Peninsula Geological Society
Spring Field Trip 2000

Salinia/Nacimiento Amalgamated Terrane
Big Sur Coast, Central California

Guidebook for the Spring Field Trip, May 19-21, 2000

Compiled by Robert Zatkin

May 2000

- Petrology and Structure of the Northern Santa Lucia Mountains
- Regional Tectonics and Structural Evolution of the Offshore Monterey Bay Region
- Hydrogeology of Coastal Watersheds—Southern Santa Cruz and Northern Monterey Counties
- Drought, Fire and Geology—Key Watershed Influences in the Northern Santa Lucia Mountain
- Botany of the Northern Santa Lucia Mountains

"Here from this mountain shore, headland beyond stormy headland plunging like dolphins through the blue sea smoke"

Robinson Jeffers
The Eye

ABOUT THE PENINSULA GEOLOGICAL SOCIETY

The Peninsula Geological Society (PGS) was established in 1954 by a group of Earth scientists. The intent in forming the PGS was to create a convivial forum for the presentation and discussion of established, and current research, concerning the geology of the San Francisco Peninsula, the greater San Francisco Bay region of California, and the western Cordilleran of North America.

PGS meets each month during the academic year for dinner and a talk presented by an Earth scientist. PGS conducts field trips as interest and scheduling permit. The operation of PGS is maintained by Earth scientists of th U.S. Geological Survey in Menlo Park, and the Stanford University School of Earth Sciences.

PGS maintains a Web site that contains information about past, and future, events including announcements and registration for our monthly dinner and talk; field trips; and, the history and participants in the PGS endeavor. The URL for our Web site is:

http://www.diggles.com/pgs/

ACKNOWLEDGMENTS

The following people have given their time and expertise to make the Peninsula Geological Society Spring Field Trip 2000 possible.

Trip Leaders:

- Gary Ernst — Petrology
- Gary Greene — Continental and Marine Structure
- Barry Hecht — Geomorphology and Hydrology
- Nick Johnson — Hydrogeology
- Jeff Norman — Botany

Supporting Members:

- Robert Zatkin — Organization, logistics and field trip guidebook
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ROAD LOG

Getting to the Starting Location

This road log begins at the California State Department of Transportation (Caltrans) rest stop located on the west side of California State Highway 1, south of the town of Aptos; and ends immediately south of Lucia located in the south central Big Coast region of Central California. The total distance is approximately 88.5 miles along Highway.

The Caltrans rest stop is approximately 2.0 miles south on Highway 1 from the intersection of Highway 1 and San Andreas Road. The rest stop, located on the west side of Highway 1, is accessed by an off ramp near the crest of a long, low angle uphill grade.

Be alert for the off ramp to the rest stop. If you drive past the off ramp, you must drive 7.5 additional miles to return to the starting location.

If you drive past the rest stop continue to the next off ramp, which is 1.8 miles south of the rest stop. You will drive over a divide and descend into the next drainage. At the bottom of the first descending grade is the intersection of Highway 1 and Buena Vista Drive. Exit at Buena Vista Drive, get back on Highway 1 going north, and return to the San Andreas Road off ramp. Exit Highway 1 at San Andreas Road, and go south (again) toward the rest stop.

Road Log Mileage

The road is log is a concatenation of the trip leaders individual efforts to identify important and noteworthy locations between the Highway 1 rest stop south of San Andreas Road near Aptos, and the area immediately south of Lucia along the Big Sur Coast. The log lists the following:

- Rod log mileage beginning at the Highway 1 rest stop.
- Geographic points of reference to most road log locations.
- Descriptive text for most road log locations.
- The leader with expertise concerning a given road log location.

Note the following about the road log:

- Locations in the road log are listed in geographic order in a southerly direction from the Highway 1 rest stop.
- Locations lacking mileage were approximated from local knowledge, maps, and interpolation to adjacent stops with known mileage.
- The road log contains two sets of mileage logs. The first set begins at the Highway 1 rest stop and ends approximately 35 miles south at Rio Road, located at the south end of the City of Carmel. The second begins at Rio Road and ends approximately 54 miles south near Lucia on the central Big Sur coast.

The best method for following the road log is to zero the odometer of your vehicle at Rio Road. In lieu of zeroing the odometer, knowledge of local geography and a road map should allow you to locate many stops in the road log, and begin registering mileage to other stops from that location.

Roadcuts along the Big Sur coast are very steep and falling rocks are common. The curves of Highway 1 are extremely sharp and mostly blind. Turnouts are too small, and there is little or no shoulder.

So… be extremely careful crossing the roadway. Do not stand in the roadway, and do not scatter rocks on the pavement!

Mileage	Location	Description	Leader
(0.0)	Rest stop on California State Highway One.	Approximately 2.0 miles south of the San Andreas Road off ramp of Highway One.	
		Monterey Bay and Monterey Canyon, one of the largest submarine canyons along the contiguous U.S. is located here and cuts deeply into the granitic rocks of the Salinian Block. It is about 15-21 my old and originated a considerable distance to the south, in the general location of Santa Barbara. This canyon has been moved to its present location by transform motion along the San Andreas fault system. See: • *Page Structure-4, figure 2.* • *Page Structure-1, Regional Tectonics and Structural Evolution Offshore Monterey Bay Region, by H. Gary Greene.* • *Page Structure-2, Fluid Flow in Offshore Monterey Bay Region, by H. Gary Greene and others.*	G. Greene
		From this vantage point the Pajaro Groundwater Basin is to the south and Soquel-Aptos Groundwater Basin is to the north. The Pajaro is a 120-mi^2 aquifer system mostly in the unconsolidated Aromas Formation and younger deposits. Pumping of nearly 70K ac-ft/yr results in overdraft of roughly 20K ac-ft/yr, a portion of which is made up by sea water intrusion. The Pajaro Valley Water Management Agency is attempting to increase recharge and import water. See: • *Page Hydrogeology-9, figure 1.* • *Page Hydrogeology-10, figure 2.*	N. Johnson

Mileage	Location	Description	Leader
		The Soquel-Aptos aquifers are mainly confined within the consolidated Purisima Formation. Although one model estimates the fresh-salt water interface is offshore, and yet to reach eustatic equilibrium following the Pleistocene, some indications of intrusion are apparent. The Parajo Valley Water Management Agency vacillates between stating it has a surplus to share, and a posture of being cautiously 'concerned'. Before continuing, we will discuss the upcoming drive over the next three groundwater areas to the south. See: • *Page Hydrogeology-2, Hydrogeology of Coastal Watersheds: Southern Santa Cruz and Northern Monterey Counties, by N. Johnson.* • *Page Hydrogeology-11, figure 3.*	
		Streams originating on the Aromas formation have a distinctive hydrology. Mean annual runoff averages from near zero to about 8 to 10 percent of mean annual precipitation at the watershed scale, compared with 25 to 40 percent in the Santa Cruz Mountains streams with watershed development in crystalline rocks or consolidated sediments. This may be attributed primarily to higher rates of infiltration through the sandy soils and sediments of the Aromas formation and younger terrace deposits. Note that significant runoff occurs in perhaps only 10 to 15 percent of all years from the sandy waters, and 60 to 80 percent of all years from most other Santa Cruz Mountains catchments. This affects not only the recharge regime of the Pajaro and adjoining valleys, but also land use, water rights, and habitat values along the streams draining the sandy watersheds. Lower rates of runoff translate to higher rates of annual recharge in this region,	B. Hecht

Mileage	Location	Description	Leader
		which receives significant rainfall, averaging between 18 and 32 inches. Higher rates of recharge through the sand hills on either side of the Pajaro Valley have been instrumental in minimizing water-quality constraints to ground-water use in this region despite a large and persistent overdraft. This recharge reduces concentrations of low dissolved solids, boron, and nitrate, which none the less approach or exceed regulatory action levels. At the site level, recharge and runoff rates within the sandy watersheds vary considerably, depending upon the textural facies within the Aromas Formation. As such, a fundamental aspect of useful geologic or hydrogeologic practice in these areas is recognition of local textural facies. See: • *Page 93, figure 3-4—Primary and channel recharge areas in the Pajaro Valley.* • *Page 94, figure 3-5—Rainfall and Annual Runoff Recurrence Curves for Streams in the Pajaro Valley and Nearby Areas.*	
(6.1 to 11 miles)	Pajaro River to Moss Landing—The 'Springfield Terrace'	The Springfiled Terrace is 'officially' designated as part of the Pajaro Basin, however it is essentially cutoff from inland recharge by Elkhorn Slough that curves behind it to the east. Few practical measures for augmenting water supply exist. Although artichokes are salt tolerant, intrusion may someday make agriculture unviable.	N. Johnson
(11 to 18 miles)	Moss Landing to immediately south of the Salinas River (17.1 miles)—The Salinas Groundwater	As we cross the mouth of the 470-mi^2 Salinas Groundwater Basin, imagine how seawater intrusion in the shallow 180-ft aquifer has extended nearly 7 mi. inland toward Salinas, encompassing 30 mi^2 (nearly 3 mi. inland and a 15 mi^2 area in the 400-ft aquifer). Although solutions	

