent mountains visible from the field trip route include New York Butte (NY), Maturango Peak (MP), Hunter Mountain (HM), and Panamint Butte (PB). Triassic strata are stippled, whereas Paleozoic strata are unpatterned. Locations are shown for two cross sections of the west flank of southern Inyo Range that appear as figure 15.

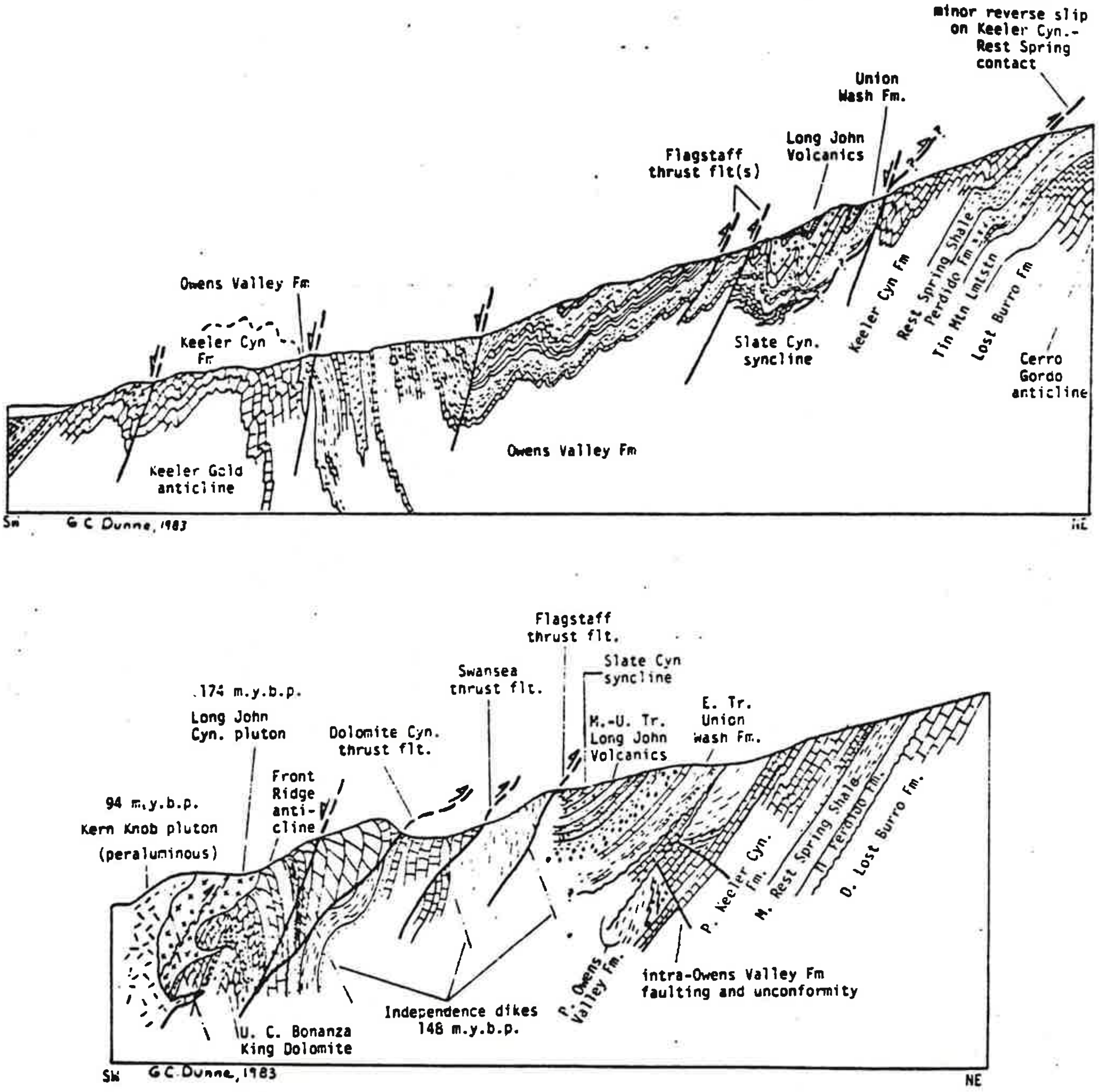
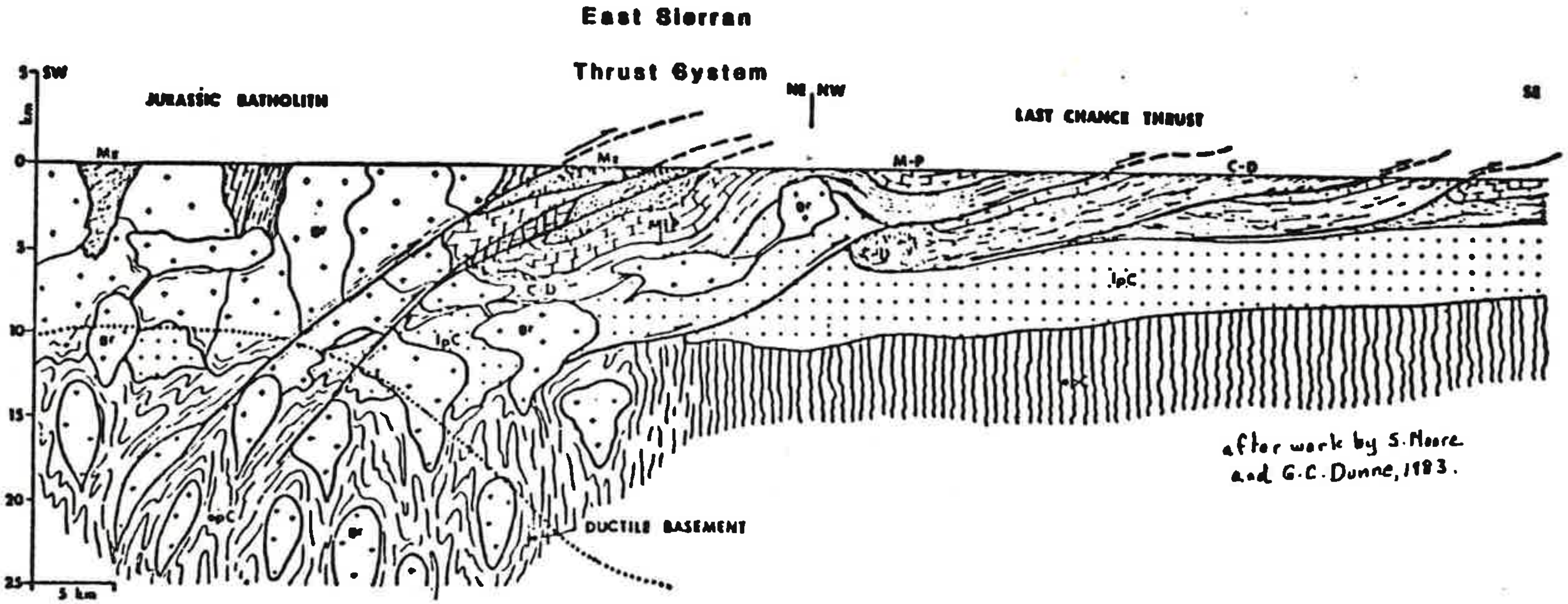


Figure 12. Schematic cross sections of the Mesozoic fold/thrust belt in the southern Inyo Range. Approximate locations of these two sections are shown in figure 12.



after work by S. Moore
and G.C. Dunne, 1983.

Figure 13. Schematic cross section transecting the Last Chance and younger East Sierran Thrust Systems in the vicinity of the Darwin Plateau (after S. Moore, 1976).

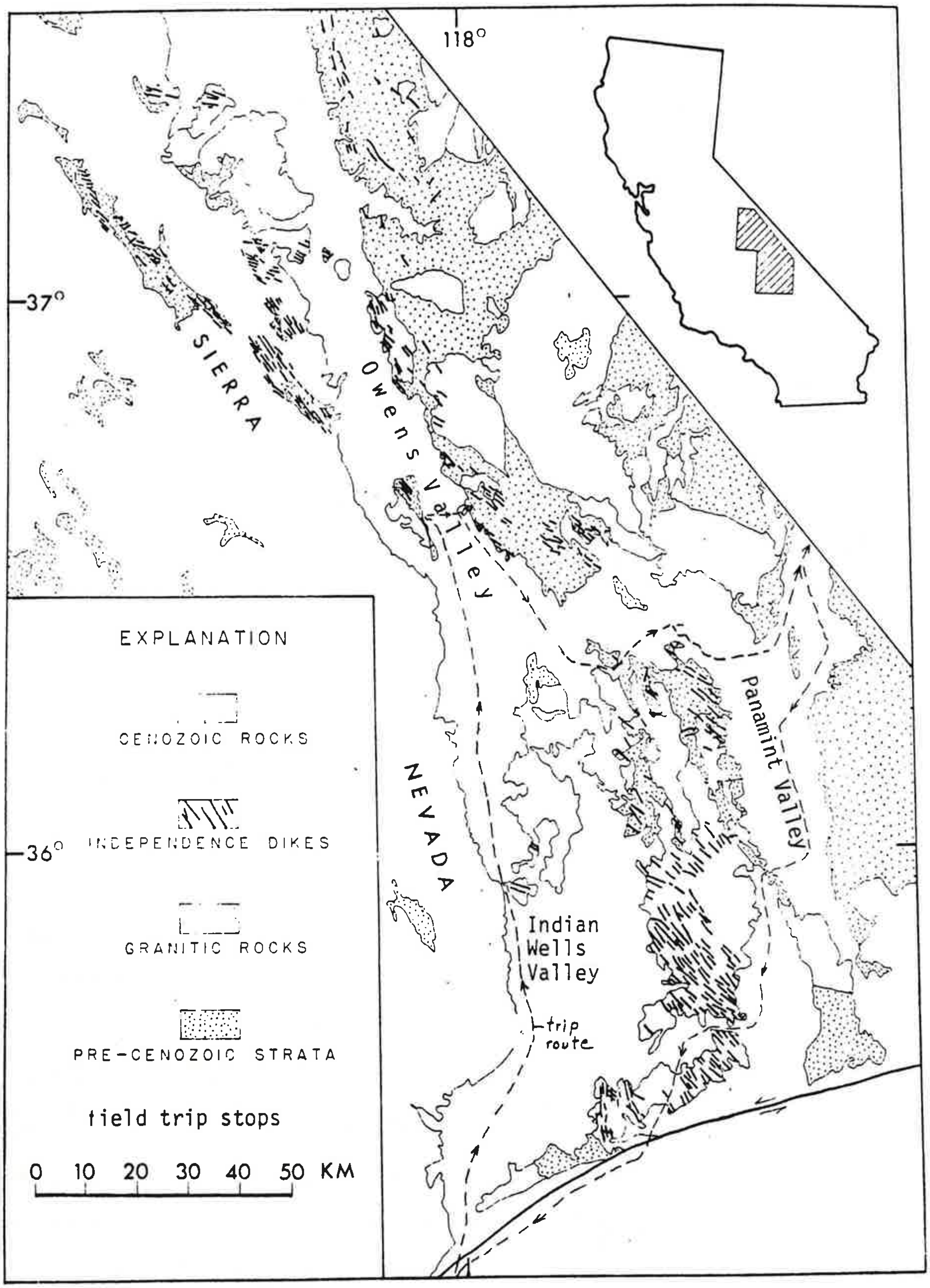


Figure 14 Generalized geologic map showing Independence dike swarm (148 m.y.b.p.) north of the Garlock fault (after Chen and Moore, 1979).

