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DEATH VALLEY AND THE PANAMINTS
LANDS OF ILLUSION

THE DEPARTMENT OF GEOLOGICAL SCIENCES PRESENTS

THE 10TH ANNUAL

SPRING SPECTACULAR
ALL-DEPARTMENT FIELD TRIP

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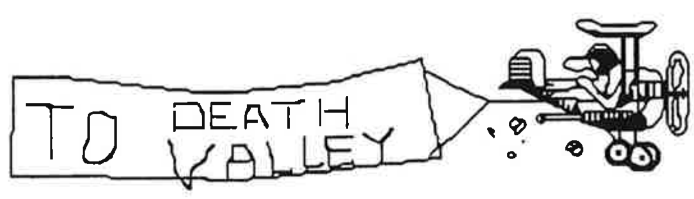
YOUR HOST: DR. GEORGE, AND HIS ALL-STAR CREW



STRATIGRAPHIC OVERVIEW, EASTERN CALIFORNIA
(consult Fig. IN-2)

Precambrian:
The region from the Sierra Nevada eastward is inferred on the basis of actual outcrops and geochemical data derived from Mesozoic plutons to be underlain by Precambrian continental basement approximately 1.7 billion years old. Scattered exposures of this basement are present as far west as the Panamint Range, just west of Death Valley.

Resting unconformably upon this basement in the Death Valley region are late Precambrian strata of the Pahrump Group (Crystal Spring, Beck Spring and Kingston Peak Formations). These formations were deposited at least in part in fault-bounded basins interpreted by some to have been "aulacogens" (failed rifts) related to one (or more) prolonged rifting events in western North America that ultimately created an 'Atlantic-type' passive continental margin (Cordilleran "geosyncline") by Early Cambrian time. 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 sometime during the interval 700-800 Ma.

Paleozoic (mostly):
Resting unconformably upon Pahrump Group rocks in some areas and upon older metamorphic basement where the Pahrump is absent are latest Precambrian (650-570 Ma) and Paleozoic miogeoclinal strata of the Cordilleran geosyncline These strata form a northwest-thickening wedge extending from the western margin of the stable platform, or craton (represented by Paleozoic sections exposed in the Las Vegas/ Grand Canyon region) to the White Mountains and adjacent Sierra Nevada (Fig. IN-2). This northwestward thickening is accomplished by three phenomena: (1) thickening of Paleozoic units; (2) in-filling of unconformities; (3) appearance and northwesterly thickening of the latest Precambrian basal clastic sequence. Northwesterly thickening of the miogeoclinal wedge is presently interpreted to have been caused by progressively greater thermal contraction and subsidence proximal to the newly rifted continental margin. Deposition of miogeoclinal strata was for the most part in a tidal flat environment (with brief intervals of fluvial deposition) during late Precambrian and Early Cambrian time, and in somewhat deeper and more varied shelf environments thereafter.

Major interruptions in this depositional setting occurred in mid-Paleozoic time in response to the Antler orogeny and during the medial Permian. Crustal thickening and resultant uplift in the Antler orogenic belt, localized along the continental margin, provided a source area from which was shed into eastern California a Mississippian clastic wedge (Rest Spring Shale in eastern California, Chainman Shale and Diamond Peak Formation in Nevada and Utah) that pinches out to the southeast, apparently lapping up against a prominent carbonate bank complex that can be traced from Canada to Mexico. This wedge (in black) stands out in the upper left portion of Figure IN-2. Medial Permian tectonism created pronounced ridge-basin submarine topography. An intra-Permian unconformity beveled the ridges, and thick flysch deposits accumulated in adjacent basins

Mesozoic (mostly):
Following the medial Permian tectonism, quiescent marine and marginal marine environments were reestablished in eastern California and southern Nevada during Late Permian and Early Triassic time. Toward the end of the Early Triassic, marine waters made a final retreat northeastward, leaving all of eastern California and most of southern Nevada emergent for the remainder of the Mesozoic.

From Middle or perhaps Late Triassic time to the end of the Cretaceous, the Sierran igneous arc evolved in eastern California, and terrestrial depositional environments prevailed eastward into southern Nevada. Hundreds of individual granitoid plutons were emplaced in the core of the batholith, and a coeval volcanic arc on the surface shed volcanic detritus eastward as far as Death Valley. Interfingering with these arc and arc-marginal strata are widespread aeolian strata such as the Early Jurassic Navajo Sandstone and correlatives. Volcanic ash periodically spread eastward as far as the Great Plains. Remnants of large volcanic calderas preserved in Sierran roof pendant rocks indicate that a classic stratocone-dominated volcanic arc much like that of the modern Cascades existed in the Sierran region.

Cenozoic:
Much of southern Nevada and eastern California were moderately highstanding and probably had mostly external drainage during early and middle Cenozoic time, explaining the rarity of deposits of this age. Marine and marginal marine environments periodically spread eastward from the California coast as far inland as the western Mojave Desert, and deposits formed in these environments are preserved there in local fault-bounded basins. Late Cenozoic strata, mostly fluvial/lacustrine sequences and basalt/rhyolite ("bimodal") volcanics, accumulated in areally restricted settings controlled by evolving mountainous topography that was generated by Basin and Range tectonism.

REGIONAL STRUCTURAL GEOLOGY

(consult Fig.IN-1)

Paleozoic:
Two episodes of tectonism affected eastern California during the Paleozoic Era. During the Late Devonian and Early Mississippian, tectonic convergence along the continental margin (Antler orogeny) caused continental slope/rise (eugeoclinal) strata to be thrust

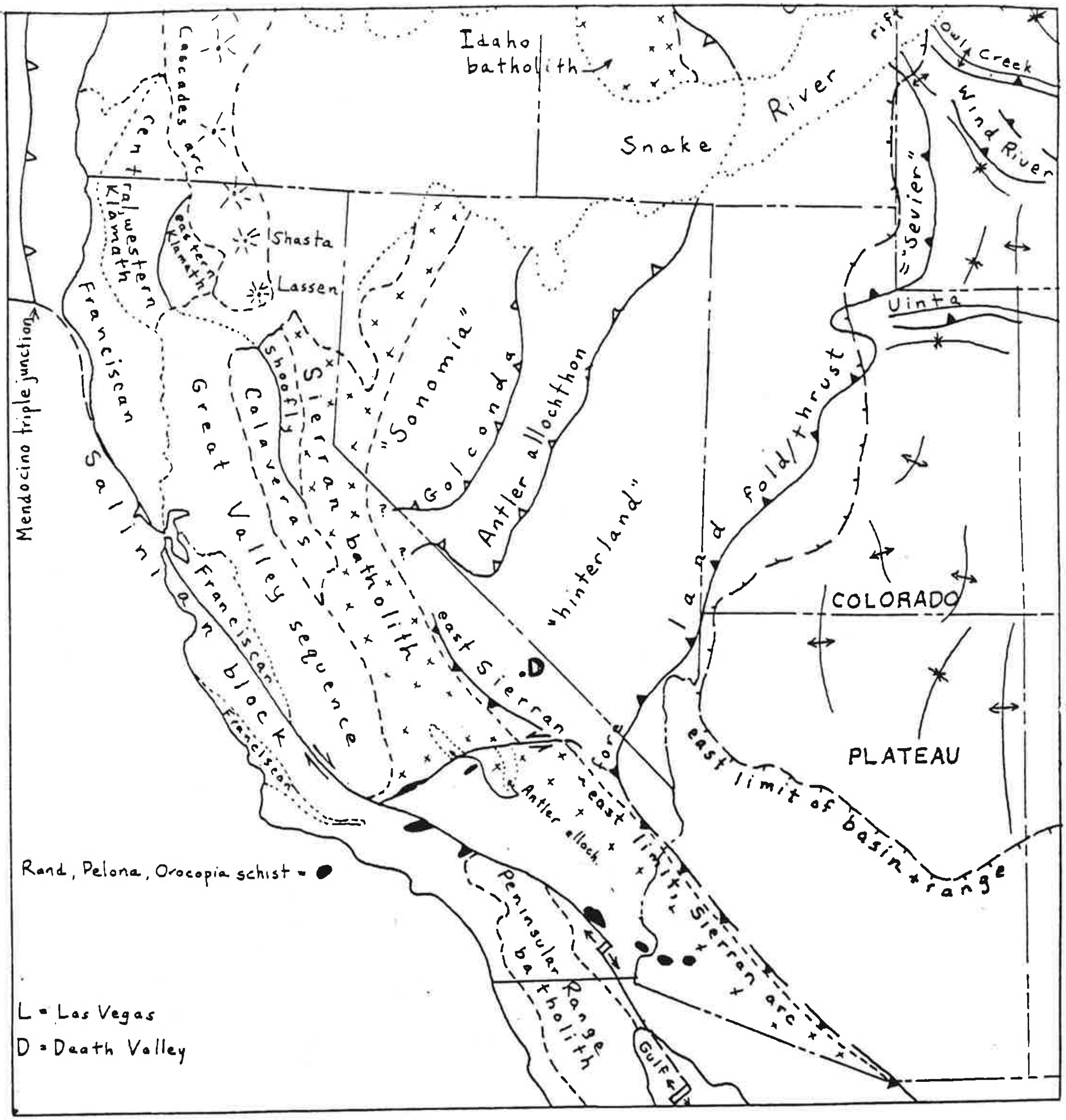


Figure IN-1. Sketchmap of major tectonostratigraphic 'entities' in the southwestern U.S. Cordillera. Note that the route between Bakersfield and Zion passes through or near a substantial number of these 'entities' which range from the relatively stable Colorado Plateau to the very mobile, suspect terrane-rich southern Sierra Nevada and adjacent northwestern Mojave Desert.

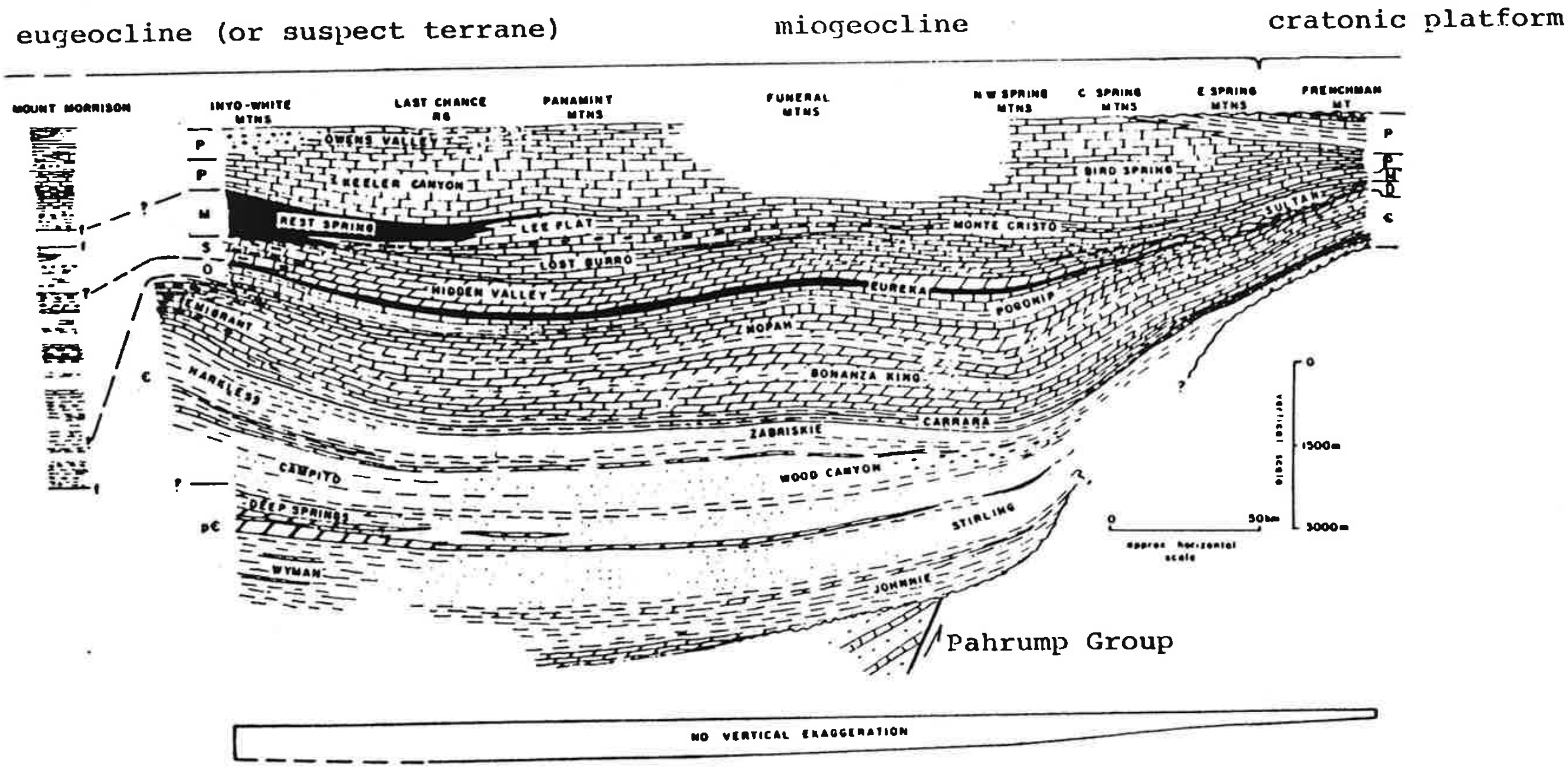


Fig.IN-2. Generalized stratigraphic framework of late Precambrian and Paleozoic rocks on a transect from near Las Vegas, Nevada (Frenchman Mountain), to near Mono Lake, California (Mount Morrison). No Pennsylvanian and Permian rocks crop out in the vicinity of the Funeral Mountains and are thus not shown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

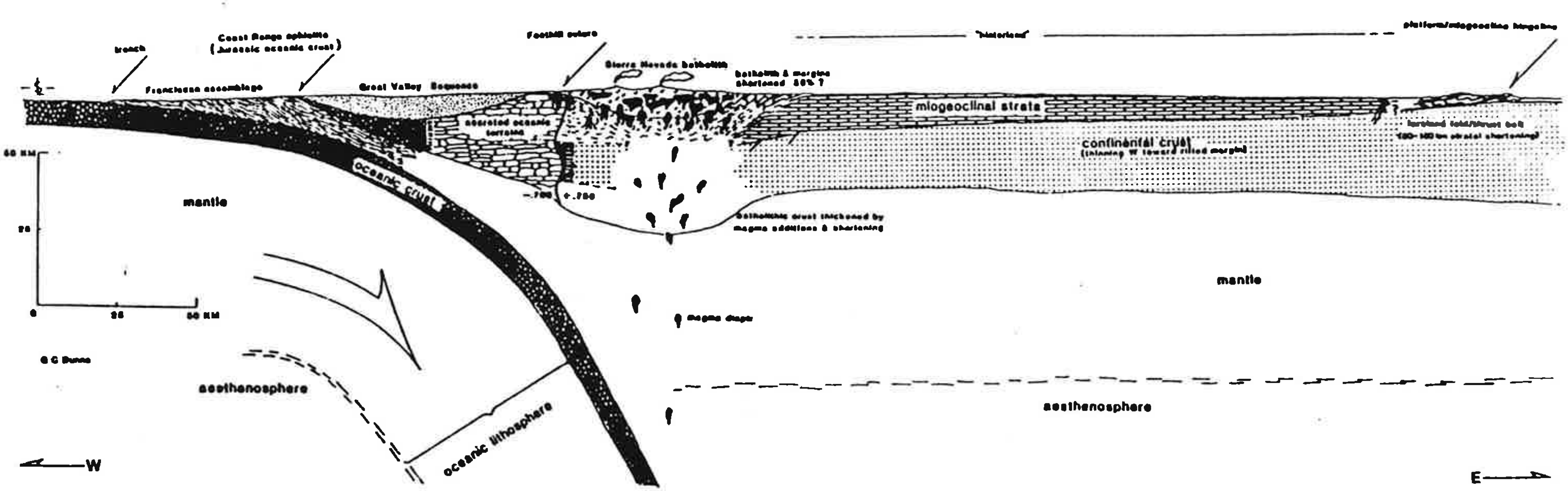
over coeval shelfal (miogeoclinal) strata. The siliceous detritus shed eastward from this uplifted orogenic belt is present in exposures west of Death Valley.

During medial Permian time, the miogeocline in eastern California was broken into a series of ridges and adjacent basins. This tectonism has been attributed by different workers to three possible causes: (1) it may have been a "distal" effect of final stages of the collision of North and South America during the Ouachita orogeny; (2) it may have been a result of major reconfiguration of the continental margin in California via transform faulting; (3) it may have resulted from collision along the California margin of an exotic volcanic arc terrane ("Sonomia").

Mesozoic:
Structures resulting from two major episodes of tectonism - one of Mesozoic age and contractile nature and the other of Cenozoic age and extensional nature- are well displayed throughout eastern California and southern Nevada. Mesozoic structures are dominated by mostly east-vergent folds and thrust/reverse faults developed during several spatially superposed phases of compressional deformation that began sometime during the interval Middle Triassic-Middle Jurassic and continued into Late Cretaceous time. During this same interval the Sierra Nevada batholith was emplaced, and numerous outlying plutons of the batholith invaded 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 beneath eastern California throughout much of Mesozoic time (Fig. IN-4). In Late Cretaceous time the dip of the subducting slab may have flattened, leading to varied structural and magmatic phenomena characteristic of the Laramide orogeny of latest Cretaceous to early Cenozoic time (Fig. IN-5).

Cenozoic:
Cutting these older contractile structures is a group of younger structures developed during extensional (Basin-and-Range) tectonism in late Cenozoic time (Fig. IN-6). Northeast-, north-, and northwest-trending faults of normal-, right-normal-oblique-, and right-strike-slip, respectively, developed either in one complex and protracted phase or perhaps in two separate phases of generally WNW-ESE-directed oblique extension (transtension) beginning possibly as long ago as early Miocene time (16 Ma) and continuing today (Fig. 6). Miocene 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 may be represented by the Timber Mountain and Bullfrog rhyolite centers northeast of Death Valley, by the southern Death Valley volcanic field, and by several granitic intrusions of Miocene age in the southern Death Valley region. Sometime between 6 and 11 Ma at the latitude of Death Valley (see top bars of Figure IN-6), the coastal subduction zone evolved into the San Andreas transform fault system.

Figure IN-4. Schematic cross section depicting pre-Laramide plate tectonic setting.