Mileage	Location	Description	Leader
	Basin	have been elusive for greater than 60 years, improved conjunctive use of river and reclaimed water may be at hand. See: • *Page Hydrogeology-13, figure 5.* • *Page Hydrogeology-14, figure 6.* • *Page Hydrogeology-15, figure 7.* • *Page Hydrogeology-16, figure 8.*	
(18 to 28 miles)	Salinas R. to Monterey—Marina/Fort Ord and Seaside Basin	Cleanup of contaminated groundwater continues at the Army's former Fort Ord military base. Pilot measures to augment limited local water supplies include desalination of seawater pumped from wells located on the beach, and aquifer storage and recovery (ASR) of wet season flows diverted from the Carmel River and transported in a pipeline to the aquifer beneath the former base. ASR is essentially a groundwater injection endeavor to replenish depleted groundwater bodies.	
(35.0 miles) 0.0 miles	Rio Road, south end of City of Carmel—Carmel River/Carmel Valley	ZERO YOUR ODOMETER!!! ROAD LOG MILEAGE IS RECALIBRATED AT RIO ROAD, LOCATED AT THE SOUTH END OF THE CITY OF CARMEL.	
		An upthrown block of granite partially blocks the 7-mi^2 Carmel Groundwater Basin from seawater intrusion. However, conflicting water demands, and environmental and legal issues have paralyzed efforts to optimize the conjunctive use of its surface and ground water resources.	N. Johnson
	Monastery Beach/ San Jose Creek	At this location one of several heads of the Carmel Canyon forms the beach. The canyon cuts the Cretaceous granodiorite porphyry of the Monterey Mass. Two other heads of the canyon are located offshore, one in Stillwater Cove and the	G. Greene

Mileage	Location	Description	Leader
		other off Point Lobos Reserve. The canyon head off Point Lobos Reserve is fault controlled by the Carmel Canyon fault segment of the Palo Colorado-San Gregorio fault zone.	
0.2 miles		Closed-cone Coniferous Forest dominated by Monterey pine (*Pinus radiata*) begins on the inland side of road. Monterey pine is considered rare and endangered by the California Native Plant Society (CNPS) and is a Federal Species of Concern. Monterey pine, which occurs in three small mainland populations in California, is hugely planted in Mediterranean climates world-wide. However, the species is presently beset with pitch canker, a fatal disease which arborists claim will kill >80% of all trees within 25 years. See: • *Page Botany 2, California's Native Monterey Pine Forest: Can It Be Saved, by M. Matthews and N. NedeffPage* • *Botany 13, Pitch Canker and Its Potential Impacts on Monterey Pine Forests in California, by T.R. Gordon and others.*	J. Norman
0.9 miles	Immediately south of San Jose Creek and Beach.	Southernmost range limit for long-petaled iris (*Iris longipetala*), in Coastal Prairie habitat east of road.	J. Norman
1.6 miles	Big pullout with view of Point Lobos.	Location of one of two naturally-occurring populations of Monterey cypress (*Cupressus macrocarpa*). The other population is across Carmel Bay at Pebble Beach. Monterey cypresses were much more widespread until sea level began rising at the close of the Pleistocene. Their distribution was likewise restricted by the advent of wildfires, to which Monterey pines are better adapted.	J. Norman
2.2 miles	Point Lobos	Mid-Cretaceous porphyritic Santa Lucia	G. Ernst

Mileage	Location	Description	Leader
	NO STOP	granodiorite of the Monterey Peninsula. Rock contains enormous euhedral K-feldspar tablets. It appears to be similar to the Cathedral Peak quartz monzonite of Yosemite Park and Sonora Pass; but of course, is not related. It is overlain along a buttress unconformity by gravels and sandstones of the Eocene Carmello Formation.	
2.6 miles	Gibson Creek	Middle reaches of this drainage support the rare Gowen cypress (*Cupressus goveniana ssp. Goveniana*) growing with rare Central Maritime Chaparral plant community on podsolized sandy soils similar to those at the S.F.B. Morse Botanical Reserve in Pebble Beach (called "Evolution Hill" by Ledyard Stebbins). Gowen cypress grows only in two locations, both inland from the two sole stations for Monterey cypress. See: • *Page Botany 18—The Santa Lucia Mountains: Diversity, endemism, and Austere Beauty, by D. Rogers.*	J. Norman
4.7 miles	Malpaso Creek	Immediately south of the bridge is where the main occurrence of the Monterey Pine Forest in Monterey County ends. South of this location are two or three sites where small groves of a few trees have been mapped. Although their native status is questionable. Monterey Pine Forest commences again just north of Cambria in San Luis Obispo County. Southernmost range limit of Hooker's manzanita (*Arctostaphylos hookeri ssp. Hookeri*) which occurs at the edge of the pine forest at this location. Hooker's manzanita is listed by the CNPS as endangered.	J. Norman
5.5 miles	Garrapata Creek	The Palo Colorado-San Gregorio fault zone comes ashore at this location. Just below the stairs a good fault contact between folded Cretaceous sandstone and granitic rocks can be seen.	G. Greene

Mileage	Location	Description	Leader
		Approximately 2 km of faulted and sheared rocks is exposed in the cliffs. This fault zone is the western margin of the granitic Salinian Block.	
		A shallow well beside Garrapata Creek ¼ mile from the coast supplies about 30 nearby homes. The California Department of Fish and Game and the State Water Resources Control Board recently contested its use. The main question posited by these State agencies was: Does the well tap a "subterranean stream" or does its yield, like the creek, derive from groundwater migrating across the watershed from areas of rainfall recharge? See: • *Page Hydrogeology 19—Source Evaluation of Groundwater Extracted from Garrapata Water Company Wells, by N. Johnson.*	N. Johnson
7.4 miles	Immediately south of Soberanes Point.	Central Maritime Chaparral growing on the inland side of the road. The chaparral is surrounded by more recently colonized, and more aggressive, Coastal Sage Scrub. The Central Maritime Chaparral is growing on granitic soil, and has been reduced to a single component taxon—chamise (*Adenostoma fasciculatum*). The presence of a single taxon is probably due to thinning of soil as sandy material has eroded away. The process may have been accelerated by fire.	J. Norman
9. 7 miles	Garrapata Beach	Big pullout at the north side of the Garrapata Creek bridge. On the east side of road the Central Maritime Chaparral on sandy soil supports endemic Carmel creeper (*Ceanothus griseus var horizontalis*), and is the northernmost range of the Little Sur manzanita (*Arctostaphylos edmundsii*), a Federal Species of Concern and CNPS List 1B species (rare and endangered). Also	J. Norman

Mileage	Location	Description	Leader
		present is seacliff buckwheat (*Eriogonum parvifolium*), host foodplant of the Federally-listed Endangered Smith's blue butterfly (*Euphilotes enoptes smithz*). This location is a documented station for the butterfly.	
10.7 miles	Rocky Point Park south of outcrop.	NE-dipping Upper Cretaceous, brown weathering Great Valley coarse sandstone, shale, and siltstone. Well-bedded clastic sedimentary strata derived from the Klamath-Sierran arc plutonic-volcanic arc.	G. Ernst
11.0 miles	Immediately south of Rocky Point Restaurant.	Coastal grassland is being overrun by French broom (*Genista monspessulana*) an invasive exotic shrub. The owner-rancher of the fields south toward Palo Colorado Canyon has used herbicide to reduce French broom.	J. Norman
	Hurricane Point NO STOP	A long coast vista allows observation of the steep tectonically uplifted and faulted seaward margin of the Santa Lucia Range. Roof pendants of Jurassic limestone are visible on the slope to the east and the tombolo at Point Sur can be seen to the south.	G. Ernst G. Greene
	Mouth of the Little Sur River	Erosion and sedimentation following the Marble-Cone fire of 1977 left deposits of sand several inches to 1.5 feet thick on the floodplain throughout the alluvial lower segments of the Little Sur River. The lagoon was largely, but not completely, sedimented because tidal and storm-wave action kept a vestigial lagoon functional. This lagoon has been studied extensively by Dr. Jerry Smith of San Jose State University. Dr. Smith has noted very high rates of Steelhead productivity in this lagoon, where some fish grow at rates sufficient for them to go so sea during their first late spring or early fall after hatching, rather than the second year which is typical for stream reared steelhead. The lagoon is considered very important not only as	B. Hecht

Mileage	Location	Description	Leader
		refuge during droughts and post-fire sedimentation episodes, but also as a locus of year-class diversification. This diversification minimizes the risk of complete brood-year loss and helps to stabilize the population of steelhead. See: • *Page Geomorphology and Hydrology 2* • *Page Hydrogeology 2—Marble Cone Fire–Effect on Erosion, by G. Cleveland.* • *Page Hydrogeology 55—The Marble–Cone Fire Ten Months Latter, by J. Giffith.*	
12.7 miles	North side of Rocky Creek.	Central Maritime Chaparral located above highway, growing in granitic soil. It is being slowly swallowed from below by Coastal Sage Scrub (of a lighter, gray-green color). Higher up at an elevation of about 1,300' above MSL, where sandy soil persists, is a greater species composition of Central Maritime Chaparral, including the southern range limit for the federally listed endangered Yadon's rein-orchid (*Piperia yadonii).* See: • *Page Botany 27—California's Coastal Sage Scrub, by S. DeSimone.*	J. Norman
12. 8 miles	Roadside turnout	Dark gray, coarse-grained, biotite-rich charnockitic tonalite; original pyroxene is now completely pseudomorphed by uralitic amphibole. The tonalite contains even darker, medium-grained inclusions or metadikes (chiefly biotite + quartz + plagioclase). Float blocks of very coarse, dead white marble suggest proximity to Paleozoic platform sedimentary rocks of the Sur Series (Coast Ridge Belt). Presumably, the tonalite intruded the carbonate strata, then both were metamorphosed.	G. Ernst
13.4 miles	Bixby Canyon and bridge.	On the east side of road, Central Maritime Chaparral is losing the battle with Cape ivy *(Delairea odorata),* an	J. Norman