Northwest-trending folds typically are east-vergent, plunge moderately NW, are distinctly asymmetric in profile and tend to change wavelength, amplitude and tightness when traced laterally or vertically . This latter phenomenon seems to be controlled in part by contrasts in mechanical properties between different lithologic units that are affected by a given fold set.

At Stop 2, in the Talc City Hills, the results of overprinting of a thrust fault (Talc City thrust) of the Last Chance thrust system by NW-trending folds will be studied. A geologic map of the Talc City thrust fault reveals its thoroughly folded geometry. A cross section through our stop locality is provided in Figure 16.

Regional stress patterns switched to different orientations at least twice during the Mesozoic. At the end of middle Jurassic time (148 m.y.b.p.), numerous NW-trending, generally mafic dikes (Independence dike swarm) were emplaced from the Sierra Nevada to the Mojave Desert (Fig. 14), manifesting NNE-SSW extension of the region that previously was experiencing a NNE-SSW compressional shortening. This can be related to a swapping of positions of σ 1 and σ 3, the greatest and least regional principal stresses, respectively. During the same interval of time, NW-trending left-slip faults formed, denoting a swapping of positions of σ 2 and σ 3, the intermediate and least regional principal stresses. These short-lived changes may reflect reorganization of subduction zones in coastal California following the Nevadan orgogeny.

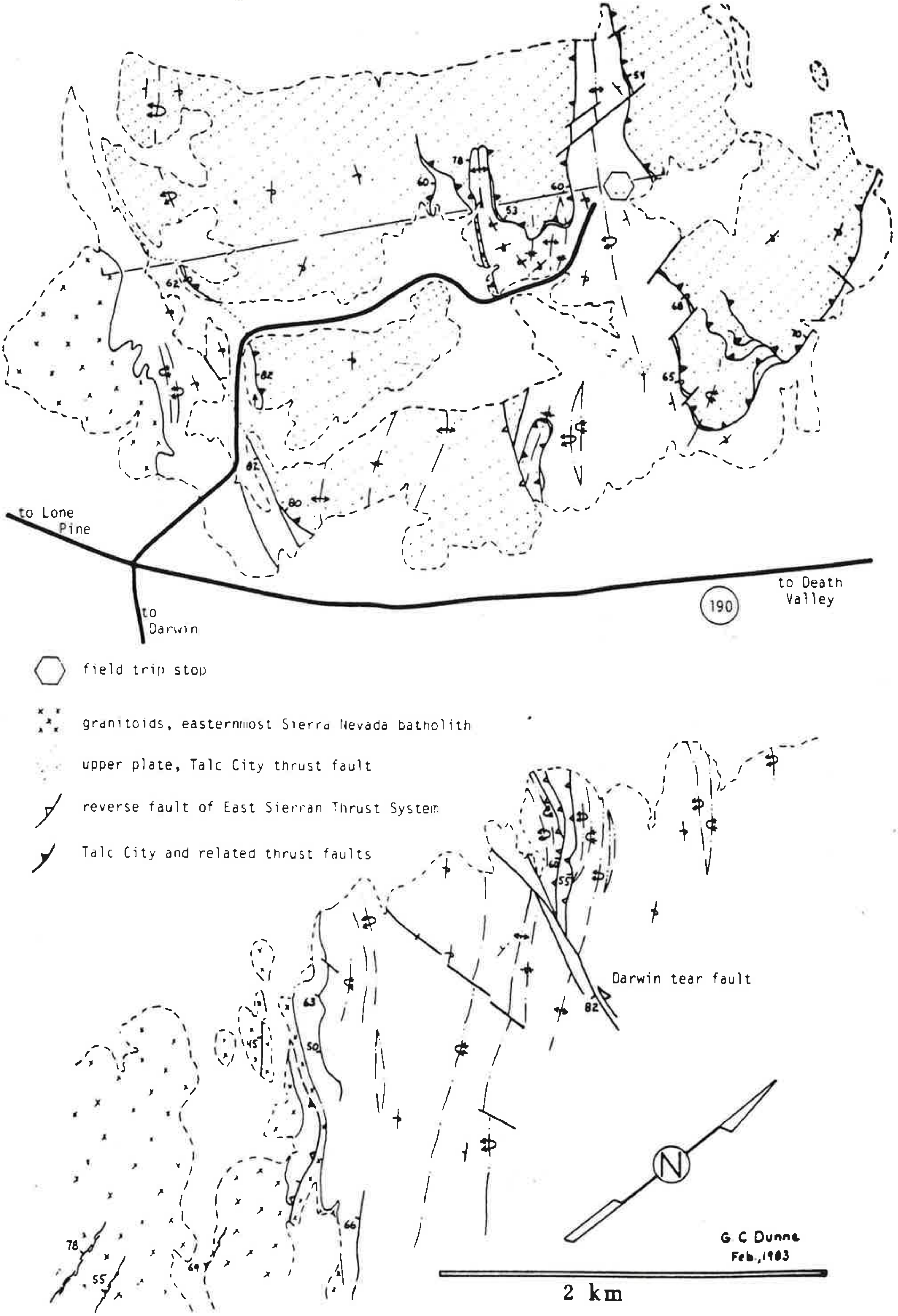


Figure 15 Structural geologic map of Talc City and northern Darwin Hills. Geologic cross section through Field Stop . is provided in figure 16

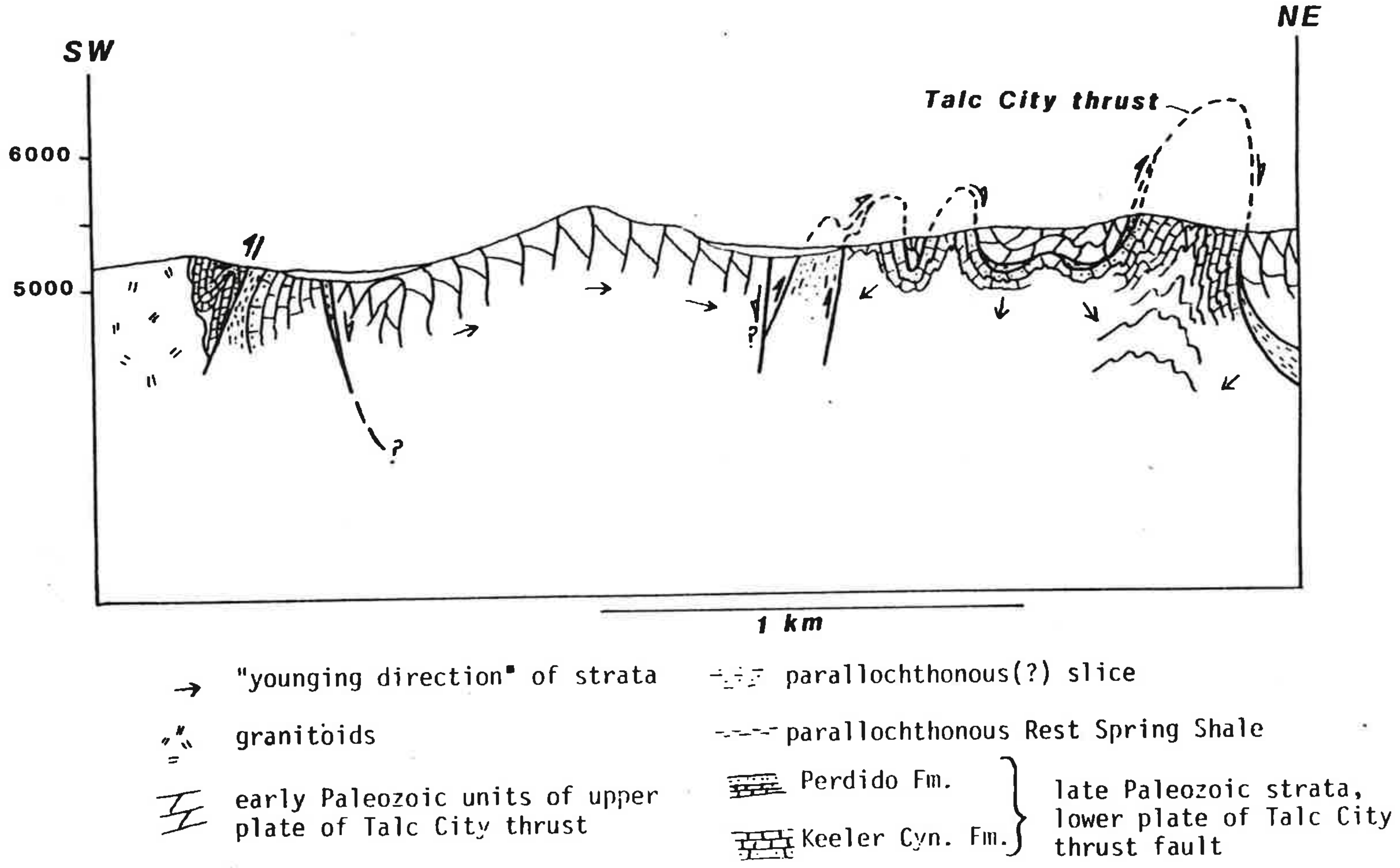
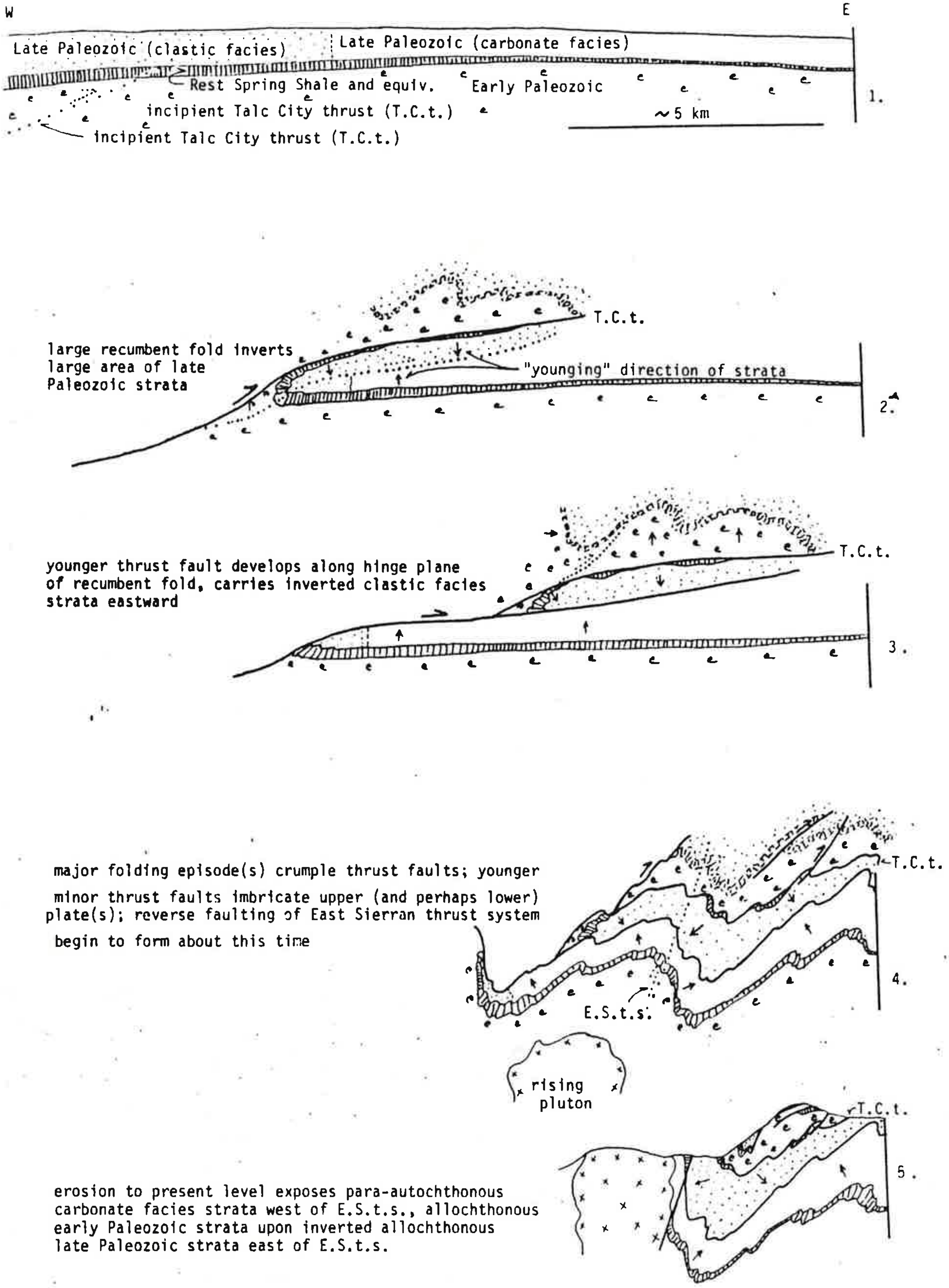


