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OWENS VALLEY TO THE PANAMINTS
LANDS OF ILLUSION

GEORGE DUNNE & JON SLOAN PRESENT

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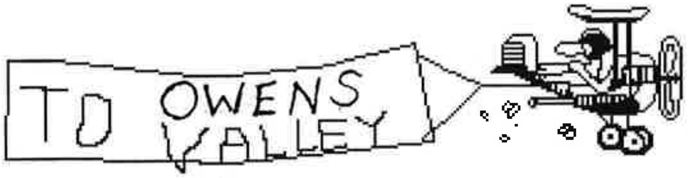


STRATIGRAPIC OVERVIEW, EASTERN CALIFORNIA
(consult Figs. 1 ->5)

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 l.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 l.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 (Fig. 5) 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. 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 5. 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. Central and western parts of the Sierra Nevada remained mostly below sea level (perhaps studded with volcanic islands), whereas terrestrial depositional environments prevailed eastward into southern Nevada (Fig.6). A northwest-trending volcanic arc developed, and it 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 in the latter half of the Mesozoic.

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.

STRUCTURAL OVERVIEW, EASTERN CALIFORNIA

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 over coeval shelfal (miogeoclinal) strata. The siliceous detritus shed eastward from this uplifted orogenic belt (Rest Spring Shale) 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 Mesozoic contractional deformation 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. Excellent examples are exposed in the southern Inyo Mountains and adjacent Darwin Plateau (Figs. 7, 8). During this same interval the Sierra Nevada batholith was emplaced as hundreds of individual plutons, outlying examples of which invaded pre-Cenozoic country rock in ranges east of Owens Valley. Hundreds of dikes belonging to the Independence dike swarm were also emplaced during the Mesozoic (Fig. 9). Both compressional deformation and intrusive activity are genetically linked to an east-dipping subduction zone that operated beneath eastern California throughout much of Mesozoic time (Fig. 10). 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. 11).

Cenozoic:

Cutting these older contractile structures is a group of younger structures developed during extensional (Basin-and-Range) tectonism in late Cenozoic time. The Owens Valley is the westernmost valley within the Basin and Range province (Fig. 12). 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. 13). 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 6), the coastal subduction zone evolved into 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 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/Las Vegas region 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. Figures 14a and 14b provide schematic maps of this region today and as it looked about 15 Ma just before extension began. Gently dipping normal detachment faults—interpreted by earlier workers as strange thrust faults—played a key role in accommodating this large amount of extension and also help explane the origin of geologic features called "metamorphic core complexes". A model picturing how these gently dipping normal detachment faults might evolve, and how they might be related to some core complexes is given in Figure 15.

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.

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, 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.

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 1800s 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 pullapart basin on the Garlock fault (Figs. 16, 17). 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. 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 Late Cretaceous and early Cenozoic time, when subduction was occurring at a low dip angle (Fig. 11).

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. These oceanic strata are vastly out of place, and they may have been brought to their present position by major left-lateral strike-slip faulting from an original location in westernmost Nevada (Fig. 18). Recent work has revealed that several roof pendants in the southern Sierra Nevada contain similar kinds of eugeoclinal strata (Fig. 19).

NORTHWEST MOJAVE TO FOSSIL FALLS

From our northwest Mojave stop, we head north across the Garlock fault, which is not exposed where it crosses beneath the highway. The Garlock is a major left-slip fault having approximately 60 km of slip that separates two major crustal blocks: the Mojave Desert block to the south and the eastern California Basin-and-Range block to the north (Figs. 16, 17). The Garlock is interpreted to be of late Cenozoic age and to be an accommodation structure that allowed the two blocks on either side to extend and rotate differently. The Garlock fault continues to be active today, but no major historic earthquakes have occurred along it.

As we enter Redrock Canyon, we cross the El Paso fault, traces of which can best be seen in outcrops just east of the highway. This fault has experienced predominantly up-down (dip-slip) motion. The first outcrops in Redrock Canyon itself consist of much-altered granitoids of Late Permian or Early Triassic age. As we leave the canyon and head north, we immediately enter the beautiful castellated exposures of the Ricardo Group. It accumulated in various fluvial and lacustrian environments. 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.

Moving north from the Ricardo exposures, we pass Abbott Drive (to our left); look to the left 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. Northward from Abbott Drive, 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.

Beyond the Highway 178 turnoff, we skirt the west side of. Indian Wells Valley. This

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 2100m to 2400m 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 northwest end of Indian Wells Valley, the highway heads for the Little Lake "notch" separating the Sierra Nevada to the west from the Coso Range to the east. These have come from the Coso Range volcanic field (Fig. 20). On the skyline east of the highway is Volcano Peak, a Pleistocene basalt cone from which very young looking lava flows originate. These flows are probably no more than 30,000 years old. The Little Lake notch was carved by the south-flowing ancestral (=glacial) Owens River, which drained a vast region extending northward to the Mono Lake basin until about 9,000 years ago. Figure 21 shows this river system and the pluvial lakes to which it was related.

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 impressive cliffs flanking the east side of the highway south of Little Lake were cut in this basalt as the ancestal Owens River finally overtopped the lava flow and cut a channel through it down into Indian Wells Valley. About l00,000 yrs. ago, a second flow spread westward until it reached the river channel, then moved southward along the channel at least l6 km, thoroughly blocking it. The impressive columnar basalt forming the east shore of Little 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 was created. These now dry falls will be our next stop.

A Geologic Aside: Geology of the Coso 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. 20). About 31 km3 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 20. 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 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.

BACK TO THE ROADLOG

As the highway starts the gentle climb up toward Little Lake, 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.

Just beyond the tiny settlement of Little Lake is Little Lake itself, a natural lake that is an important stop of the Pacific Flyway. Little Lake marks the south end of Rose Valley. A prominent red cinder cone (Red Hill) on line with the highway should now be coming into view. We will turn east on Fossil Falls Road just before getting to this cinder cone, and hike to a dry water fall that was located on the ancestral Owens River.

Continuing northward across Rose Valley following our Fossil Falls stop, we can look eastward and readily observe the numerous rhyolite domes capping the Coso Range. These sit atop a magma chamber located several kilometers below the surface. A geothermal powerplant that makes use of the heated rock above this magma chamber is located just behind (east of) the largest dome.

Looking west, we can spot several scarps of faults that facilitated the uplift of the Sierra Nevada. Some lie right at the base of the main escarpment, whereas others are closer to the highway and commonly are marked by green vegetation.

At the northwest end of Rose Valley, the highway begins a gentle climb up a series of alluvial fans derived from the Sierra Nevada. To the east of the highway you will note an erosional gap (Haiwee notch). 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. Just north of the slide we see pale-colored bluffs on the east side of Haiwee Reservoir (at the base of the alluvial fans). Thes bluffs are lake-bed deposits of the Coso Formation of Miocene and Pliocene age. These alluvial fans are still active, and debris flows periodically bury the highway. Note the large boulders that have been carried down these fans.

Just north of Haiwee Reservoir, we descend gently into the south end of Owens Valley, an extensional basin of late Cenozoic age (Fig. 22).

The remainder of Day 1 will be spent in vicinity of Owens Lake, with a number of possible stops to be decided by student interests.

DAY TWO

OWENS VALLEY / INYO MOUNTAINS COMMENTARY

We will stop along the range front 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.

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 (Fig. 22). 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 approximatly 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 l9l3 led to rapid desiccation of the lake, as well as of the Owens Valley floor which had been an oasis of irrigated farms, orchards 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 l872 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 VALLEY TO PANAMINT VALLEY ROADLOG

This leg first 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. These are part of the East Sierran thrust system. The highway climbs gently onto the Darwin Plateau, which is transected by the East Sierran thrust system (Figs. 7, 23). 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° - 80° 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°E. that is manifested both by elongation lineations and by Hansen analysis of asymmetric

folds found in partially to thoroughly transposed rock adjacent to the faults.

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 8.

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.

FATHER CROWLEY STOP

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. Figures 24, 25, 26, and 27 will be utilized at this stop. To benefit from this stop, review the following geologic background material before we arrive there.

Cenozoic Rock Units

The Cenozoic depositional history of the Death Valley/Panamint Valley area extends back to the Oligocene (Fig. 28). The Titus Canyon Fm., the oldest Cenozoic unit in Death Valley, 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.

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 Ma. The Timber Mountain and Bullfrog centers spread rhyolite air-fall and ash-flow tuff over much of northeast 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.

During middle and late Miocene time (l4 -> 5 Ma) 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 north) 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. Volcanic rocks from the two volcanic centers previously mentioned periodically spilled into these basins. 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 l000 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 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 l80 m before drying up about ll,000 yrs ago (Fig.21). 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/l000 yrs.

The effects of Cenozoic extensional tectonism are spectacularly displayed in this area. A major, west-dipping extensional detachment fault 'daylights' at the west base of the Spring Mountains, and all of the ranges westward 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. Review Figure 15.

FATHER CROWLEY POINT TO WILDROSE CANYON COMMENTARY

Heading downhill from Father Crowley Point, we pass through late Cenozoic basalt flows and cinder cones, alternating with exposures of Permian miogeoclinal strata. Late Paleozoic strata form the north end of the Argus Range located south of the highway. Numerous dark dikes cutting these strata are part of the Late Jurassic Independence dike swarm. At the bottom of the grade, we pass through Middle Jurassic granitic rocks as we cross the wash draining Darwin Canyon, shortly before reaching Panamint Springs. Low hills to the north side of the highway just east of Panmint Springs are eroded remnants of a fan delta complex that built up at the margin of Lake Panamint at the mouth of Darwin Canyon.

In Panamint Valley we encounter several Cenozoic extensional structures including: l) 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. 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.

Near the middle of the Valley we turn south on Panamint Valley Road and follow it to the junction of Wildrose Road, where we turn left, and begin our climb up the alluvial fan toward the Panamint Range. As we approach the front of the Panamint Range, we pass through a 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 (north Panamint fault) that has uplifted the range; this is the other side of the graben. About 1 km upcanyon from the rangefront, we pass through the conjoined Towne Pass and Emigrant detachment faults which separate hanging wall Nova Fanglomerate from MUCH older, MUCH more metamorphosed strata of the late Precambrian Pahrump Group. We'll slow and/or stop to see if we can find this contact. 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 turning northward from 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 'klippen'. Hills west of the road expose the Nova Formation. It 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 Formation accumulated in this basin as the basin continued to widen via extensional faulting. Again review Figure 15.

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

extensional collapse of Owens, Panamint and Death Valley during the last 3 or 4 million years.

From the paved road crossing the flat, we turn eastward and follow the dirt road to Aguereberry Flat. We pass through the south "tail" of the Skidoo pluton, a Late Cretaceous leucocratic pluton that may be a crustal melt. The western contact of the pluton against rocks of the late Precambrian Kingston Peak and Noonday Formations is the west-dippingEmigrant detachment fault., whereas the eastern contact is igneous. Just east of the eastern pluton contact, we cross the trace of the older Harrisburg detachment fault which places slivers of east-dipping Noonday and Johnnie onto Kingston Peak rocks. We continue eastward upsection in the upper plate Johnnie, then Stirling and Wood Canyon strata, ending up at the point in the Early Cambrian Zabriskie Quartzite A sketchmap and cross section of the geology along the ridge north of our dirt road is provided on a following page. A wonderful expression of Cenozoic extensional tectonism is seen in the family of detachment faults exposed at Tucki Mountain. 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 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 (Figs. 29, 30, and 31). 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.

AGUEREBERRY POINT TO TOWNE PASS TO PANAMINT VALLEY

After getting a regional eyeful at the point, we return to the paved road. Traveling northward from Harrisburg Flats, we drop into Emigrant Canyon, and soon enter the pale gray exposures of the main body of the peraluminous two-mica Skidoo pluton. The northern contact against Nova Formation is the Emigrant detachment fault. The

remaining exposures between here and the intersection with Highway 190 are of Nova Formation fanglomerate containing scattered lenses of landslide breccia (gray, and resistant), lakebeds (pale gray, thin bedded limestone), and basalt flows. We will turn uphill (west) at the junction and head over Towne Pass.

As we 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.

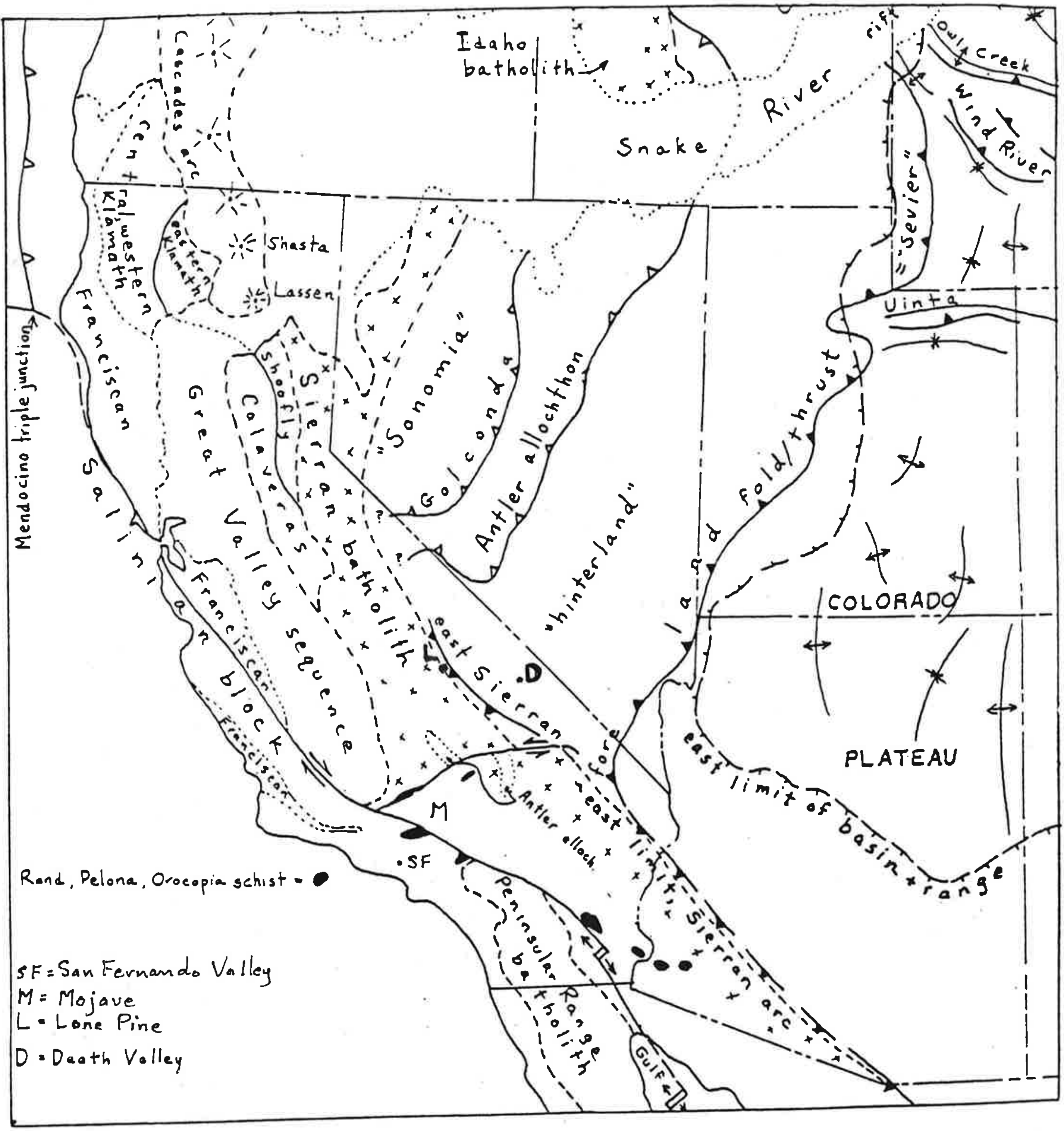
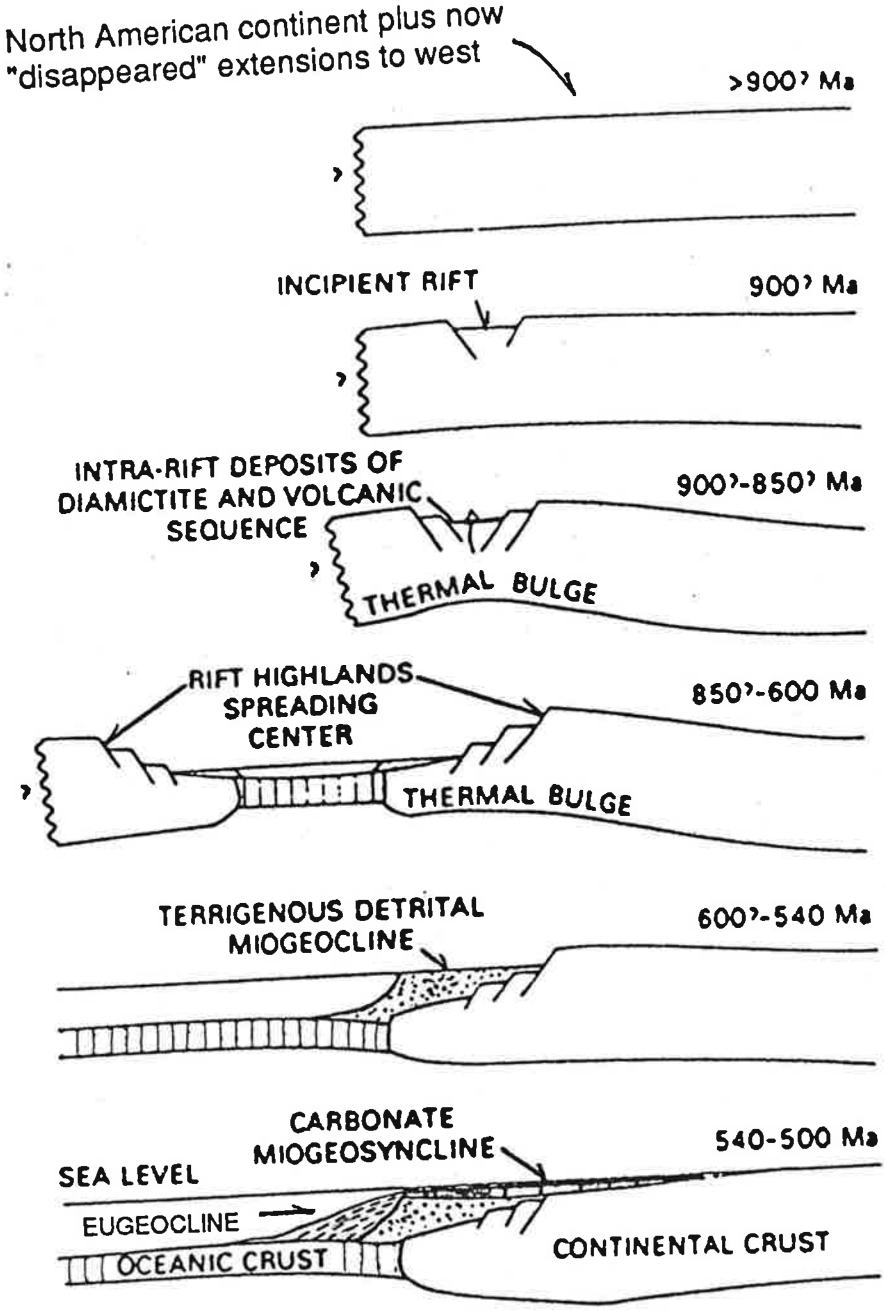