Mileage	Location	Description	Leader
		invasive exotic from South Africa. In the Riparian Woodland of Bixby Creek, Cape ivy has extirpated the southernmost range limit of the CNPS Iisted rare and endangered plant, maple-leaved sidalcea *(Sidalcea malachroides),* extant until about 1980. Southern range limit for California rose-bay *(Rhododendron macrophyllum)* is in this drainage, associated with Central Maritime Chaparral and Redwood Forest.	
14.3 miles	Roadside turnout	Light-colored graphitic marbles of the Sur Series (Coast Ridge Belt), striking NS, dipping about 60^{o}E. Associated metasedimentary rocks (pelitic schists, slates?) can be seen down the cliff along beach. South end of outcrop looks like a poorly exposed Great Valley arkosic sandstone layer (buttress or angular unconformity?). In places, looks like massive, saccroidal granite, but contains subangular to moderately rounded grains, and lacks phenocrysts. Nice big pullout.	G. Ernst
14. 6 miles	Pullout at Hurricane Point	Growing in Northern Coastal Scrub/Coastal Bluff Scrub at the edge of the pavement are specimens of Hutchinson's larkspur *(Delphinium hutchinsoniae)* in bloom on east side of road on 23 April 2000. This plant is a Monterey County endemic, and a federal Species of Concern, and a CNPS List IB (rare and endangered).	J. Norman
15.0 miles	NO STOP	Conglomeratic Upper Cretaceous Great Valley sandstone on east side.	G. Ernst
17. 0 miles	NO STOP	Sand dunes on east. Material derived from the abundant nearby granitoids (and Great Valley sediments). Cross from Salinia to Nacimiento block.	G. Ernst
17. 2miles	Dunes south of Little Sur River.	At this location "trees similar to present-day Monterey Pine, Bishop Pine (*Pinus muricata*) and Gowen Cypress grew together 10,000 years ago." James R. Griffin, "What's So Special About	J. Norman

Mileage	Location	Description	Leader
		Huckleberry Hill on the Monterey Peninsula?" California Native Plant Society Newsletter (pre-*Fremontia),* Vol. 8 No.2, July 1972.	
18.0 miles	NO STOP	To the distant west is a tombolo with a perched lighthouse atop Point Sur. The bedrock is a large knob of Franciscan greenstone.	G. Ernst
18. 6 miles	Pullout opposite Point Sur.	Great Central Maritime Chaparral on greenstone at "The Rock." Lots of Little Sur manzanita.	J. Norman
	Point Sur	Point Sur is a rock, former sea stack, of more resistant Franciscan Formation that is attached to the mainland by a tombolo. Note the extensive sand dune development here indicating a southward transport of sediment along a very windy part of the California coast.	G. Ernst
21. 0 miles	North boundary of Andrew Molera State Park.	The private El Sur Ranch grazes cattle, a practice that began with a Mexican land grant in 1834. The south half of the land grant became a state park in 1971, at which time cattle were removed. The ensuing regrowth of Northern Coastal Scrub dominated by coyote brush (*Baccharis pilularis)* on state lands is dramatic and demarcates the boundary between the present and former locations of grazing.	J. Norman
21.3 miles	Andrew Molera State Park	Entrance to Andrew Molera State Park is on west side of Highway One. Directly opposite on the east side is the southern entrance to the old Coast Road, a beautiful 10.4 mi-long gravel road drive through bucollic alpine meadows and valley redwood groves. Serpentinite is exposed at 1.4 mi, but exposures of Salinian block granitoids and metamorphics to north are intensely weathered. This is an optional route on return north.	G. Ernst

Mileage	Location	Description	Leader
		Mouth of the Big Sur River contains a relatively undeveloped alluvial aquifer that may be of adequate volume and sufficient quality to be considered a resource.	N. Johnson
21.8 miles	Old Coast Road (alternative return route)	Granitic, metamorphic, and sedimentary rocks are exposed along the road. These rocks types impart varying major ion signatures to ground water and late summer baseflows emanating from ground water.	B. Hecht
	Big Sur River streamflow gage	Aggradation of the Big Sur River following the Marble-Cone fire was so large and rapid at this gage that it overwhelmed the ability of USGS WRD staff to maintain the gage. USGS reports that the peak flow for the 1978 water year occurred on January 9, 1978. Yet, very little or no rainfall was reported for this date, or for the previous week, at all six rain gages which were operating in this watershed or on the ridges at its edges. Much larger storms occurred during the Christmas week, later in January, in mid-February and early March. Each of these storms produced records of large storm crests at other gages in the region. I believe that the reported high flows for the day represent aggradation at the gaging station from sediment delivered from the burnt hill slopes to the channel during the late December storms. Floodflows during the following week likely initiated the post-event downcutting cycle, as they did in the Carmel watershed to the east (See page 149, figure 2.). Because most gages are maintained approximately monthly, USGS-WRD staff may not have been aware of the sand ‘wave’ which passed through the Big Sur gage leading to misinterpretation of the water level record. The report of peak flows on January 9 is one manifestation of the rapid rate at which erosion and channel	B. Hecht

Mileage	Location	Description	Leader
		sedimentation occur following episodic events. It also serves as a caution about the extra care warranted in the use of gaging records collected during bed sedimenting episodes. In such cases, hydrologists should probably turn to the primary data, such as instrument read-out and the observers' log of conditions and measurements made at the station.	
	Big Sur River watershed	Discussion of the finding of research from the Marble Cone fire of 1977. Discussion of paper South of the Spotted Owl: Restoration Strategies for Episodic Channels and Riparian Corridors in Central California. See: • *Page Geomorphology and Hydrology 10—South of the Spotted Owl: Restoration Strategies for Episodic Channels and Riparian Corridors in Central California, by B. Hecht.* • *Page Geomorphology and Hydrology 62—Sequential Changes in Bed Habitat Conditions, by B. Hecht.*	B. Hecht
21. 5 miles	South end of Big Sur Valley	The Riparian Woodland of the Big Sur River. Dominant species are black cottonwood *(Populus balsamifera* ssp. *Trichocarpa),* white alder *(Ainus rhombifolia),* western sycamore *(Platanus racemosa),* and arroyo willow *(Salix lasiolepis*).	J. Norman
22.6 miles		Entering the Redwood Forest plant community, dominated by coast redwood (*Sequoia sempervirens*). This tree reaches its southernmost range limit in Monterey County, at Soda Springs Creek near the south end of the Big Sur Coast, about 48 miles south of this location.	J. Norman
23.1 miles	High Bridge Creek	The stream here flows down the top of a ridge (!) formed by alluvial deposition.	J. Norman

Mileage	Location	Description	Leader
24.5 miles	Juan Higuera Creek	See: • *Page Geomorphology and Hydrology 33—Dating and Recurrence Frequency of Prehistoric Mudflows Near Big Sur, Monterey County, California, by L. Jackson.*	B. Hecht
24.5 miles	Juan Higuera Creek	There is a substantial kill-off of tan-oak *(Uthocarpus densiflorus)* here, due to the mysterious “tan-oak disease” (probably a fungus). Locally, the vast number of dead tan-oaks become host to three oak beetle taxa; when these emerge, they infest other tan-oaks and also coast live oaks *(Quercus agrifolia*). They destroy cambium tissue, and also inoculate their new hosts with “tan-oak disease.” The secondary kill-off of coast live oaks is now becoming epidemic.	J. Norman
25.8 miles	Pfeiffer-Big Sur State Park	Hills to west of Big Sur State Park entrance are in the Franciscan Complex, but are poorly exposed. Typical! Here is where we camp.	G. Ernst
26.1 miles	Cedar Flat	Named for a volunteer incense cedar (*Calocedrus decurrens)* which probably grew after a seed from high altitude populations, was deposited during flooding >100 years ago. The tree fell during the strong winds and heavy rain of 3 February 1998. John Pfeiffer grew potatoes here at the turn of the century. It is now a State Park septic system leachfield.	J. Norman
26.7 miles	Entrance to Pfeiffer-Big Sur State Park	The land that is now the P-BS SP was acquired from John Pfeiffer by the State of California in 1933. A mudslide in 1973, a by-product of 1972 Molera Fire, carried seeds of Arroyo Seco bushmallow *(Malacothamnus palmeri var.lucianus),* in alluvium originating at high elevations of Mt. Manuel, to this location. Here they germinated, and several clonal groups	J. Norman

Mileage	Location	Description	Leader
		persist. Arroyo Seco bushmallow is a federal Species of Concern, and CNPS list 1B species (rare and endangered).	
27.1 miles		Most tan-oaks in the Post Creek drainage, which you are now ascending,) are dead or dying due to "tan-oak disease."	J. Norman
28.0 miles	NO STOP	Franciscan graywacke and a greenstone pod crop out along west side of CA State Highway 11 near the crest at Post Ranch Inn (west) and Ventana Inn (east), and ~0.2 mi north of Nepenthe. Beyond, cross from Nacimiento to Salinia block.	G. Ernst
29.2 miles	Sycamore Canyon Road	Sycamore Canyon Road, on west side highway off our route. The southern range limit for Little Sur manzanita, the rare Monterey Indian paintbrush (*Castilleja latifolia*), bear grass (*Xerophyllum tenax*); and the northern range limit for California peony (*Paeonia californica*) are located at the end of the road to the Pfeiffer Beach area.	J. Norman
29. 1 miles	Roadside parking	Sheared serpentinite on west, dark Franciscan shale across road on east. Good parking.	G. Ernst
29.9 miles		Serpentine plug on west side of highway supports Coastal Sage Scrub invaded by French broom. Foothill needlegrass *(Nassella* [= *Stipa] lepida)* also occurs here.	J. Norman
29.9 miles	CONSTRICTE D SPACE ON CURVE FOR PARKING.	Sur Series marbles and quartzites + feldspathic gneisses of the Coast Ridge Belt. Mineralogy includes uralite after clinopyroxene, red garnet, graphite • rare, unaltered clinopyroxene.	G. Ernst
30.7 miles	Pull out	Flat-lying Sur Series (Coast Ridge Belt) marbles, metasiltstones, and quartzites. Same neoblastic minerals as at stop 29.9 mile.	G. Ernst
31.2 miles	Pull out	Coarse-grained graniodiorite. On the south is dark, very coarse-grained biotite	G. Ernst