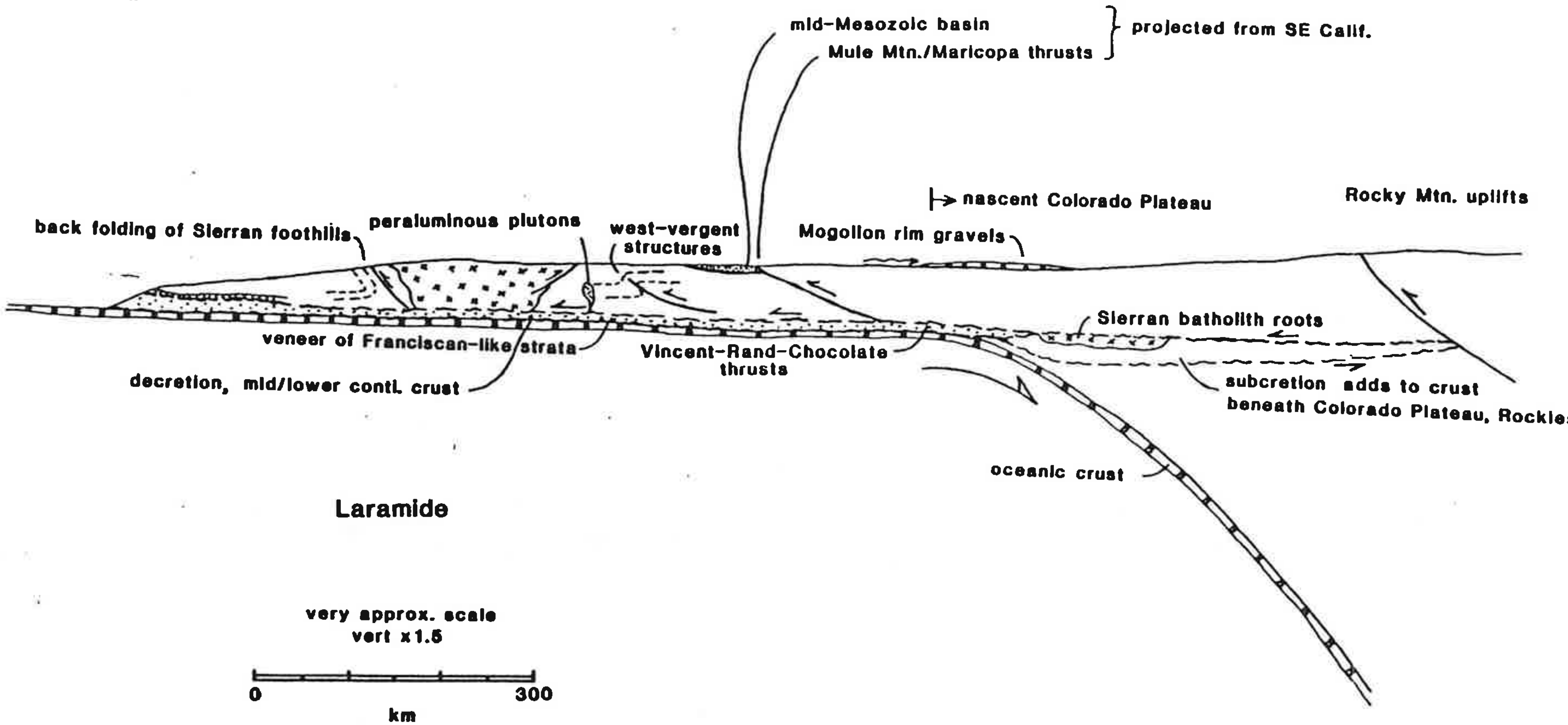


Fig. IN-5. A plate tectonic scenario for the Laramide orogeny (from ideas of Stan Keith, Peter Bird).

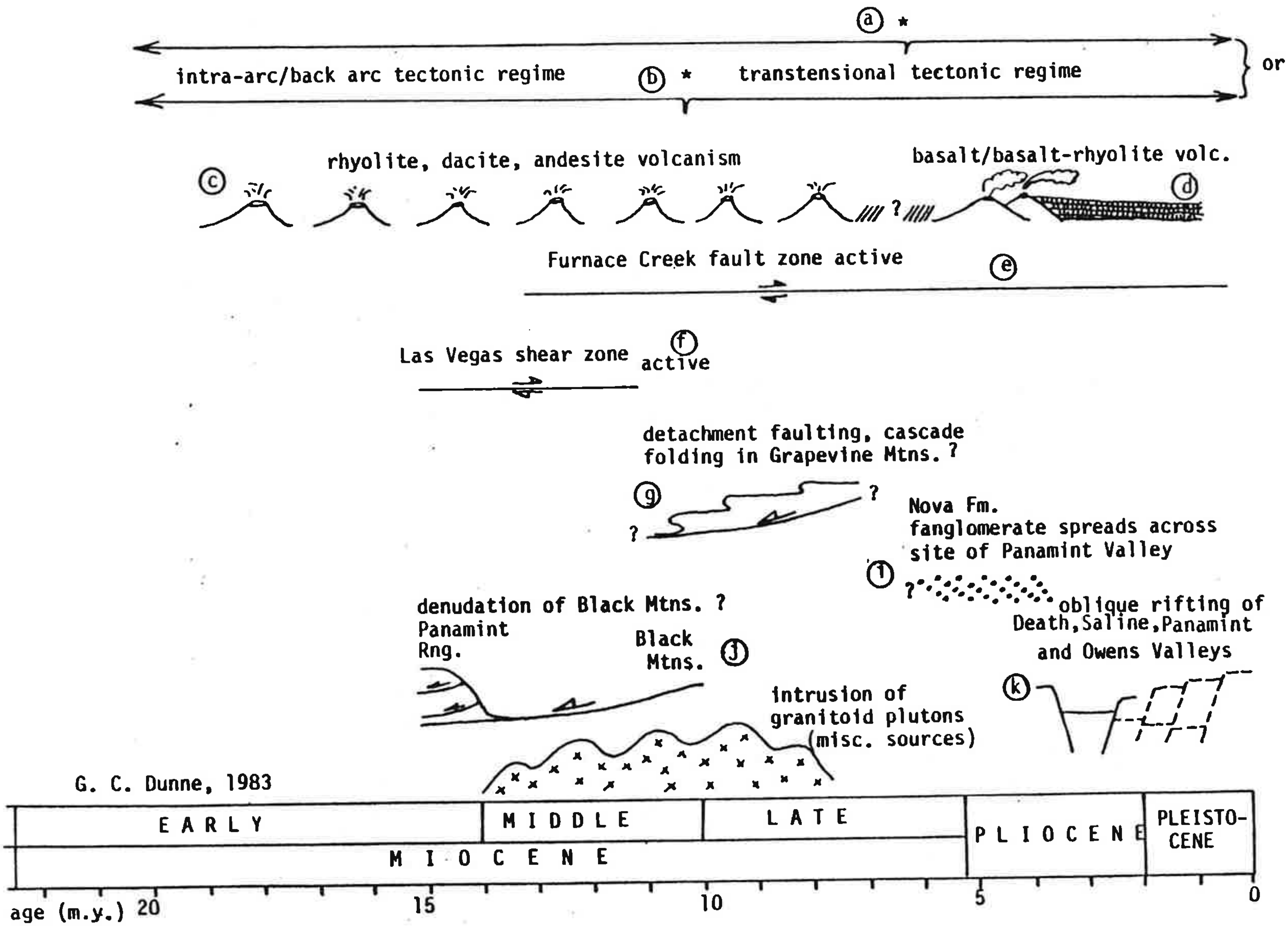


Figure IN-6. Schematic time/event chart for Neogene evolution of Death Valley area. The symbol * represents the interval during which Mendocino triple junction moved north along the coast past latitude of Death Valley, causing switch from back-arc extensional regime to transform-influenced extension (oblique rifting). Circled letters denote literature sources not cited here.

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 development of a more right-oblique (transtensional) style of tectonism. Major accumulations of predominantly basaltic lava extruded during this interval are exposed at numerous points along our route.

The amount of WNW-ESE extension across the width of the Basin & Range province (that is, between the Colorado Plateau and the Sierra) during late Cenozoic time is presently estimated to be about 250 km, representing at least a doubling of the original width of this region. Estimates of total extension across this region have in recent years yielded larger values as geologists have recognized the importance of gently dipping normal faults (detachment faults) that in previous years commonly were interpreted to be oddball thrust faults. 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. A model picturing how these gently dipping normal detachment faults might evolve, and how they might be related to some metamorphic "core complexes" is given in Figure IN-7.

DAY ONE

CSUN TO NORTHWEST MOJAVE DESERT TRAVEL COMMENTARY

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.

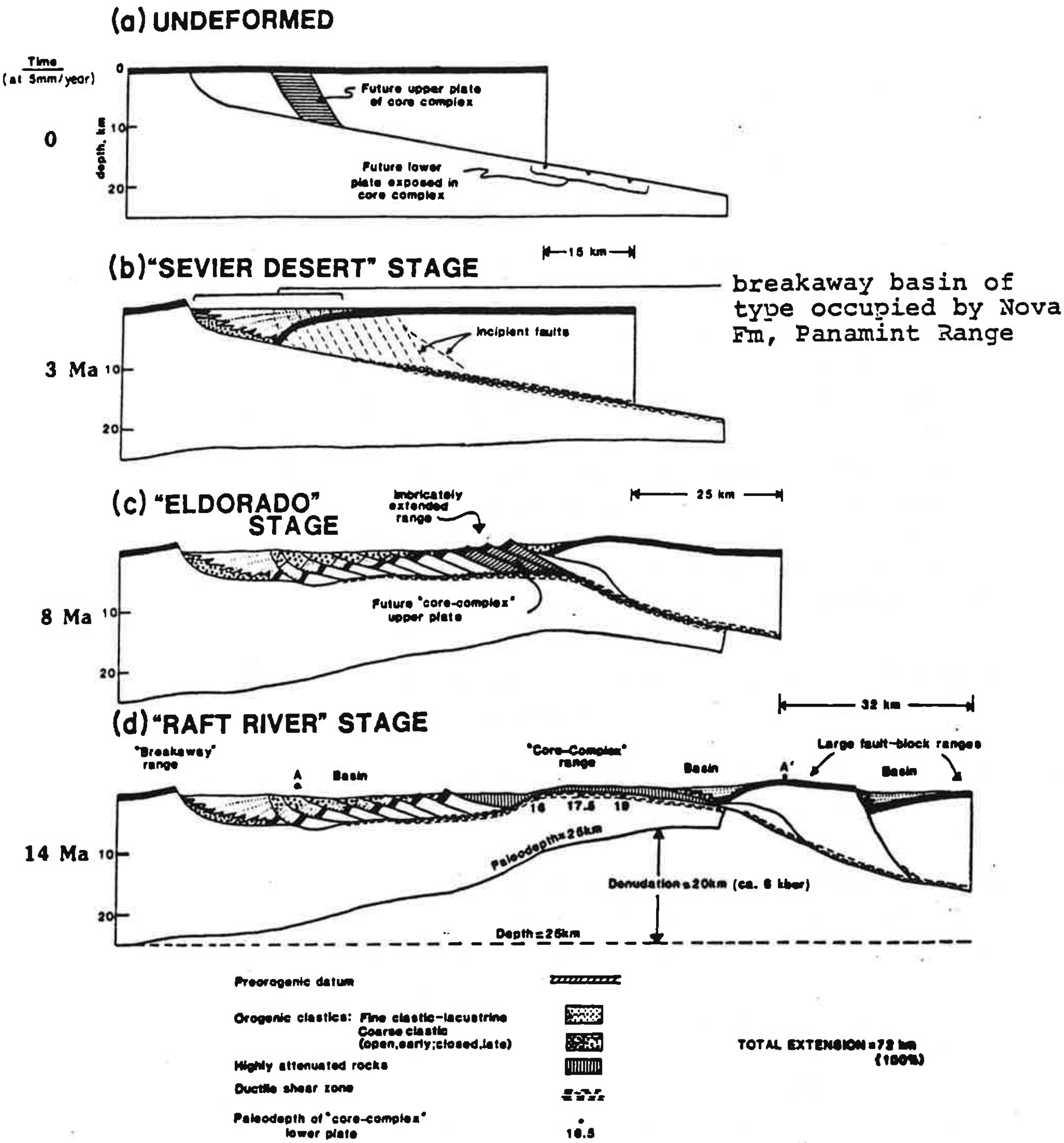


Fig. IN-7 Developmental model of an extensional shear system in the upper and middle continental crust, showing in particular how mid-crustal rocks may be reworked in an extensional shear zone under greenschist or amphibolite facies conditions (*b*), cool through geochronometric blocking temperatures (*c*), and be reworked under brittle conditions 5–10 Ma later, assuming probable strain rates and extension magnitudes. For simplicity, no attempt is made to palinspastically account for the volume of clastic detritus deposited during rifting. Mechanisms of upper-plate dilation include sedimentary infilling (*b*), imbricate distension (*c*), and wholesale subaerial denudation (*d*). (from Wernicke, 1985)

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 oil field, one of the oldest in California. 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 exposed in the roadcuts lie near the base of the Mint Canyon Formation. To the north this conglomerate is progressively replaced by sandstone and shale, whereas to the south this conglomerate becomes even coarser than it is here. 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 Agua 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 Ma intrusion 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 miles beyond the Kern County line we pass over the Rosamond Hills. These are composed of Mesozoic granitoids overlain by volcanic and sedimentary strata of the Tropico Group of middle Tertiary age. The Tropico group is host to rich deposits of borate minerals to the east near Boron, and to gold and silver deposits in volcanic necks located along and to the west of the freeway. Note the numerous mines developed to exploit the gold and silver deposit from the late 1800's to World War II. More recently, disseminated gold deposits have been exploited by two huge open-pit mines. One of these is just west of the highway.

NORTHWEST MOJAVE DESERT STOP COMMENTARY

We stop at the southwest corner of Cantil (or Koehn) Valley, a pull-apart basin on the Garlock fault (Fig. NW-1). From this location we can see rocks that bear on some of the most puzzling unsolved problems in California geology. We are still close enough to the present (and former) edge of the Cordilleran continental margin that we must continue to worry about the presence of "suspect terranes" and the effects of collisional accretion of such terranes as well as the effects of different and unusual modes of subduction. All of these phenomena have contributed to the complexity of the pre-Cenozoic geology of the northwest Mojave Desert.

Rocks in the mountains to the north and south of Cantil Valley are of equally mysterious origins. The Rand Mountains form the south margin of Cantil Valley. The lower slopes expose Rand Schist (Fig. IN-1), whereas the crest of the range is capped by granitoid of Mesozoic age. These two bedrock rock units are separated by a subhorizontal 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 Complex that were underthrust 100 + km inland beneath the west margin of cratonic North America during early Cenozoic time.

The bedrock of the El Paso Mountains is comprised of a large roof pendent of Paleozoic strata enclosed in granitoids as old as 260 Ma! 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 ....? (see Fig. IN-1)

NORTHWEST MOJAVE TO TRONA LEG TRAVEL COMMENTARY

From our northwest Mojave stop, we head northeast along the base of the El Paso Mountains (to our left) and parallel to the trace of the Garlock fault, which starts out to our right, then passes beneath the road (Fig. NW-2). As we near Highway 395, we enter poor but extensive exposures of the Jurassic portion of the Sierra Nevada batholith; these continue as we leave 395 and again head northeast toward Trona across a highland of gently undulating topography called the Spangler Hills. We drop down to and "T" into Highway 178 in Salt Wells Valley, which lies at the south end of the Argus Range. This valley is filled with pale gray lake deposits dating to the last Ice Age, during which a major drainage pathway connecting the Mono Lake basin far to the northwest with Panamint Valley to the east traversed the valley and periodically filled with lakes (Figure NW-3). Let's digress for a moment and discuss the glacial lake and river system that existed in eastern California. During the most recent Ice Age, increased rainfall as well as glacial meltwater led to the development of a series of large freshwater lakes in eastern California. During wetter intervals, several of the largest of these were connected by rivers, forming an interconnecting chain stretching from Mono Lake (pluvial Lake Russel) to an "ultimate baselevel" in Death Valley (Fig. NW-3). Owens Lake in southern Owens Valley occasionally overtopped its southern margin, sending a river (glacial Owens River) southward through the Little Lake notch into Lake China that filled Indian Wells Valley.

As we head east of 178, we pass through outcrops of more Jurassic plutons of the Sierran batholith. Here, the plutons are cut by dozens of mafic dikes that are part of the largest dike swarm in California, the Independence dike swarm that was emplaced at 148 Ma. Many of these subvertical, northwest-trending dikes are less resistant than the enclosing granitoid, and thus weather out so as to form a linear depression. As we near the edge of Searles Drylake, look south to see "The Pinnacles", which are tufa buildups that formed where freshwater springs occurred on the floor of Searles Lake. The interaction between saline lake water and fresh spring water led to the creation of tufa. As the road makes a prominent turn to the north (left), the resistant, dark, aligned, tomb-stone like outcrop band coming down to the corner from the northwest is a resistant Independence dike. Driving north into Trona, look for lake shoreline benches on the sandy slopes to your left.

Searles Lake basin is filled with about 910 m of sediment that began accumulating at the start of the last Ice Age in this region, approximately 3.1 m.y. ago. During this time, the crest of the Sierra to the west was about 1300 m lower than today, permitting as much as

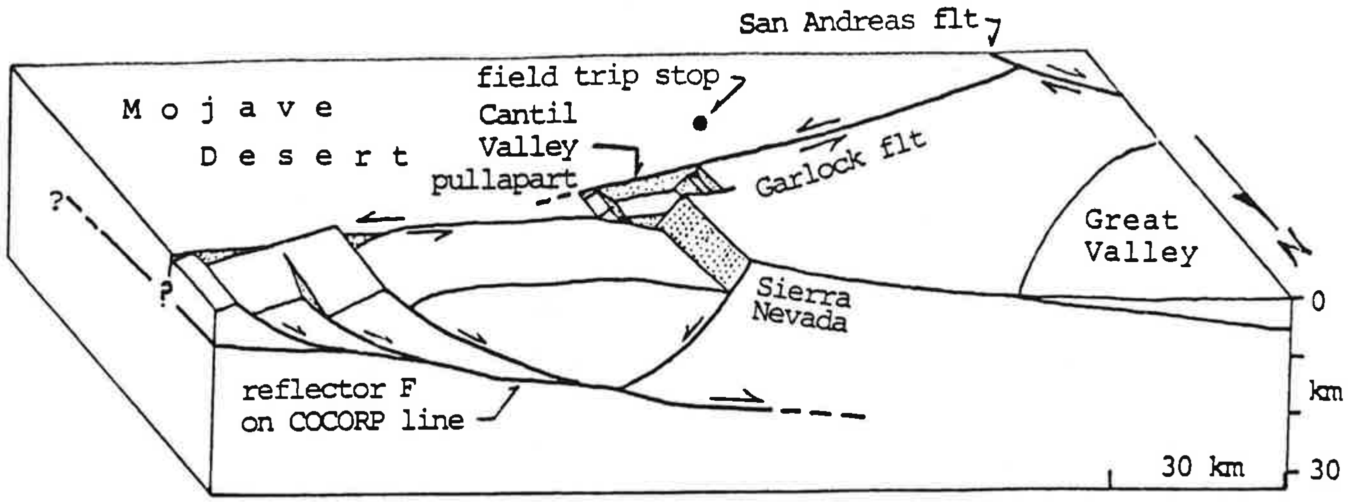


Figure NW-1. Southward view of Garlock fault and Cantil Valley.