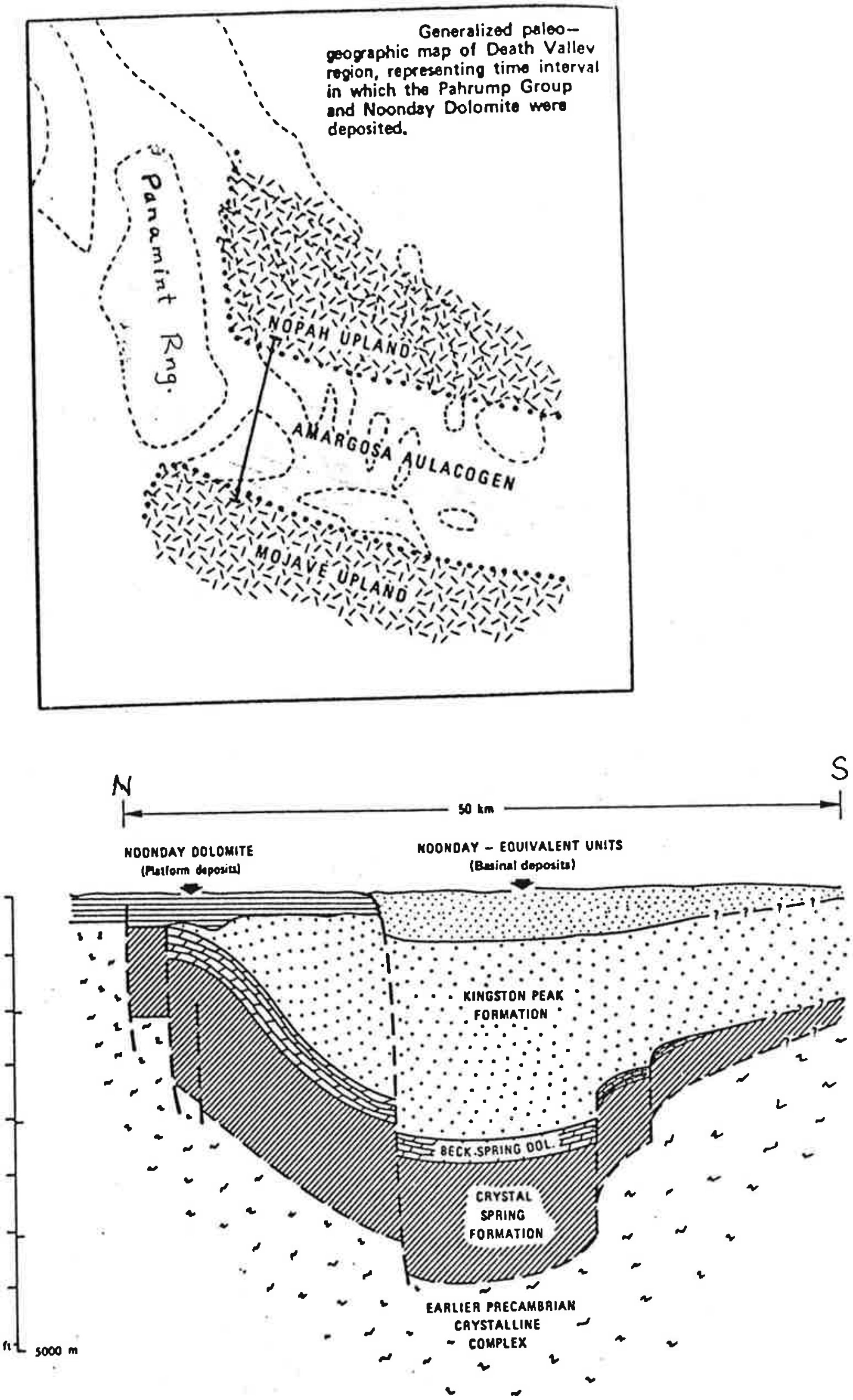
Figure 1. Sketchmap of major tectonostratigraphic 'entities' in the southwestern U.S. Cordillera. Note that the route between Bakersfield and Zion passes through or near a substantial number of these 'entities which range from the relatively stable Colorado Plateau to the very mobile, suspect terrane-rich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



North American continent plus now "disappeared" extensions to west

newly created western continental margin for North America

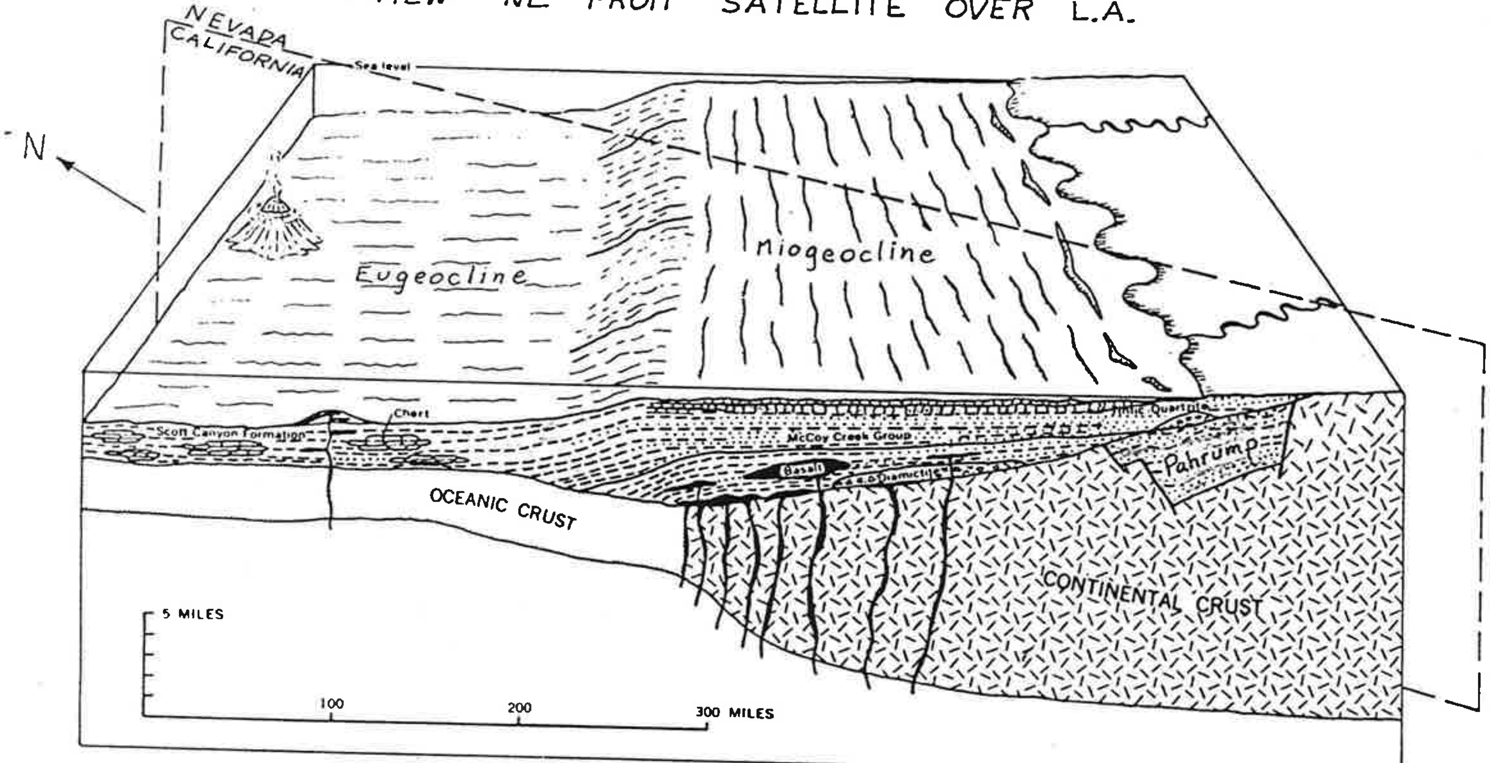
Figure 2.



Generalized paleogeographic map of Death Valley region, representing time interval in which the Pahrump Group and Noonday Dolomite were deposited.

Figure 3.

VIEW NE FROM SATELLITE OVER L.A.



Diagrammatic cross section showing upper Precambrian and Lower Cambrian rocks in the northern Great Basin, Nevada and Utah.

Figure 4.

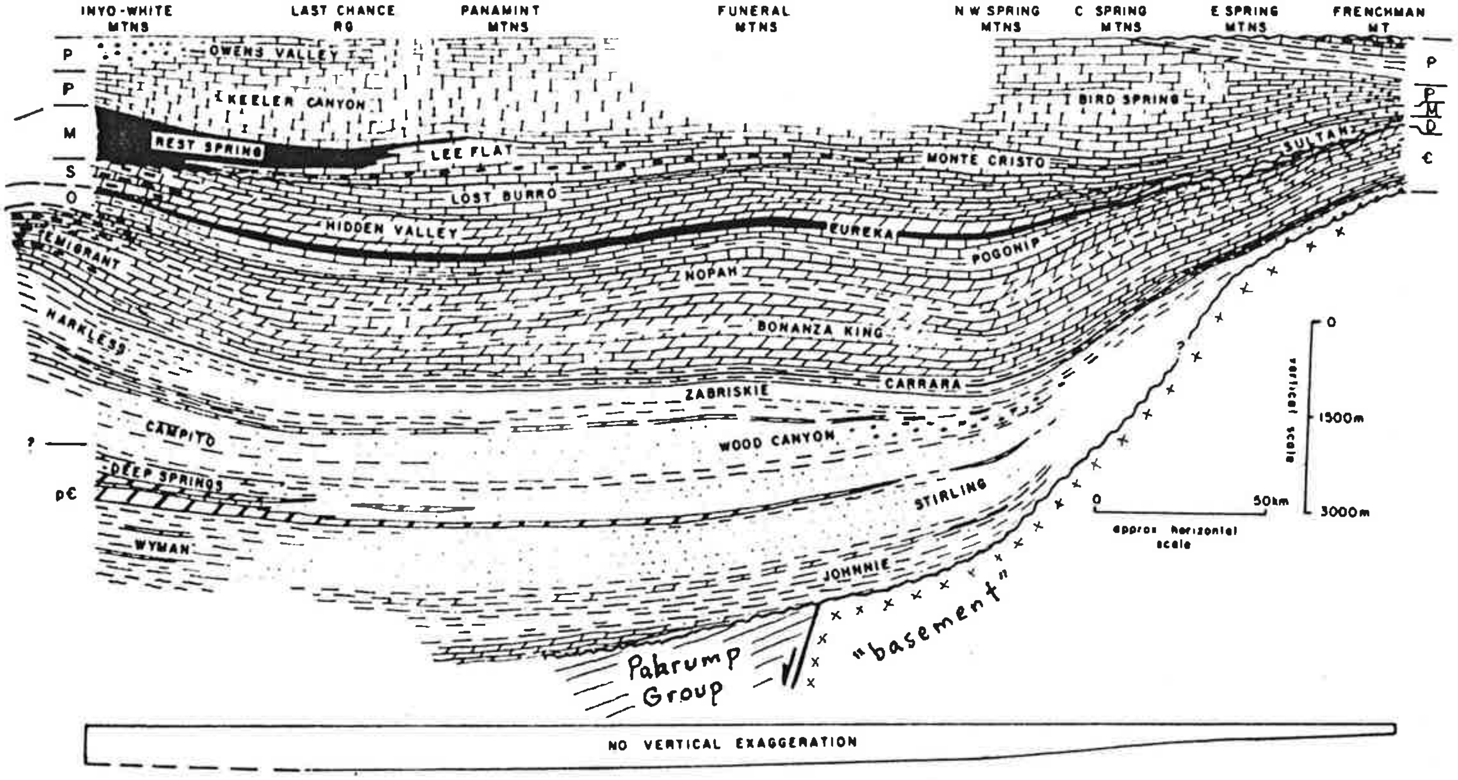


Figure 5. Schematic stratigraphic cross section from vicinity of Las V Vegas (Frenchman Mtn.) to White-Inyo Ranges. This wedge-like sequence is the Cordilleran miogeocline, bounded to the east by the 'craton' (sections like that at Frenchman Mtn. and the Grand Canyon) and grading westward into the "eugeocline', which represents continental slope and rise strata.