Mileage	Location	Description	Leader
		+ hornblende-bearing, weathered charnockitic tonalite.	
31.5 miles	Parking area	Coarse, dark gray charnockite with stringers of white alaskite at stop, and in ravine down near beach. Charnockitic tonalite contains a large, fine-grained, plate-like mafic granulite body consisting chiefly of biotite + hornblende + plagioclase, representing a wall rock inclusion or an early, mafic igneous border phase or relict mafic dike. It is clearly intruded by dark tonalite and by even later, pale alaskite. Well-exposed, banded charnockite crops out southward to bridge at 32.8 miles.	G. Ernst
31.7 miles		Typical Coastal Sage Scrub growing on colluvial soil; dominated by California sagebrush *(Artemisia californica)* and black sage *(Salvia mellifera)*. Some nice virgin's bower *(Clematis lasiantha)* clambering over scrub, in full bloom on 22 April 2000.	J. Norman
32.5 miles		Grimes Point. Dwarf form of California buckwheat brush *(Eriogonumfasciculatum);* could be a hybrid with seacliff buckwheat *(E. parvifolium*).	J. Norman
32.7 miles		Spanish bayonet, or yucca (*Yucca whipplel)* in bloom on inland side of road is near its northernmost coastal range limit. Also found at this location along roadside is the northernmost specimen of chicory-Heaved stephanomeria *(Stephanomeria cichoriacea).*	J. Norman
33.7 miles	South end Torre Creek Bridge.	South end Torre Creek bridge. Location of rediscovery in 1969 of the 'extinct' Hutchinson' s larkspur (*Delphinium hutchinsoniae).* The Coastal Sage Scrub habitat which supported this plant has been greatly reduced by French broom incursion, and Hutchinson's larkspur can no	J. Norman

Mileage	Location	Description	Leader
		longer be found here. Some 10 locations exist for the taxon.	
34.8 miles	Sycamore Draw	Work to repair landslide here (which occurred in early 1983) created massive areas of disturbed soil, which has been colonized by pampas grass *(Cortaderiajubata),* French broom, and sticky eupatorium (*Ageratina adenophora),* which is poisonous to horses.	J. Norman
36.5 miles	Off road parking	Traveling through brown, weathered charnockitic tonalite to the road stop at commodius off-the-road parking. Hornblendic charnockite contains felsic layers and stringers (migmatitic sweatouts or Cretaceous granitoids?). Sur Series marble float suggests that the intrusive contact with the Coast Ridge Belt is nearby.	G. Ernst
36.7 miles	Julia Pfeiffer Burns State Park	Lunch and rest stop. If you take the ocean trail from the parking lot to observe a seacliff waterfall, note the exposure of Miocene Monterey Formation porcellanite.	G. Ernst
37.8 miles	Julia Pfeiffer Burns Slide of 1983 (AKA 'Big Slide').	Millions of yards moved from here by Caltrans, 1983-84. Sidecasting ruined the nearshore, subtidal Julia Pfeiffer Burns Underwater Park and Area of Special Biological Significance. Uncompacted fill continues to erode and the highway is nearly undercut here at present.	J. Norman
37.9 miles	NO STOP	Coarse conglomerate of the Great Valley Series on the east side of road. Mostly granitic closets, this unit is probably proximal to the Salinian granite source terrane.	G. Ernst
39.8 miles	Burns Creek	Type locality of Smith's blue butterfly. The butterfly's habitat at this location was greatly disturbed by recent bridge rebuilding which required replanting of	J. Norman

Mileage	Location	Description	Leader
		the buttetfly's host foodplant as mitigation for the construction.	
40.1 miles	Pull out	Fantastic exposure of heavy conglomerate of the Great Valley Series. Locally, the conglomerate appears to be transected by medium-grained, cm-thick alaskite stringers. Really???	G. Ernst
40.5 miles	Buck Creek	Northernmost range limit for wishbone bush (*Mirabilis californica)* in middle reaches of this drainage.	J. Norman
40.9 miles (approx.)	NO STOP	Cross from Salinia to Nacimiento block.	G. Ernst
41.2 miles	Hot Springs Creek, Eslan Institute	Blue gum trees *(Eucalyptus globulus)* planted here to support overwintering masses of Monarch butterfly *(Danaus plexippus).*	J. Norman
41.9 miles	Lime Creek, John Little State Reserve	Elizabeth Livermore planted Torrey pines *(Pinus torreyana)* at this location, probably in the late 1920s or early 1930s, which have naturalized. Where Torrey pine occurs in native stands, it is considered a federal Species of Concern, and CNPS List 1B species (rare and endangered).	J. Norman
42.4 miles	Roadside parking	Franciscan greenstone knocker, somewhat weathered, with vague pillows and more obvious pillow breccia. Calcite epidote veins transect the pod.	G. Ernst
42.7 miles	Roadside parking	Very well endurated, disrupted Franciscan graywacke, siltstone, and dark shale. Beautiful tectonic mélange.	G. Ernst
43.0 miles	NO STOP	Greenstone lens in Franciscan mélange at this location and at 43.8 miles.	G. Ernst
44.0 miles	Roadside parking	Really large Franciscan greenstone lenses, approximately 2 km long. Subhorizontal flow layering is well displayed. Abundant calcite + epidote veins and hydrothermal alteration.	G. Ernst

Mileage	Location	Description	Leader
		Pillows are present ~0.3 mi east of this stop.	
	Big Creek Reserve	This is an area of alternating Cretaceous sandstone and Franciscan Formation rocks that are deformed and fractured along the Sur-Nacimiento fault zone. The high relief and rock offshore region is attractive to rockfish and the reserve has been established to preserve the fisheries here.	G. Ernst
44.0 to 49.0 miles		Lots of gigantic landslides–this is the Caltrans sandbox. Look uphill for hummocky ground (where not landscaped), chaotic blocks and hard knockers of Franciscan, and swales in the semicontinuously patched/repaved roadway.	G. Ernst
44.2 miles	Rat Creek	Coast redwoods here were severely burned during the Rat Creek Fire of 1985.	J. Norman
44.8 miles	Wing Gulch	This gully was created when a 19th-Century rancher built a wing fence far up the hillside above today's highway. This caused his cattle to erode the hillside, where the herd was diverted at a steep area. The erosion made a gully which today is very nearly a perennial stream. It is a regular source of winter road closures.	J. Norman
45.5 miles	Pull out	Square Black Rock in the nearshore. The north half of this sea-stack (which had a NE-SW trending cleft all the way through) fell in the ocean during an earthquake in 1972. A rancher above the town of Lucia (ca. 35 mi. distant) heard the splash. Inland, the Rat Creek Fire of 1985 started at elevation 1,450' above MSL following a lightening strike. Blue-blossom (*Ceanothus thyrsiflorus)* above highway is a fire-follower from this event. "Banded" vegetation pattern is	J. Norman

Mileage	Location	Description	Leader
		probably a result of soil depth with ceanothus occurring in deeper soil.	
46.2 miles	Big Creek Bridge	University of California's Landels-Hill Big Creek Reserve at south end of bridge. The concrete used to make this bridge incorporated sand taken from the beach below. There is evidently enough greenstone in the beach sand to give this bridge a slightly greenish cast.	G. Ernst
47.3 miles	NO STOP	Tectonic block of Franciscan chert.	G. Ernst
47.5 miles	Rigdon Fountain	During construction of Highway 1, the location where north-bound crews met south- bound crews in 1934. Named for promoter of the highway, State Sen. Elmer Rigdon of Cambria. Rigdon was known for swindling mercury miners in San Luis Obispo County. He owned a brick works, and convinced the local school board, of which he was a member, to use his inferior bricks to enlarge the Hesperian School. His bricks contained substantial amounts of shell and chert from Indian midden deposits.	J. Norman
47.7 miles		Nice red jasper east of road.	J. Norman
47.8 miles	Pull out	Small, indistinct outcrop of serpentinite, which is the California state rock. This is hydrated mantle, but from what plate-tectonic environment?	G. Ernst
48.2 miles	Immediately south of Gamboa Point.	Inland, much vegetation damaged by the Hare Creek Fire of 1999 can be seen.	J. Norman
48.6 miles	Vicente Creek	Inland, more damage from Hare Creek Fire.	J. Norman
48.9 miles	NO STOP	Franciscan shaley mélange.	G. Ernst
49.6 miles	Lucia	AKA, Landslide City.	J. Norman
49.8 miles		Coast redwoods show typical damage to foliage, as browning and kill-off, caused	J. Norman

Mileage	Location	Description	Leader
		by exposure to high wind driven salt spray from ocean.	
51.0 miles	Lime Kiln Canyon	Landslide—a truly big honker mass slumpage.	G. Ernst
51.2 miles	Grandpa•s Elbow	Caltrans 'fixed' this location in 1998. Redwoods here have long been losing fight with gravity, and lately some real leaners have developed.	J. Norman
51.5 miles	Limekiln Creek	South end of the bridge is the entrance to Limekiln Canyon State Park.	G. Ernst
51.5 miles	Lucia Lodge	The motel cabins located north of the lodge on the ocean side of road, were built about 1936. At the time of construction the ridgepoles of the four cabins were in a straight line. After substantial drifting, they were realigned in 1974. Presently, they look about they way they did prior to the 1974 work.	J. Norman
52.0 miles	'New' Dani Creek	Centerline of Dani Creek as it flowed after the 1906 Earthquake (as per George Harlan, then 13 years old). Harlan also observed water sloshing out of a farm pond next to his home, above here at elev. 800'.	J. Norman
52.1 miles	Point 16	In the 1930s, the gardener for then-owner Edward Moore recommended pampas grass to stabilize the substratum (the owner was worried that unstable soil might undercut the mansion). The mansion slipped into the ocean in the early 1940s; the pampas grass remains (everywhere).	J. Norman
52.4 miles	Dani Creek	According to George Harlan, the centerline of Dani Creek prior to 1906 was different from that of today. The former topography is shown on the Lucia 15' USGS quadrangle, 1921. The shift evidently occurred at about 1,000' above MSL.	J. Norman

Mileage	Location	Description	Leader
53.6 miles	Limekiln Creek	Cone Peak, elevation 5,155' above MSL, can be seen inland from this bridge. One of the steepest gradients along this coast, and supporting a diverse and numerous progression of plant communities from sea level to the summit. Atop Cone Peak many Sierra Nevada disjunct plant species are found, including: sugar pine *(Pinus lambertiana)*; Santa Lucia Mountains endemics, such as Santa Lucia fir *(Abies bracteata)*; Cone Peak bedstraw *(Galium californicum ssp.luciense);* and, Santa Lucia bed straw (*G. clementis)*.	J. Norman
Th th th th tha aa atsss all, f f f f folks!!			