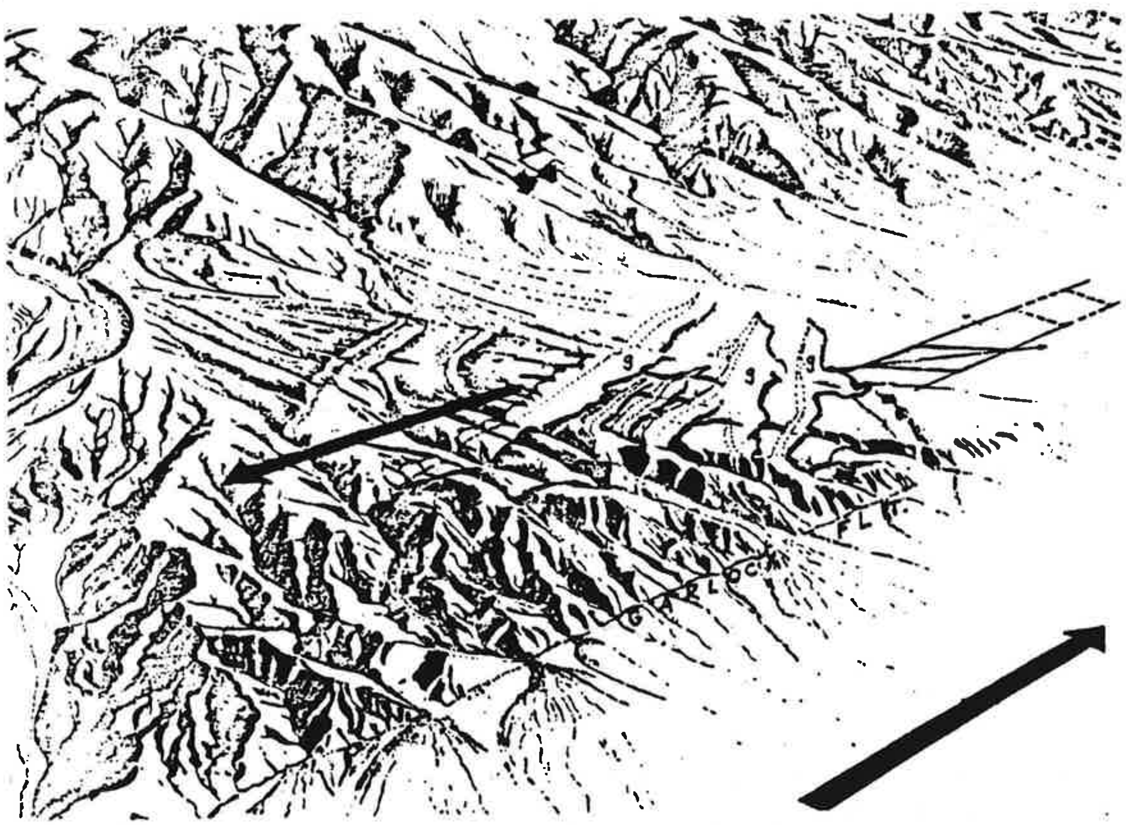


Figure NW-2. Pen and ink sketch (derived from air photo) of a portion of the Garlock fault. Thick black arrows indicate left slip sense on fault. Several extensional grabens (marked 'g') on block away from viewer are oriented obliquely relative to the Garlock in a pattern characteristic of left-slip faults.

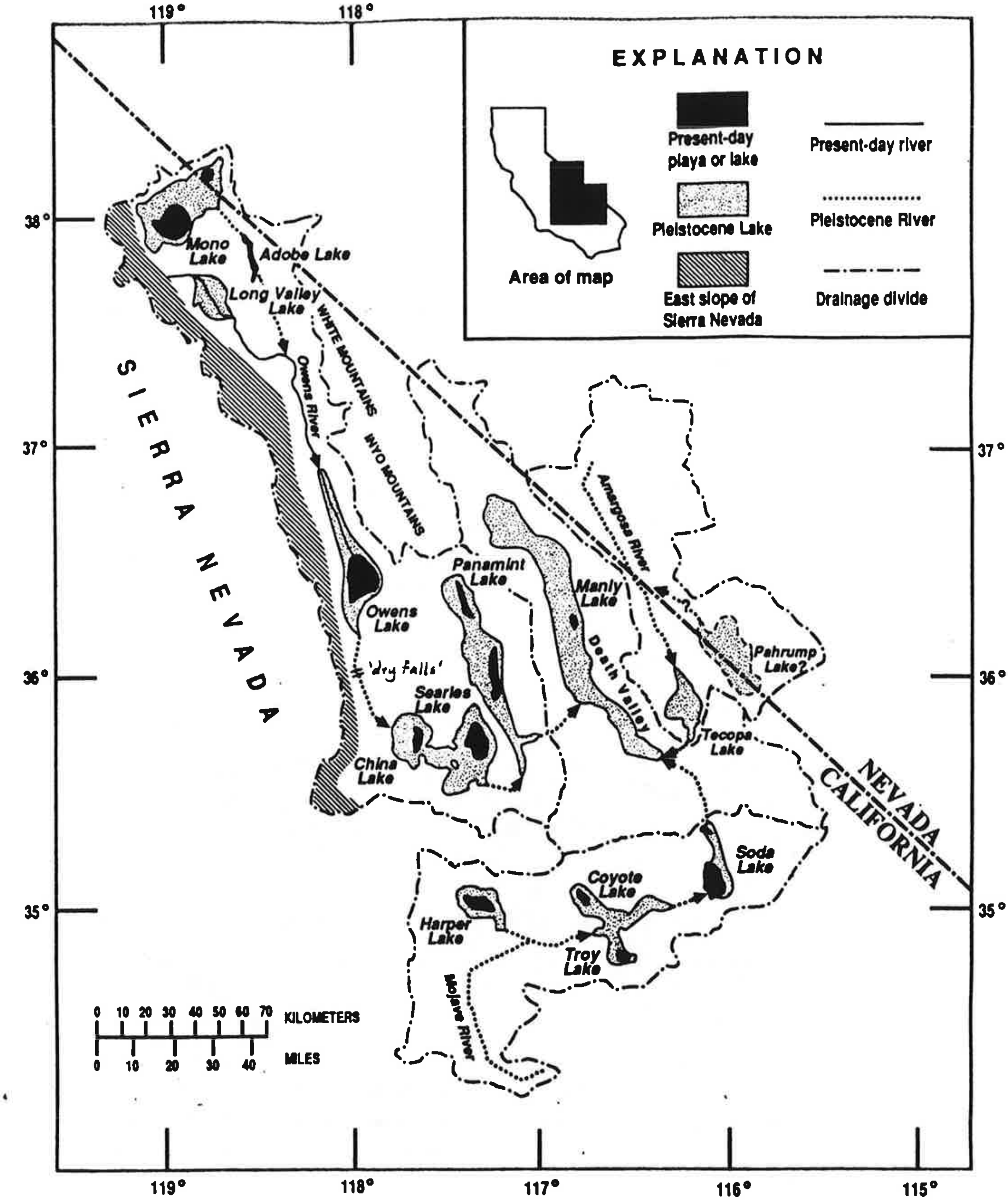


Fig. NW-3. Map showing locations and drainage patterns of the paleo-Owens, -Amargosa, and -Mojave River systems.

50% more moisture from the Pacific Ocean to reach the Death Valley area. During times of maximum precipitation, Searles Lake reached a depth of about 650 ft. before spilling over its southeast rim and draining eastward into Panamint Valley.

TRONA TO PANAMINT VALLEY LEG TRAVEL COMMENTARY

Driving north from Trona, we have the Argus Range on the left (all Jurassic plutons of the Sierran batholith) and the Slate Range to the right. The Slate Range is composed of Paleozoic and Mesozoic strata intruded by numerous plutons. Along its west face are several west-dipping thrust faults that carried various rock units up and east during middle to late Mesozoic time. These thrust faults are portions of the east Sierran thrust belt. The promontory jutting westward into the valley is the Ophir Complex (see Figure SP-1) that was most recently mapped by Julie Fowler, a graduate student at CSUN. As we climb out of the north end of Searles Valley over Slate Range Crossing, we pass through additional exposures of the east Sierran thrust belt (see Figure SP-2), and then drop down through Permian miogeoclinal strata into Panamint Valley. Do you see any evidence that the Argus Range (to our left) has been tilted to the east?

PANAMINT VALLEY STOP COMMENTARY

Panamint Valley is an excellent example of an oblique pull-apart basin that formed within the past 5 m.y. (and is still forming) in response to the Basin & Range orogeny. We will discuss the various features associated with this ongoing tectonism, and also note the pre-Cenozoic bedrock geology exposed on the walls of the bounding ranges.

PANAMINT VALLEY TO DEATH VALLEY LEG TRAVEL COMMENTARY

OVERVIEW

Most rock exposures along this leg consist of two main rock units: the Pahrump Group of late Paleozoic age and the Nova Formation. Isn't it interesting that the 10 km of latest Precambrian and Paleozoic strata that should be present between these two units is missing! Was it kidnapped by space aliens. or ....??? The Pahrump Group was described earlier in this guide. The Nova Formation is of late Miocene and early Pliocene age. It is approximately 3 km thick and consists mostly of terrestrial fanglomerate plus minor amounts of basalt to rhyolite lava, carbonate landslide breccia, and pale-gray lakebed deposits. It was deposited in a northeast-trending basin that developed in response to growth of a major low-dipping extensional detachment fault, the Emigrant fault, the trace of which our field trip route roughly follows to Death Valley. In structural terms, the Nova basin was a "breakaway basin", and the Nova

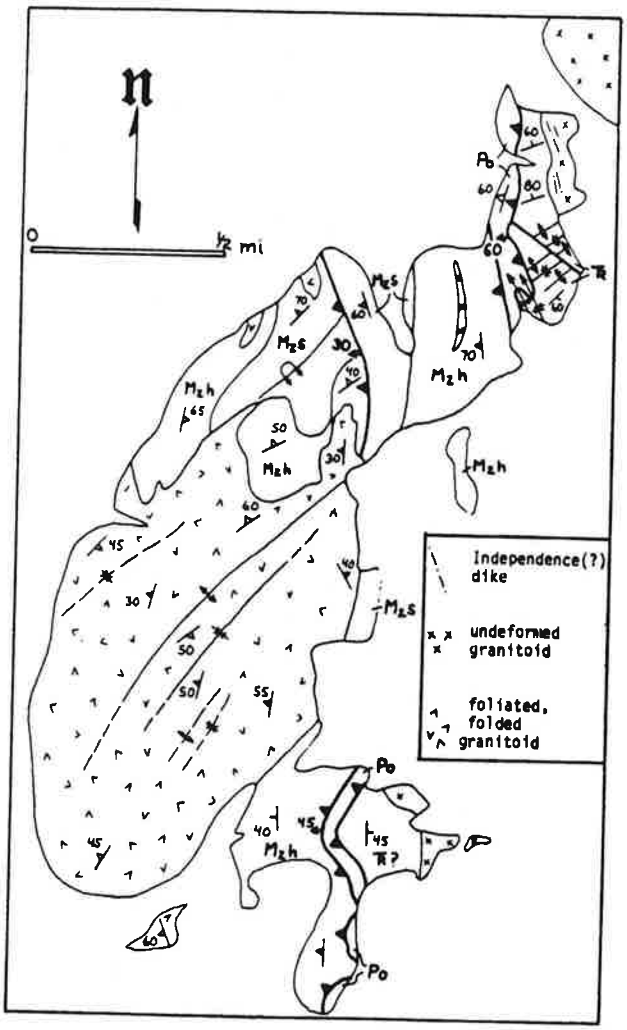


Fig.SP-1. Geologic sketch map of Ophir complex, central Slate Range. Data from Fowler (1982) and Dunne (unpublished).

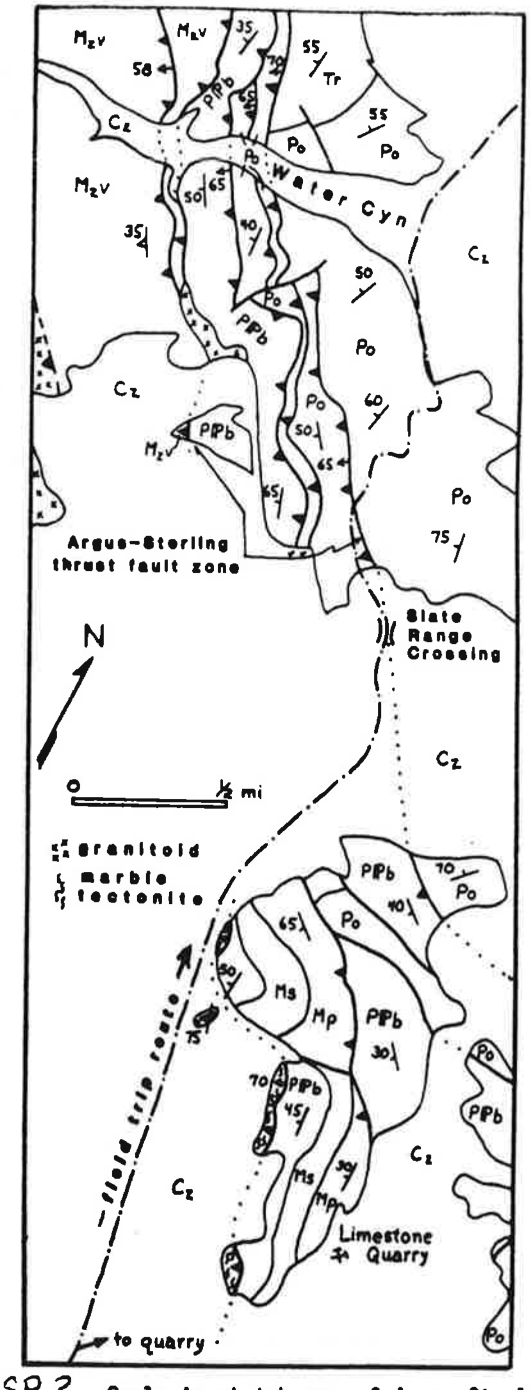


Fig.SP-2. Geologic sketch map of Argus-Sterling thrust fault zone at Slate Range crossing and vicinity. Data from Moore (1976) and Stone (1984).

Formation accumulated in this basin as the basin continued to widen via extensional faulting (Fig. IN-7). The thick section of Paleozoic strata that once lay on the Pahrump Group was carried off to the northwest by this fault, and the Nova Formation was deposited on the 'denuded' Pahrump basement. Neat trick, eh? A map, cross section and stratigraphic column for the Nova basin area are provided in Figures Sp-3, -4, and -5.

TRAVEL COMMENTARY

At the road junction, we head uphill and northeast toward Wildrose Canyon. As we drive up the sloping alluvial fan and approach the front of the Panamint Range, we pass through topographic step that drops down to the east. This is the scarp of an antithetic normal fault and forms the west wall of the Wildrose graben. About 1 mile farther up the road, and right at the base of the range, we pass through the scarp of the main frontal fault that has uplifted the range; this is the other (east) side of the graben. In the lower part of the canyon, exposures are of the Nova Formation. We then cross the Emigrant detachment fault into the Pahrump Group. Between here and Harrisburg Flat, most exposures of the Pahrump are present within fault slices along the Emigrant detachment fault, and the rocks are jumbled to brecciated in response to extensional faulting.

After branching northward out of Wildrose Canyon, we round various spurs underlain by the Kingston Peak Formation (Pahrump Group), and come upon one consisting of "stretch-pebble" conglomerate. We will stop briefly to examine this (no collecting, please; we do not have a permit!). 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 'klippe'.

A few miles farther, 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.

Traveling northward from Harrisburg Flats, we drop into Emigrant Canyon, and soon enter the pale gray exposures of the Skidoo pluton of Cretaceous age. This is a peraluminous granite bearing both muscovite and biotite. The remaining exposures between here and Death Valley are of Nova Formation fanglomerate containing scattered lenses of landslide breccia (gray, and resistant), lakebeds (pale gray, thin bedded limestone), and basalt flows.

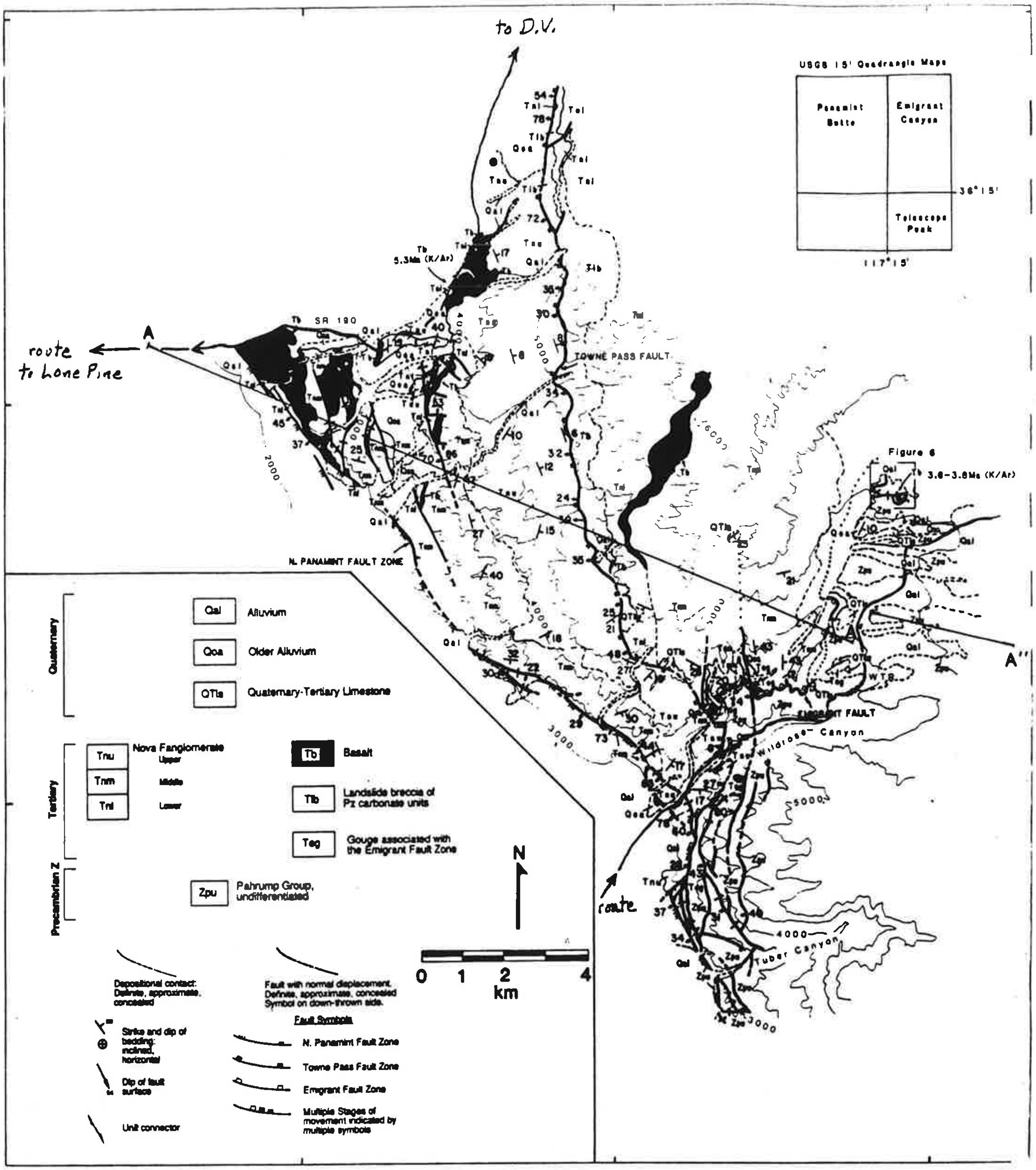


Fig. SP-3 . Tectonic map and cross section of the Nova basin and surroundings. See key for units, symbols, and scale.