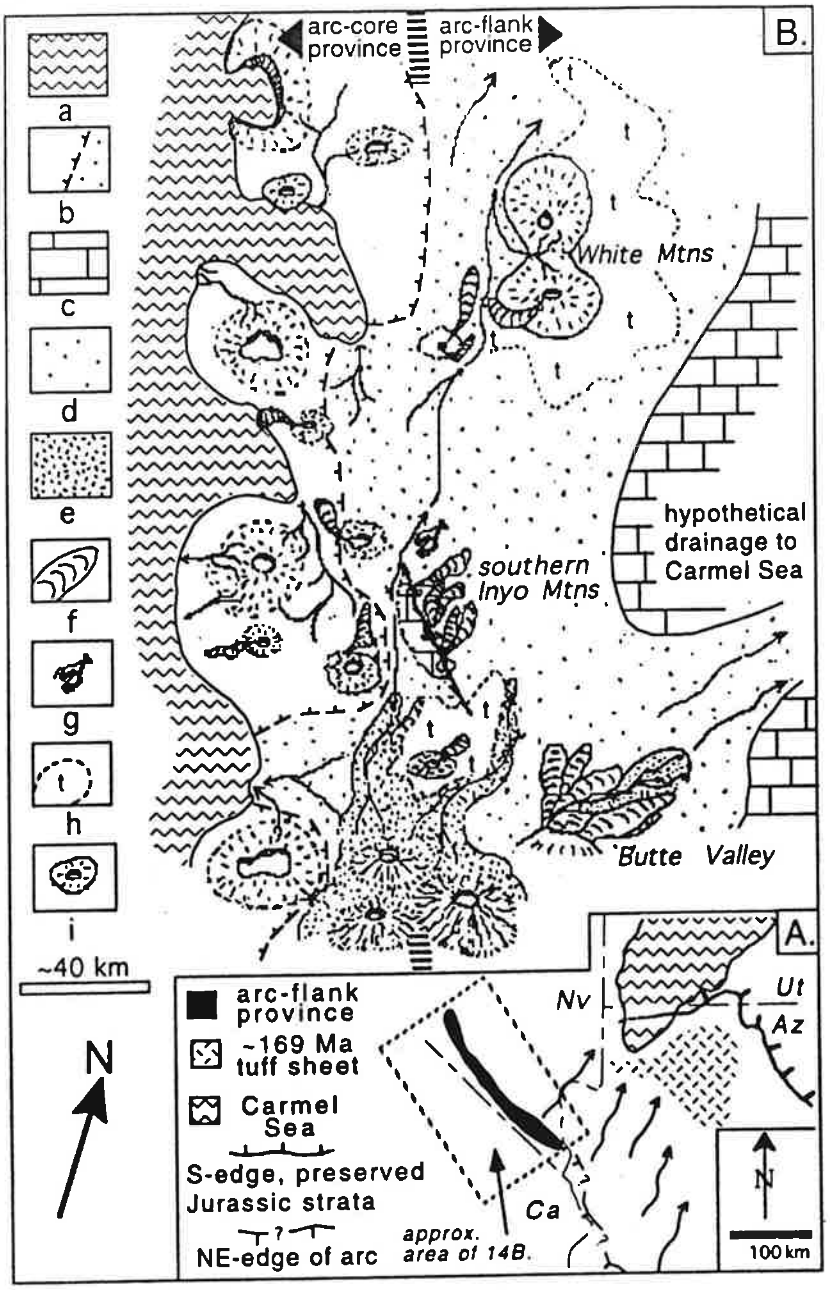


FIG. 6 Schematic paleogeography of Middle to Late Jurassic volcanic provinces . A. Middle Jurassic regional setting, showing positions of arc-flank province and northeastern edge of arc as palinspastically restored for Mesozoic contraction and Cenozoic extension by Marzolf (1994). Features in northwestern Arizona and southwestern Utah are from Blakey and Parnell (1995). B. Middle to Late Jurassic paleogeography of arc-core and arc-flank provinces in east-central California. Elements depicted in arc-core province are best documented for Middle Jurassic time; elements of arc-flank province are documented for both Middle and Late Jurassic time. Legend: a = marine environments; b = fluctuating inland edge of periodically inundated coastal plain (unpatterned) covered mostly by slightly reworked ash and minor epiclastic sediment; c = pre-arc strata; d = predominantly epiclastic sediments accumulating in fluvial settings; e = alluvial-fan complexes; f = mafic to intermediate lava flows; g = felsic lava flows; h = ash-flow tuff sheets; i = volcanic edifices.

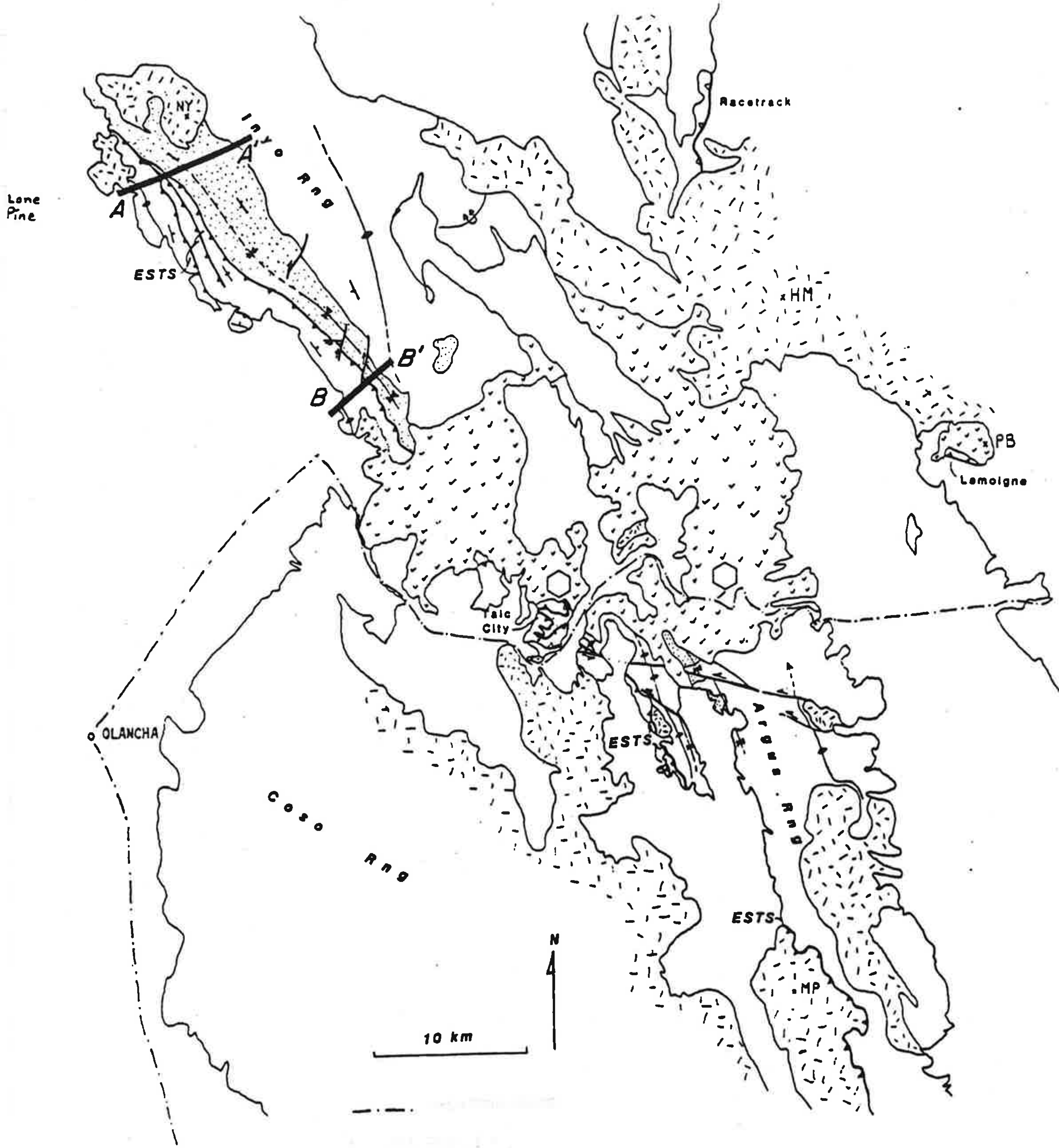


Figure 7. Principal compressional structures and rock units of Mesozoic age in the southern Inyo Range, Darwin area, Argus Range and Panamint Range. Prominent mountains visible from the field trip route include New York Butte (NY), Maturango Peak (MP), Hunter Mountain (HM), and Panamint Butte (PB). Triassic 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 8.

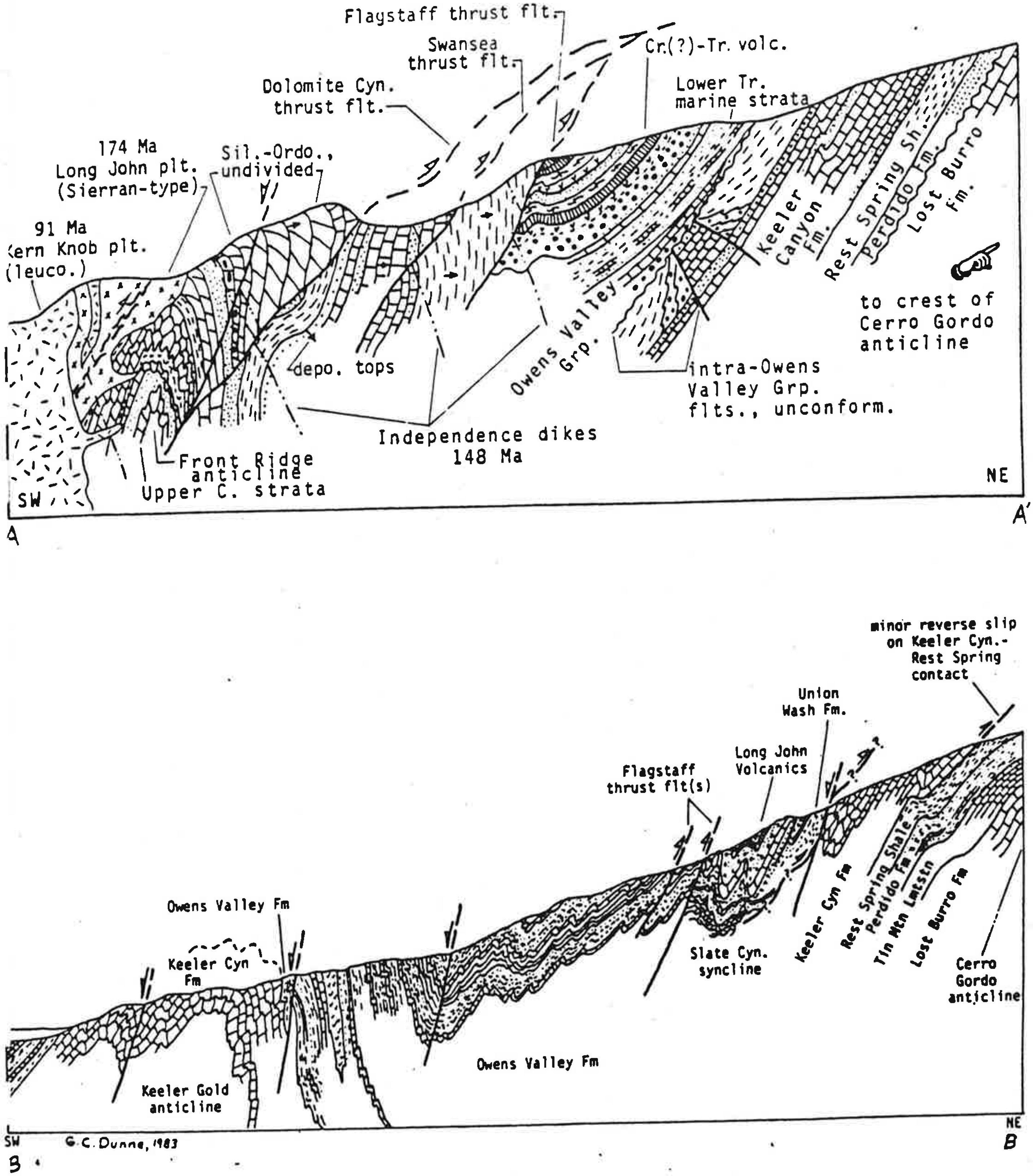


Figure 8 Schematic cross sections of the Mesozoic fold/thrust belt in the southern Inyo Range. Approximate locations of these two sections are shown in figure 7.

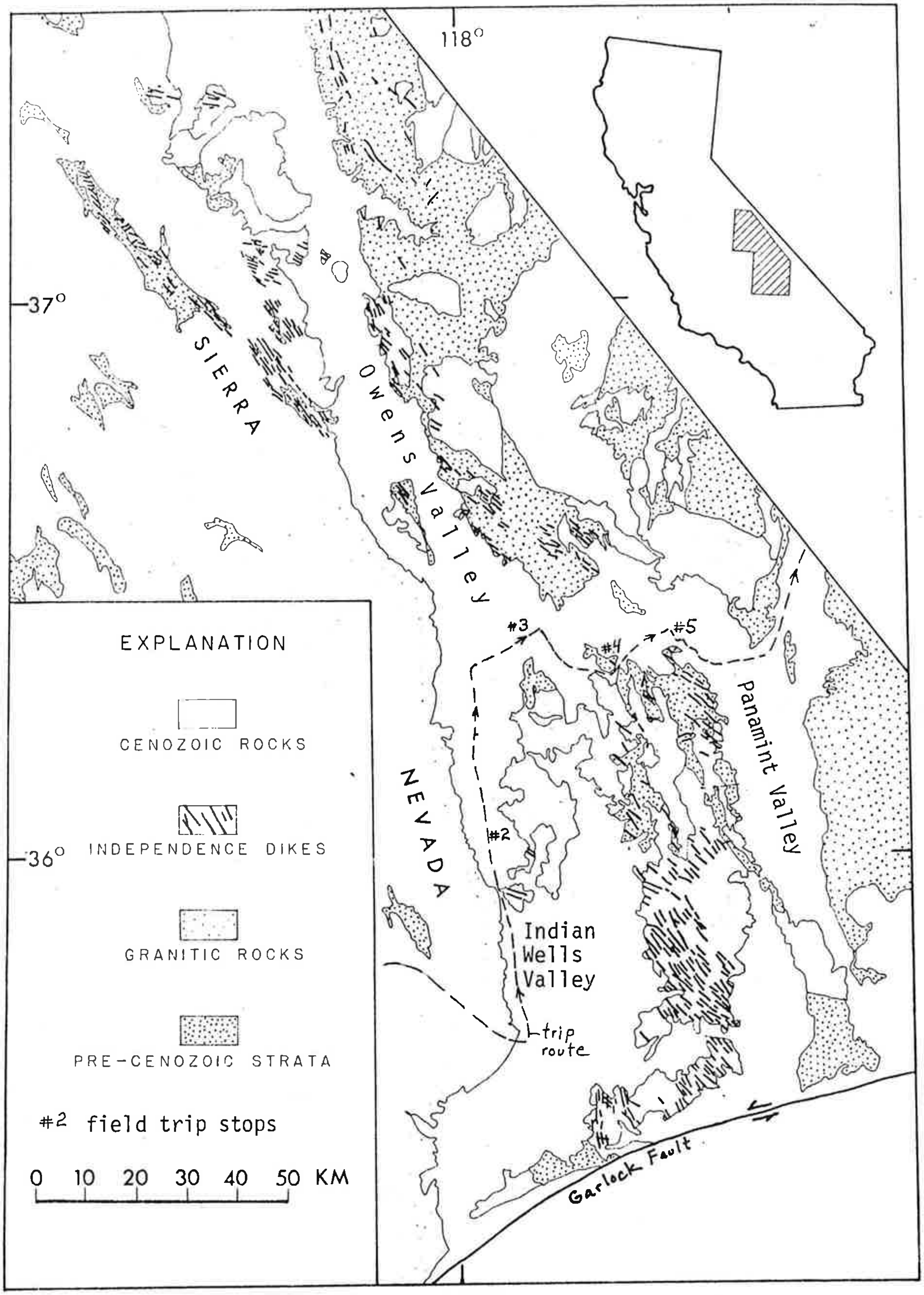
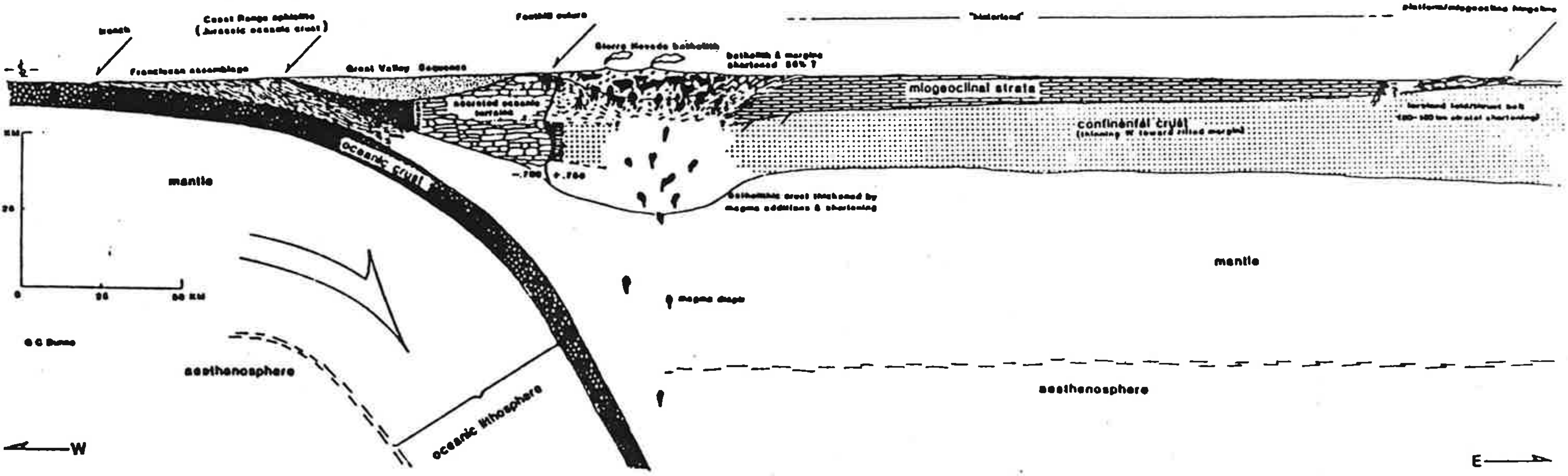