GEOLOGY

W. G. Ernst

Introduction

The central California Coast ranges contain a telescoped lithotectonic complex representing stages in the geologic evolution of the Mesozoic margin of California. Important maps and cross-sections have been published by Ross (1976a,b, 1977, 1983), Ross and McCulloch (1979), and Hall (1991). Physiographic provinces and rock assemblages include: (1) the landward Andean (Sierran) calcalkaline plutonic-volcanic arc + Northwest Foothills upper Paleozoic-lower Mesozoic metamorphic belt; (2) the Upper Jurassic-Cretaceous Central Valley (Great Valley forearc basin turbiditic strata); and (3), the contemporaneous deep-water trench deposits (Franciscan Complex). Neogene dextral slip along the San Andreas system transected the old continental margin from an internal, landward position on the south in the present Gulf of California, to an external, oceanward position near Cape Mendocino on the north, reflecting the fact that the North American continental crust-capped plate progressively overran the outboard East Pacific Rise spreading center during late Oligocene time. Right-lateral motion along the San Andreas thus has duplicated the Mesozoic continental margin along the Big Sur coast—(1) Salinian silicic, calcalkaline granitoids + Paleozoic Sur Series metamorphics, (2) Great Valley first-cycle detrital sediments depositionally resting on the Salinian basement, and tectonically thrust over the outboard Franciscan Complex, and (3), Nacimiento graywackes, greenstones, and cherts of the Franciscan mélange. The nature of the Neogene strike slip is quite apparent, but the antecedant history of rock sections disposed along the Sur-Nacimiento fault is not.

What is clear is that the Sur Series + Salinian granitic rocks share petrochemical and geochronologic characteristics with inboard granitoids of the western Mojave Desert and the Tehachapi Mountains (miogeoclinal upper Paleozoic-Triassic Calaveras Complex = platform strata of the Paleozoic Sur Series?). In sharp contrast, the Franciscan is everywhere a dog's breakfast of oceanic affinity (far-traveled oceanic crust + hemipelagic chert) overlain by voluminous masses of calcalkaline arc-derived first-cycle clastics, all intensely tectonized within the North American/paleo-Pacific plate-boundary subduction zone. The facts that Salinian tonalites have been recrystallized to pyroxene(s) ± garnet-bearing phase assemblages (i. e., charnockites) and associated aluminous metapelitic rocks contain sillimanite suggest high temperatures and considerable depths of origin. Somewhat similar, deep-seated, garnetiferous tonalites in the eastern Transverse Ranges have been described by Sams and Saleeby (1987); therefore, a palinspastic restoration (approximately 310 km) of the Big Sur region against the farther inboard Tehachapis + western Mojave is plausible. Eocene to lower Miocene strata of the northern Santa Lucia Range were deposited in a basin adjacent to analogous rocks exposed in the San Emigdio area of the Transverse Ranges just east of the San Andreas (Nilsen and Link, 1975), supporting such a Neogene offset. The more oceanic, deep-sea Franciscan assemblages along the Big Sur coast have been exhumed from much shallower subduction depths compared with along-strike metagraywacke terranes cropping out farther south in the San Luis Obispo area (Ernst, 1980), but comparable rocks crop out from the Oregon border at least as far south as central Baja.

Various scenarios regarding the plate-tectonic assembly of the Salinia/Nacimiento amalgamated terrane have been proposed. At the end of this road log, abstracts are presented by Page (1981), Dickinson (1983), Hall (1991) and Dickinson and Butler (1998). Interepretations for the origin and evolution of the Coast Range ophiolite are summarized by Dickinson et al. (1996). In addition, handouts describing the Salinian (Ross, 1983; James and Mattinson, 1987) and Nacimiento (Ernst, 1980) blocks are presented for further study and hours of boundless enjoyment. Field trip stops and points of reference are presented below.

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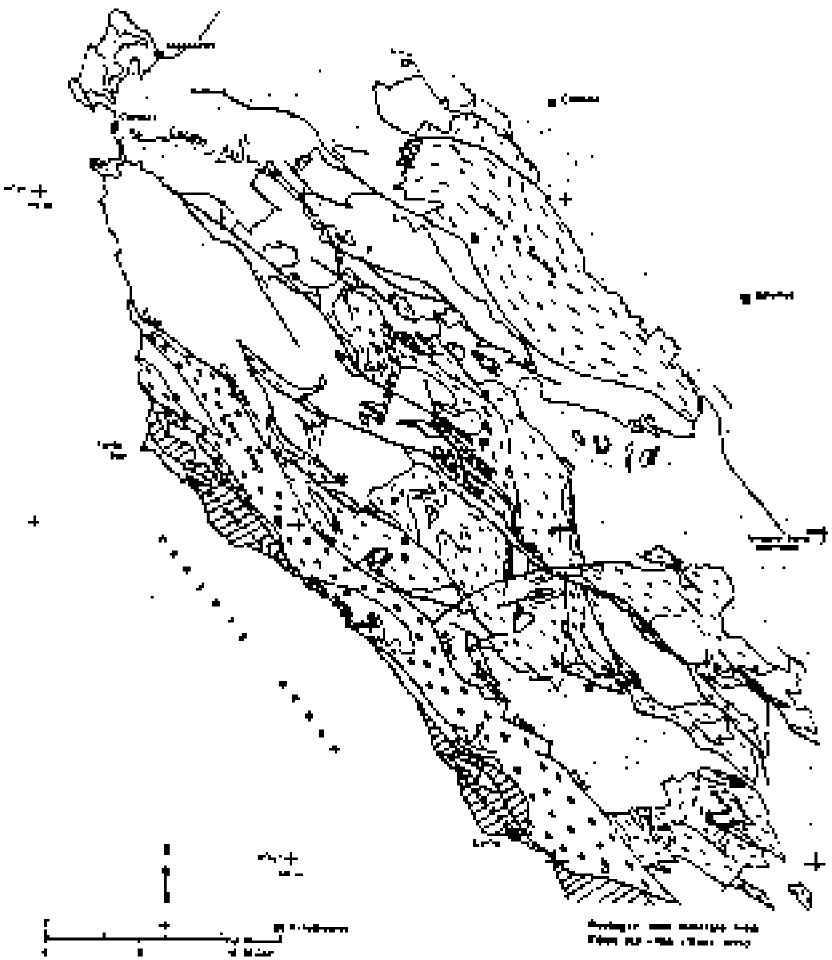

FIGURE 4. ORTHOPYROXENE AND SILLIMANITE

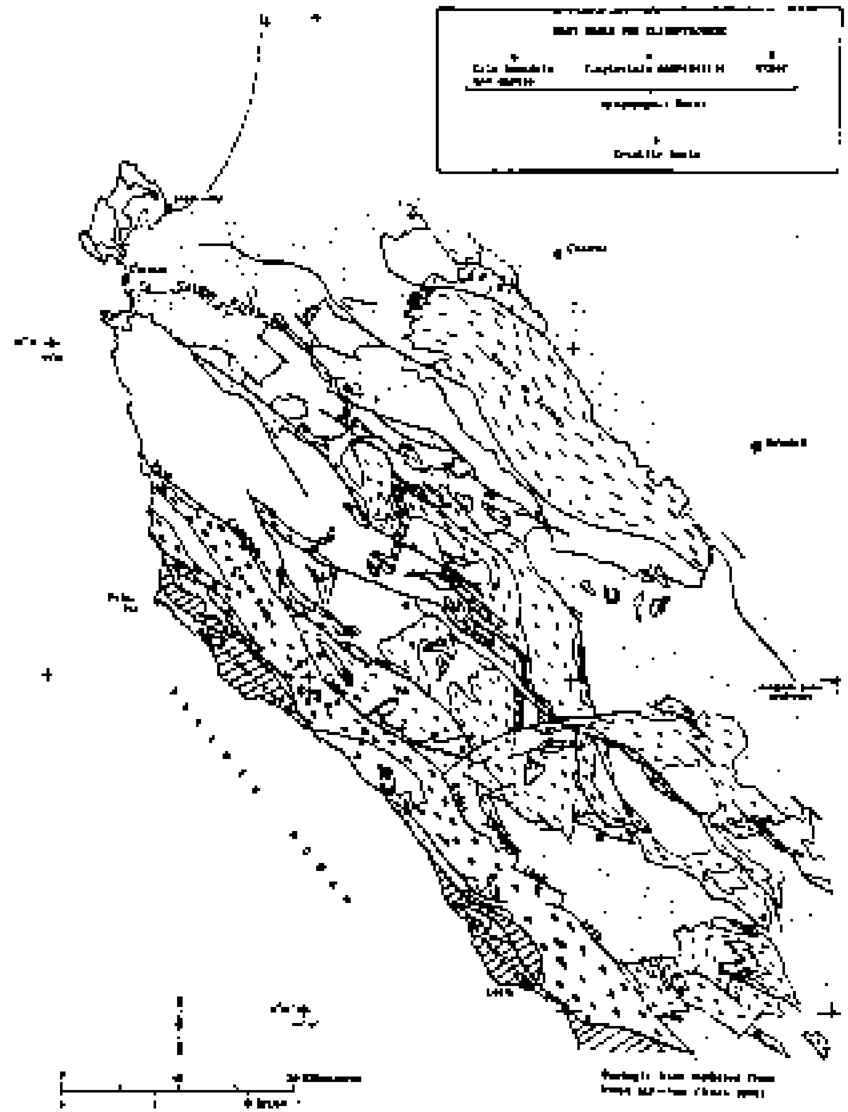

FIGURE 5. CLINOP[redacted]