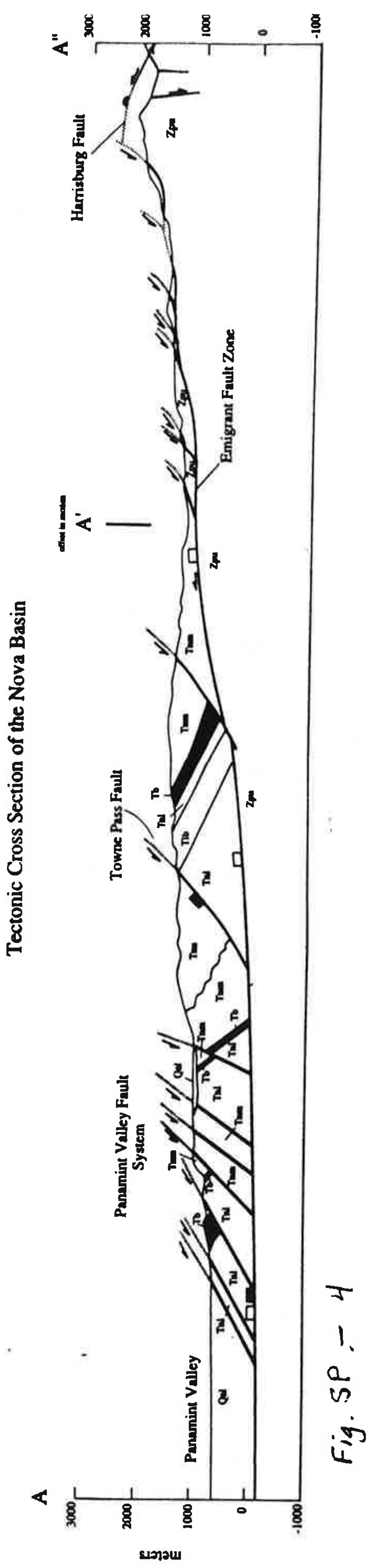


Fig. SP - 4

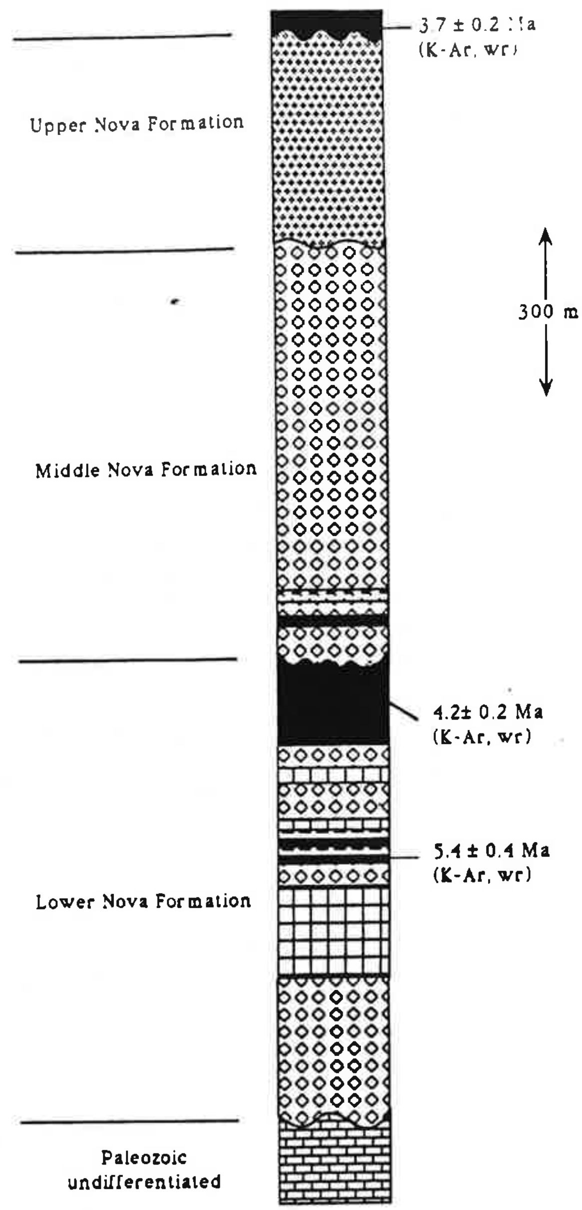


Fig. SP-5. Stratigraphy of the upper Miocene to lower Pliocene Nova Formation, with radiometric age constraints as indicated. Other consistent K-Ar ages are available for the sequence (e.g., W. Hildreth, unpublished data), but the stratigraphic positions of the dated units are less certain than those noted here.

DEATH VALLEY AREA -- GEOLOGIC OVERVIEW

Stratigraphic Overview

Paleozoic + latest Precambrian sections exposed from Las Vegas westward to the Panamint Range increase in thickness from approximately 8,000 ft to 29,000 ft as we move from the cratonic facies well out into the westward-thickening miogeoclinal wedge of the Cordilleran geosyncline (or passive continental margin in plate tectonic terms). Review Figure IN-2.

Mesozoic sections in the Las Vegas region are like those all across the Colorado Plateau. Westward from Las Vegas to Death Valley (and beyond), the cratonic Mesozoic sections interfinger with westward-derived conglomerate- and volcanic-rich tongues shed from the continental-margin (Sierran) igneous arc.

Structural Overview

The Mesozoic foreland fold/thrust belt and at least one other similar contractile belt that lay farther west in the Cordilleran 'hinterland' probably converged southward and passed through the Las Vegas/Death Valley region and thence into the eastern Mojave Desert. There, the geometry and trend of these fold/thrust belts changed greatly as they encountered the thermally softened lithosphere along the east margin the Sierran igneous arc. Our view of the regional geometry of the fold/thrust belts as they once existed in the Las Vegas/Death Valley region is somewhat imprecise because the late Cenozoic extensional tectonism that was superimposed upon them has greatly fragmented the Mesozoic structures and scattered remnants of them far off to the northwest (Fig. DV-1).

The effects of Cenozoic extensional tectonism are spectacularly displayed in the Death Valley area. A major, west-dipping extensional detachment fault 'daylights' at the west base of the Spring Mountains, and all of the ranges westward through Death Valley to the Sierra Nevada were variably rotated, tilted, and 'denuded' (meaning some or all of the original stratigraphic cover was removed by detachment faults) during Cenozoic extension. The Black Mountains along the east side of Death Valley were stripped of much of their Paleozoic cover by detachment faults, and Cenozoic strata that were deposited directly on Precambrian basement are in turn being detached from and faulted off of the basement. Figure DV-2 shows the principal Cenozoic extensional faults in the Death Valley area.

Cenozoic Rock Units

Cenozoic rocks can be divided into those that formed prior to the development of the Furnace Creek fault zone (Titus Canyon Formation, Horse Spring Formation, Bat Mountain Formation), and those that formed after the fault zone began to influence

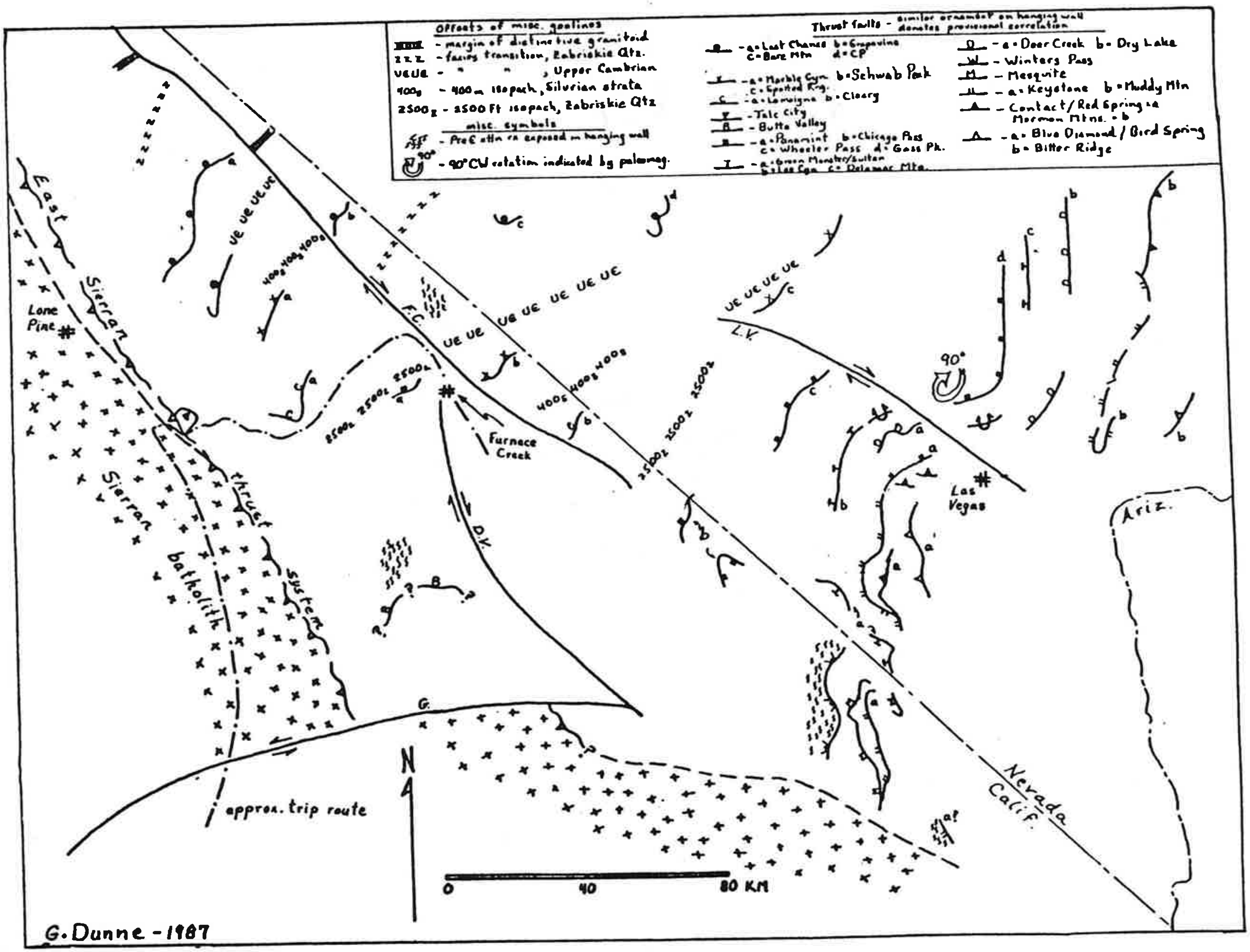
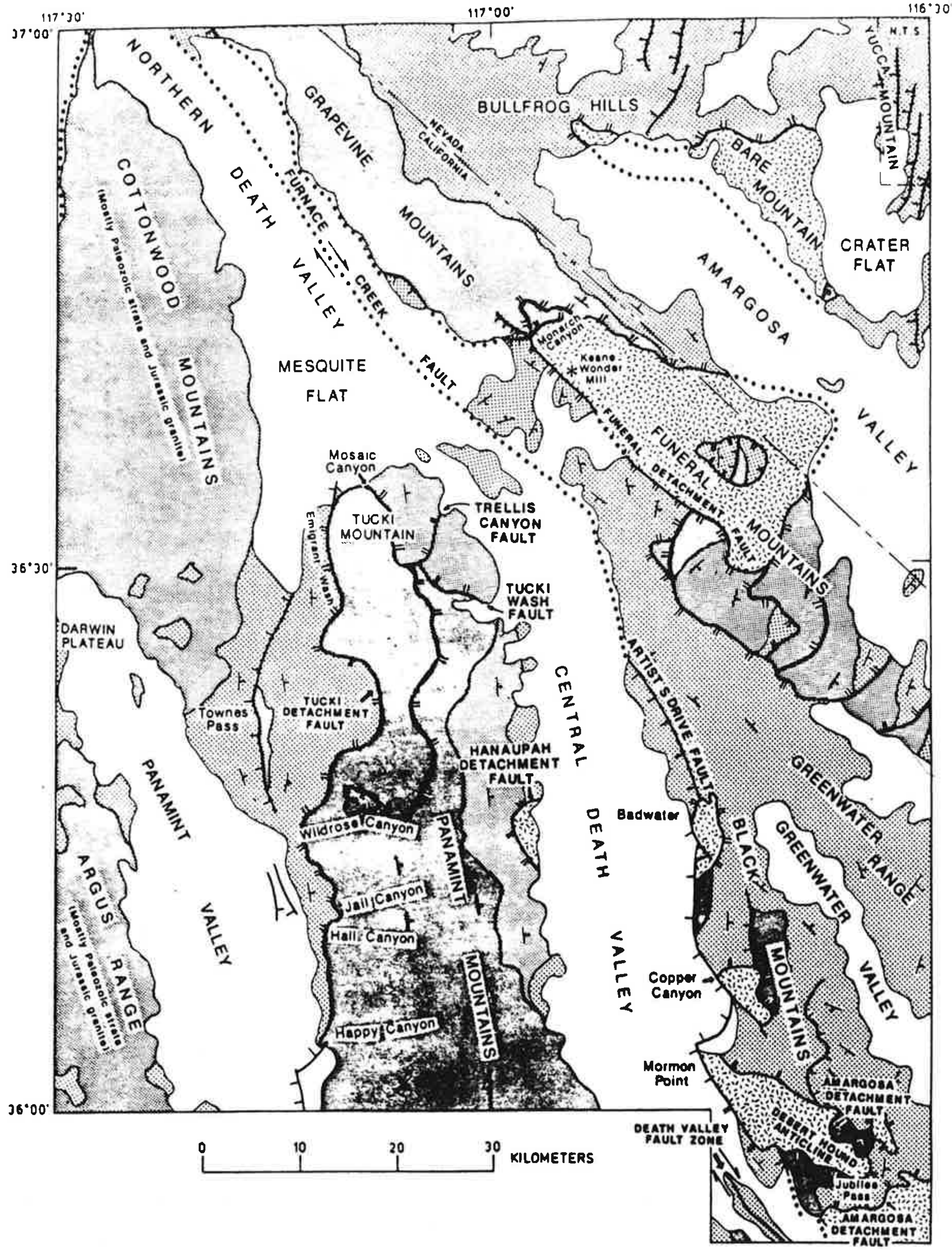


Figure DV-1. Cordilleran foreland fold-thrust belt in southern Nevada, eastern California, showing provisional correlations.



Quaternary materials

UPPER-PLATE ROCKS

Tertiary, sedimentary and volcanic rocks, Oligocene through Pliocene

Paleozoic, includes Mesozoic granitic rocks

Precambrian, Middle Proterozoic plutonic rocks and Late Proterozoic sedimentary and metasedimentary rocks

LOWER-PLATE ROCKS

Metamorphic and plutonic rocks, of diverse ages, below lowest exposed faults

Faults, dotted where concealed

Strike-slip, arrows indicate relative movement

Normal, hachured on downthrown side

Detachment faults and normal faults rotated to gentle dips, hachures on upper plate

Figure DV-2.

sedimentation (Artist Drive Formation, Furnace Creek Formation, Funeral Formation) (Fig. DV-3).

The older sequence is not exposed in our field trip area, so I'll comment on it only briefly. It consists of various combinations of alluvial fan deposits, lake deposits and mostly silicic volcanic tuffs, that were distributed across the region in a manner that suggests that no localized basins controlled by the 'modern' structures such as the Furnace Creek fault and the Death Valley graben, had yet formed.

The younger sequence, which began to be deposited about 14 Ma (middle Miocene) is well represented by exposures near Furnace Creek. At about this time, an irregular chain of lake-filled, alluvial-fan-rimmed basins formed along a northwest trend from southern Death Valley to east of the White Mountains, coincident with the present trace of the Furnace Creek fault zone. These basins are interpreted to have formed as pull-aparts, tipped fault wedges or sags along the active right-slip fault. The basins filled with alluvial fan, river, and lacustrine deposits, plus scattered tuffs and lava flows. The climate dried and warmed during deposition in these basins, as documented by the presence of evaporites in their deposits.

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

Radiocarbon dating of organic muds recovered from drill holes on the floor of Death Valley suggest sediment accumulation rates of 0.9 m per 1000 yrs over the past several hundred years. If this rate were representative of longer intervals, it would take somewhat over 3 Ma. to accumulate the 3 km 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 about 180 m before drying up about 11,000 yrs ago. Careful study of lake shorelines and the development history of alluvial fans (the oldest surviving fans are about 50,000 yrs old) show that the valley floor and adjacent fans have continued to tilt eastward during the past 2000 yrs. If most of this tilting movement has been accommodated by normal slip on the Black Mountains frontal fault, then the average slip rate approaches 6 m/1000 yrs.