Figure 16. Geologic cross section through exposures of the Talc City thrust fault at Field Stop 2.

Schematic Structural Evolution – Talc City Hills



large recumbent fold inverts large area of late Paleozoic strata

younger thrust fault develops along hinge plane of recumbent fold, carries inverted clastic facies strata eastward

major folding episode(s) crumple thrust faults; younger minor thrust faults imbricate upper (and perhaps lower) plate(s); reverse faulting of East Sierran thrust system begin to form about this time

erosion to present level exposes para-autochthonous carbonate facies strata west of E.S.t.s., allochthonous early Paleozoic strata upon inverted allochthonous late Paleozoic strata east of E.S.t.s.

Fig. 17

After a resumption of NE-SW compressive stresses, a second interval of altered stress patterns began during mid-Cretaceous time, when NE-vergent reverse faulting and folding was largely supplanted by conjugate strike-slip faulting. The maximum principal stress seems not to have substantially changed orientation, but clearly $\delta 2$ and $\delta 3$ again swapped positions. This changed orientation may reflect a substantially decreased dip of the coastal subduction zone.

Panamint Valley Region

The Father Crowley overlook provides an excellent viewpoint from which to study the Panamint and Argus Ranges, Hunter Mountain, and Panamint Valley. First, let us synopsize the pre-Cenozoic geology. Directly east, the boldly stratified mountain is Panamint Butte. The layered rocks are Paleozoic strata ranging in age from Middle Cambrian to Permian. At the upper left corner of these exposures, just below the basalt cap, the flat-lying beds curve upward, then overturn toward the southeast below a faintly visible line that is inclined moderately northward. That inclined line is the trace of the Lemoigne thrust fault, and the upcurved beds represent drag features. The upper plate has moved southeastward many kilometers, making this fault one of the more important ones within the early Mesozoic Last Chance thrust system.

The Paleozoic strata of Panamint Butte are terminated northward by the uniformly medium-gray granitoids of the Hunter Mountain batholith, which takes its name from the flat-topped mountain (remnant of Pliocene erosion surface) that closes off the north end of Panamint Valley. These granitoids are alkalic in chemistry and form a composite nested intrusion emplaced during the

Middle Jurassic (179+ to 160 m.y.b.p.). The Lemoigne thrust fault is inferred to be intruded by the oldest phase of this batholith.

Looking farther south, the west face of the central portion of the Panamint Range (below flat-topped Telescope Peak) exposes principally late Precambrian strata of the Pahrump Group resting upon early Precambrian gneiss. All were thoroughly metamorphosed during the middle and/or late Mesozoic. Metamorphic isotherms were relatively flat-lying and closely-spaced, such that overlying Paleozoic strata now exposed on the crest and east slopes of the Panamint Range were not obviously affected by this metamorphic event. Bedding attitudes in the Pahrump Group and overlying strata define a broad, gently plunging, N-trending anticline that formed in mid-Mesozoic time.

Turning southward to view the north end of the Argus Range, late Paleozoic strata dip N and NW, forming the nose of a large N-plunging anticline that occupies the core of the northern Argus Range. Because it plunges directly toward us, the fold is not apparent from this viewpoint. A broad syncline lying between the Argus Range and the Darwin Hills to the west contains strata as young as Early Triassic; these strata are designated as Permian on all maps published to date. Dark-weathering, steeply dipping dikes of the Independence swarm cut the east flank of the Argus Range. Light-colored, bouldery outcrops on the crest and west flank of the range cap the Zinc Hill pluton of late Mesozoic age.

Turning to Cenozoic geology, the face of Panamint Butte is marked by numerous normal faults and landslides that record a substantial interval of extensional tectonism (Figs. 18, 19, 20). Major faults can be placed in two groups. A

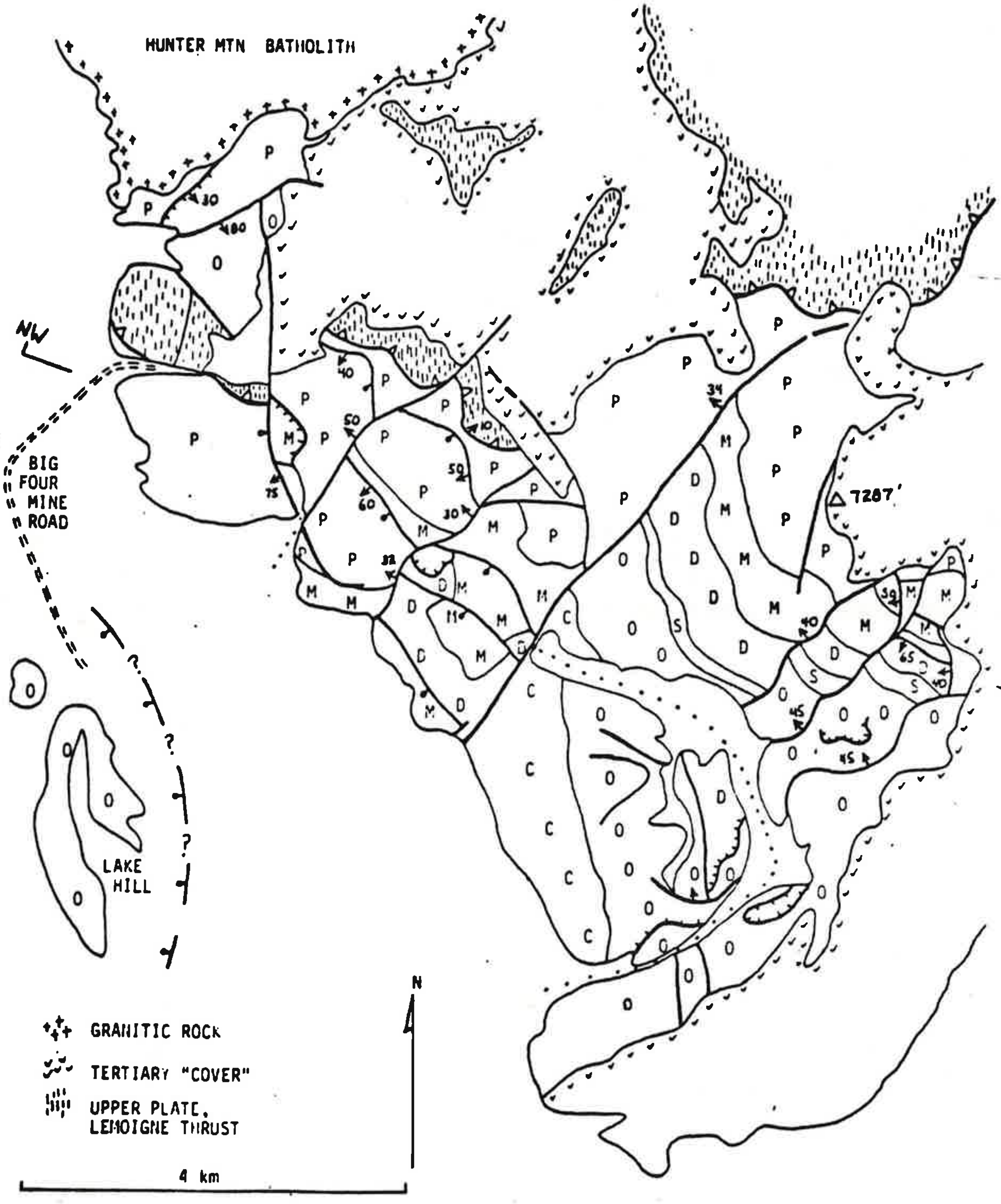
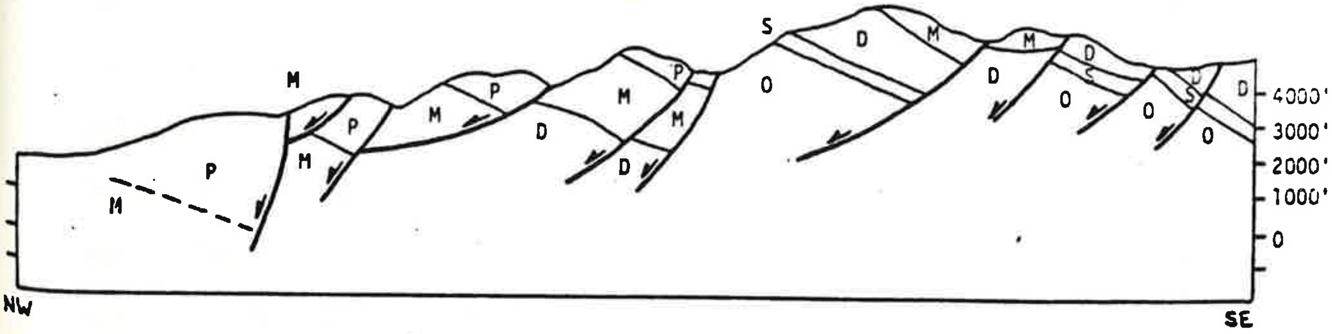