Coastal and Baja California paleomagnetism reconsidered

William R. Dickinson*
Robert F. Butler
Department of Geosciences, University of Arizona, Tucson, Arizona 85721

ABSTRACT

Systematic reappraisal of paleomagnetic data from upper Mesozoic and lower Cenozoic sedimentary rocks and igneous rocks of late Mesozoic age in coastal and Baja California indicates that plunge [illegible] and shallowing of paleomagnetic directions by sedimentary compaction resolve observed discordances with the North American apparent polar wander (APW) path when the best available reference paleopoles are used for comparison. The hypothesis of major tectonic transport in excess of distances inherent in current models for evolution of the San Andreas transform system is unnecessary and in conflict with geologic observations. Fresh insights derived from recent data sets and improved analysis include the following. (1) The limited paleomagnetic data recording primary remanence for Upper Jurassic and Lower Cretaceous volcanic rocks in coastal California are concordant with the North American APW path. (2) The tilt of the Peninsular Ranges batholith inferred from paleobarometric data eliminates its declination discordance and reduces its inclination discordance to a level where ovals of confidence for observed and expected paleomagnetic directions overlap. (3) Key Cretaceous and Paleogene red-bed successions on the Salinian block of coastal California and in Baja California have yielded concordant paleolatitudes. (4) The discordances of different apparent paleolatitudes inferred from Cretaceous and Paleogene marine sedimentary strata lie within a range that can be attributed to compaction shallowing on the basis of both experimental information and observations from elsewhere. (5) Turbidites are more susceptible to compaction shallowing than shelf and deltaic strata. (6) The uniform rotation of paleomagnetic directions inferred previously for peninsular California is not supported by the full array of data now available from multiple localities. (7) Emplacement age of the Salinian block in California and of the Baja California peninsula in the continental interior precludes any hypothesis for dramatic transport much in excess of San Andreas transform slip.

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GSA TODAY

A Publication of the Geological Society of America

Alternate Origins of the Coast Range Ophiolite (California): Introduction and Implications

William R. Dickinson, Department of Geosciences, University of Arizona, Tucson, AZ 85721
Clifford A. Hopson, Department of Geological Sciences, University of California, Santa Barbara, CA 93106
Jason B. Saleeby, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125

ABSTRACT

Correctly interpreting the tectonic evolution of the California continental margin requires understanding the origin of the Jurassic Coast Range Ophiolite, which represents a fragment of mafic to ultramafic crust of oceanic character lying depositionally beneath the western flank of the Great Valley forearc basin in fault contact with the Franciscan subduction complex of the California Coast Ranges. Three contrasting hypotheses for genesis of the ophiolite as oceanic crust are each based on internally consistent logic within the framework of plate tectonics, but are mutually exclusive and lead to strikingly different interpretations of regional tectonic relations, even though each assumes that the Sierra Nevada batholith in the east represents the eroded roots of a magmatic arc linked to subduction along the Mesozoic continental margin. To encourage the further work or study needed to develop a definitive interpretation, summary arguments for each hypothesis of Coast Range Ophiolite genesis in mid- to late Jurassic time are presented in parallel: (1) backarc spreading behind an east-facing intraoceanic island arc that then collided and amalgamated with the Sierran continental-margin arc, (2) paleoequatorial midocean spreading to form oceanic lithosphere that was then drawn northward toward a subduction zone in front of the Sierran continental-margin arc, and (3) forearc spreading within the forearc region of the Sierran continental-margin arc in response to transtensional deformation during slab rollback.

Geology of the Point Sur–Lopez Point region, Coast Ranges, California: A part of the Southern California allochthon

Clarence A. Hall, Jr.
Department of Earth and Space Science, University of California, Los Angeles, California 90024

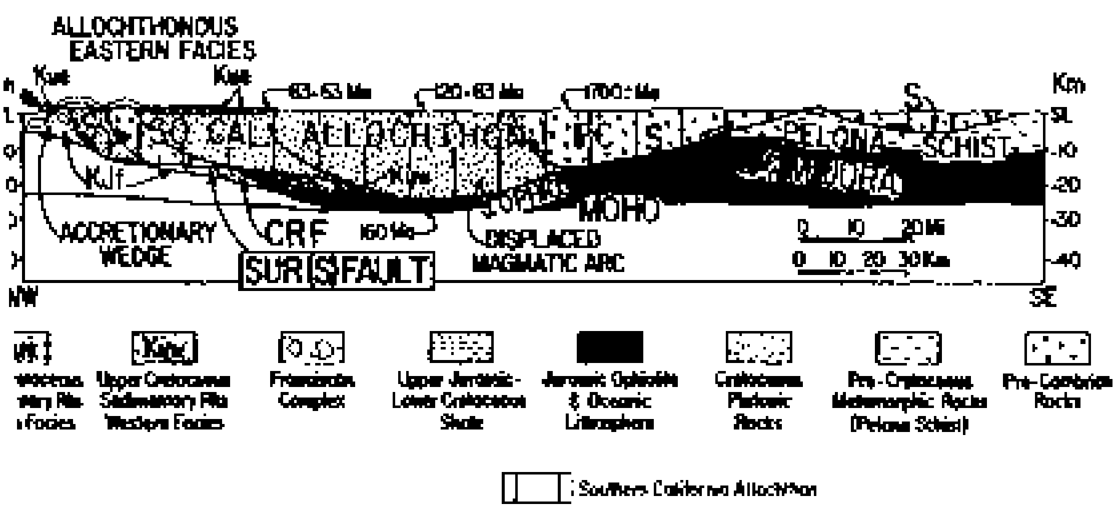
ABSTRACT

This volume delineates the Southern California allochthon (SCA) and proposes reconstruction of the pre-Eocene geology of western California. The reconstruction is based on: (1) the structural relations between the pre-Cretaceous igneous and metamorphic complexes and unconformably overlying Upper Cretaceous rocks of late Campanian–early Maastrichtian age and the structurally lower Franciscan Complex and associated slabs of Late Cretaceous age (possibly Cenomanian to Campanian in age) in the Point Sur–Lopez Point region of coastal western central California; (2) the restoration of offset stratigraphic assemblages of rocks along faults within the San Andreas fault system; and (3) the counterclockwise back-rotation of the Transverse Ranges.

In Late Cretaceous time the SCA was in eastern California and Arizona, with the generally north-south–oriented Coast Range fault and Cretaceous–early Tertiary subduction zone lying to the west. It is proposed that the Sur thrust forms the sole of the SCA, which includes Salinia. The allochthon was thrust westward or northwestward a minimum of 180 km (110 mi) from the Mojave and eastern Peninsular Ranges provinces of southwestern North America during early Paleocene time (Danian, ~65 to 62 Ma; and possibly early Ynezian, ~60 Ma) and perhaps during a second pulse in late Paleocene time (Bulitian, ~57 to 55 Ma). The allochthon was thrust over the Pelona Schist, Great Valley sequence, and Franciscan Complex. Thrusting occurred prior to the allochthon being slivered and translated northwestward along the San Andreas fault system, and possibly being flexed in the Santa Cruz oroclino during Neogene time. Today, the dismembered allochthon extends in the north from Point Arena, in northwestern California, southward to the Chocolate Mountains in southeastern California.

The driving force for moving the SCA northwestward or westward relative to the Sierra Nevada–Peninsular Ranges trend is hypothesized to have been provided by the conveyor beltlike action of oblique subduction that was accompanied by tectonic erosion of the underside of the allochthon.

Hall, C. A., Jr., Geology of the Point Sur–Lopez Point region, Coast Ranges, California: A part of the Southern California allochthon: Geological Society of America Special Paper 266.