TUCKI MOUNTAIN / MOSAIC CANYON COMMENTARY (see Figs. DV-4, -5)

It has been recognized since the mid-1960's that much if not all of the late Precambrian through Paleozoic strata of Tucki Mountain are allochthonous, separated from

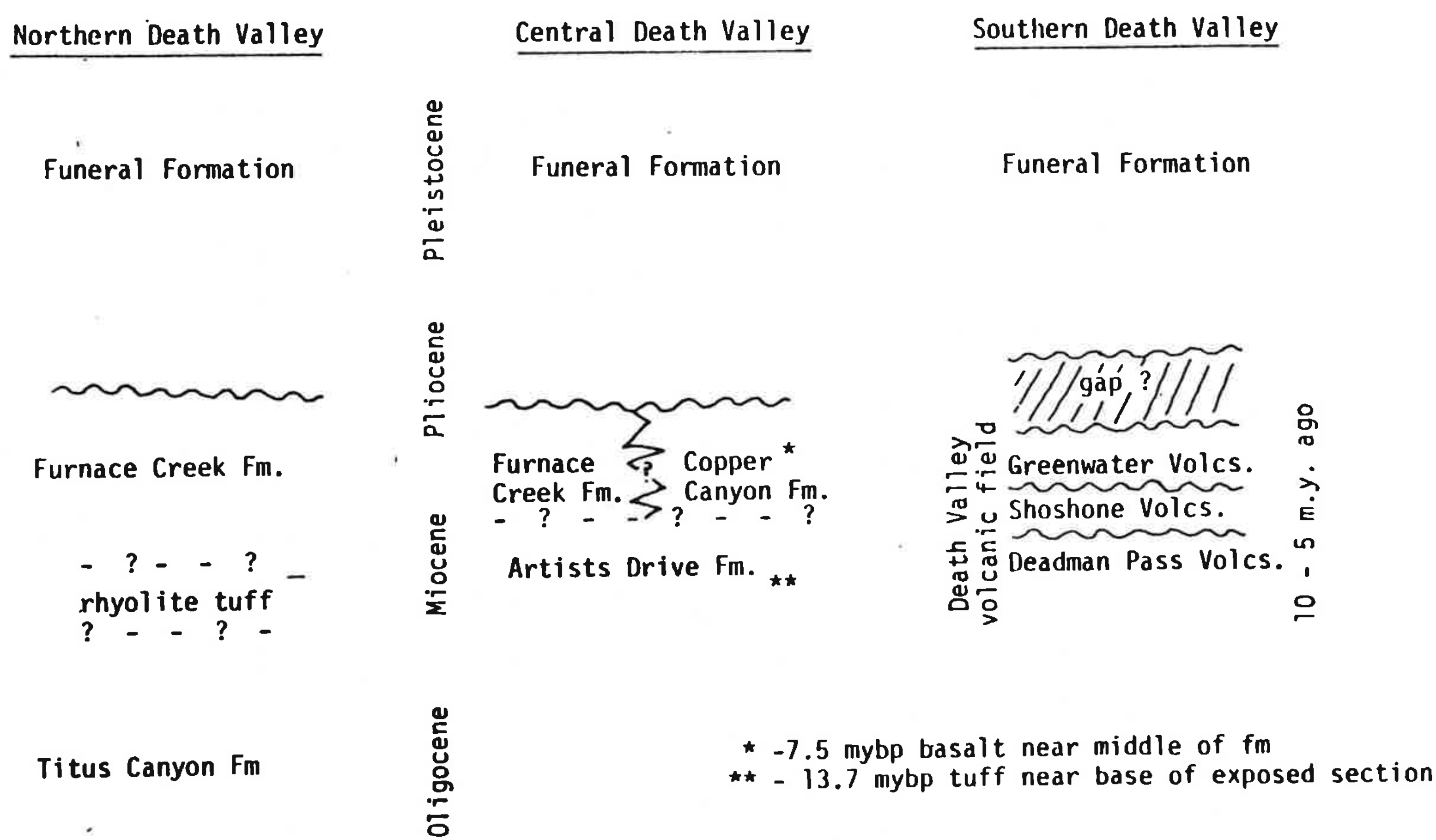


Figure DV-3. General correlations of major Cenozoic rock units in the Death Valley area.

metamorphosed late Precambrian autochthonous (relatively speaking) strata by a family of antiformally arched faults. Hunt and Mabey (1966) mapped these faults and provisionally interpreted them as an unusual westward-moving "thrust" (Amargosa Thrust), although noting that these faults cut out rather than repeat section, always placing younger rock upon older. Wright and Troxel (1973) re-interpreted these faults to be part of a listric normal fault system, and Stewart (1983) added to this concept the idea that both exposed basement as well as Paleozoic strata of Tucki Mountain have slipped many tens of kilometers northwest from the vicinity of the Black Mountains.

Work by Wernicke, Hodges and Walker (1986) has greatly improved our understanding of extensional faulting at Tucki Mountain. They have mapped three major low-angle normal (detachment) faults (Fig. DV-4). The oldest two faults (Harrisburg and Mosaic Canyon) are warped by a NNW-trending anticline, whereas the next younger fault (Emigrant) is not warped, instead seeming to be exposed near its breakaway point. The arching of the Harrisburg and Mosaic Canyon faults is attributed to rollover above a younger detachment fault underlying the entire range and/or to isostatic rebound.

At Mosaic Canyon we have an excellent view of the Mosaic Canyon detachment fault just east of the parking lot. Here the fault dips about 30°ENE and is marked by several meters of gouge. In contrast, much of the upper portion of the footwall (here, metamorphosed marble of the late Precambrian Noonday or Johnnie Formations) contains abundant, variably ductile extensional structures. These latter are interpreted to have formed at considerable depth early in the extensional deformation, whereas the brittle gouge represents more recent deformation during movement under relatively shallow cover.

The unmetamorphosed Stirling Quartzite and younger strata in the hanging wall are units that normally rest stratigraphically upon the Johnnie Formation. However, these younger strata have thicknesses and facies reminiscent of equivalent strata in the Resting Spring Range. This, plus their lack of metamorphism, (in contrast to the footwall), supports the notion that the hanging wall strata were derived from many tens of kilometers to the southeast. The original section of Stirling and younger strata that once rested stratigraphically upon the footwall presumably were removed to the northwest by the Harrisburg detachment fault prior to arrival of the Mosaic Canyon allochthon.

High altitude airphoto E provides an overview of this region.

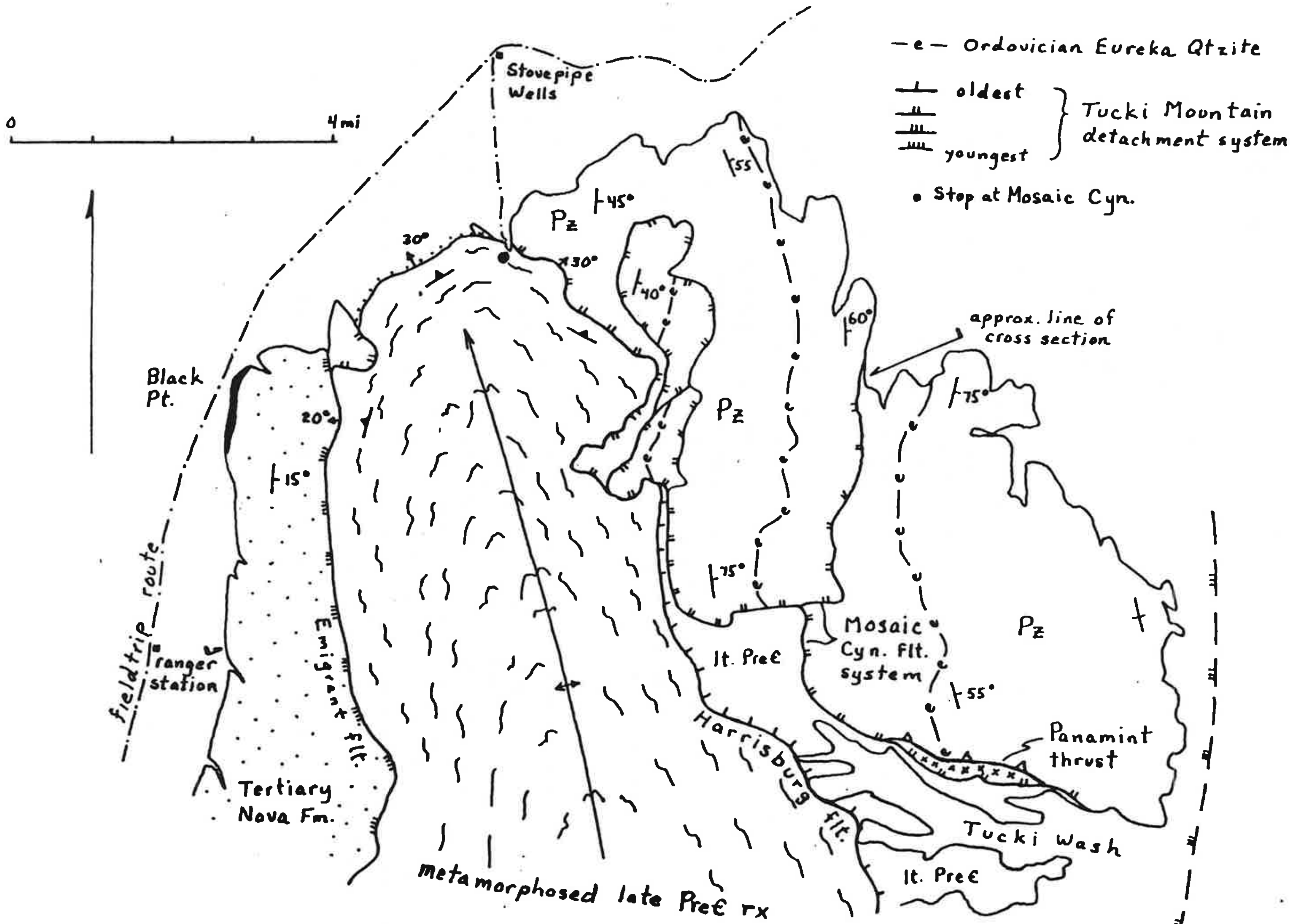


Figure DV-4. Geologic sketch map of Tucki Mountain detachment fault complex. Schematic cross section is provided in figure DV-5. Geology after Hunt and Mabey (1966) and Wernicke and others (1985).

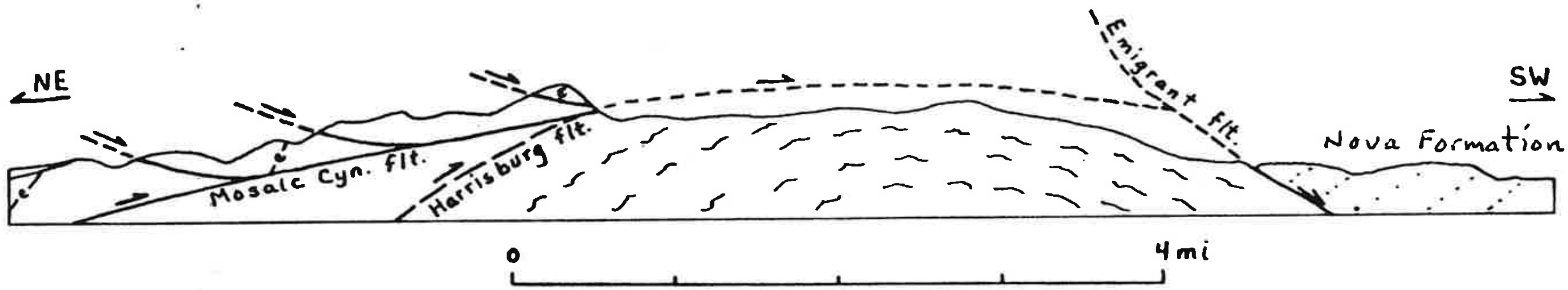


Fig. DV-5. Schematic cross section of Tucki Mountain detachment complex, derived from map relations shown in Fig. DV-2. Note that view direction of section has been reversed from map so as to show the complex as it would appear to us as we look south from Mosaic Canyon.

DAY TWO

Today we will focus on two geologic objectives: 1) Drive south along the east side of Death Valley to Badwater, the lowest spot in the United States, looking at Tertiary formations and evidence of very young normal faulting as we go. 2) Drive southeast up Furnace Creek Wash to the Billie Borate Mine and go on a tour of that facility courtesy of one of our graduates, Fred Johnson. We will then return to the Furnace Creek Ranch area, possibly in time to wander about before the Visitor's Center closes. A geologic sketch map of the Furnace Creek area is provided in Figure DV-6.

FURNACE CREEK TO BADWATER

As we move south along the east side of the valley, compare the size and color of the alluvial fans along our route with those at the foot of the Panamint Range to the west. Why do you suppose these fans are so different? What can we note about the location (east side, west side or center?) of the lowest portions of the valley floor? What evidence do you see that there is a very young and active normal fault system along the base of the Black Mountains to our left? As we approach Badwater, look for a very young, arched fault called the Badwater 'turtleback' exposed on the lower flank of the Black Mountains.

FURNACE CREEK TO BILLIE BORATE MINE

We move southeast up Furnace Creek Wash, parallel to the Furnace Creek fault, which lies close to the base of the Funeral Mountains to our left. These mountains are underlain by the Paleozoic miogeoclinal section and its Pahrump basement, both cut by numerous normal faults. Tilted conglomeratic strata exposed along the road are part of the Furnace Creek Formation of latest Miocene age (5-6 Ma) and the Funeral Formation of Pliocene age (4-5 Ma). A geologic sketch map and cross section of the Billie borate mine area is provided in Figure DV-7.

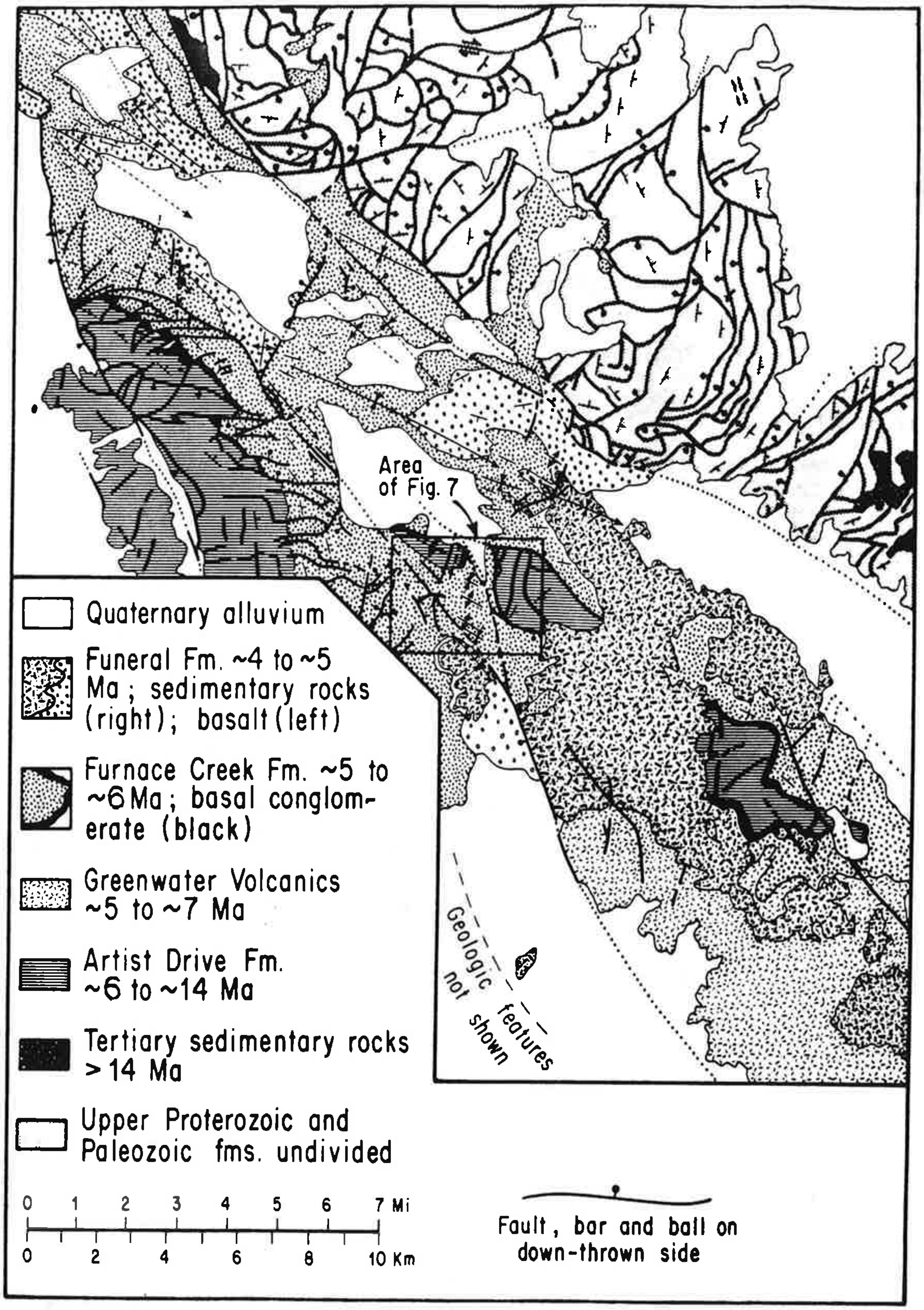
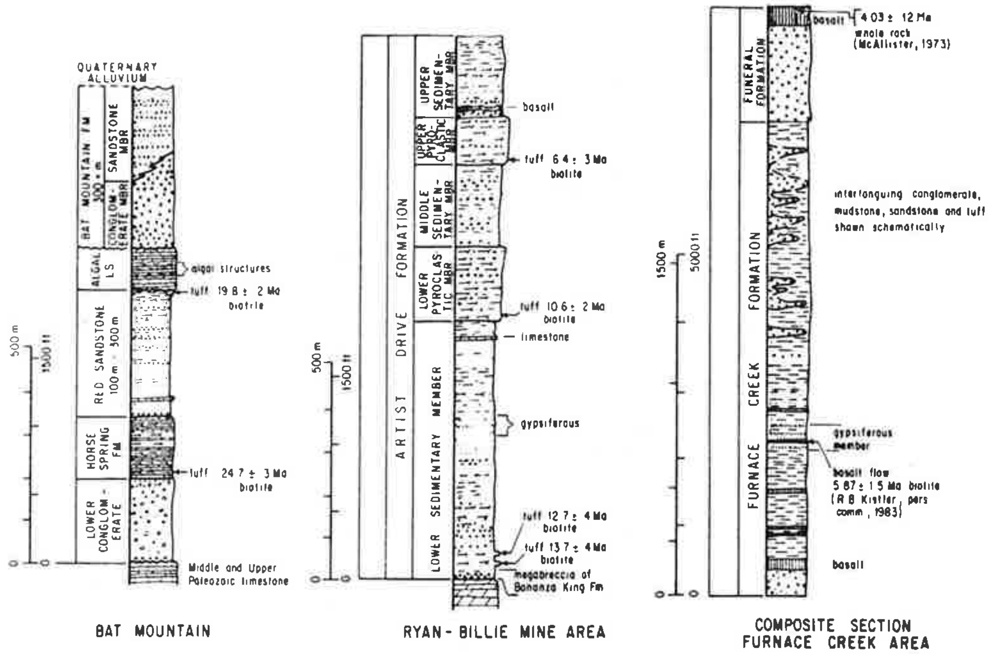


Fig. DV-6. —Generalized geologic map of the central and northwestern parts of the Furnace Creek Basin and vicinity, showing distribution of the Artist Drive, Furnace Creek, and Funeral Formations.