Figure 18 . Geologic sketch map of Panamint Butte, modified from Hall, 1971. Cross section is provided in figure 25. Capitol letters designate rock systems (C = Cambrian, etc.).

Figure 19. Aerial view of Panamint Butte, revealing shuffled look created by variable rotation of blocks as they slipped down into Panamint Valley (foreground). Tucki Mountain and Death Valley appear at upper edge of photo.



igure 20. Geologic cross section of Panamint Butte (after Hall, 1971).

A younger group consists of normal faults that trend NW parallel to the mountain face and dip moderately to steeply (~ 50°) valleyward. These formed in response to the development of a "free face" on the west flank of the Panamint Range, and thus represent a relatively localized extensional regime. The second, older group of extensional structures consists of NE-trending listric normal faults with moderate to low dips (25°-70°) to the NW. I provisionally interpret these faults to have developed during a major episode of extension that at least partly predated the development in Pliocene time of the NW-trending right-normal faults that define the present horst-and-graben structure. This older group of faults is overlapped by, and hence predates, Late Miocene and younger fanglomerate north of the Towne Pass Road. Some of the older, NE-trending normal faults exposed on the face of Panamint Butte contain sub-horizontal mullions and slickensides, suggesting that they may have reactivated to serve as tear faults separating blocks moving valleyward on the younger NW-trending normal faults for different distances or at different times or rates.

Farther south along the west slopes of the Panamint Range, numerous major extensional fault features are well exposed. Capping west-pointing ridges between Harrisburg Flat and Wildrose Canyon are several large block-glide "klippen" derived from source formations located 1 to 2 km upslope to the east. These blocks, up to 1 km long, are bounded downward by spoon-shaped, gently W-dipping normal faults.

South of Wildrose Canyon, great masses of landslide breccia mantle the lower western slopes. These masses, which are underlain by listric slide surfaces dipping 5° to 50° west, are up to 1 km thick and have moved westward nearly 3 km from identified source rock higher on the slope. These landslide masses post-date the emplacement of the block-glide masses described above.

Important evidence concerning the timing of Basin-and-Range tectonism in this region is contained in the Late Miocene to Early Pleistocene Nova Formation, which is composed of fanglomerate with interbedded basalt and landslide breccia, having a total thickness of perhaps as much as 8000 feet. The Nova Formation is exposed on the west flank of the Panamint Range between Panamint Butte and the great landslides to the south. It comprises grey-brown exposures locally featuring muted badland topography. Two intervals within the formation are recognized. Distinctive properties of the older interval are that it rests unconformably upon Paleozoic bedrock, consists mostly of clasts of Precambrian rock clearly derived from the SE, contains no basalt debris, but does contain abundant masses of landslide breccia derived from Paleozoic formations, is tilted SE between 20° and 40°, and has a 5.1 m.y. old basalt interbedded near its top. A small exposure of this unit is present along Highway 190 approximately 1 mile west of Panamint Spring, at the east base of the Argus Range. Unconformably overlying this lower fanglomerate unit is a second sequence consisting of 4.2 m.y. old basalt and overlying fanglomerate, both of which dip between 4° and 20° SE, thus resting with angular discordance upon the older unit. This younger fanglomerate is compositionally similar to the underlying unit except that it contains clasts of basalt throughout.

The composition, distribution, and differing dips of these two intervals within the Nova Formation provide the bases of the following interpretations about the late Cenozoic tectonism of northern Panamint Valley and environs:

1. Substantial topographic relief and rapid erosion of and landsliding from relatively uplifted areas to the south began early during deposition of the Nova Formation, perhaps during Late Miocene time.

2. Presence of lower and upper Nova Formation strata in the Argus Range, combined with a SE source for these strata, suggests that Panamint Valley had not yet formed by 4 m.y. ago.

3. The systematic SE inclination of the Nova Formation and the angular discordance between upper and lower sequences, together with the presence of landslide debris in the lower interval, suggest that NW-directed extensional tectonism was operative throughout deposition of the Nova Formation in Late Miocene (?) through early Pleistocene time.

The Cenozoic geology of the northern Argus Range is consistent with this timing. This range is an east-tilted "half horst". Four million years old basalt flows that were apparently laid down on a nearly flat-lying erosional surface of moderate relief across the future site of the range, now dip eastward at approximately 15° from the crest of the range to the floor of Panamint Valley, thus providing a measure of tilting during Basin-and-Range deformation. A major north-trending, west-dipping normal fault zone along the west base of the Argus Range has down-stepped this basalt, forming two east-tilted benches. A small basaltic cinder cone and related flow, dated at 2.5

m.y. old, developed atop one of these faults on the existing west-dipping topography, suggesting that the Argus Range was uplifted and tilted between 4.5 m.y. ago and 2.5 m.y. ago, in agreement with the timing of development of Panamint Valley.

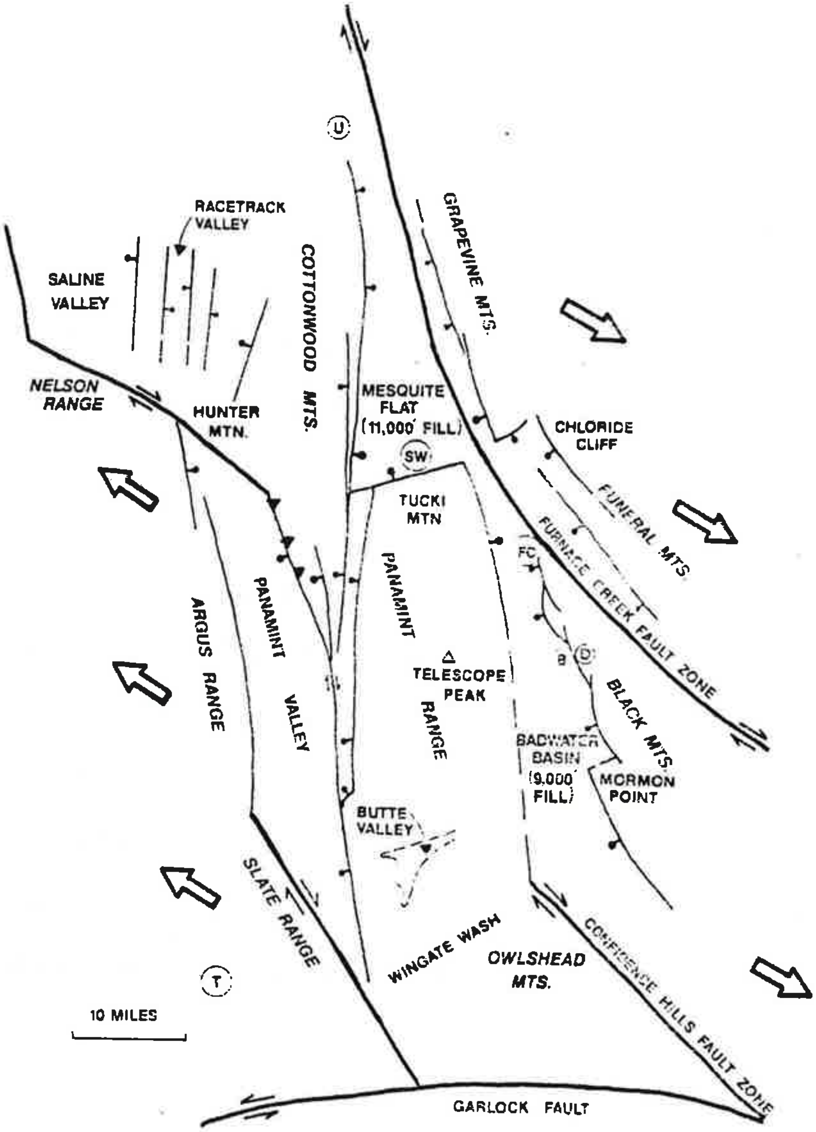
The Quaternary structural history of Panamint Valley and the Panamint Range has been well documented by researchers at Cal Tech. The most impressive feature seen from Crowley Point is the Panamint Valley fault zone along the east side of the valley. Pre-Quaternary and Quaternary dip slip on this family of faults totals nearly 30,000 feet. South of Ballarat, the nearly planar 4000 feet high west face of the range may be a little-modified normal fault scarp. It dips about 25°, and some faults in bedrock near the base of the range have observed dips of approximately 30°.