Cross Section F-F' Showing Southern California allochthon lying above Sur fault

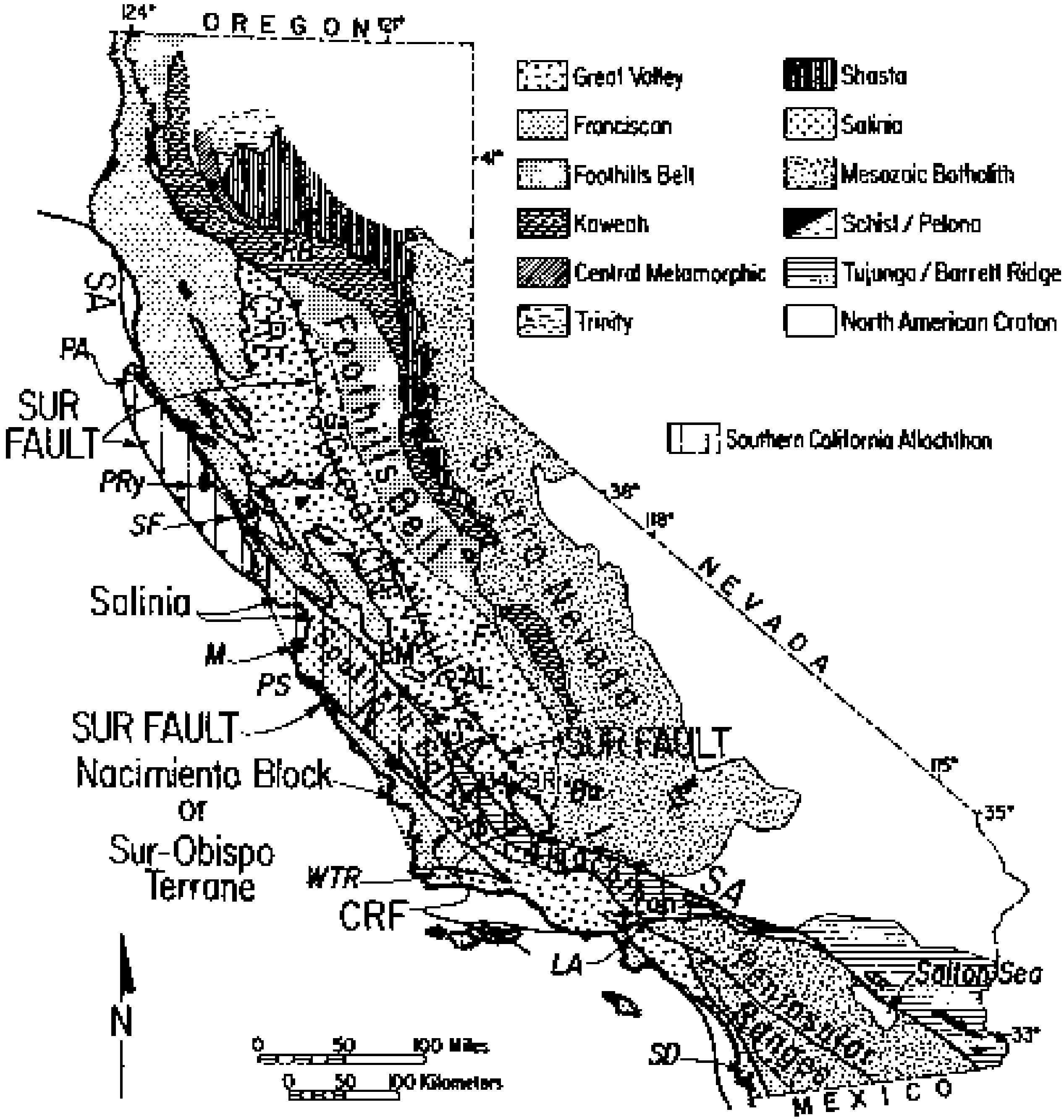


Figure 1. Stratigraphic terranes of a part of California. Modified and generalized from Blake and others (1982). Interpretations also based on American Association of Petroleum Geologists (1951, 1957, 1958 [Amerada Lawton, AL on map, well 58-26, sec. 26,T. 17S.,R. 19E., Upper Cretaceous rocks 1,190 m, or ~3,900 ft thick]); Fishburn and McJannett (1989) [well 934-29R on map, 2,238 ft south and 1,704 ft east from northwest corner sec. 29,T. 30S.,R. 23E.]; Page and others (1978); Ross and McCulloch (1979) [RM on map]. Upper Cretaceous rocks, 6,250 m, or ~20,000 ft thick; and Suppe (1978). See Plate 2a note for explanation of symbols.

The Southern Coast Ranges
by Ben Page
Department of Geology
Stanford University
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ABSTRACT

The Southern Coast Ranges include a subduction zone complex (the Franciscan), forearc basin sediments (the Great Valley Sequence), and a magmatic arc (plutonic and metamorphic rocks of the Salinian Block). These assemblages all contain quasi-contemporary Late Mesozoic rocks. The Salinian Block magmatic arc has been displaced hundreds of kilometers from its original position, and is now flanked tectonically on both sides by the Franciscan Complex. The NE boundary of the Block is the San Andreas fault, and the SW boundary is the Sur-Nacimiento fault zone.

The Franciscan Complex consists of melanges and large coherent rock units. Both oceanic and terrigenous materials are represented. Coherent units include bedded Cretaceous sandstone, chert-graywacke sequences, and Upper Jurassic chert-greenstone units. Melanges include blocks of similar materials, plus serpentinite, blueschist, conglomerate, and other rocks, all of which are enveloped in a pervasively sheared argillaceous matrix. Most of the clastic sedimentary rocks appear to have been derived from a Sierra Nevada-type active continental margin. Many of the coherent units and blocks in melanges have undergone blueschist-facies metamorphism resulting from high P/T conditions ascribed to subduction. Although these rocks evidently reached depths of 15 to 30 km, they avoided overheating and somehow returned to the surface. The rise to the surface was probably accomplished in part by the wedging action of tapered slices of "off-scrapings" and deformed slope deposits, but was more largely effected by subduction-driven viscous upward flow of subducted material (Cowan and Silling, 1978), coupled with buoyant rise influenced by a dense "hanging wall." Competent bodies in the subduction complex were dismembered, and the fragments were dispersed and mixed, possibly by the action of olistostromes on the inner trench slope plus recurrent partial subduction. Probably very large strike-slip movements affected the Franciscan during its evolution, but the details and timing are not understood, and the structural features that may have resulted from such events have not yet been recognized in the Southern Coast Ranges.

The Great Valley Sequence and its equivalents mainly consist of stratified terrigenous clastic sediment derived from the Klamath-Sierra Nevada terrane and its former southward continuation. Much of the sediment accumulated in deep-sea fans. The oldest parts of the GVS and its allochthonous counterparts are uppermost Jurassic and Lower Cretaceous and rest on an ophiolite basement beneath which the Franciscan has been thrust. The Franciscan was at first subducted beneath the GVS ophiolite, but probably in the Paleocene it was pushed farther under, en masse, creating the Coast Range thrust.

The out-of-place Salinian Block basement includes metasedimentary rocks that have not been definitely correlated with sequences elsewhere. Wherever these rocks originated, in the late Mesozoic they were situated between the sites of the Sierra Nevada and Peninsular-Baja California ranges, and they were invaded by granitic plutons forming a southward continuation of the axial belt of Cretaceous potassic Sierran intrusives. In the Paleocene (?) the Sierran-Peninsular plutonic belt was intersected obliquely by the ancestral San Andreas fault (essentially on the site of the present SAF) along which the Salinian Block moved 200 km northwestward, probably motivated by oblique plate convergence. During a long hiatus in this motion, Eocene marine sediments were spread across the SAF, and large movements were not resumed until the mid-Miocene (ca. 15 m.y.b.p.) Subduction had ceased at the latitude of the Southern Coast Ranges and was succeeded by a Neogene transform regime. The transport of the Salinian Block and motion along the SAF accelerated about 4.5 m.y.b.p. at the inception of spreading in the Gulf of California. Probably the northernmost part of the Block has moved 80 to 115 km farther than the main part, for a total of about 600 km. The extra motion was accomplished by slip on the San Gregorio-Hosgri fault, which transects the Block at an acute angle.

A large terrane that existed along the SW side of the Salinian Block has been lost, either by mega-strike-slip or by piecemeal subduction, probably in the Paleocene. This impressive but cryptic incident poses one of the major tectonic problems of the Southern Coast Ranges.

Neogene transform tectonics created en echelon compressional basins of deposition, en echelon folds, NW-trending strike-slip faults, and lesser E-W trending thrust faults. Some of these structures are probably still evolving, but this is only well documented for strike-slip faults. Average right-hand relative motion between the Pacific and North American plates appears to be 5.6 cm/yr in a N35W direction in the region of the Southern Coast Ranges (Minster and Jordan, 1978). Of the average annual motion, the SAF and its immediate neighbors may accommodate 3.2 to 3.7 cm/yr (Savage and Burford, 1973), the balance being distributed in a broad zone of deformation and slip.

An important enigma is posed by the Plio-Pleistocene formation and rise of individual ranges and the subsidence of structural valleys. These events took place within the Neogene transform regime, but cannot be readily explained by the familiar kinematics of transform tectonics.

Cretaceous Sinistral Strike Slip Along Nacimiento Fault in Coastal California[1]

WILLIAM R. DICKINSON[2]