–Generalized columnar sections of the sedimentary and volcanic successions exposed at Bat Mountain and vicinity and in the Furnace Creek Basin. Unless otherwise indicated radiometric age determination are by R. E. Drake. Age determination of basalt flow in lower part of Furnace Creek Formation is by P. E. Damon.

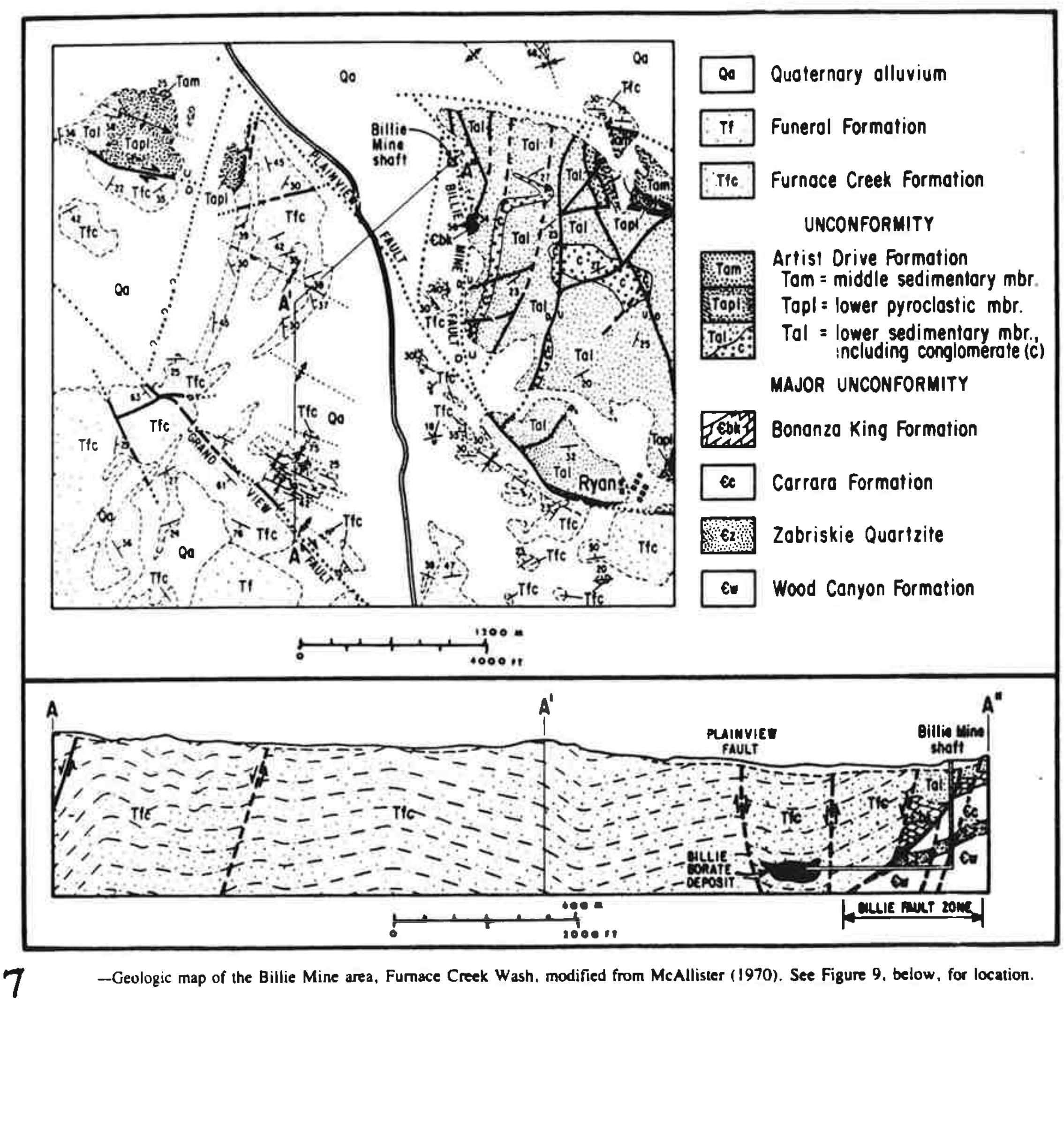


Fig. DV-7 —Geologic map of the Billie Mine area, Furnace Creek Wash, modified from McAllister (1970). See Figure 9, below, for location.

DAY THREE

Today we start with a hiking stop to fondle high-grade metamorphic rocks in the core of the Funeral detachment fault. We will then head west out of Death Valley over Towne Pass, across Panamint Valley, and up onto the Darwin Plateau beyond. If weather and time permit, we will make brief view stops at Father Crowley Overlook and at the south end of Owens Valley. We then continue west to U.S. 395 and head home.

Stratigraphic Overview

As we travel westward to the edge of the Sierra Nevada batholith, we note that Paleozoic strata are like those in Death Valley, except that we will pass into the eastern wedge-edge of the Antler-derived siliciclastic flysch deposits of Mississippian age, a sign that we are drawing nearer to the Paleozoic continental margin. In the Inyo Mountains, just east of the Sierra, we will encounter Mesozoic strata which include the stratigraphic transition from pre-arc quiescent marine environments that prevailed during Early Triassic time (Union Wash Formation) to tectonically active, volcanic-dominated emergent environments that prevailed from Middle(?) Triassic time through the Cretaceous. We also pass through excellent exposures of the late Cenozoic Nova Formation exposed across nearly the full width of the Panamint Range (review Figs. Sp-3, -4,-5). Recall that these strata represent the uplifted fill of a breakaway basin that evolved adjacent to a detachment fault (Emigrant fault). Second, formerly coherent, widespread late Cenozoic basalt fields now separated by a major graben (Panamint Valley) place important contraints on the timing and style of faulting that created Panamint Valley.

Structural Overview

We will pass near several fragments of Mesozoic foreland (and perhaps hinterland) fold/thrust structures, including the prominent exposure of the Lemoigne thrust on the west face of the Panamint Range, to be viewed from our second stop (review Fig. DV-1). The Lemoigne thrust and imbricate cousins to the northwest (part of the Last Chance thrust system) differ from typical faults elsewhere in the foreland fold/thrust belt in that the former are older than 185 Ma (early Middle Jurassic on most time scales). Moving farther west, we will stop (or at least slow down) in view of the west base of the southern Inyo Mountains to observe from a distance structures typical of the East Sierran thrust system.

We will encounter both detachment-style and classic horst-and-graben-style Cenozoic extensional structures along this leg. At the Father Crowley Overlook, we'll discuss how the horst-and-graben surface geology of Panamint Valley and its bounding ranges relates to underlying gently dipping detachment faults. Finally, as we move west into Owens Valley, we'll see the evidence for and discuss the very recent right-oblique extensional history of this area as well as the controversy regarding the mechanism of late Cenozoic uplift of the the Sierra Nevada Range to the west.

FURNACE CREEK TO FUNERAL RANGE CORE COMPLEX

Heading north from Furnace Creek, we have to our right low hills exposing Furnace Creek and Funeral Formations. About 3 miles north of the Park Service residential area, we cross the trace of the Furnace Creek fault zone, a right-lateral extensional tear fault with 40+miles of slip. At Beatty Junction we bear right, and in a couple of miles pass over a gravel shoreline bar of pluvial Lake Manley. Another mile or two up the road, we will park on the right shoulder, then hike ~1.5 miles east across the fan to look at the highest grade metamorphic rocks in eastern California, the geologic significance of which is discussed in the next paragraph.

These exposures are in the heart of the Funeral Range "core complex". They expose thoroughly metamorphosed strata of the late Precambrian Pahrump Group, and locally patches of the underlying "old boy", the ancient (1.7 Ga) craton of western North America. Extensive petrographic, radiometric and microprobe studies of these rocks reveal that they experienced moderately high temperatures (~ 550°C), but very high pressures (~9 kb, or ~34 km of burial depth) in Early Cretaceous time. Common mineral assemblage in pelitic protoliths is kyanite±sillimanite +garnet+biotite (Fig. PO-1). Research data also reveal that these rocks experienced a decompression equivalent to removing about 18 km of overburden, during Late Cretaceous time. Both the source of the high pressure and the phenomenon responsible for its removal are mysteries. It is supposed that one or more thick thrust plates, no remnant of which we currently recognize, were pushed over this area, and then removed by extensional faulting.

These ancient high-grade rocks are exposed at the surface because within the past 7 m.y., ~11-14 km of overlying rock were stripped off and transported off to the northwest by the Boundary Canyon detachment fault. If time and interest permit, we will drive east toward Daylight Pass and look at this detachment where it crosses the highway.

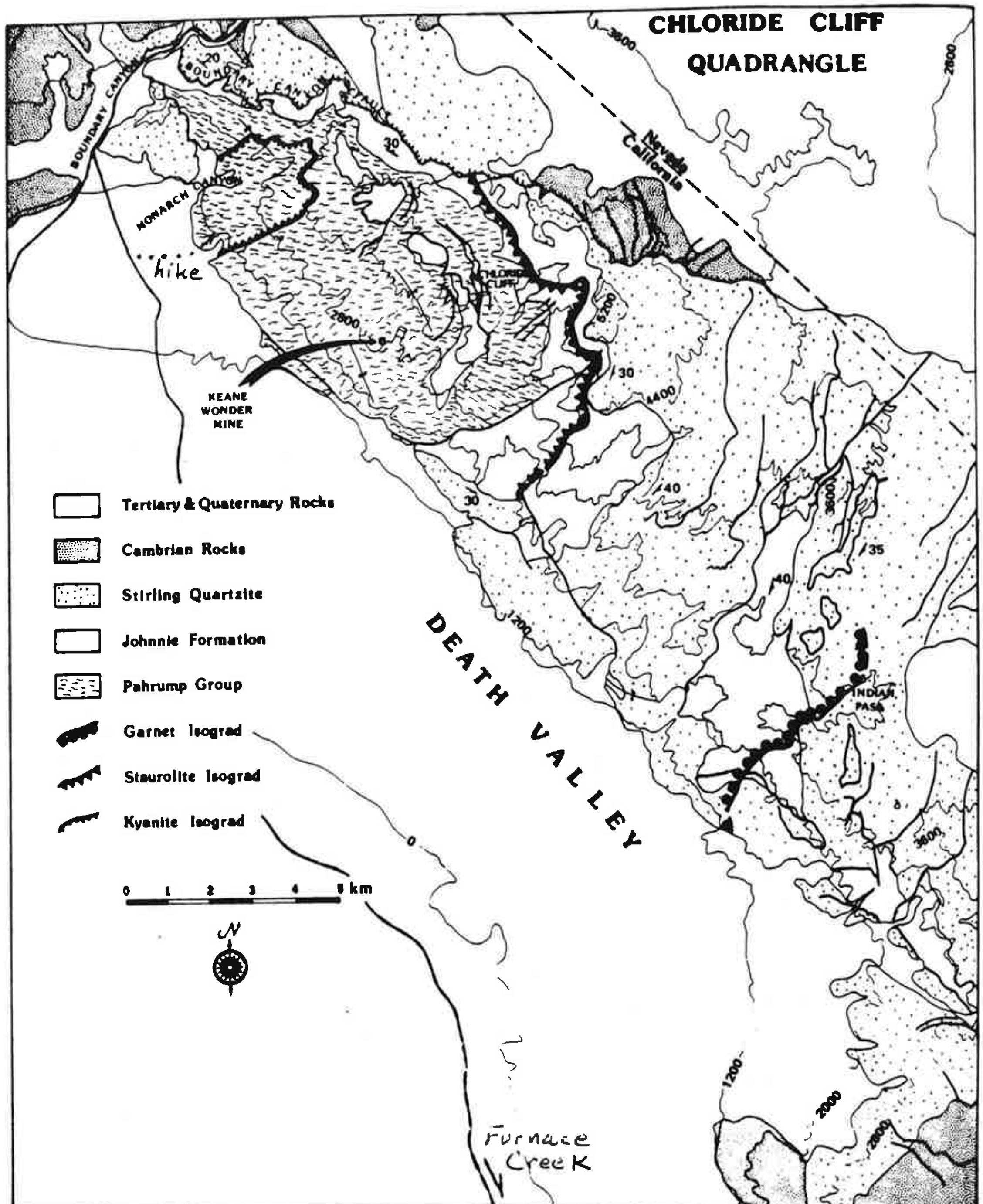


Fig. PU-1. Geologic map of the Chloride Cliff quadrangle, simplified from unpublished mapping of L. A. Wright and B. W. Troxel. Isograds are taken from Labotka (1980). The garnet zone is characterized by the coexistence of garnet and chlorite. In the staurolite zone, staurolite + biotite assemblages occur. The kyanite zone contains rocks with the assemblage kyanite + garnet + biotite; staurolite has broken down.

FUNERAL RANGE-TO-PANAMINT OVERLOOK LEG TRAVEL COMMENTARY

Heading west and downhill from Hells Gate, we first pass the Death Valley Buttes to our right, which are composed of Cambrian strata of the Zabriskie and Wood Canyon Formations. Farther downhill we pass through the Kit Fox Hills composed of the Furnace Creek Formation. At the base of the hills, just before reaching the road junction, we again cross the trace of the Furnace Creek fault. After jogging left then right, we traverse west across the Devil's cornfield, loop around the north toe of Tucki Mountain, pass through Stovepipe Wells, then head up the long grade to Towne Pass. The low gray-brown hills to our left are the Nova Formation, as are the dark basalt flows on our right; all of these layers are dipping to the southeast toward the Emigrant detachment fault, which underlies all of the Nova Formation and transported this unit off toward the northwest. As we cross Towne Pass,we see steep rugged cliffs to the south. These are brecciated Paleozoic strata that form a slice along the Towne Pass fault, a normal detachment fault slightly younger than the Emigrant detachment. As we head down to Panamint Valley, roadcuts provide excellent exposures of the various components on the Nova Formation. To our right, the rugged, banded cliffs of Panamint Butte come into view. Cambrian to Permian formations are exposed, cut by two different groups of normal faults. The older faults, which trend northeast, are associated with the Emigrant and Towne Pass detachment faults, whereas the younger faults trend northwest and are part of the normal fault system that has opened Panamint Valley (Fig. PO-2).

As we drop into Panamint Valley we encounter several Cenozoic extensional structures including: 1) the Ash Hill fault, the pronounced scarp of which can be seen south of the highway from a point between Panamint Springs and the turnoff to Panamint Valley Road (see Airphoto B); 2) the Panamint Valley fault zone, which forms scarplets on either side of our route at the west base of the lowest basalt/fanglomerate sequence at the foot of the Panamint Range (see Airphoto B); 3) Lake Hill, jutting up from the valley floor N of the highway, a jumbled mass of Paleozoic rock that probably formed as a landslide off Panamint Butte.

Pleistocene Lake Panamint filled Panamint Valley to a maximum depth of 300 m, with the shoreline reaching to within 30 m of the crest of Lake Hill. Low hills of gently dipping sandy strata just N of the highway east of Panamint Springs are interpreted to be remnants of a river delta formed by Darwin Wash as it entered Lake Panamint. The main strandline of this lake has been measurably deformed by ongoing extensional tectonism, being warped down to the northeast by several tens of meters.

Our route next passes the north end of the Argus Range as it climbs up through scattered exposures of Permian strata and more abundant Pliocene basalt units to Father Crowley Overlook.

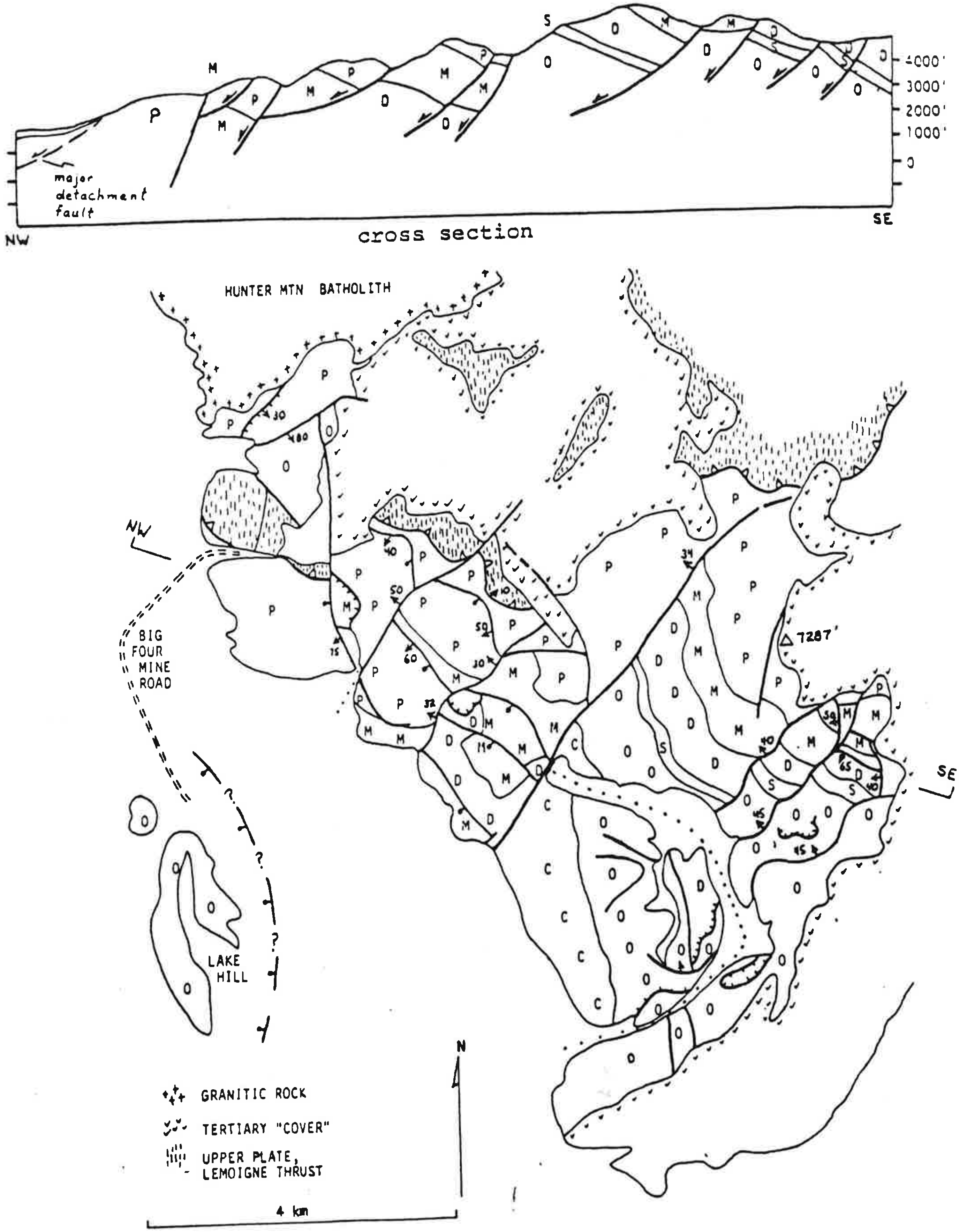


Figure PO-2. Geologic sketch map and cross section of PanamintButte, as derived from mapping of W. Hall (1971). Capitol letters designate rock systems (C = Cambrian, etc.).