Quaternary slip in this fault zone has a substantial component of right slip. Right separations of levees and channels on alluvial fans have been observed at numerous places along the the fault zone. Correlation of a landslide breccia mass on one fan with its probable bedrock source area suggests as much as 15,000 feet of right slip. Where traced N of Highway 190, the Panamint Valley fault zone seems to bend to a NW trend and splay out into poorly marked traces. From this same point, a presently inactive N-trending fault trace can be followed through granitic rock along the top of the alluvial fans at the foot of Hunter Mountain. This trace is marked by a zone of crushed granitic rock up to 100 feet thick that dips about 25° NE beneath Hunter Mountain. Followed NW, this crush zone bends W to a trend of approximately N.55°W and progressively becomes vertical, featuring horizontal slickensides and right-separated stream traces as it crosses the divide between Panamint Valley and Saline Valley to the NW.

Before discussing the interpretation of this geometry, one other set of observations and interpretations needs to be presented. Since the mid-1960's, various authors have proposed that Death Valley, Panamint Valley, and Saline Valley originated as oblique-rifting structures called "pull-aparts" (transtensional structures in the modern vernacular). Figure 2.1 shows a schematic of this interpretation for that area. In this interpretation, previously existing faults or those formed during transtension would have different slip senses depending on their orientations. NE-trending faults would have pure normal slip, NW-trending faults would have right-slip, and high-angle faults trending NNW, N, or NNE would have right-normal slip.

In light of these observations and interpretations, R.S.V. Smith at Cal Tech has developed the following story. After formation of Panamint Valley by oblique-rifting, the orientation of lateral shearing became more northerly. Right-slip faults came to occupy N- and-NW trending normal fault zones such as the Panamint Valley fault zone that had earlier formed the horst-and-graben structure. At the NE corner of Panamint Valley, where the N-trending, right-oblique fault zone joined the NW trending right-slip fault, renewed right slip of a more northerly orientation was accommodated at first by underthrusting of the Panamint Valley block beneath Hunter Mountain and later by a bypassing of this restraining bend as the fault zone straightened its course.

Late Pleistocene and Holocene deformation has been studied by Smith utilizing shorelines of pluvial Lake Panamint, which in its heyday during the interval 120,000 to 14,000 years ago reached a maximum depth and surface area of at least 950 feet and 300 mi^2, respectively. Once-horizontal shorelines 40,000 years old now are inclined northward with structural relief of up to 370 feet,



PULL-APART MODEL FOR SALINE, PANAMINT, DEATH VALLEY

Eastern California is extending in a NW-SE direction, as shown by the heavy arrows. Crustal blocks bounded for the most part by generally north-trending faults commonly are linked by connecting faults that trend northwest, parallel to the extension direction. As extension proceeds, the northwest-trending faults experience right strike slip, whereas north-trending faults experience right normal slip. Several of the resulting rhomboid-shaped blocks have dropped several thousand feet, forming the major valleys of this part of the Basin and Range

Fig. 21

perhaps the result of underthrusting of northern Panamint Valley beneath Hunter Mountain. He further notes that the Argus Range west of the Ash Hill fault has dropped absolutely about 40 feet whereas the Panamint Valley block just east of the Ash Hill fault has risen about the same amount. Fractures intersecting the Ash Hill fault at acute clockwise angles suggest a component of right slip during more recent movements.

Finally, Smith notes that post-pluvial deformation rates in the region are high. Vertical movement rates may be as high as 4.5 feet/1000 years, whereas right-lateral slip may be occurring at rates as high as 6 feet/1000 years.

The basalt flows that are well exposed on the north wall of Rainbow Canyon just N of Crowley Point range in age from 7.7 to 4.3 m.y.b.p. ago. Study of normal faults that cut or are cut by various flows reveals the occurrence of three episodes of variably-oriented extensional faulting beginning about 5.8 m.y. ago.

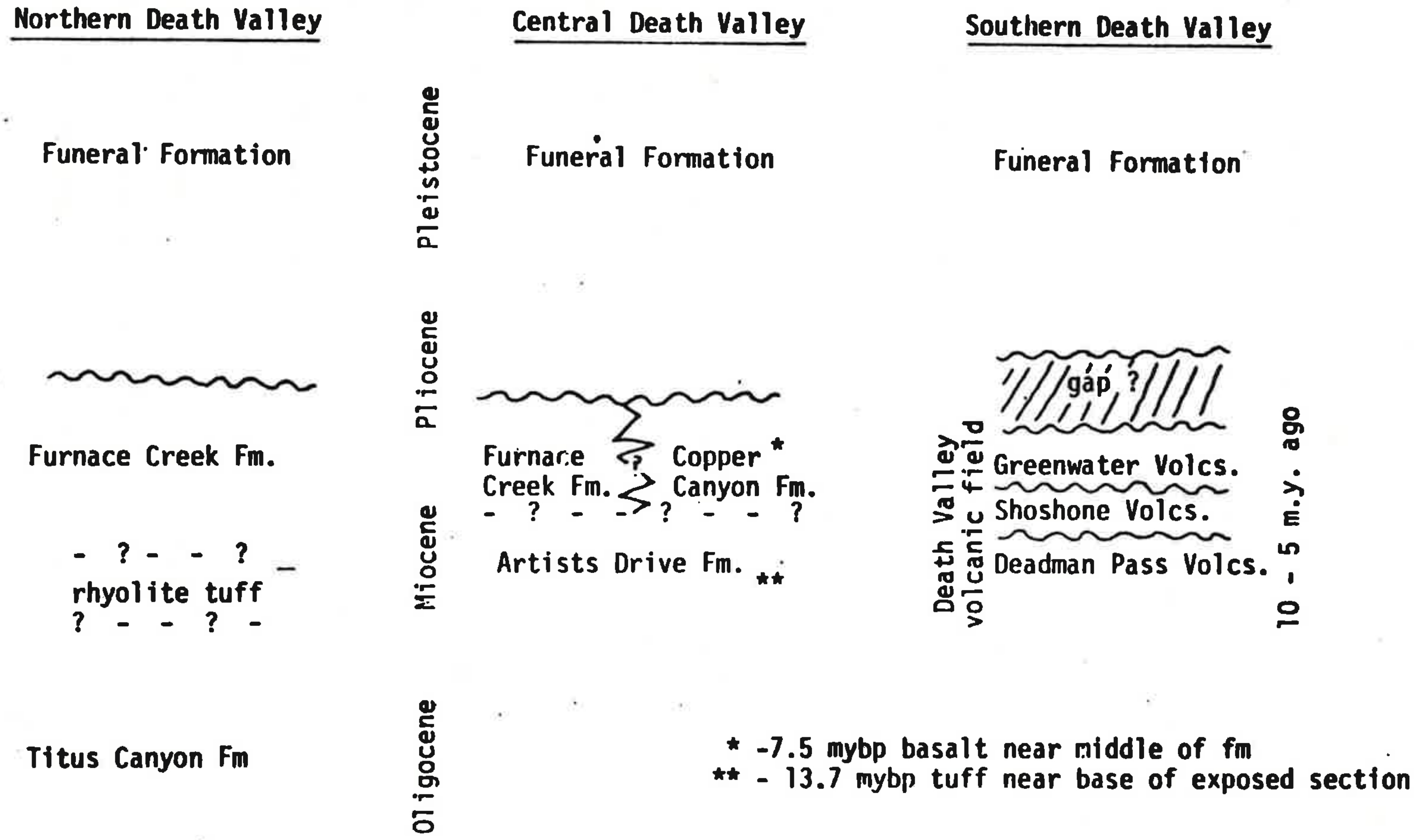
Death Valley

Compressional structures of Mesozoic age are less abundant in Death Valley than in areas to the west, reflecting an eastward change in style and intensity of development of the compressional belt marginal to the Sierran batholith. East-directed thrust faults and a few related folds are present in the Panamint Range north of Highway 190 (Marble Canyon thrust fault) and in the Grapevine Mountains east of the valley (Grapevine thrust fault).

Structures and rock units related to the Cenozoic extensional history of eastern California are abundant, very informative, and spectacularly exposed in the Death Valley area. The Cenozoic depositional history extends back to the Oligocene (Fig. 22). The Titus Canyon Fm. consists of lacustrian and fluvial sedimentary rocks that become increasingly tuffaceous upward. Locally abundant vertebrate and plant fossils reveal the climate to have been moist and mild, suggesting that ranges to the west (Panamint, Inyo, Sierra) had not yet been uplifted to form the present rainshadow. Interbedded monolithologic breccias of probable landslide origin near the base of the formation suggest the local development of steep slopes that may have been fault controlled. Whether or not such faults are manifestations of a very early episode of extensional deformation is unclear.

Beginning in Early to Middle Miocene time, silicic volcanism broke out, first at the Timber Mountain and Bullfrog calderas N and W of Beatty, then in southern Death Valley. Volcanism continued in both areas until about 5 or 6 m.y. ago. The Timber Mountain and Bullfrog centers spread rhyolite air-fall and ash-flow tuff over much of NE Death Valley, and distribution of the ash flows is such as to suggest that Death Valley still had not yet become a major topographic depression.

By late Miocene time (12 - 5 m.y. ago) an irregular chain of lake-filled, alluvial fan-rimmed basins (Furnace Creek and Copper Canyon Fms of Death Valley and Esmeralda Fm of Fish Lake Valley to the N) formed along a NW trend from southern Death Valley to east of the White Mountains along the present trace of the Furnace Creek fault zone. Volcanic rocks from the two volcanic centers previously mentioned periodically spilled into these basins. The climate dried and warmed during deposition in these basins. The climate dried



* -7.5 mybp basalt near middle of fm
** - 13.7 mybp tuff near base of exposed section

Figure 22. General correlations of major Cenozoic rock units in the Death Valley area.

and warmed during deposition in these lakes, as documented by the presence of evaporites in their deposits.

During the Pliocene, fanglomerates with interbedded and capping basalt flows (Funeral Fm) spread across much of eastern Death Valley. Megabreccia deposits of probable landslide origin are locally abundant near the base of the formation.