Figure 9. Generalized geologic map showing Independence dike swarm (148 m.y.b.p.) north of the Garlock fault (after Chen and Moore, 1979).

Figure 10 Schematic cross section depicting pre-Laramide plate tectonic setting.



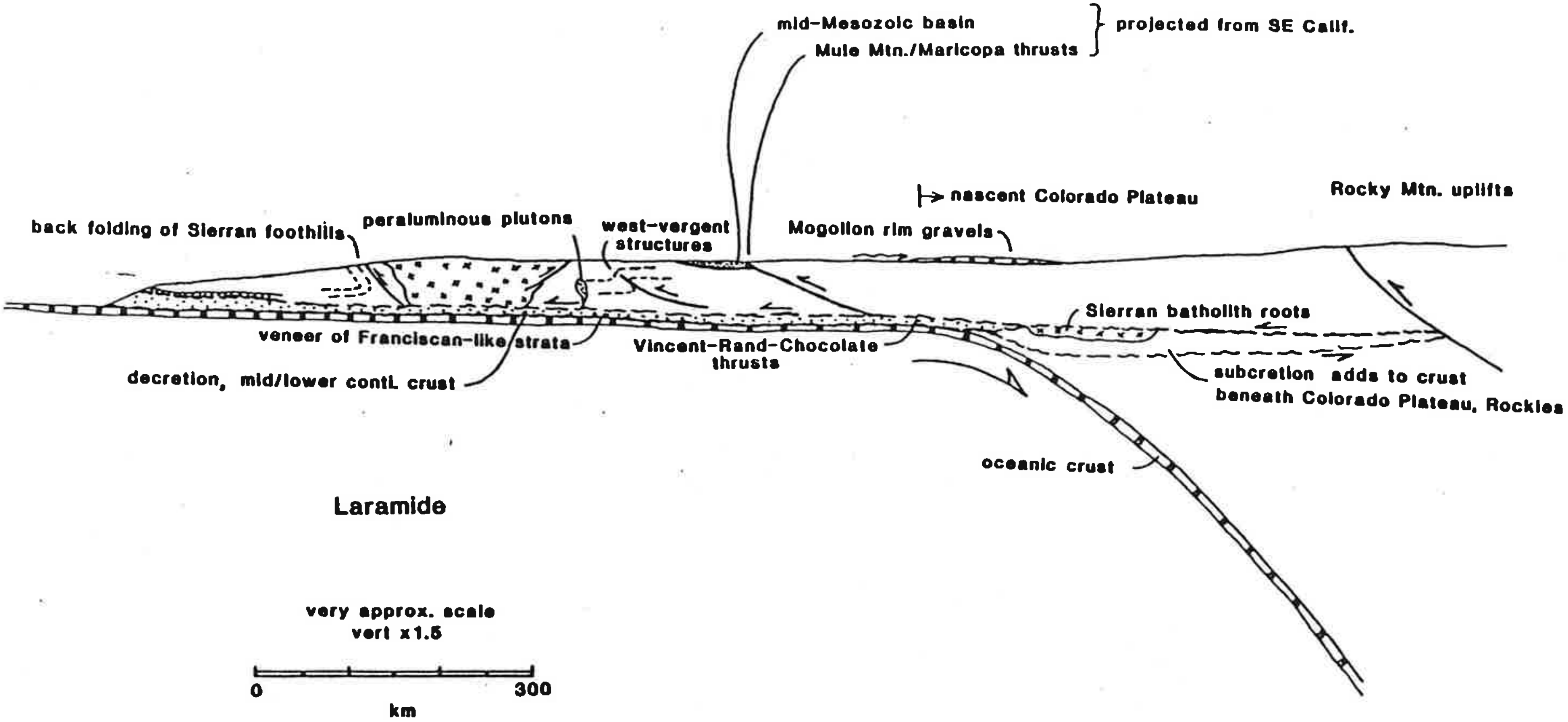


Fig. 11 . A plate tectonic scenario for the Laramide orogeny (from ideas of Stan Keith, Peter Bird).

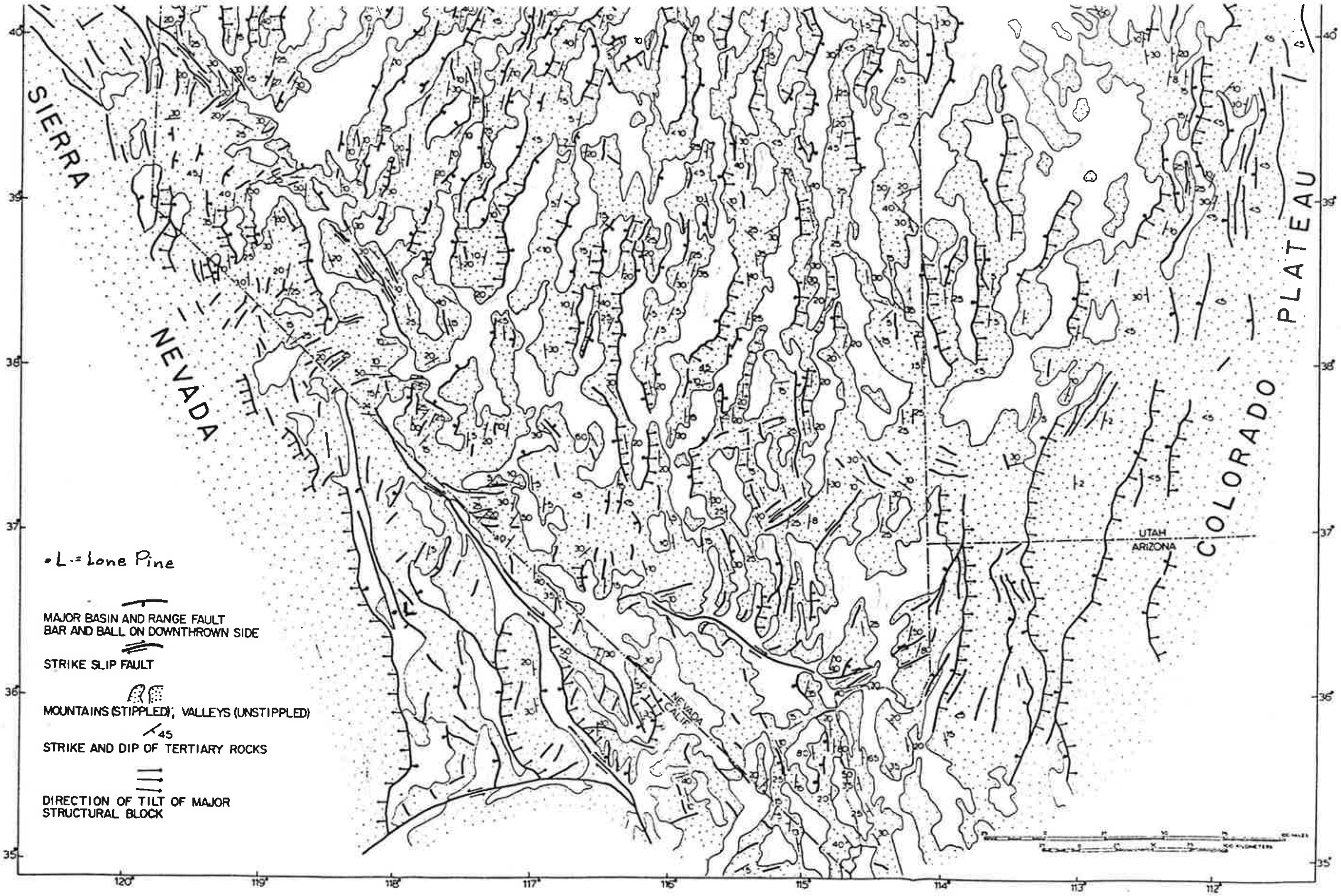

SIERRA NEVADA
COLORADO PLATEAU
UTAH
ARIZONA
NEVADA
CALIF.
• L = Lone Pine
MAJOR BASIN AND RANGE FAULT
BAR AND BALL ON DOWNTHROWN SIDE
STRIKE SLIP FAULT
MOUNTAINS (STIPPLED); VALLEYS (UNSTIPPLED)
45
STRIKE AND DIP OF TERTIARY ROCKS
DIRECTION OF TILT OF MAJOR STRUCTURAL BLOCK
40°
39°
38°
37°
36°
35°
120°
119°
118°
117°
116°
115°
114°
113°
112°

Figure 12.

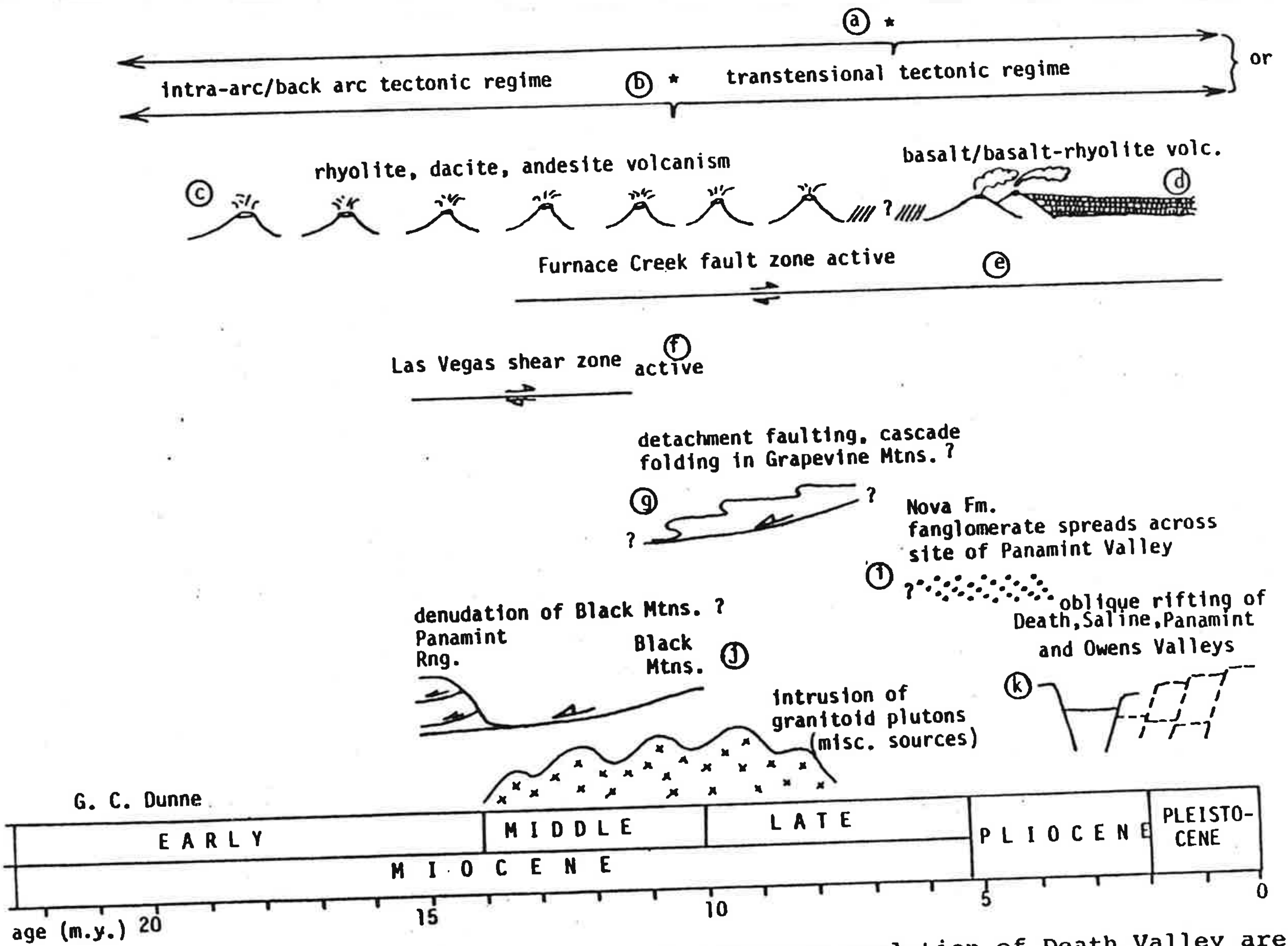


Figure 13 Schematic time/event chart for Neogene evolution of Death Valley area. The symbol * represents the interval during which Mendocino triple junction moved north along the coast past latitude of Death Valley, causing switch from back-arc extensional regime to transform-influenced extension (oblique rifting). Circled letters denote literature sources not cited here.