FATHER CROWLEY STOP COMMENTARY

From this point we have sweeping vistas of the east margin of the Darwin Plateau (upon which we are standing), the Panamint Range to the east, and the Argus Range to the south. We will discuss briefly some features of the pre-Cenozoic geology, then focus on the Cenozoic extensional tectonism, to which Figure PO-3 and Airphotos A, B, and D pertain.

FATHER CROWLEY OVERLOOK-TO-TALC CITY HILLS LEG COMMENTARY

As we move westward across the basalt-covered Darwin Plateau toward the Talc City Hills, we again enter the East Sierran fold/thrust system (ESTS on Fig. PO-4). This system, which can be recognized from the White Mountains north of our route to the Mojave Desert, parallels the eastern edge of the Sierran batholith, and, like the batholith, is mostly of middle to late Mesozoic age, thus suggesting a genetic link between the two. The East Sierran fold/thrust system consists of NW-trending, NE-vergent thrust and reverse faults, and of N- to NW-trending folds with well-developed axial cleavage. Faults of this system are characterized by moderate to steep dip (45^{o} - 80^{o} SW), modest slip (a total of a few to perhaps several km at any one transect across the system), and by a relatively uniform slip direction averaging N85^{o}E. Northwest-trending folds in this region typically are east-vergent, plunge moderately W or NW, are commonly reclined, and are distinctly asymmetric in profile. Two cross sections transecting the fold/thrust belt on the west slope of the southern Inyo Range are provided in Figure PO-5.

The East Sierran fold/thrust system clearly overprints an assemblage of large-slip, low-dip, NE-trending imbricate thrust faults and NE-trending folds that are collectively named the Last Chance thrust system. The Lemoigne thrust exposed on the west face of the Panamint Range belongs to this latter system. Might the Last Chance thrust system be the southern continuation of the Eureka belt or the hinterland-ward portion of the Sevier belt? We won't be able to answer this question until we have better constraints on the age intervals during which these belts were active, and until we can backstrip from this region the large (±100%) Cenozoic extensional deformation that has overprinted and greatly redistributed Mesozoic structures.

TALC CITY HILLS (OPTIONAL) STOP COMMENTARY

A geologic map of this field trip stop area is provided in Figure PO-6. We will trace out a portion of the Talc City thrust fault in order to appreciate its style and its folded nature. If you wish, you may sketch out what we observe on the topo map provided as Figure x.

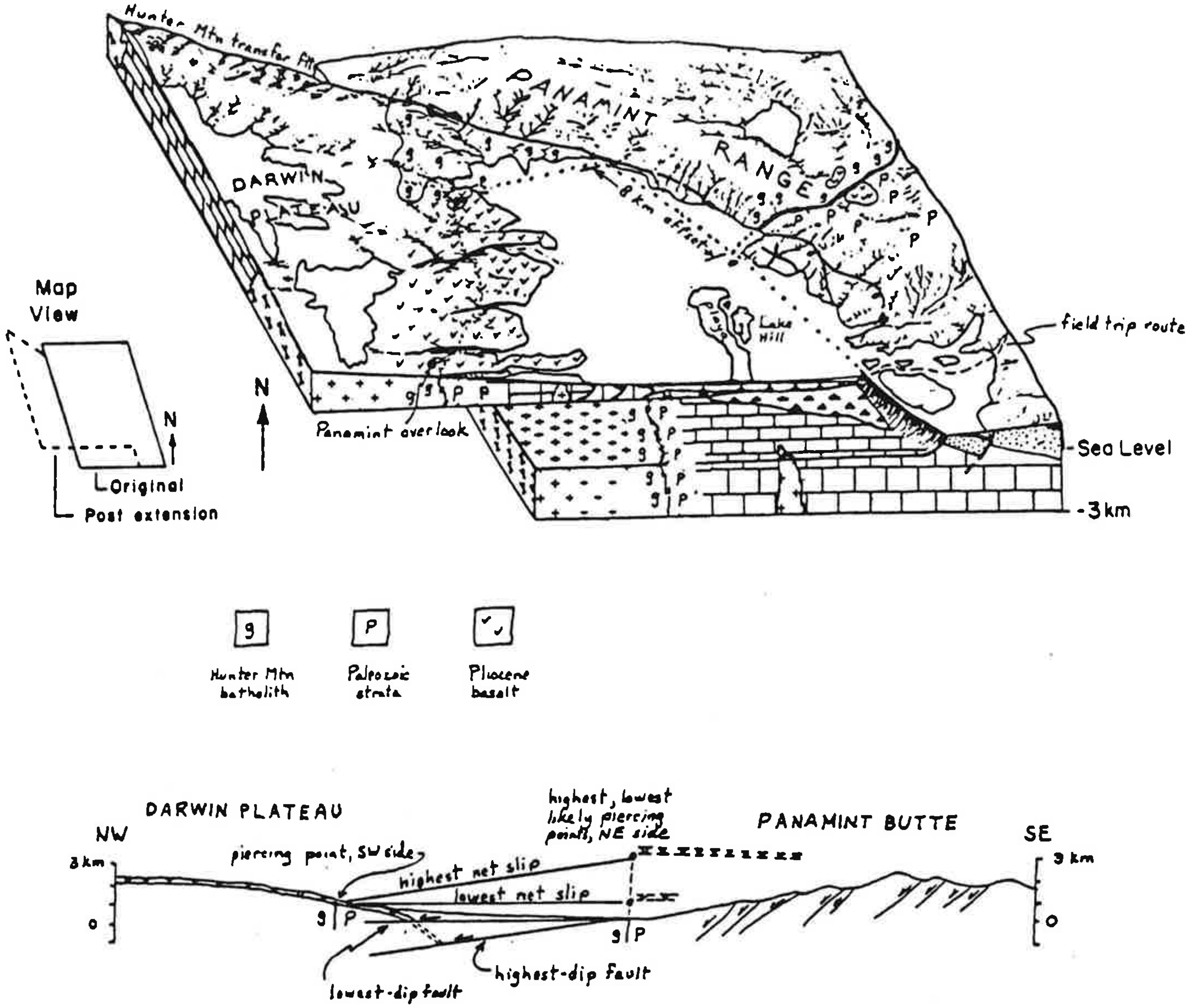


Figure PO-3. This two-part figure illustrates our present understanding of the extensional opening of northern Panamint Valley based on recent work by Clark Burchfiel and colleagues at MIT. The perspective block view shows the hanging wall of the Panamint Valley fault having been displaced obliquely down and northwestward from its in-place footwall. The fault is shown to be very gently dipping, based on drill hole data, several kinds of geophysical data, and on a classic structural geology construction that is illustrated in the cross section. The section is drawn parallel to the trace of the fault, and projected onto the section are the piercing points of a geologic line created by the intersection of the vertical granite/Paleozoic contact with overlying basalt. The two possible piercing points on the NE side of the fault reflect maximum uncertainty in projecting data into the cross section plane. Using either of these points yields a gently dipping fault, in agreement with geophysical data that indicate valley fill to be between 0.5 and 3 km thick with no basalt beneath it.

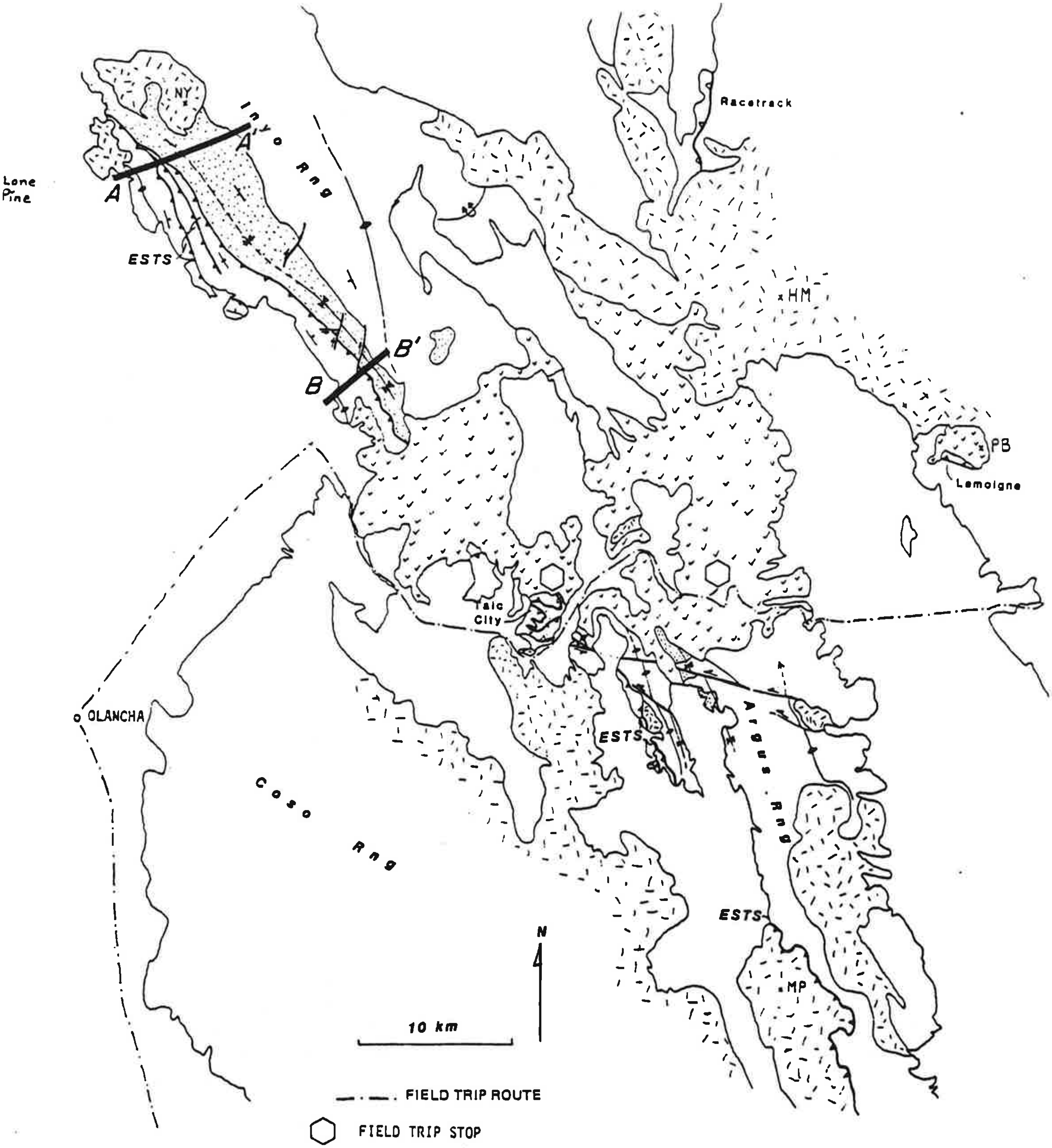


Figure PO-4. Principal compressional structures and rock units of Mesozoic age in the southern Inyo Range, Darwin area, Argus Range and Panamint Range. Prominent mountains visible from the field trip route include New York Butte (NY), Maturango Peak (MP), Hunter Mountain (HM), and Panamint Butte (PB). Triassic strata are stippled, Cenozoic volcanics have v pattern, granitoids have a random short line pattern and Paleozoic strata are unpatterned. Locations are shown for two cross sections of the west flank of southern Inyo Range that appear as figure

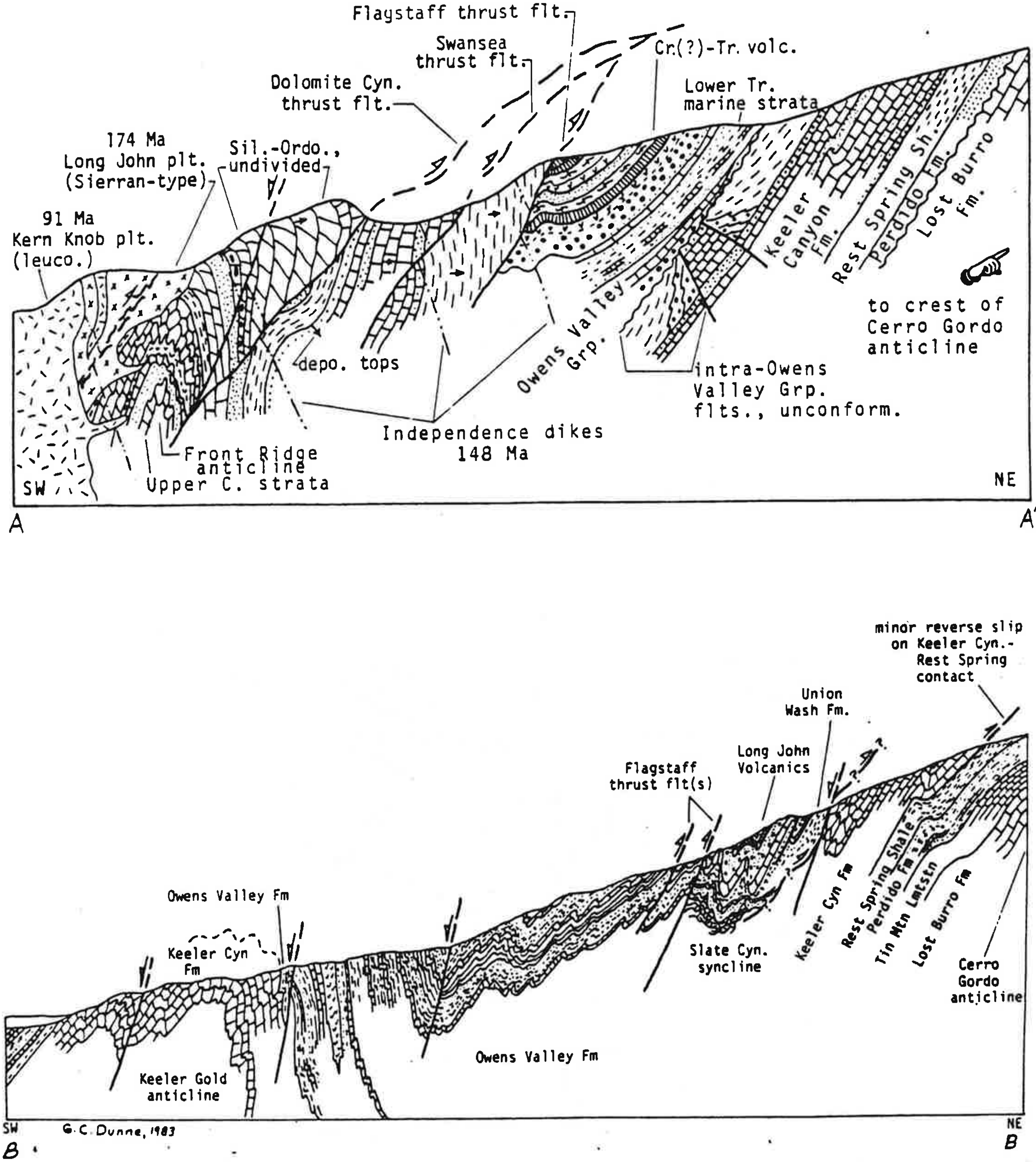


Figure PO-5 Schematic cross sections of the Mesozoic fold/thrust belt in the southern Inyo Range. Approximate locations of these two sections are shown in figure PO-4.

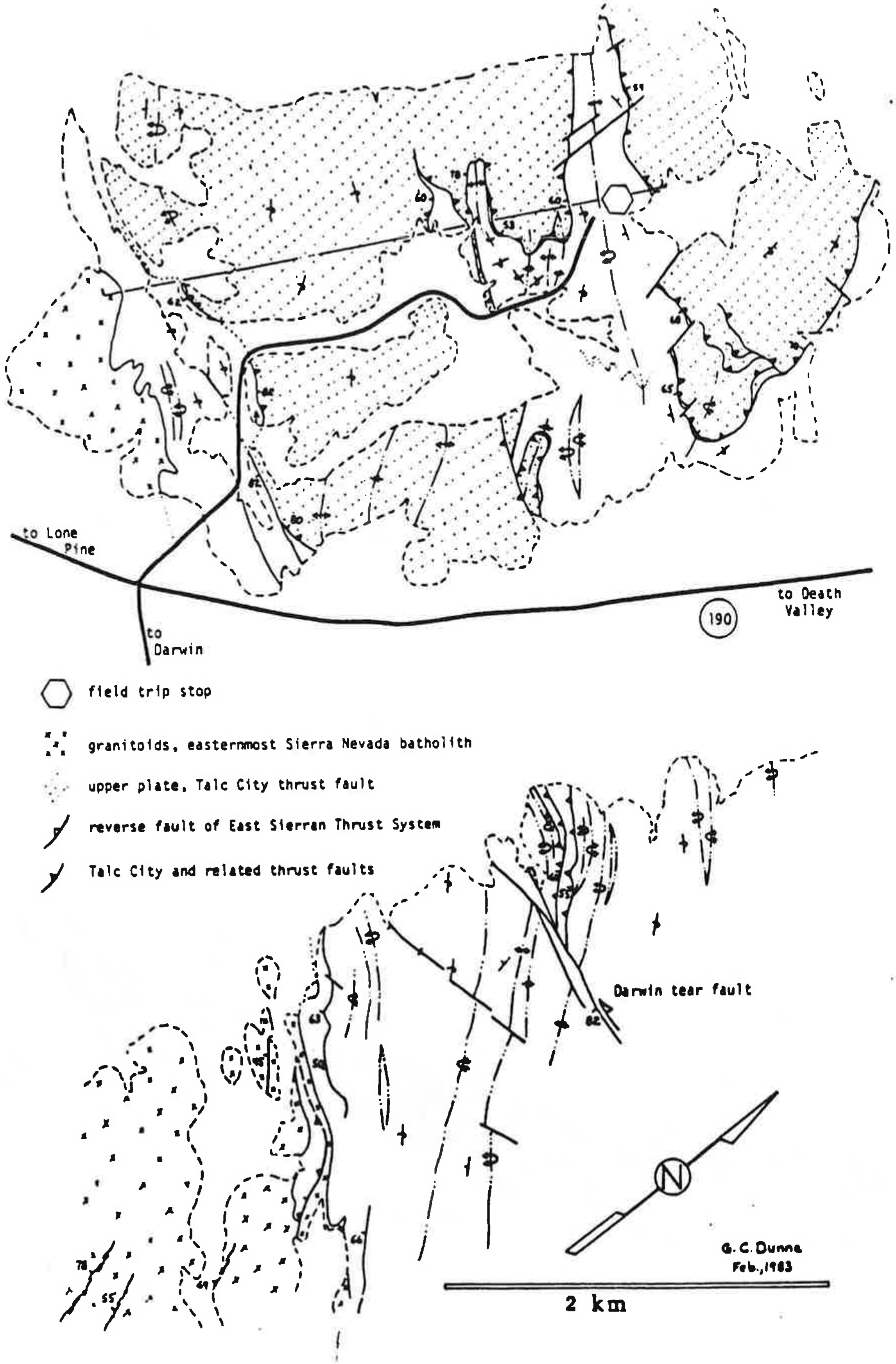


Fig. PO-6 . Structural sketch map of the Talc City Hills area.