Two episodes of extensional tectonics, each with a distinctly different style, are inferred to have affected the Death Valley area during mid- and late-Cenozoic time (Fig. 4). The earlier episode of extensional tectonism probably roughly coincided with activity in the Timber Mountain/Bullfrog and southern Death Valley silicic volcanic centers in Middle to Late Miocene time. Several quartz monzonite plutons with rapakivi texture were emplaced around Death Valley during this same interval. The interpretation that extensional tectonism occurred at this time follows from numerous observations in the Basin-and-Range province showing that rhyolitic volcanism - and limited plutonism - often just preceded and/or accompanied extensional tectonism. Supporting this timing in the Death Valley area was the development in late Middle and Late Miocene time of elongate basins along the trace of the Furnace Creek fault zone, suggesting that it was active during this early extensional interval. These basins are interpreted to have formed as pull-aparts, tipped fault wedges, or sags along the active right-slip fault. This timing coincides in part with active right slip along the sub-parallel Las Vegas shear zone southeast of Death Valley. The probable genetic relationship between these right-slip faults and extensional tectonism is discussed below.

An episode of low-angle detachment faulting is inferred to have tectonically denuded the Black Mountains and Funeral Mountains during this interval. John Stewart of the U.S.G.S. has noted that some time between 15± 3 m.y. ago and 9± m.y. ago, about 9 km (28,000') of late Precambrian through Mesozoic strata were removed from the Precambrian metamorphic basement of the Black Mountains. He proposes that this cover sequence was detached along a low-angle normal fault, now exposed atop the turtleback surfaces and in the chaos structures in the Black Mountains, and slid 80 km NW, stopping to become the present Panamint Range. As this occurred, the upper plate (hanging wall) was greatly extended by NW-directed normal slip on numerous gently NW-dipping faults that are well exposed along the crest and east flank of the Panamint Range. These faults and other related structural phenomena were widely recognized by earlier workers, but interpreted by them to be a Tertiary thrust fault system (Amargosa thrust) (Fig. 23). Such confusion between low-angles normal faults and thrust faults has been a common occurrence in Basin-and-Range geologic studies.

In the Funeral Mountains, a family of low-angle normal faults separates pre-Pliocene hanging wall rock from an antiformal footwall composed of late Precambrian Pahrump Group strata that were metamorphosed to kyanite grade (conservatively estimated to be 5 kb press., ~ 15 km depth) during early- to mid-Mesozoic time. In many respects, the Funeral Mountains structural/metamorphic ensemble resembles what are termed metamorphic core complexes elsewhere in the Basin-and-Range. Mitch Reynolds has determined that the Funeral Mountains detachment fault family developed during the interval 11 - 7 m.y. ago, thus overlapping the proposed time of development of the Black Mountains detachment fault (Fig.24).

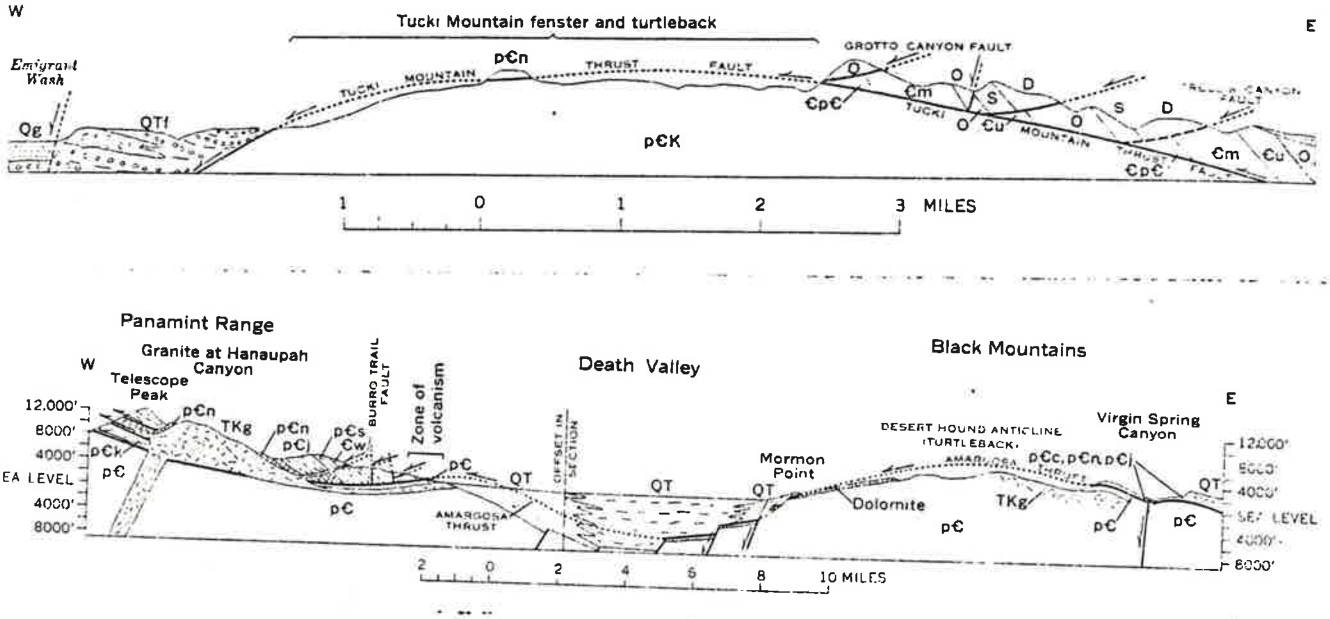
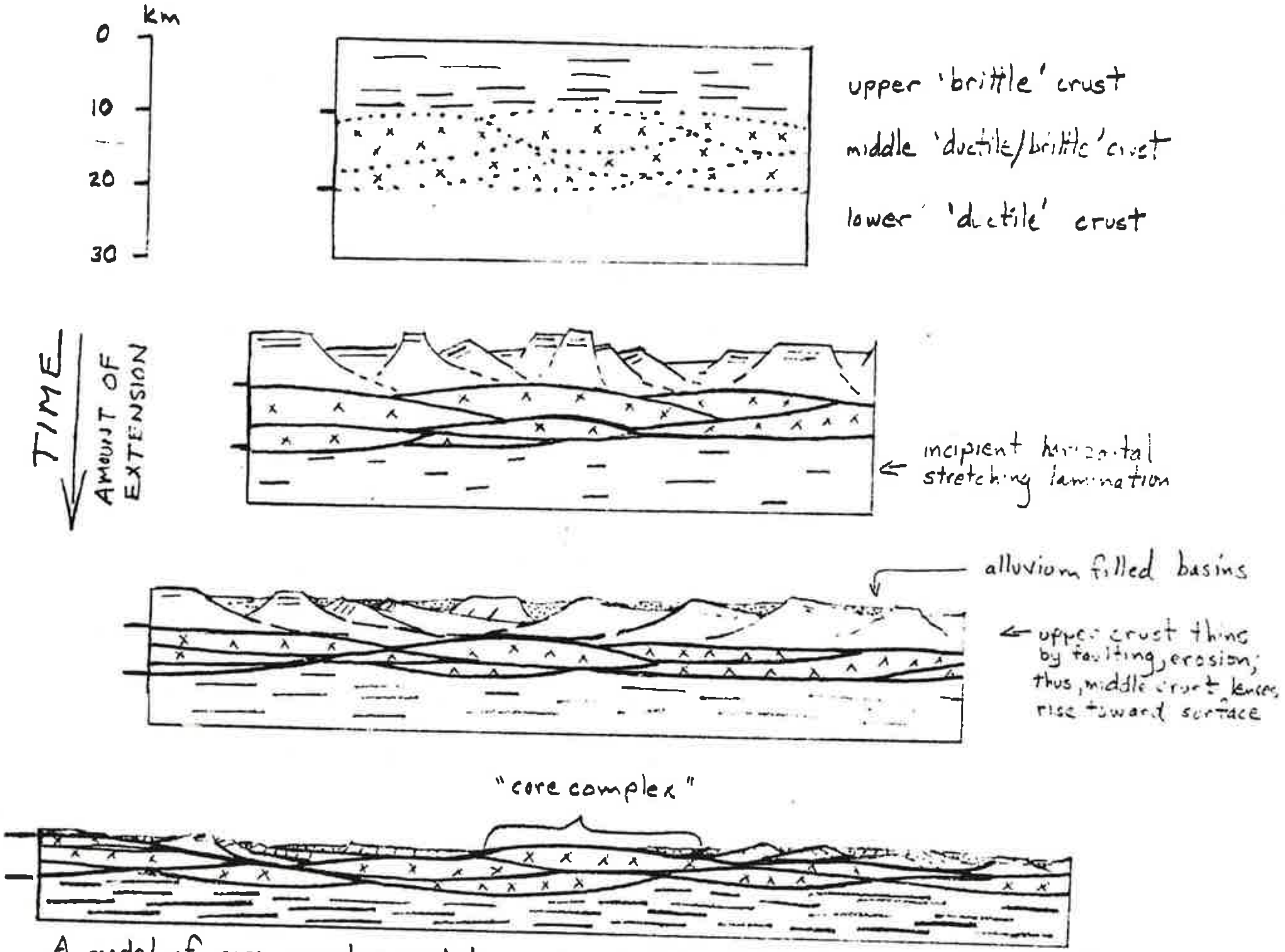


Figure 23. Geologic cross sections across the Black Mountains and Panamint Range as perceived by Hunt and Mabey (1966) following the ideas of Noble (1941) regarding the nature of the Armagosa chaos structure. The Tucki Mtn and Amargosa thrust faults are now perceived by many workers to be low angle normal faults (lag faults).



A model of core complex evolution; sketched by GCD from idea of W. Hamilton

Fig 24.

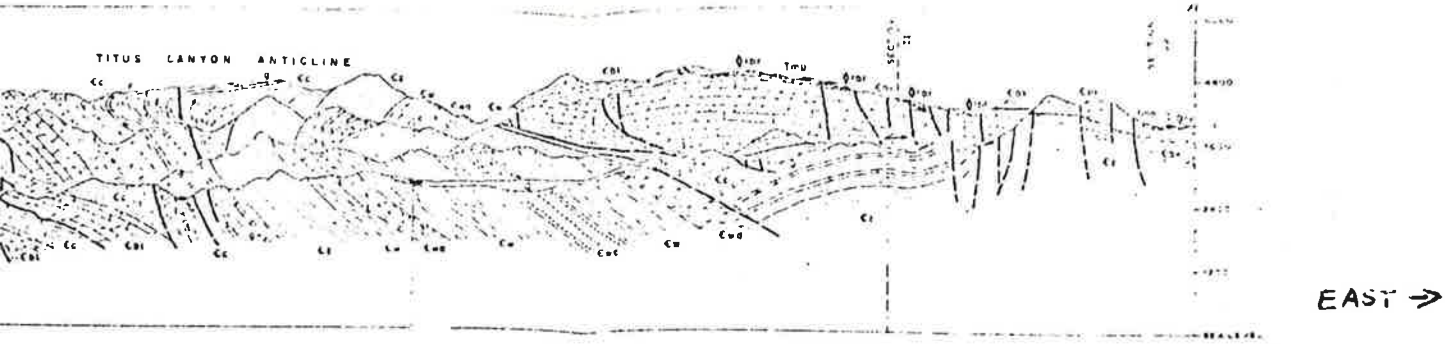
Apparently related to this episode of extension in the Funeral Mountains was the development in the Paleozoic strata of the hanging wall of not only numerous low-angle normal faults, but of two large west-vergent recumbent folds as well. These are interpreted to be gravitationally induced cascade folds. The core of one large synformal cascade fold is visible near the top of Corkscrew Peak, on the skyline NE of Stovepipe Wells.