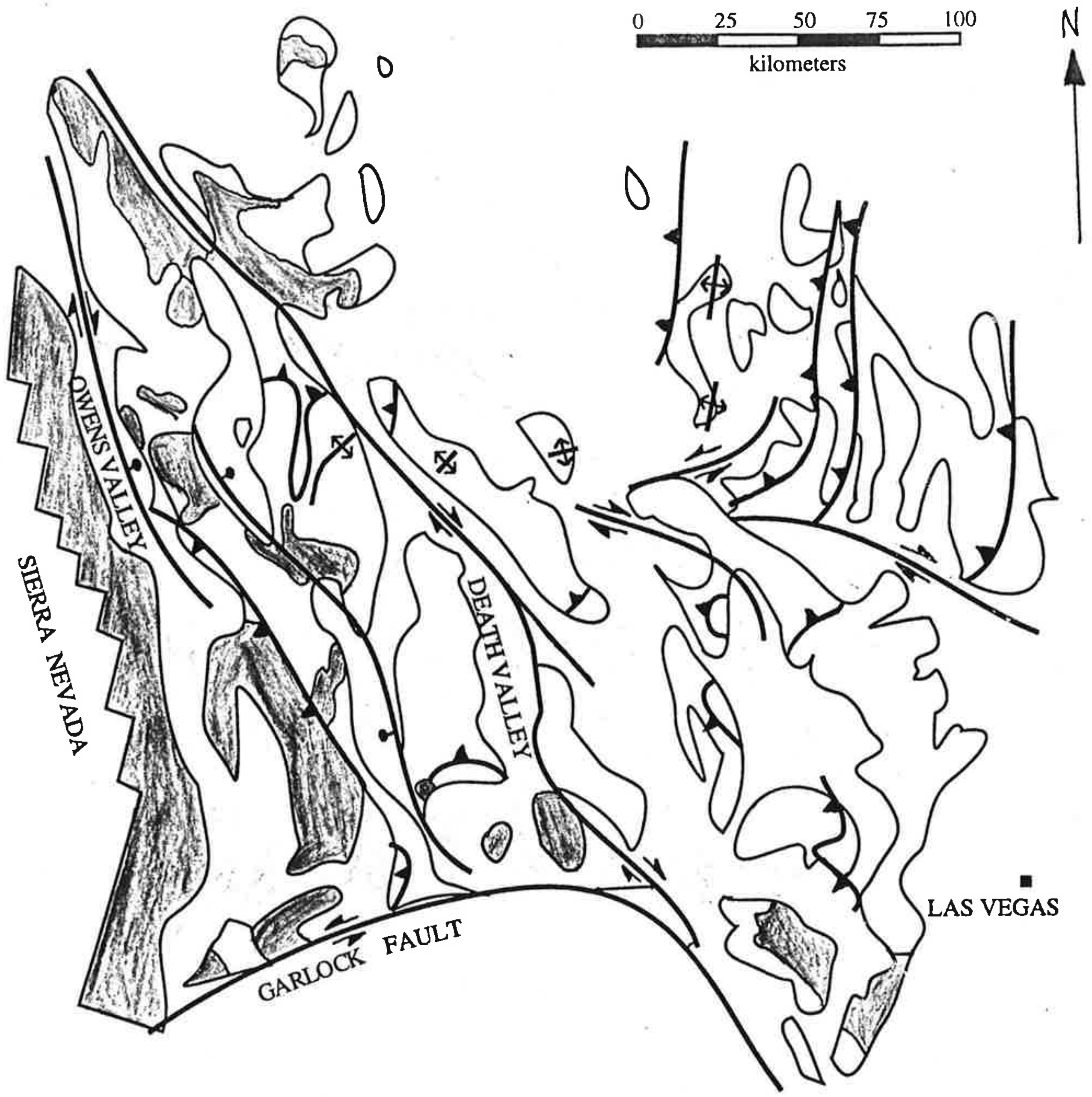

0
25
50
75
100
kilometers
N
OWENS VALLEY
SIERRA NEVADA
DEATH VALLEY
GARLOCK FAULT
LAS VEGAS

Figure 14a.

At ~15 Ma

Figure 14b.

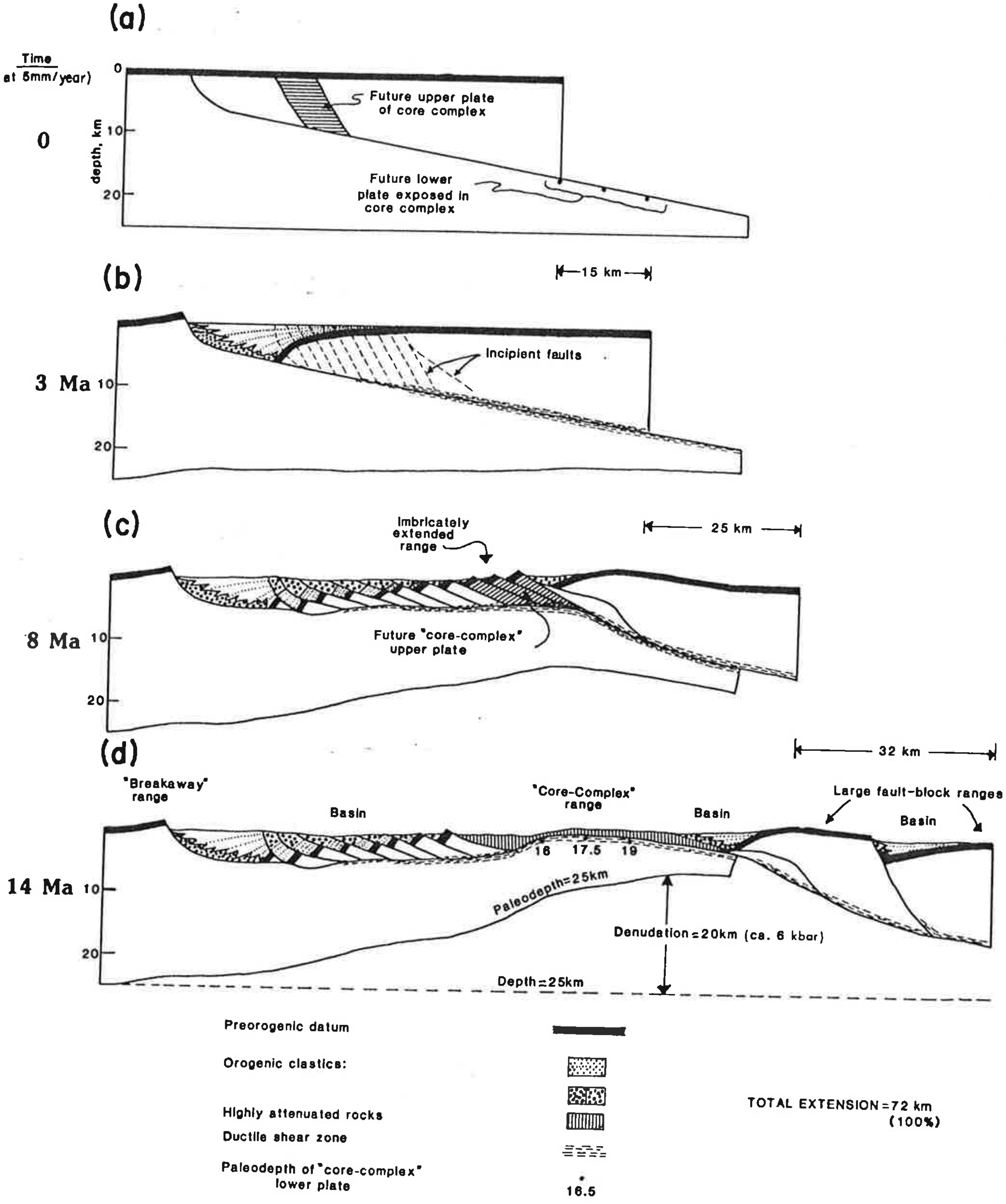

(a)
Time
at 5mm/year)
0
depth, km
0
10
20
Future upper plate of core complex
Future lower plate exposed in core complex
(b)
15 km
3 Ma
10
20
Incipient faults
(c)
Imbricately extended range
25 km
8 Ma
10
20
Future "core-complex" upper plate
(d)
32 km
"Breakaway" range
Basin
"Core-Complex" range
Basin
Large fault-block ranges
Basin
16
17.5
19
14 Ma
10
20
Paleodepth=25km
Denudation≈20km (ca. 6 kbar)
Depth≈25km
Preorogenic datum
Orogenic clastics:
Highly attenuated rocks
Ductile shear zone
Paleodepth of "core-complex" lower plate
16.5
TOTAL EXTENSION=72 km (100%)

Figure 15.

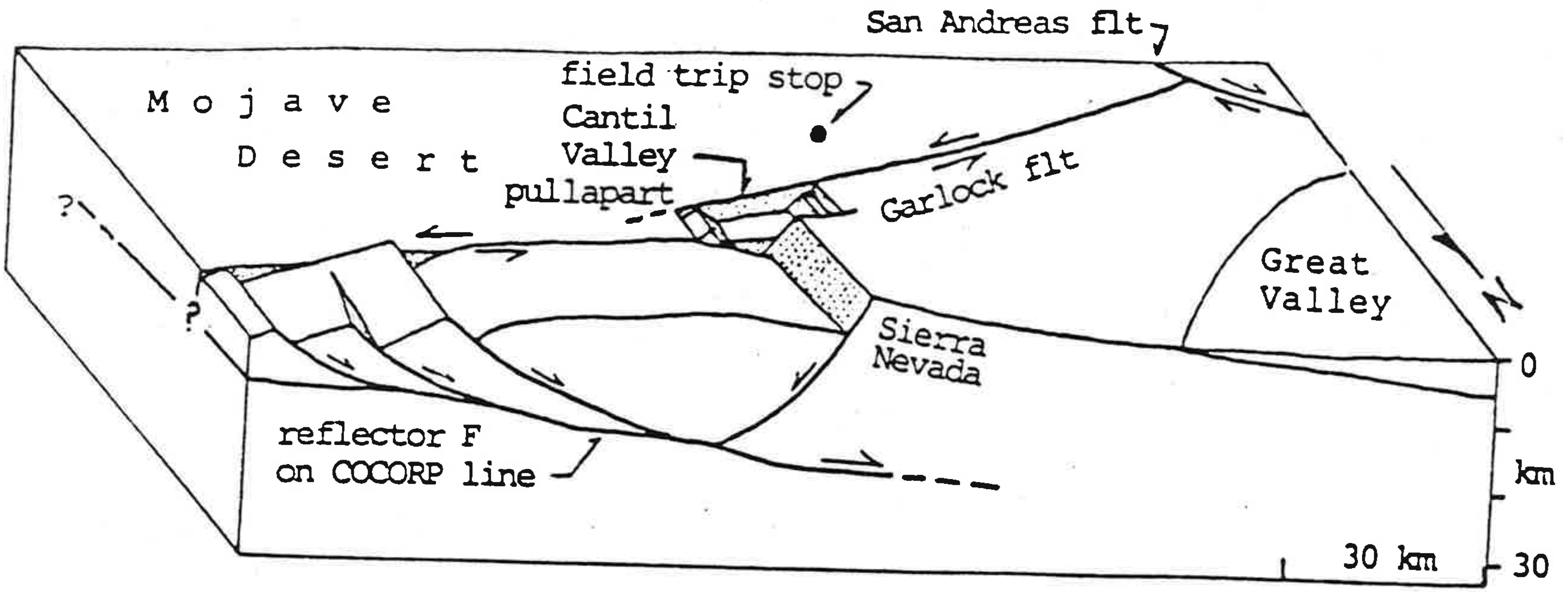
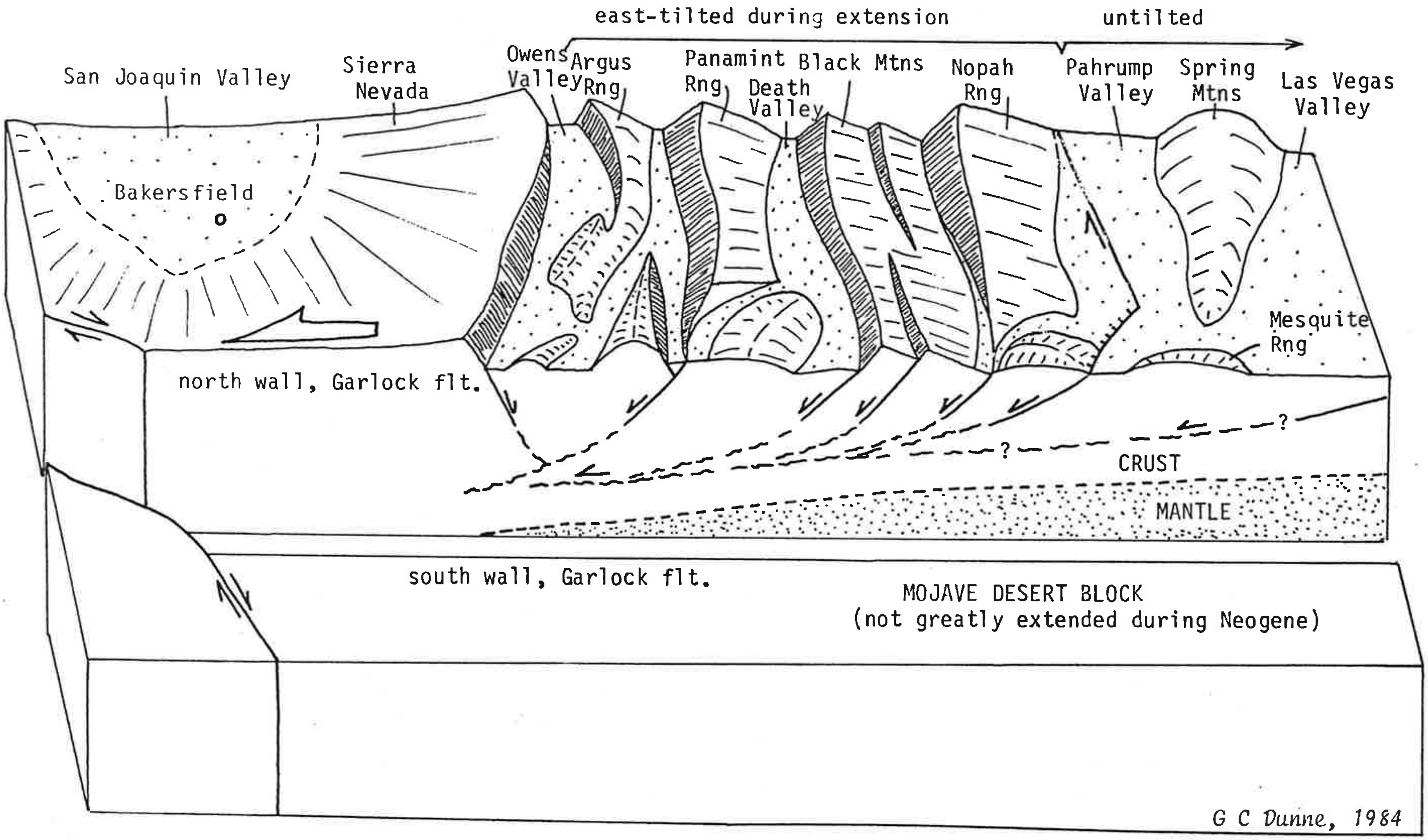


Figure 16 Southward view of Garlock fault and Cantil Valley.



G C Dunne, 1984

Figure 17. Exploded block diagram of Garlock fault and region to north depicting the Garlock as a tear fault separating highly extended terrain to the north from relatively unextended terrain to the south in the Mojave Desert block. Terrain to north also topographically much higher than the Mojave block.