Then we will walk over to the top of the hill to the NE in order to gain a view of one of the large folds that affects the Talc City thrust. This fold has a geometry characteristic of many of the large NW-trending folds in this region, namely a tendency 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.

TALC CITY TO OWENS LAKE LEG

This leg takes us through a portion of the Coso volcanic field, which here extends out of the Coso Mountains to the SW and buries the southern end of the Inyo Mountains beneath 5 Ma basalts. Interfingering with the volcanic field are pale gray exposures of the Coso Formation, a Mio-Pliocene unit of fluvial-lacustrine origin. Substantial changes in depositional environments of the Coso Formation at about 3.5 Ma are inferred to reflect the beginning of opening of the southern part of Owens Valley. Along this leg, the east margin of the Sierra Nevada batholith is clearly seen to swing eastward toward the Darwin Hills. Numerous NW-trending, SW-dipping reverse-slip shear zones cut this eastern portion of the batholith and locally thrust it eastward over its Paleozoic wallrocks.

SOUTHERN INYO MOUNTAINS / OWENS VALLEY COMMENTARY

We will stop along the range front in order to eyeball the west slope of the southern Inyo Mountains, where structures typical of the Mesozoic East Sierran thrust system are exposed. We will also discuss the Cenozoic extensional tectonics of this western margin the of the Basin and Range. A sketch map showing the extent of the East Sierran thrust system relative to our trip route was provided in Figure DV-1.

Turning to the Cenozoic geology of this area, 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 (Figs.PO-7, -8). An erosion surface beveled upon bedrock in the area of thickest valley fill lies at an elevation of -6,000 ft, whereas its counterpart on the crest of the Sierra lies at an elevation of approximately 13,000 ft. Much of this 19,000 ft of relief has developed during the past 2.5 to 3.0 Ma.

As an historic aside, Owens (dry) Lake had a (wet) surface area of 160 mi^2 and a depth averaging 20 ft at the turn of the century, down from a surface area of 240 mi^2 and depths of 330 ft 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, as well as of the Owens Valley floor which had been an oasis of irrigated farms, orchards

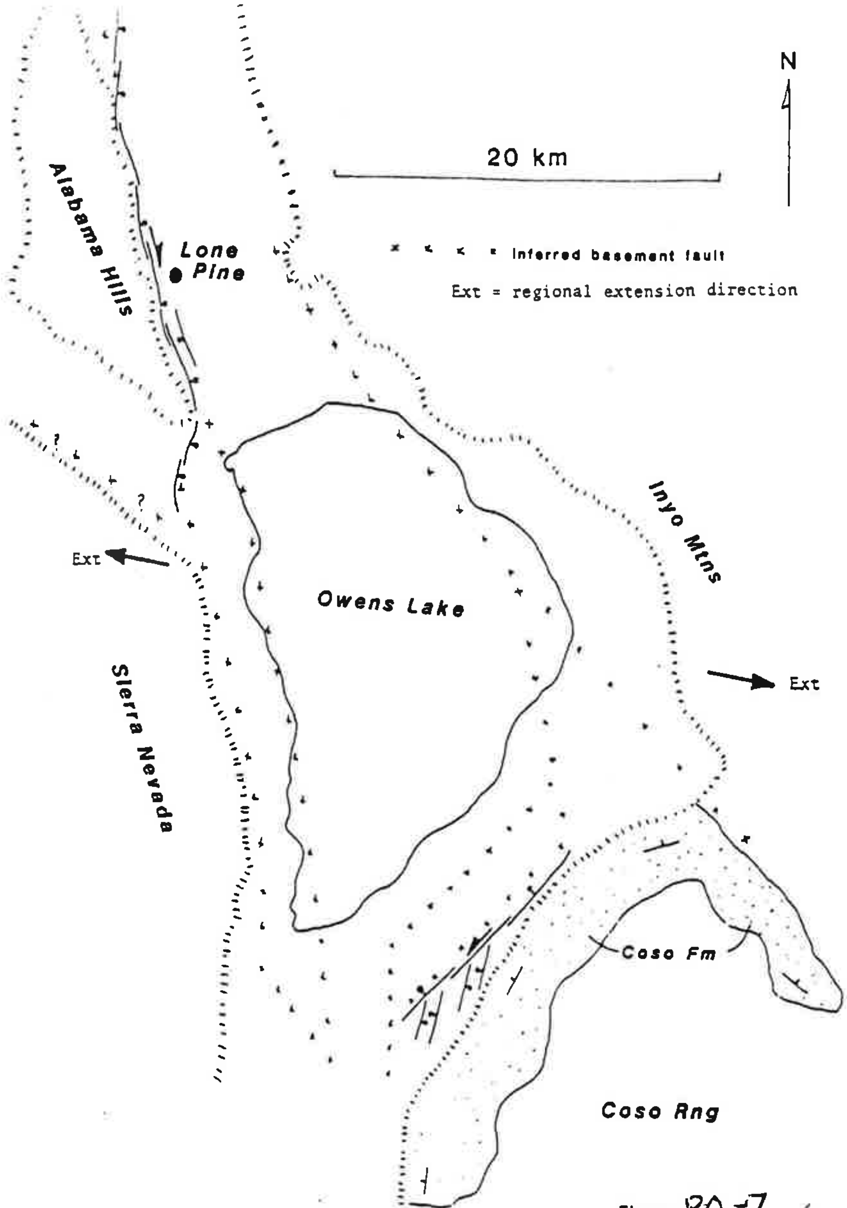


Figure PO-7

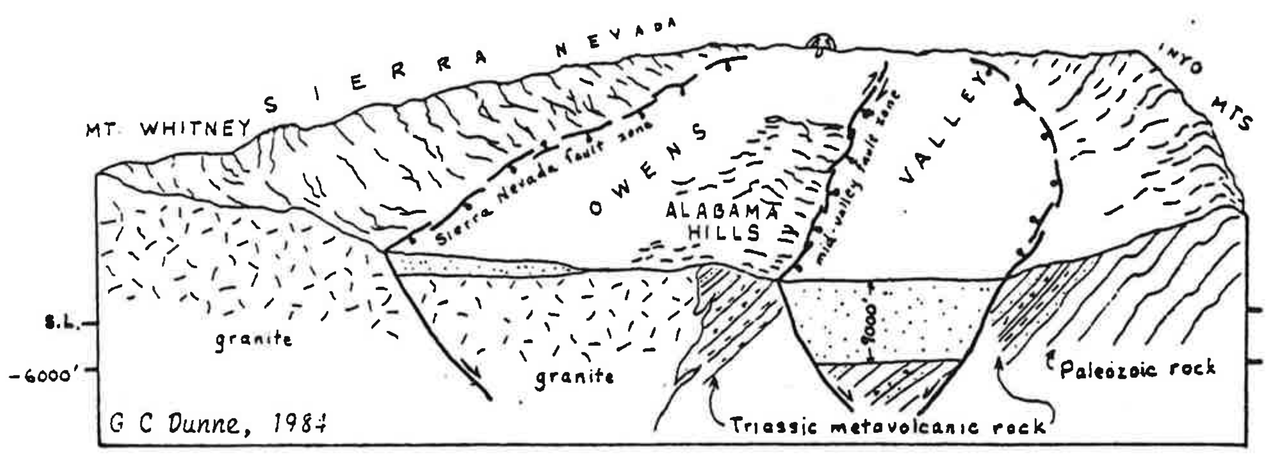


Figure PO-8. Diagrammatic cross section of Owens Valley and bounding ranges near the town of Lone Pine showing 'classic' basin-and-range structure. Redrawn from Von Huene and others, 1963.

and grassy rangelands.

The extensional neotectonics of the southern Owens Valley mimics that of the Coso Range to the south, past which we will travel shortly. Conjugate right- and left-oblique-slip faults seem to be a direct response to the regional tectonic extension direction). The major (M=8+) Lone Pine earthquake of 1872 caused as much as 6.5 m of right slip and 3.5 m of normal slip on the fault system fronting the Alabama Hills. Westward tilting of the hanging wall (Owens Valley floor) is suggested by relative uplift of the east shore of Owens Lake.

OWENS LAKE TO INDIAN WELLS VALLEY LEG COMMENTARY

Overview

This leg passes around a substantial part of the Coso Range, a high-standing block that separates Indian Wells Valley on the south from Owens Valley to the north. 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. PO-9). About 31 km^3 of volcanic rock were extruded prior to about 2.5 Ma., being composed of basalt, rhyodacite, dacite, andesite, and rhyolite in decreasing order of abundance. Beginning about 1.2 Ma, sub-equal amounts of basalt and rhyolite (so-called "bimodal" volcanism) have been extruded, totaling about 4 km^3 in volume. Rhyolite domes such as Sugar Loaf Mountain formed as recently as 77,000 years ago east of Rose Valley, and basalt flows were extruded from Volcano Peak as recently as 30,000 (±30,000!) years ago. Geophysical evidence suggests the presence of a magma body at mid-crustal depths below the rhyolite domes, and numerous hot springs exist among the domes. A geothermal power plant is now operating near one of these springs.

A coherent picture for effects of Basin-and Range tectonism in 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 and the resulting extension direction in eastern California for the past several million years. The averaged orientation of the principal extension direction has been sketched on Figure PO-9. 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 S_1-S_2 stress plane, have experienced primarily dip slip. Movements on these groups of faults have

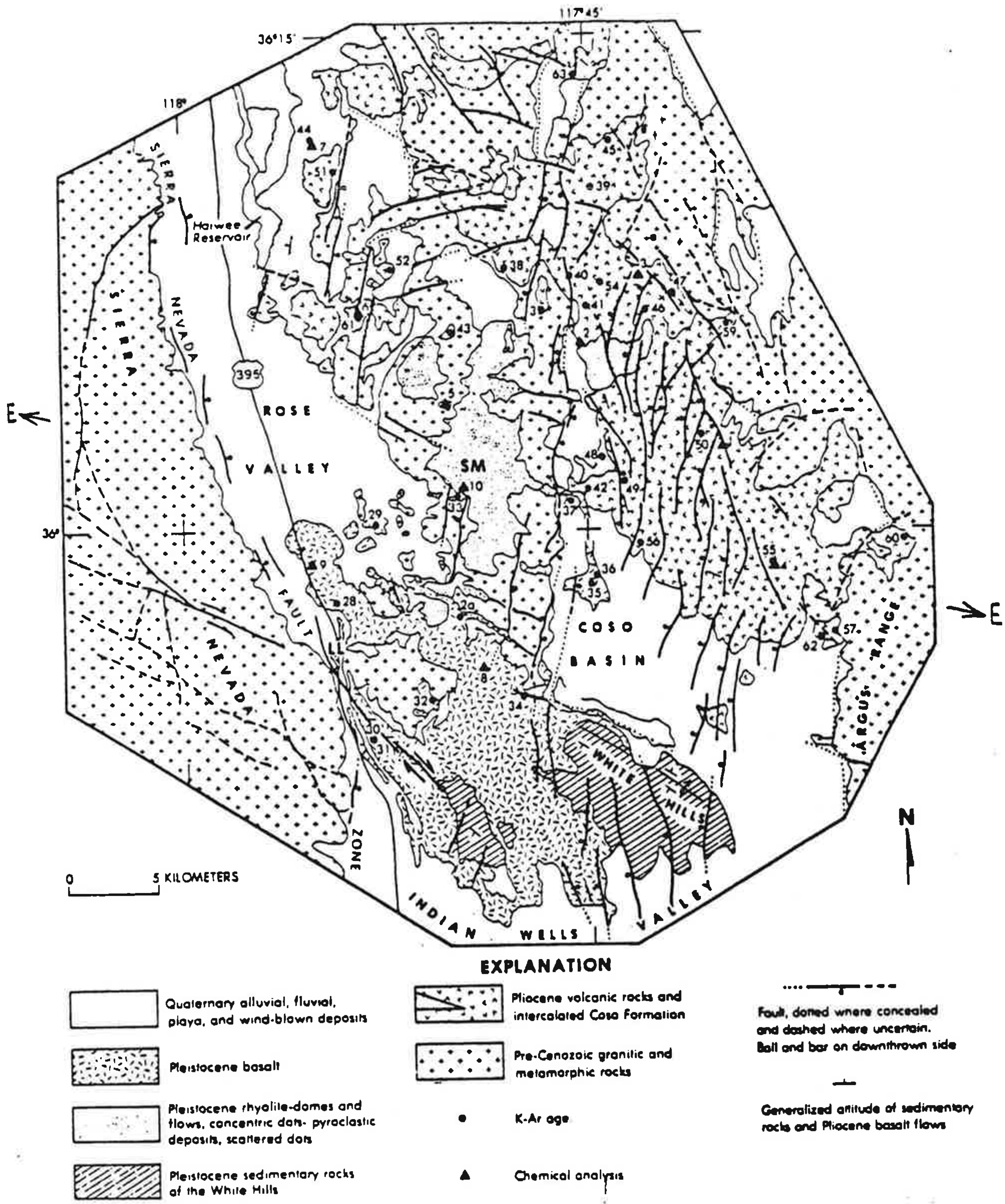


Figure PO-9. Geologic map of the Coso volcanic field, from Duffield and Bacon, 1980. Principle extension direction shown by arrows marked 'E' along sides. Two locations marked by capital letters LL and SM are Little Lake and Sugar Loaf Mountain respectively.

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 lava flow and cut a channel through it down into Indian Wells Valley. About 100,000 yrs. ago, a second flow spread westward until it reached the river channel, then moved southward along the channel at least 16 km, thoroughly blocking it. The impressive columnar basalt forming the east shore of the lake belongs to this flow. Finally, about 30,000 (±50%) yrs. ago, after the river had again established a channel across the second flow, a third eruption, centered at Red Hill sent a third and final flow into the channel. This, too, was quickly breached by the river, and a spectacular 60-ft-high waterfall ('dry falls' of Fig. NW-3) was created. Owens River continued to transport significant quantities of water into China Lake in Indian Wells Valley until about 10,000 yrs. ago. 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 3 km wide here. A large ancient landslide mass occurs high on the Sierran slopes above the notch.

Southward, beyond the Little Lake notch, we enter Indian Wells Valley.

INDIAN WELLS VALLEY/CANTIL VALLEY LEG COMMENTARY

Indian Wells Valley is bounded on the east by the south end of 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 and Spangler Hills lie to the south. Geophysical studies of Indian Wells Valley show it to be an irregularly shaped, fault-bounded graben. A maximum of 2000 m of valley fill rests on a gently west-tilted Pliocene(?) basement surface that lies about 1200 m below sea level. Remnants of the (presumably) same erosion surface are exposed at elevations of 2100 m to 2400 m in the Sierra Nevada west of Indian Wells Valley, attesting to vertical separation during Basin-and-Range tectonism of as much as 3300 m in this area, with high-standing blocks apparently moving absolutely upward while low-standing blocks moved absolutely downward.

At the south end of Indian Wells Valley our route climbs over a series of broad alluvial fans dipping gently eastward from the Sierra (note the large erosional "inselberg" of Cretaceous granitoid high on the fan just south of the Highway 178 turnoff), and then descends through exposures of the Miocene Ricardo Group toward Red Rock Canyon. As we pass Abbott Drive (to our right) , look to the right and note that the northwest-dipping strata of the Ricardo have been beveled by a smooth erosion surface (= "pediment") that is itself in turn now being destroyed by erosion. During Paleocene and Early Eocene time, strata of the Golar Formation were deposited in mixed continental and shallow marine environments in this area. Following uplift, tilting and erosion, the continental strata of the Ricardo Group were deposited unconformably on accommodated the WNW-directed tectonic extension of the Coso Range of about 10%. The relative abundance of NW-striking right- and right-normal-slip faults presumably reflect the 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.

The onset of extensional basin development in this area is recorded in the strata of the Coso Formation found immediately to the east of the Sierra. Sedimentologic studies of the Coso Formation, which fringes the Coso Range, suggest that it was deposited in a tectonically quiescent lacustrine/fluvial environment during Late Miocene and Early Pliocene time, then in a terrane of pronounced relief and/or rapid erosion beginning about 3.0 Ma. 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 Ma, with Owens Valley becoming a relatively down-dropped block near the end of this interval.

Travel Commentary

Moving south from the southwest corner of Owens Lake, the highway traverses a series of alluvial fans derived from the Sierra Nevada. These fans are still active, and debris flows periodically bury the highway. Note the large boulders that have been carried down these fans. The white bluffs on the east side of Haiwee Reservoir (at the base of the fans) are lake-bed deposits of the Coso Formation.

As we drop down into the north end of Rose Valley, an erosional gap (Haiwee notch) can be seen east of the highway.. This notch was cut by the glacial Owens River. The headwall scarp of a large landslide developed 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 glacial Owens River.

As we traverse southward across Rose Valley, we can look eastward and readily observe the numerous rhyolite domes capping the Coso Range. The geothermal powerplant noted earlier lies just behind the largest dome.

After passing the prominent red cinder cone (Red Hill) that lies just east of the highway, we drop down and through the Little Lake notch, a passageway between the Sierra Nevada and the Coso Range. Basalt flows from the Coso Mountains volcanic field filled the Little Lake notch three times, at least once causing a temporary lake to form in Rose Valley, just north of Little Lake. The first blockage occurred when the Lower Little Lake Ranch flow, originating from a vent SE of Little Lake, moved southward through the notch and spread out across the NW corner of Indian Wells Valley about 440,000 yrs. ago.

the Golar. It is the Ricardo strata that form the castellated outcrops exposed on either side of the highway. The dark ledge-forming basalt flow marks the approximate middle of the Ricardo Group, and underlying it (downcanyon) note the massive pink rhyolite tuff layer. Alternating basic and felsic eruptions constitute what is called "bimodal" volcanism, a common phenomenon in regions of extension. The Ricardo Group ranges in age from late early Miocene to late Miocene, and it consists of at least two formations, that have a composite thickness of at least 1.75 km.

The lowest and last outcrops in Redrock Canyon itself consist of much-altered granitoids of Late Permian or Early Triassic age. As we leave the canyon and head south into the northwest corner of the Mojave Desert, we rejoin our route of the first day, put our brains on auto-pilot, and head home.

The End