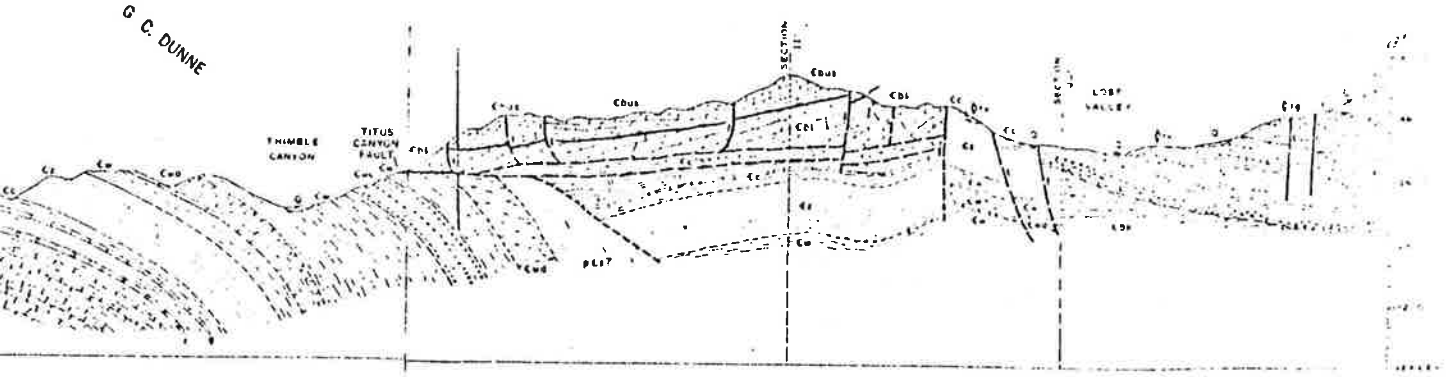
Following suggestions of Hamilton and Myers, (1966) and Atwater (1970), it has been widely supposed that the right-slip components on numerous NW-trending faults east of the Sierra Nevada (Furnace Creek, Panamint Valley, Las Vegas fault zones, among others) are sympathetic, inland responses to development of the San Andreas fault in coastal California. An alternative viewpoint, championed for the Las Vegas fault zone by Bob Fleck (1970), Anderson and others (1972) and Liggett and Childs (1974), is that it and the Furnace Creek fault are small-scale transform faults separating terranes that were extending in opposite directions (SW side toward the NW), or extending in the same direction but with the SW side extending farther, or they separated a non-extending terrane to the NE from a NW-ward extending terrane to the SW. Supporting this transform fault interpretation are two important observations:

1. The Furnace Creek and Las Vegas faults seem to end very abruptly, a phenomenon easy to explain in terms of transform faults.

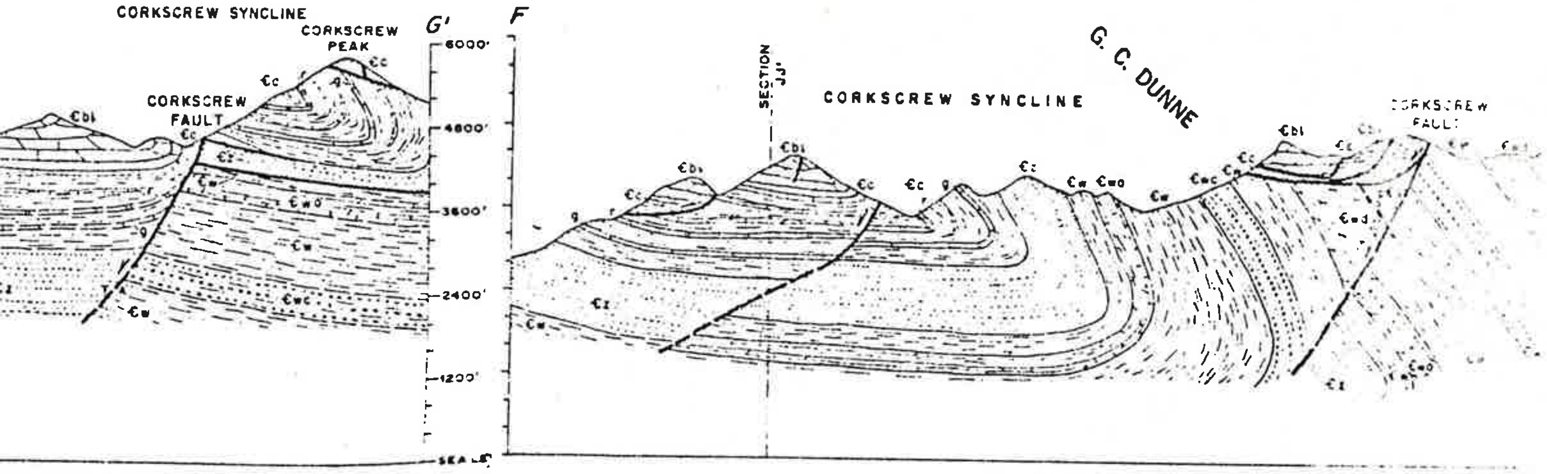
2. These two faults were active prior to development of the San Andreas at the latitude of Death Valley.

John Steward applies this transform concept to the Furnace Creek fault zone, suggesting that it detached NW-ward extending terrane in the Black Mountains





GEOLOGY BY MITCH REYNOLDS



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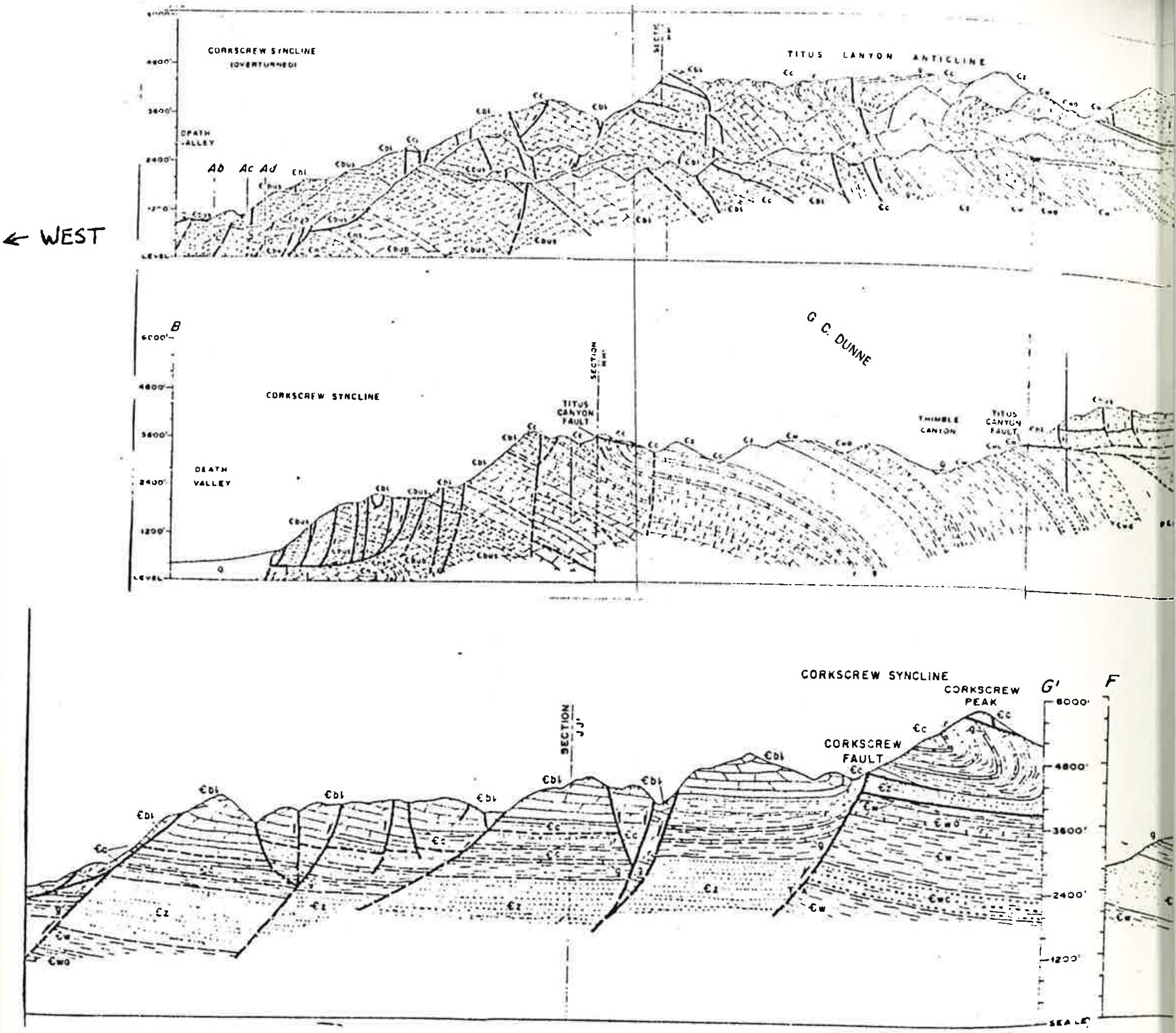

GEOLOGIC X-SECTIONS OF GRAPEVINE MTNS N. OF DAYLIGHT PASS.
SECTIONS. F AND G SECTIONS ARE JUST N OF DAYLIGHT PAS
SEEN FROM HIGHWAY 190.