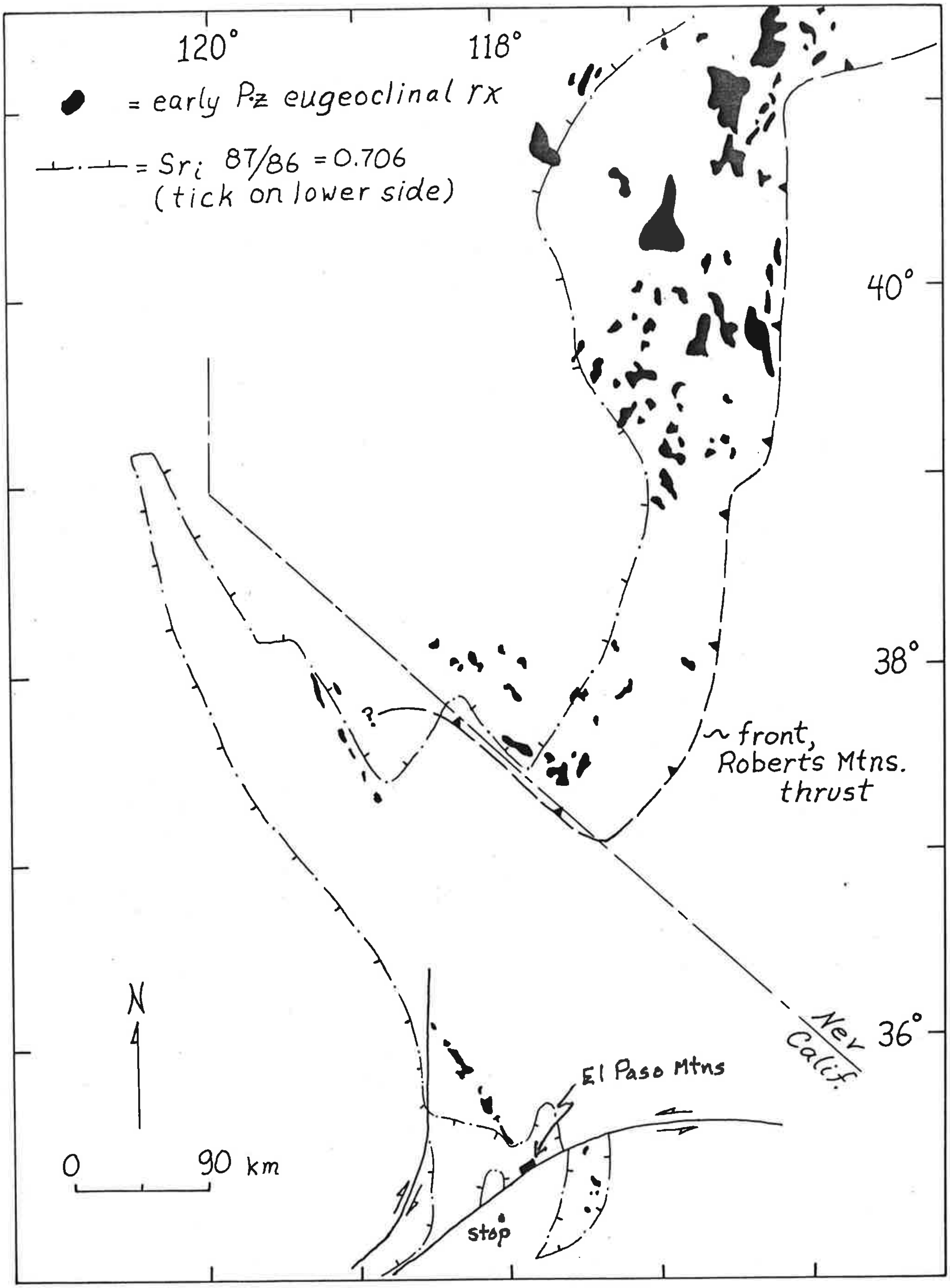
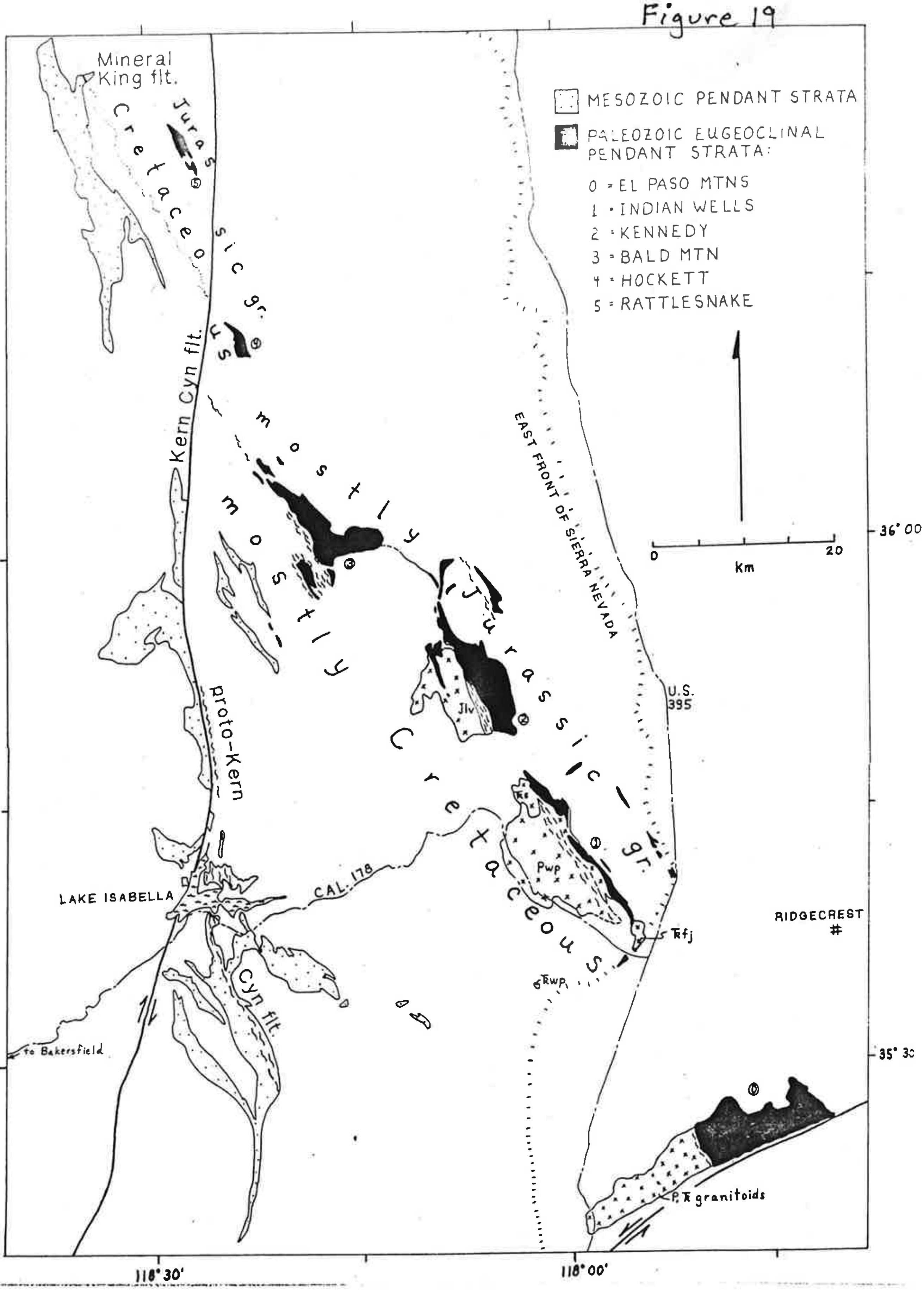

120°
118°
= early Pz eugeoclinal rx
= Sri 87/86 = 0.706
(tick on lower side)
40°
38°
36°
~ front, Roberts Mtns. thrust
?
Nev
Calif.
El Paso Mtns
stop
N
0
90 km

Figure 18.

Figure 19



MESOZOIC PENDANT STRATA
PALEOZOIC EUGEOCLINAL PENDANT STRATA:
0 = EL PASO MTNS
1 = INDIAN WELLS
2 = KENNEDY
3 = BALD MTN
4 = HOCKETT
5 = RATTLESNAKE
0
20
Km
Mineral King flt.
Jurassic gr.
Cretaceous
Kern Cyn flt.
mostly
mostly
proto-Kern
Jurassic - gr.
Cretaceous
EAST FRONT OF SIERRA NEVADA
U.S. 395
Jlv
Pwp
TRfj
TRwp
RIDGECREST
LAKE ISABELLA
CAL. 178
Cyn flt.
to Bakersfield
P TR granitoids
⑤
④
③
②
①
⓪
36° 00'
35° 30
118° 30'
118° 00'

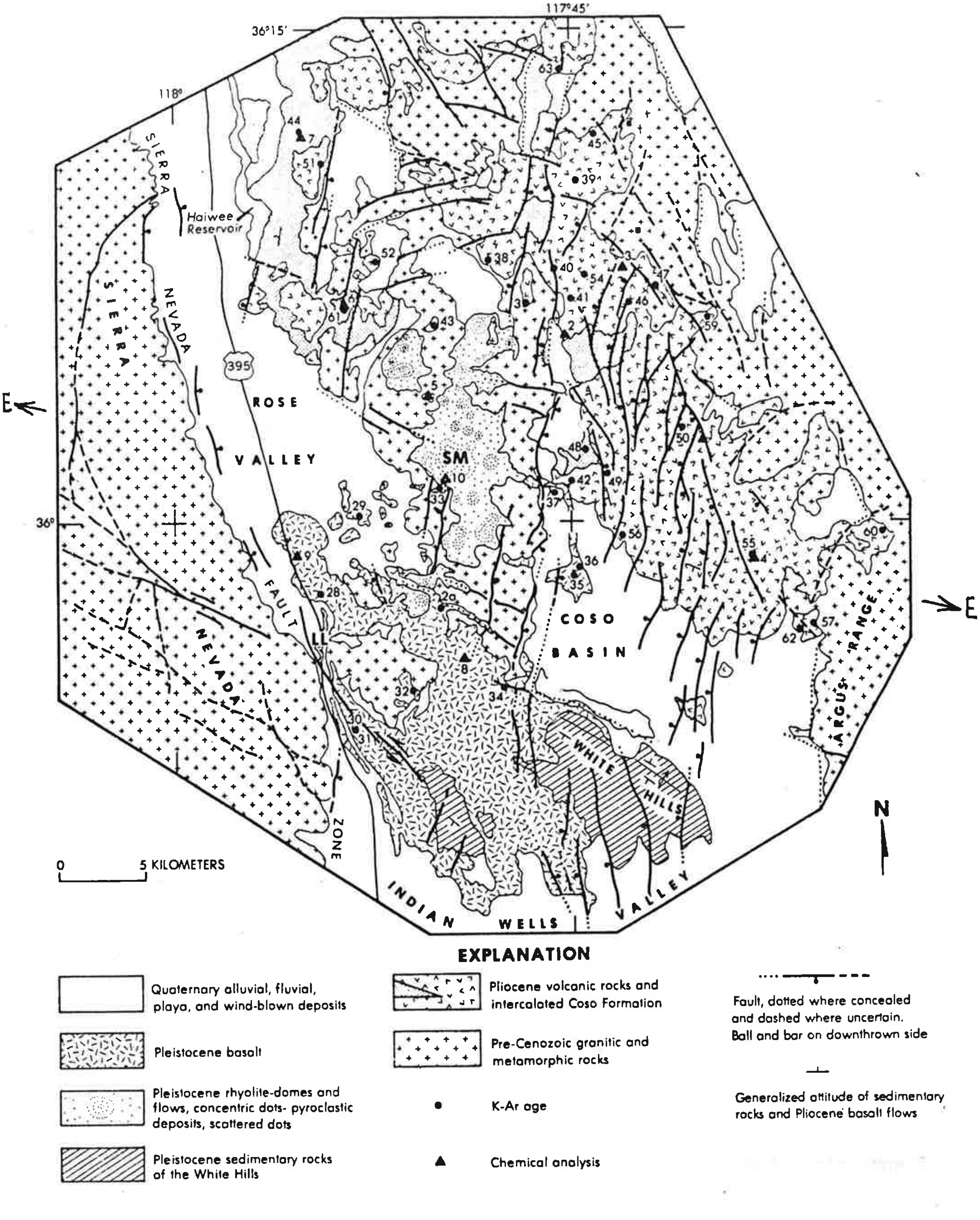


Figure 20. Geologic map of the Coso volcanic field, from Duffield and Bacon, 1980. Principle extension direction shown by arrows marked 'E' along sides. Two locations marked by capital letters LL and SM are Little Lake and Sugar Loaf Mountain respectively.

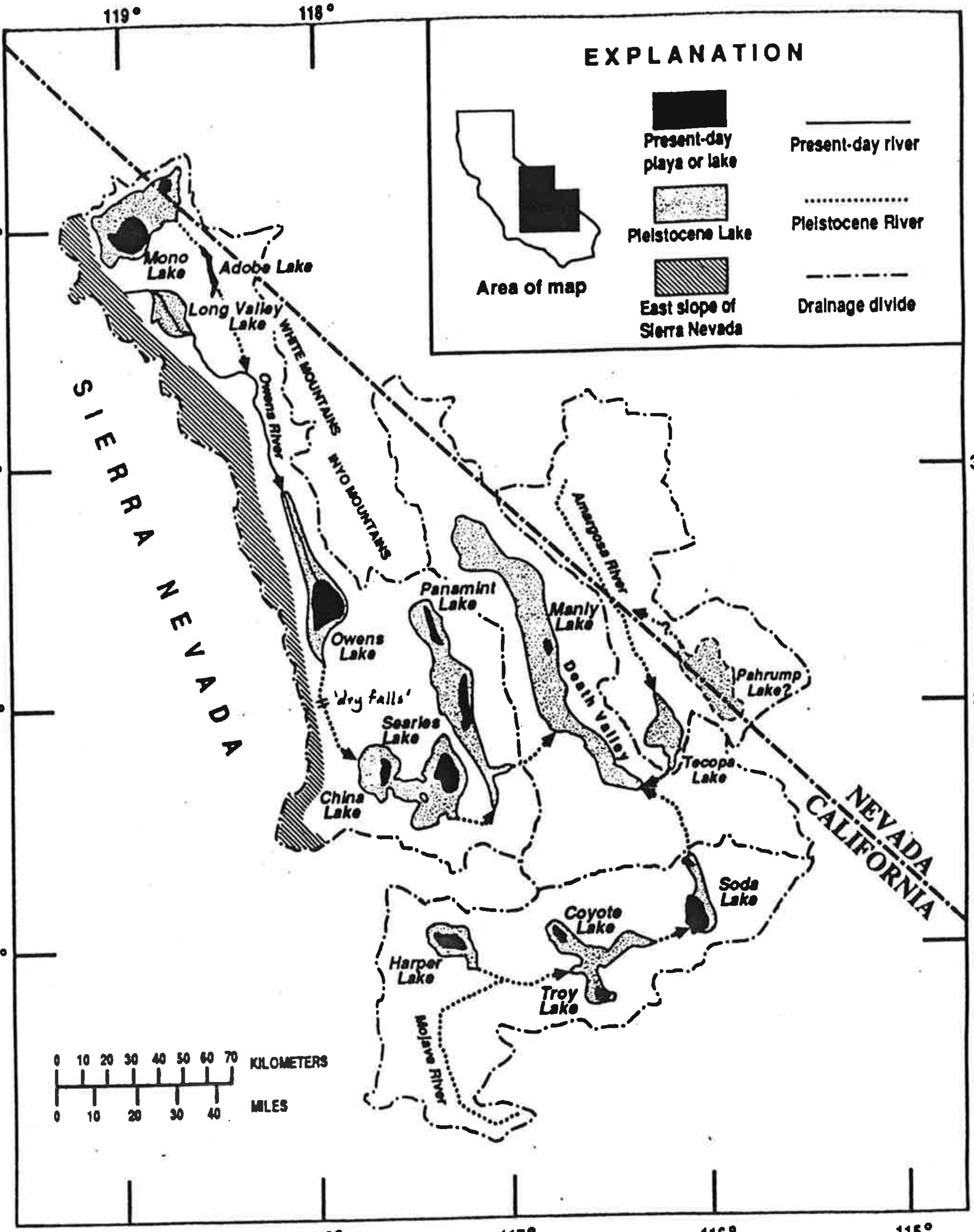
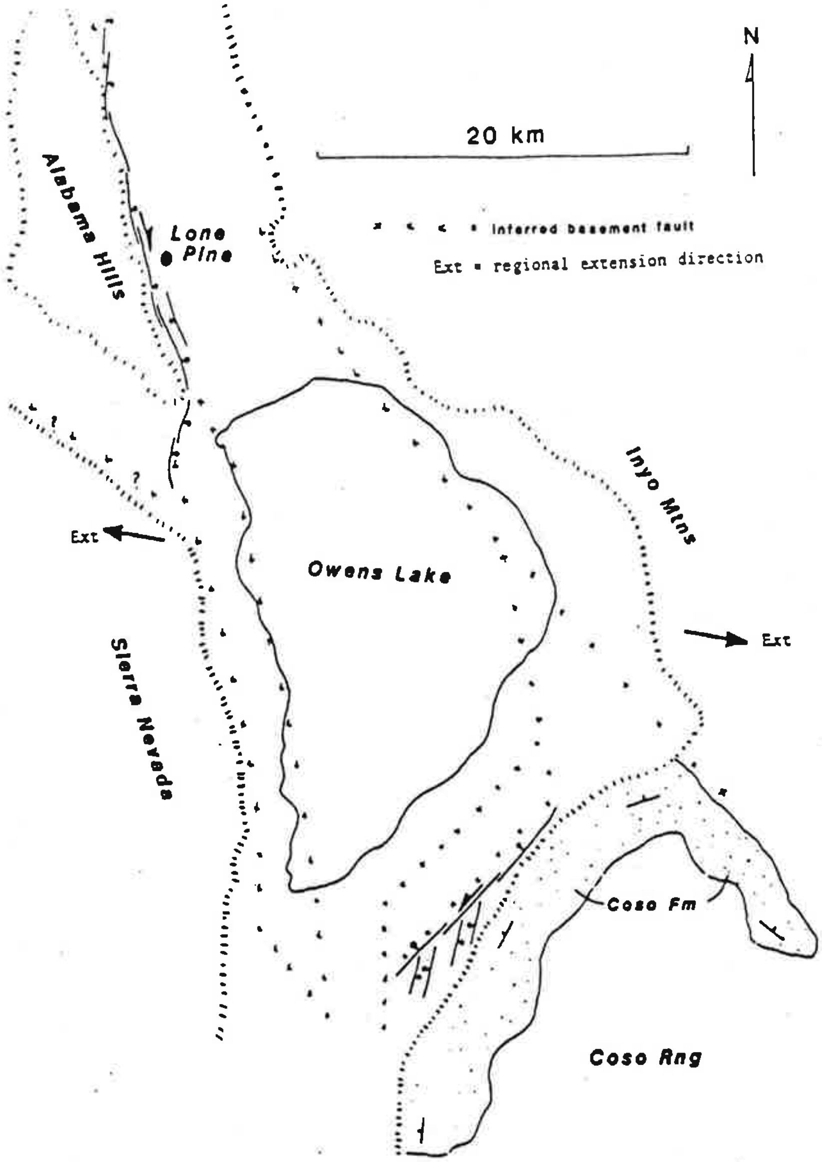