Radiocarbon dating of organic muds recovered from drill holes on the floor of Death Valley suggest sediment accumulation rates of 3 feet/1000 years over the and Panamint Ranges from less-extended terrane NE of the fault. That the Furnace Creek fault (and Las Vegas fault zone) was active during the Miocene when an extensional episode was occurring in the Death Valley region is supportive of this interpretation.

Offset of several different geologic markers between southern Nevada and the Inyo Range suggest a total right shift (faulting plus bending) of 75 to 100 km across this wide zone of differential NW-ward extension.

The younger episode of extensional tectonism in the Death Valley region began approximately 3 to 4 m.y. ago and is responsible for shaping most of the present spectacular topography. Roughly N-trending normal or right normal faults developed, many terminating against NW-trending faults that either already were in existence (such as the Furnace Creek fault) or developed concurrently with the N-trending right-normal faults. Continued application of NNW-oriented extensional stress caused the region to undergo oblique-rifting; as high-standing blocks moved apart, intervening blocks such as Death Valley and Panamint Valley dropped downward. Principal slip occurred on W-dipping listric faults along the east sides of the valleys, causing crustal blocks to tilt eastward. A lesser N-ward tilt is also evident in Panamint and Death Valleys. The bedrock bottom of Death Valley lies between 9,000 and 11,000 feet below sea level beneath a roughly equal thickness of alluvial fill, attesting to the magnitude of absolute downward movement of valley floors.

Radiocarbon dating of organic muds recovered from drill holes on the floor of Death Valley suggest sediment accumulation rates of 3 feet/1000 years over the past several hundred years. If this rate were representative of longer intervals, it would take somewhat over 3 m.y. to accumulate the 10,000 feet of alluvium filling parts of Death Valley. This figure corresponds nicely - albeit, perhaps, fortuitously - with the inferred start-up time for this most recent episode of extension.

During the late Pleistocene, pluvial Lake Manly filled Death Valley to a depth of at least 600 feet before drying up about 11,000 years ago. Careful study of lake shorelines and the development history of alluvial fans (the oldest surviving fans are about 50,000 years old) show that the valley floor and adjacent fans have continued to tilt eastward during the past 2,000 years. If most of this tilting movement has been accommodated by normal slip on the Black Mountains frontal fault, then the average slip rate approaches 20 feet per 1000 years.

Third Day - Extended Commentary

Time, weather and road conditions permitting, we will start our last day with a brief visit to Mosaic Canyon, just south of Stovepipe Wells. The name 'Mosaic' derives from the recemented dolomite breccia exposed near the mouth of the canyon. Of greater interest is the Tucki Mountain detachment (neé thrust) fault along which the canyon has been eroded. On the southwest wall of the canyon is exposed the Kingston Peak Formation of late Precambrian age. Torn loose from this basement rock, and lying above the detachment fault, are east-tilted strata of latest Precambrian and Cambrian age. At the mouth of the canyon is the Stirling Quartzite, followed by the Wood Canyon Formation, Zabriskie Quartzite and Carrara Formation, with Bonanza King Formation atop the ridge.

After driving up the alluvial fan toward Towne Pass, we will turn south up Emigrant Canyon at the Emigrant Ranger Station. The canyon walls are composed of Nova Formation fanglomerate containing scattered lenses of landslide breccia (gray, and resistant), lakebeds (pale gray, thin bedded limestone), and basalt flows. About 5 miles up the canyon, we will enter exposures of the Skidoo pluton of Cretaceous age. This is a peraluminous granite bearing both muscovite and biotite.

A few miles beyond the pluton, we arrive at Harrisburg Flats, a rolling upland that is probably the remnant of a region - wide erosion surface of Pliocene age. All of the Death Valley to Owens Valley region may have looked much like Harrisburg Flats prior to the collapse of Owens, Panamint and Death Valley during the last 3 or 4 million years.

If time permits, we shall take a side trip eastward across Harrisburg Flats to visit Aguereberry Point, where a spectacular vista of Death Valley may be had. The path out to the point is on Zabriskie Quartzite. The low saddle beyond the point is cut in Carrara Formation, whereas the gray banded ridge beyond is of Bonanza King Dolomite.

Traveling southward from Harrisburg Flats, we cross several west-trending spurs that expose Kingston Peak Formation. Resting upon some of the ridge tops are patches of light tan to orange-weathering rock. These are 'klippen' of younger Noonday Dolomite that have slid downhill for a few to several kilometers from source beds that can be seen high on the slopes to the east.

As we round the last few curves before coming to Nemo Canyon, we will stop briefly to examine exposures of the well-known 'stretch-pebble conglomerate' member of the Kingston Peak Formation. During Mesozoic deformation, relatively equant pebbles of the Kingston Peak were stretched into elongate flattened ovals as the rock mass around them deformed in response to regional, generally E-W-directed compression. The exposure at the road is variably brecciated and probably is within a landslide 'klippen'.

After traveling another 5 miles, we enter Wildrose Canyon, and we follow it down to Panamint Valley through rather monotonous-looking exposures of Kingston Peak Formation, then through Nova Formation fanglomerates at the mouth of the canyon.

About 1 mile down the alluvial fan, we cross the Wildrose graben, a normal-fault-bounded trough formed within the past 500,000 years.

Beyond Wildrose graben, we proceed down to the floor of Panamint Valley and drive several miles before stopping to discuss the geology exposed on the west face of the Panamint Range.

Beyond the turnoff to Ballarat, the highway turns west and over the next 3 miles crosses several strands of the Ash Hill fault zone. These faults bound generally N-S-elongate ridges present on both sides of the road. Just as the road turns south and heads for the grade over Slate Range Pass, we leave the Death Valley map sheet and enter the Trona sheet. Strata exposed along the roadcuts of the grade are of Permian age. On both sides of the Pass are northwest-trending East Sierran thrust system faults which we again cross as we did at the Darwin Plateau. Dropping down into Searles Valley, we see exposed to the left strata of the Pennsylvanian and Permian Keeler Canyon and Owens Valley Formations. Hogbacks of white rock at the base of the range are thrust sheets of tectonized marble within the East Sierran thrust system. The grey-brown rocks that form the Argus Range on the west side of Searles Valley of granitoids of Jurassic age that comprise the east margin of the Sierra Nevada batholith.

As we pass through Trona and Westend, scan the hills west of town for numerous beach strand lines of pluvial Searles Lake.

Rounding 'the point' and heading west-southwest, we will follow a canyon through which flowed the pluvial river connecting Searles and China Lakes. Searles lake periodically filled and backed up this canyon, and you can see remnants of lakebeds (patches of white, horizontal, thin-bedded deposits) perched up various side canyons. The bedrock through this canyon is granitoids of the Sierra Nevada batholith, here cut by numerous dark-weathering dikes of the Independence dike swarm (149 million years old).

Moving southwest, we cross the Spangler Hills, also underlain by the Sierra Nevada batholith.

Approximately 1.5 mi beyond the Junction with U.S. 395, the highway makes a sweeping turn to the west. At this point, we cross the trace of the Garlock fault, which here has experienced about 80 km of left slip.

Ahead of us, forming the south margin of Koehn Valley, are the Rand Mountains. The lower slopes expose Rand Schist, whereas the crest of the range is capped by granitoid of Mesozoic age. These two bedrock rock units are separated by a subhorizontal thrust fault. Rand Schist protoliths include graywacke, chert, basalt, quartzite and minor ultramafic rock thought to have been deposited upon "oceanic" crust during the Mesozoic. Some workers believe the Rand Schist and correlative units (Pelona Schist, Orocopia Schist) are parts of the Franciscan ‘formation’ that were underthrust 100 + km inland beneath the west margin of cratonic North America during early Cenozoic time.

Turning west on Garlock Road, our path will parallel the south flank of the El Paso Mountains, the bedrock of which is comprised of a large roof pendent of Paleozoic strata enclosed in granitoids as old as 250 million years! These Paleozoic strata range in age from Ordovician to Permian. They have elicited much interest because they are oceanic in character (pillow basalts, graywacke turbidites, bedded radiolarian chert), whereas coeval rocks exposed in surrounding regions to the north, east and south are of shallow shelf (miogeoclinal) character. Most geologists believe these oceanic strata are vastly out of place, having been brought to their present position from northwest Nevada, from somewhere west of the Sierra, or - - - -(from Mars?!).

LIST OF PARTICIPANTS

FALL FIELD FROLIC, OCT. 1983

NAME	CLASS STANDING/AFFILIATION
Donald Bianchi	Dean, School of Science & Math
Larry Collins	mineralogy/petrology professor
Diana Donaghe	junior
George Dunne	trip leader; structural geologist
Rachel Gulliver-Dunne	prof. geologist, working/MESA^2
Aleta Dunne	junior geologist
*George Freitag	junior
A. Eugene Fritsche	depart. chair; sed. petrology
Sue Fritsche	outdoors person
Pattie Geis	graduate student
Jeff Geraci	junior
Mike Kirby	junior
Darren Leaver	junior
Phil Martin	junior
Craig Messerman	senior
Ken patton	alumnus; working/Robt. Stone
Cliff Plumb	alumnus
Stan Popelar	graduate student
Keith Putirka	junior
Ralph Roug	senior
Gerry Simila	seismology professor
Jon Sloan	micropaleontology professor
Cathy Sloan	biologist
Barry Temple	graduate student
Bob Taylor	senior
Peter Weigand	professor of petrology, geochemistry
Dave White	graduate student
Robert Wood	graduate student

* Scot Eliot

Day 2 left camp @ 8:00 a.m.

depart funeral core complex 9.45
hit red 1st pass +1405 Canyon rd 1045
hit Red Pass at 11:15 - stay for 15 min
small mine area
Lead field — 12:15 — lunch
arrived at pavement at mouth of titus Cyn.
at 2:05 p.m.

2:50 Reached Furnace Creek

1st DAY

Departed 7:09 Am

hit Coso Rest area ~10:50 Am
15 minute pit stop + geologic overview
hit lone pine ~ 11:30 Am - got gas, then
visited fault scarp for ~ 20 min
stop at store in town 11:50 → 12:35
to Interagency Visitors Center for lunch
12:10 → 12:40

arrived at center of Talc City Hills at 2:00, coming
along the "old road"; armwaved, stopped at
old talc mine tailings

out to 190 for brief armwaving stop
Father Crowley overlook ≈3:00pm to 3:20pm.

3:40 - stop for 5 min at alkali granite nr
highway maint. station