Fig. 21 . Map showing locations and drainage patterns of the paleo-Owens, -Amargosa, and -Mojave River systems.



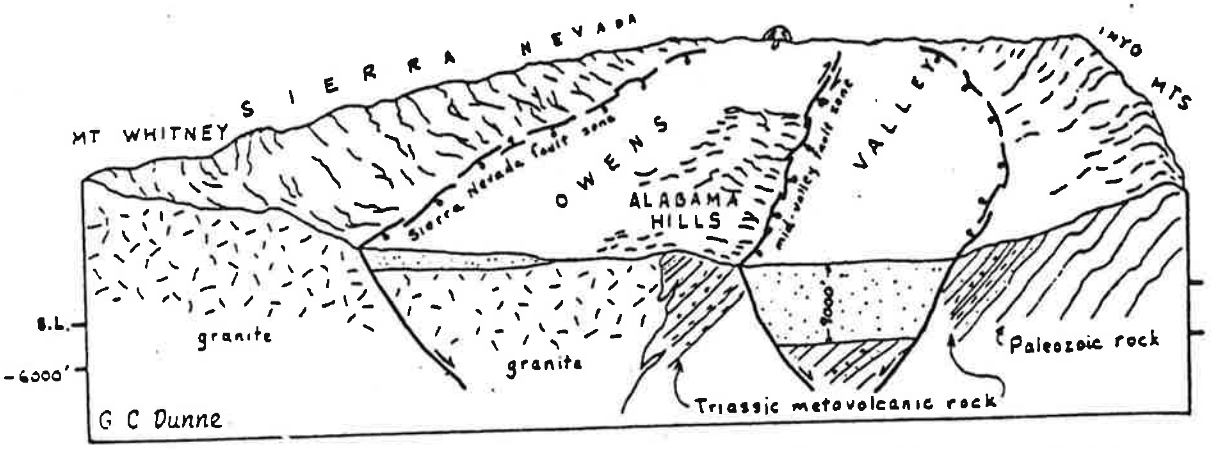


Figure 22 . Diagrammatic cross section of Owens Valley and bounding ranges near the town of Lone Pine showing 'classic' basin-and-range structure. Redrawn from Von Huene and others, 1963.

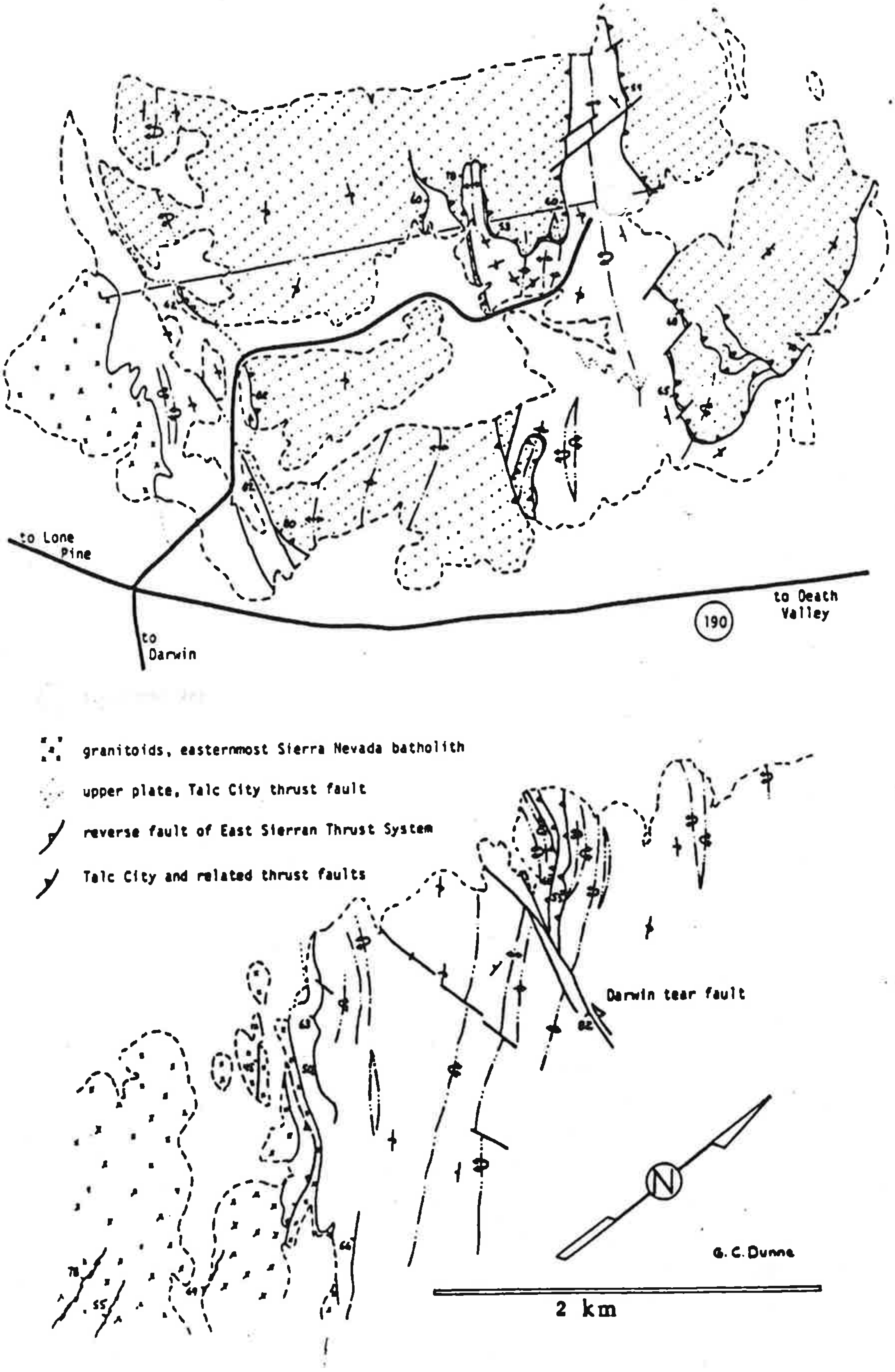


Fig. 23 . Structural sketch map of the Talc City Hills area.

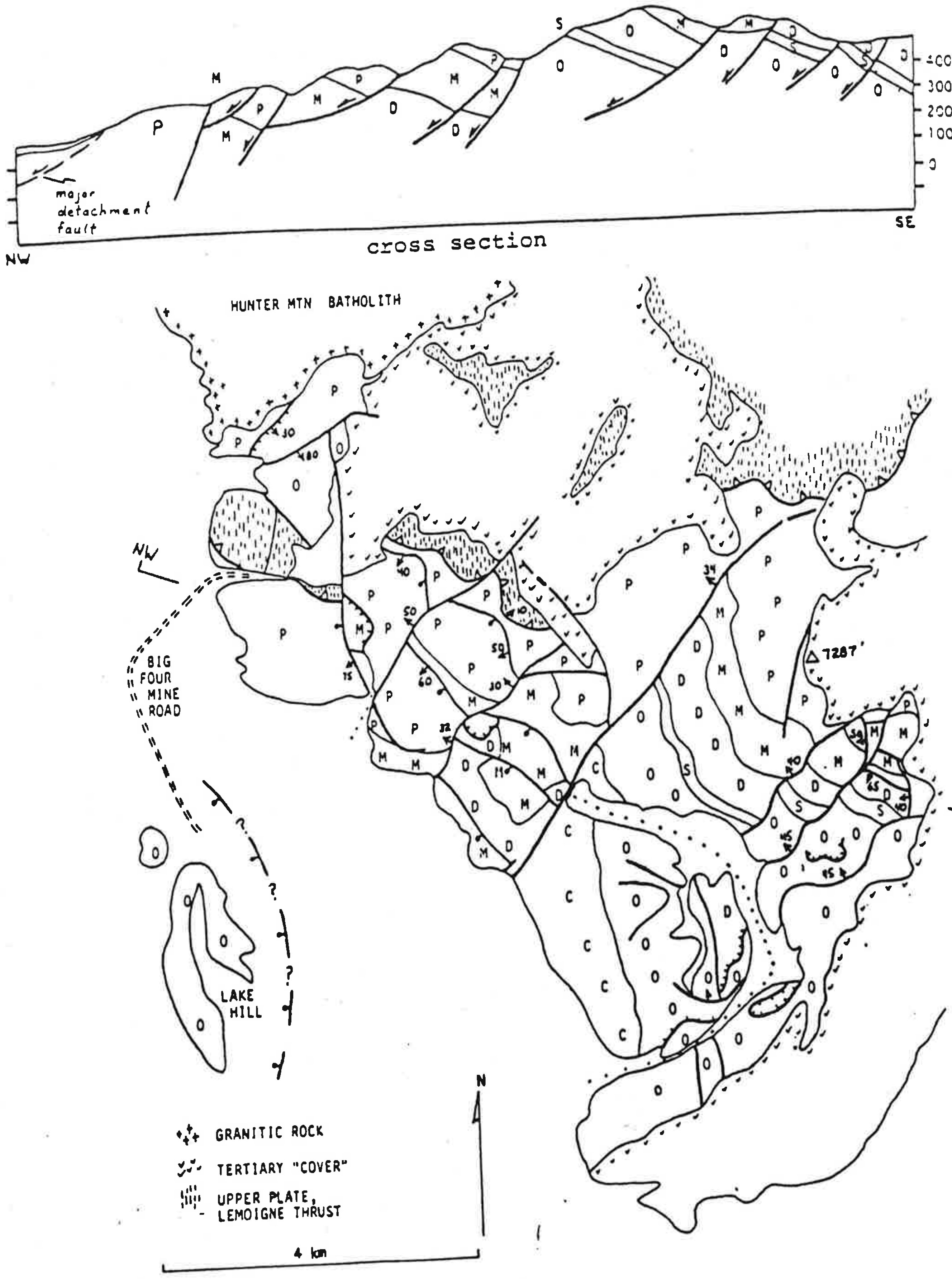
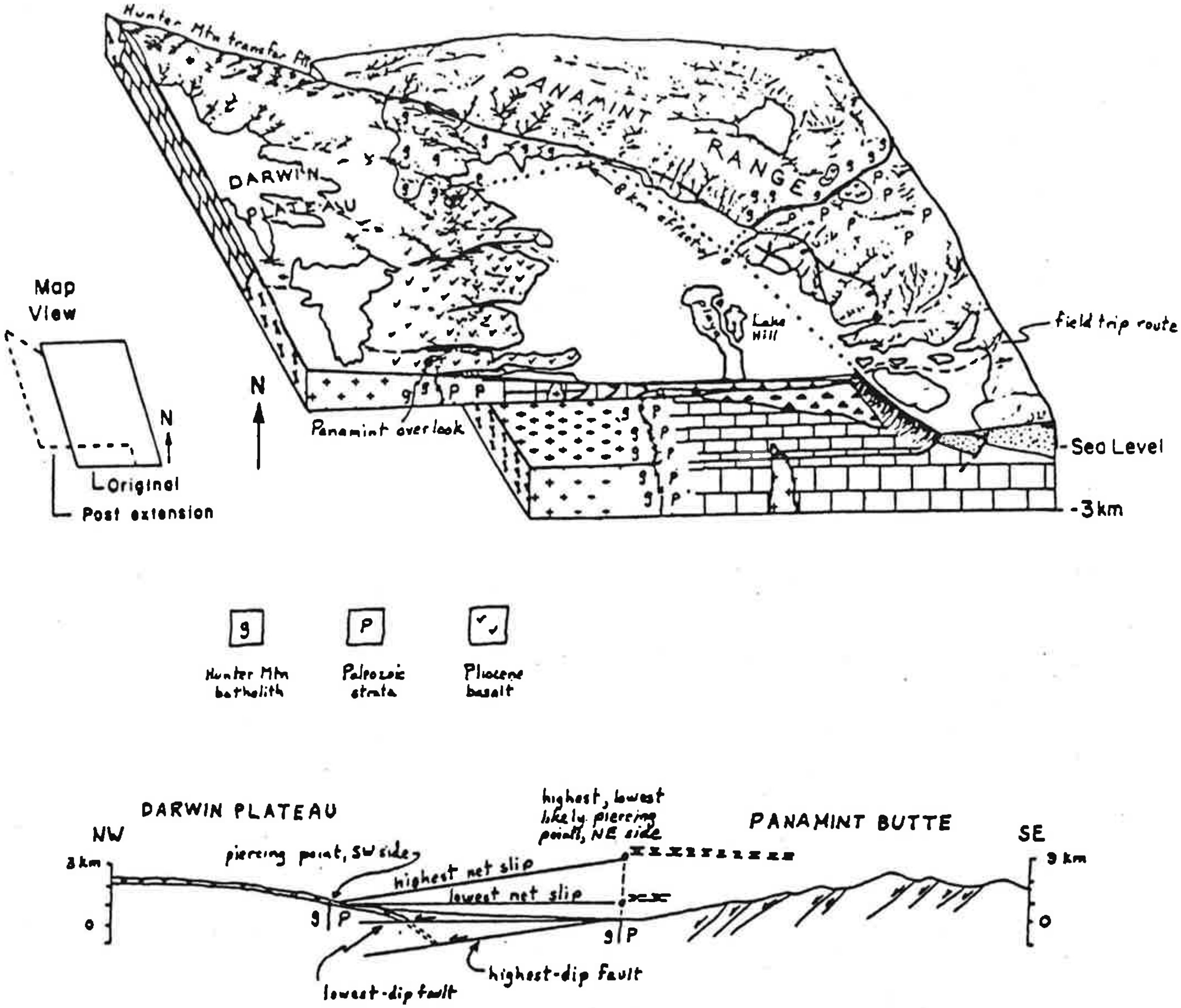


Figure 24 Geologic sketch map and cross section of PanamintButte, as derived from mapping of W. Hall (1971). Capitol letters designate rock systems (C = Cambrian, etc.).



igure 25 . 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.

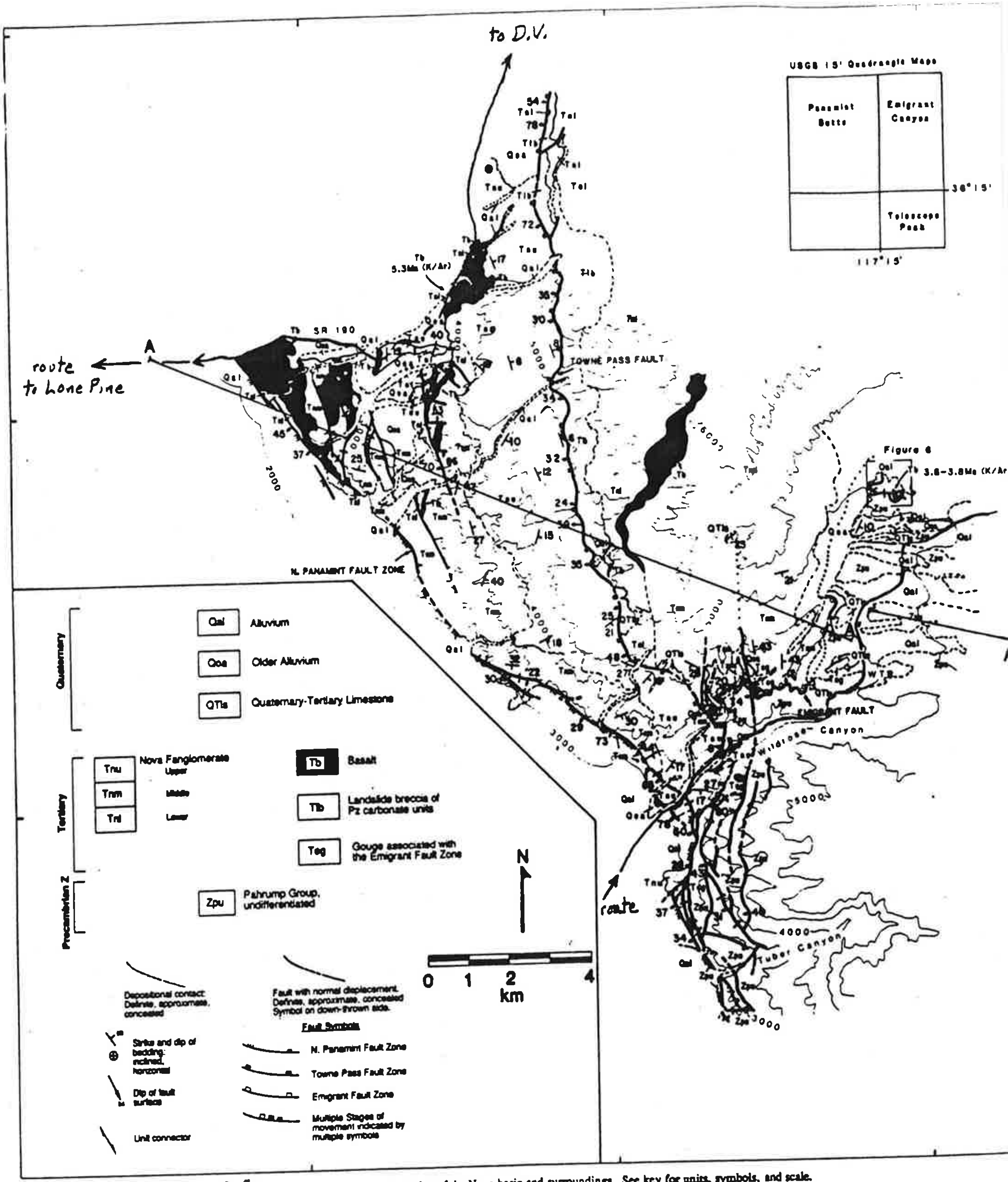


Fig. 26 Tectonic map and cross section of the Nova basin and surroundings. See key for units, symbols, and scale.

Tectonic Cross Section of the Nova Basin

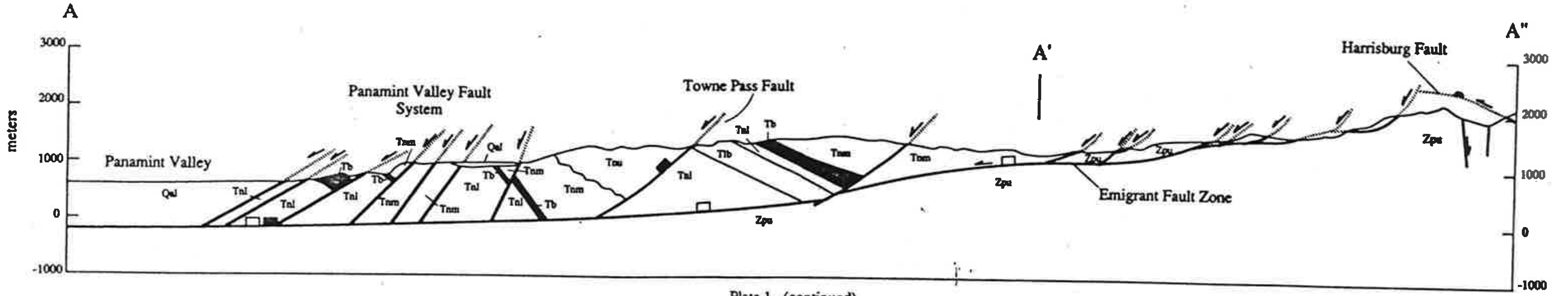


Plate 1. (continued)

Figure 27

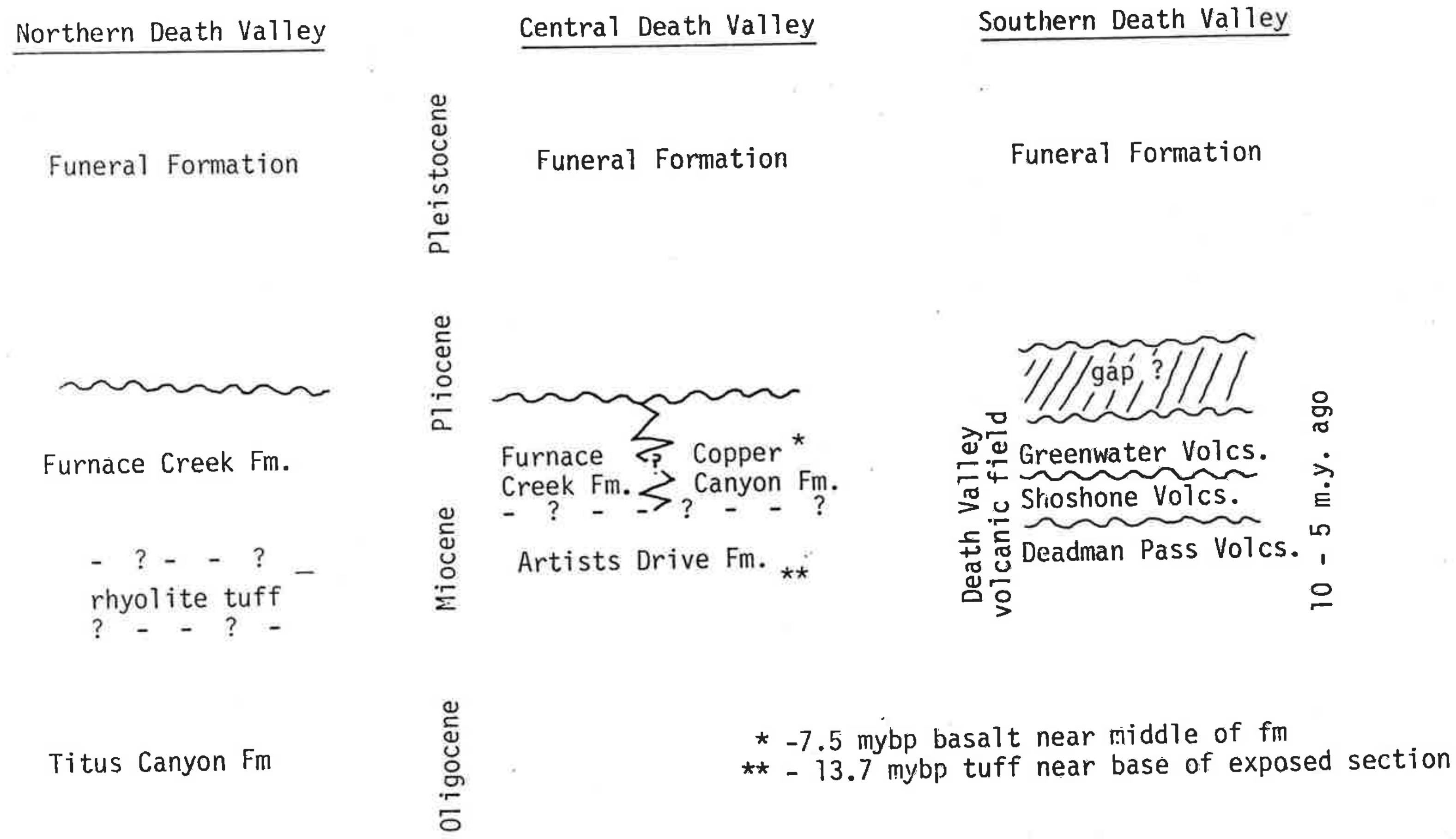


Figure 28. General correlations of major Cenozoic rock units in the Death Valley area.

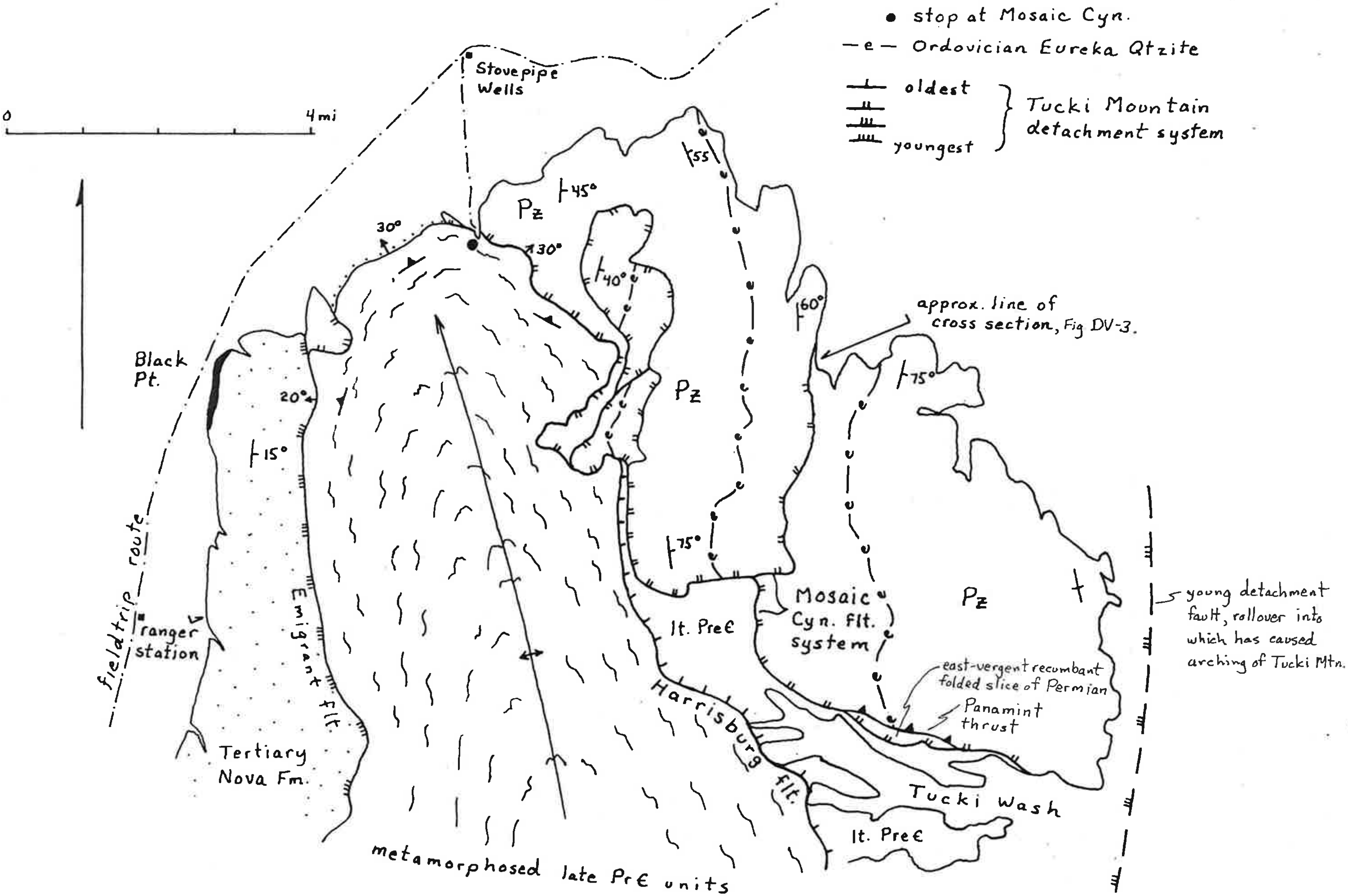


Figure 29 Geologic sketch map of Tucki Mountain detachment fault complex. Schematic cross section is provided in figure 30. Geology after Hunt and Mabey (1966) and Wernicke and others (1986).

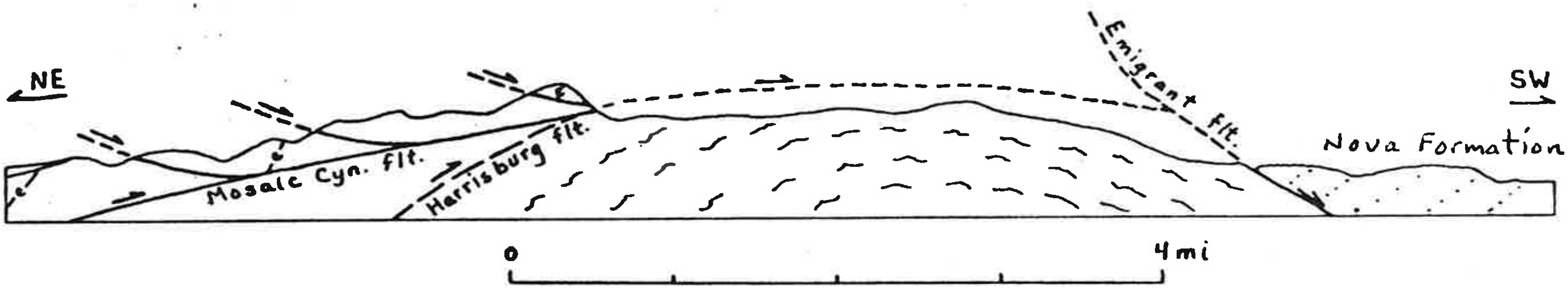


Fig. 30. Schematic cross section of Tucki Mountain detachment complex, derived from map relations shown in Fig. DV-2. Note that view direction of section has been reversed from map so as to show the complex as it would appear to us as we look south from Mosaic Canyon.

Figure 31.

Schematic evolution of Basin & Range extensional faults in a Black Mtns to Panamint Valley transect