ABSTRACT

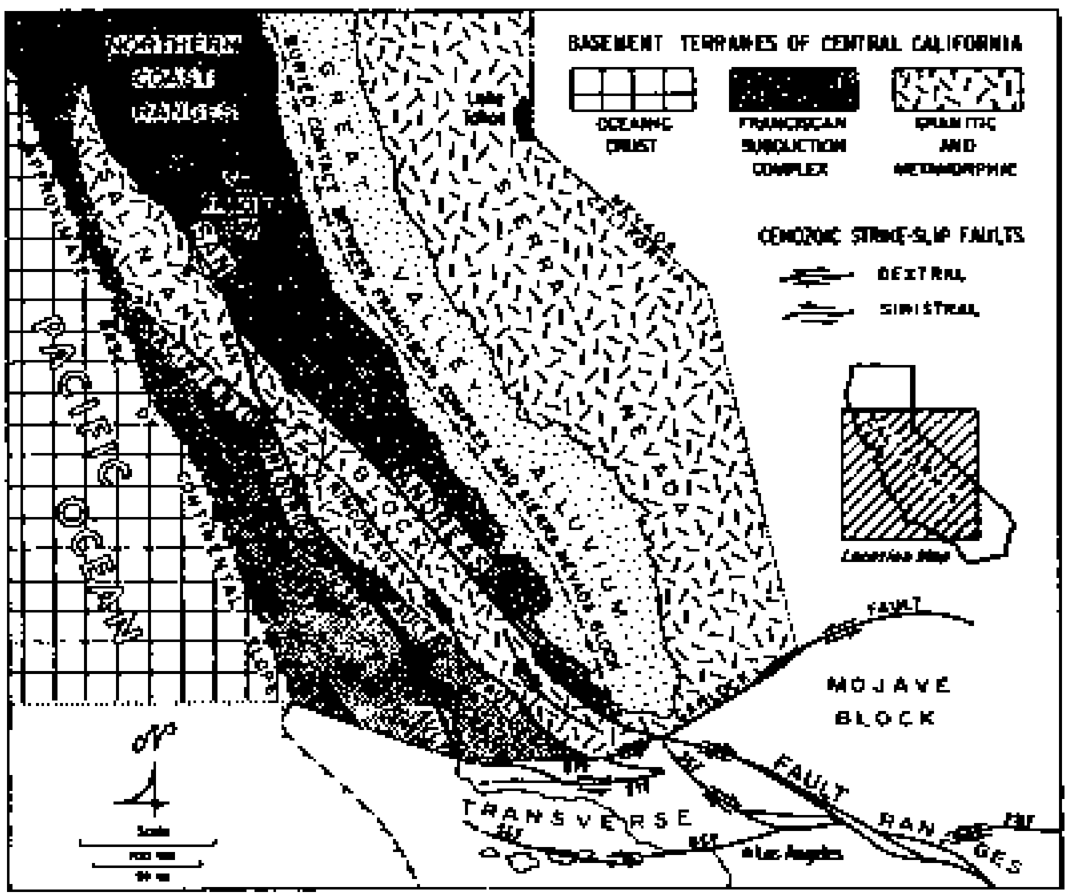


FIG. 1—Tectonic relations of Salinian block in coastal California. Fault abbreviations: BPF, Big Pine; MCF, Malibu Coast; PMF, Pine Mountain; SCF, Santa Cruz Island; SGF, San Gabriel; SYF, Santa Ynez. Offshore relations modified after Silver et al (1971) and Hoskins and Griffiths (1971). See Figure 4 for course of San Gregorio–Hosgri fault and Figure 7 for detail in western Transverse Ranges.

Regional Tectonics And Structural Evolution Offshore Monterey Bay Region

By H. Gary Greene

The tectonic and structural evolution of the Monterey Bay region of central California is complex and diverse. The region has been subjected to at least two different types of tectonic forces; to a pre-Neogene orthogonal converging plate (subduction) and a Neogene-Quaternary obliquely converging plate (transform) tectonic influence. Present-day structural fabric, however, appears to have formed during the translation from a subducting regime to a transform regime and since has been modified by both strike-slip and thrust movement.

Monterey Bay region is part of an exotic allochthonous structural feature known as the Salinian block or Salinia tectonistratigraphic terrane. This block is proposed to have originated as part of a volcanic arc a considerable distance south of its present location, somewhere in the vicinity of the southern Sierra-Nevada Mountain Range. It consists of Cretaceous granodiorite basement with an incomplete cover of Tertiary strata. Paleocene rocks are scarce, evidently stripped from the block during a time of emergence in the Oligocene time.

The Ascension-Monterey Canyon system, one of the largest submarine canyon systems in the world, is located on and adjacent to the Salinian block. The system is composed of two parts which contain a total of six canyons: 1) the Ascension part to the north, which includes Ascension, Año Nuevo and Cabrillo canyons, and 2) the Monterey part to the south, which includes Monterey Canyon and its distributaries, Soquel and Carmel canyons. The ancestral Monterey Canyon originated in early Miocene time, cutting east-west into the crystalline basement rocks. Since that time (~21 Ma), the Salinian block, riding on the Pacific Plate, moved northward along the San Andreas fault zone. During this period of transport the Monterey Bay region was subjected to several episodes of submergence (sedimentation) and emergence (erosion) that alternately caused sedimentary infilling and exhumation. The present configuration of the Ascension-Monterey canyon system is the result of tectonic displacement of a long-lived Monterey Canyon, with associated canyons representing the faulted offsets of past Monterey Canyon channels. Slivering of the Salinian block along several fault zones trending parallel or sub-parallel to the San Andreas fault zone (i.e., the Palo Colorado-San Gregorio fault zone) displaced to the north the westerly parts of Monterey Canyon. In this manner Monterey Canyon "fathered" many of the canyons to the north (i.e., Pioneer and Ascension canyons).

Tectonics continues to dictate the morphology and processes active in the canyon system today. Erosion has formed a seafloor physiography that is significantly greater in relief than onshore. The Palo Colorado-San Gregorio fault zone marks the continental shelf boundary in the Monterey Bay region and divides the canyon system into two parts, the Ascension and Monterey parts. The Monterey canyon part is youthful with heads that lie at, or close to, the shoreline and its present morphology is the product of active erosion originating near the canyon heads. This canyon system is the main regional conduit for the transport of terrestrial sediments to the abyssal plain. In contrast, the Ascension Canyon part heads far out on the continental shelf, far removed from the littoral drift, but still subjected to erosion from mass wasting, some possibly fluid induced.

Fluid Flow In The Offshore Monterey Bay Region

By **H. Gary Greene**
Moss Landing Marine Laboratories and Monterey Bay Aquarium Research Institute
Moss Landing, CA 95039,

Norman Maher, Thomas H. Naehr
Monterey Bay Aquarium Research Institute
Moss Landing, CA 95039

and

Daniel L. Orange
Department of Earth Sciences
Univ. California, Santa Cruz
Santa Cruz, CA 95064

Abstract

Fluid flow out of the seafloor offshore Monterey Bay region is extensive. To date 16 major active and ancient, or dormant, seep sites have been identified and many of these sites are composed of smaller sites too numerous to map at a regional scale. These seeps have been identified by the presence of chemosynthetic communities that are primarily composed of chemoautotrophic organisms or by carbonate deposition and buildups. Of the 17 identified sites, 9 active cold seep sites support living chemosynthethic communities. Seven major dormant seep sites have been identified based upon the presence of carbonate deposits or buildups.

Identified seep sites are primarily concentrated along fault trends associated with the boundary of the Salinian block or Palo Colorado-San Gregorio fault zone, and along the lower flanks and crests of tectonically uplifting slopes. A combination of transpressional squeezing and overburden pressures, vertical advection through hydrocarbon and organic-rich sediment, and seaward flow of meteoric waters supply fluids to the seep sites.

Introduction

Monterey Bay is located within the active transform boundary that separates the Pacific Plate from the North American Plate (Fig. 1). In central California this boundary is over 100 km wide and includes offshore faults of the Palo Colorado-San Gregorio and Monterey Bay fault zones (Fig. 2). These fault zones are seismically active and in many places offset the seafloor or Quaternary sedimentary rocks (Greene et al., 1973, 1989; Greene, 1977, 1990; McCulloch and Greene, 1990). The Palo Colorado-San Gregorio fault zone is a 200 km long fault zone that trends nearly N30^{0}W and defines the western boundary of the Salinian block in the Monterey Bay region (Page, 1970,; Page and Engerbretsen, 1984; Greene, 1977, 1990). The Salinian block is a sliver of southern Sierran granitic rocks that is being carried northward on the Pacific Plate, sliding along the San Andreas fault proper (Page and Engerbretsen, 1984).

The Monterey Bay region can be divided into two major physiographic and tectonic provinces; (1) an eastern allochthonous (Salinian) block and strike-slip fault sheared and slivered province and (2), a western allochthonous (San Simeon) block and transpressionally faulted and deformed or continental slope accretionary province (Greene et al., 1997). These provinces are separated by the Palo Colorado-San Gregorio fault zone, the local western boundary of the Salinian block (Fig. 1).

Figure 1. Generalized sketch map showing the allochthonous Salinian block of Sierran granitic basement rocks. Modified after Greene (1990).

The Palo Colorado-San Gregorio fault zone juxtaposes the Tertiary marine sedimentary rocks and their underlying Mesozoic basement units of the two allochthoneous blocks. West of the fault zone continental slope sediments are subjected to transpressional forces associated with the oblique convergence of the Pacific Plate against the North American Plate (Nagel and Mullins, 1983; Greene, 1990). Here Greene et al. (1997) and Orange et al. (1993, 1995, in press) interpret that two areas (Smooth ridge and Sur slope) are being uplifted by the oblique fault motion associated with the Palo Colorado-San Gregorio fault zone. This compression is probably causing interstitial fluids to migrate up through the sediments and seep out along the surface trace of the faults where extensive areas of carbonate slabs have been found.

Within the Salinian block, the Monterey Bay fault zone is comprised primarily of short (2-3 km long), discontinuous, en echelon faults oriented primarily NW-SE (Greene et al., 1973; Greene, 1977, 1990; Gardner-Taggart et al., 1993). Two longer faults within the Monterey Bay fault zone, the offshore extensions of the Chupines and Navy faults (25-30 km long offshore), mapped onshore near the towns of Seaside and Monterey (Rosenberg and Clark, 1994), are exceptions to this. These two faults generally define the boundaries of this fault zone which is restricted to Monterey Bay and the onshore area to the southeast, in the northern Santa Lucia Range. The Monterey Bay fault zone merges with the Palo Colorado-San Gregorio fault zone offshore of Santa Cruz and southward along the trend of Carmel Canyon (Fig. 2). Gardner-Taggart et al.

(1993) reports that two types of faults occur in the southern part of the Monterey Bay fault zone, strike-slip and thrust. The primary NW-SE oriented faults appear as right-lateral strike-slip faults, whereas conjugate faults are thrust faults that generally trend east-west. Rosenberg and Clark (1994) reported similar fault relationships onshore.

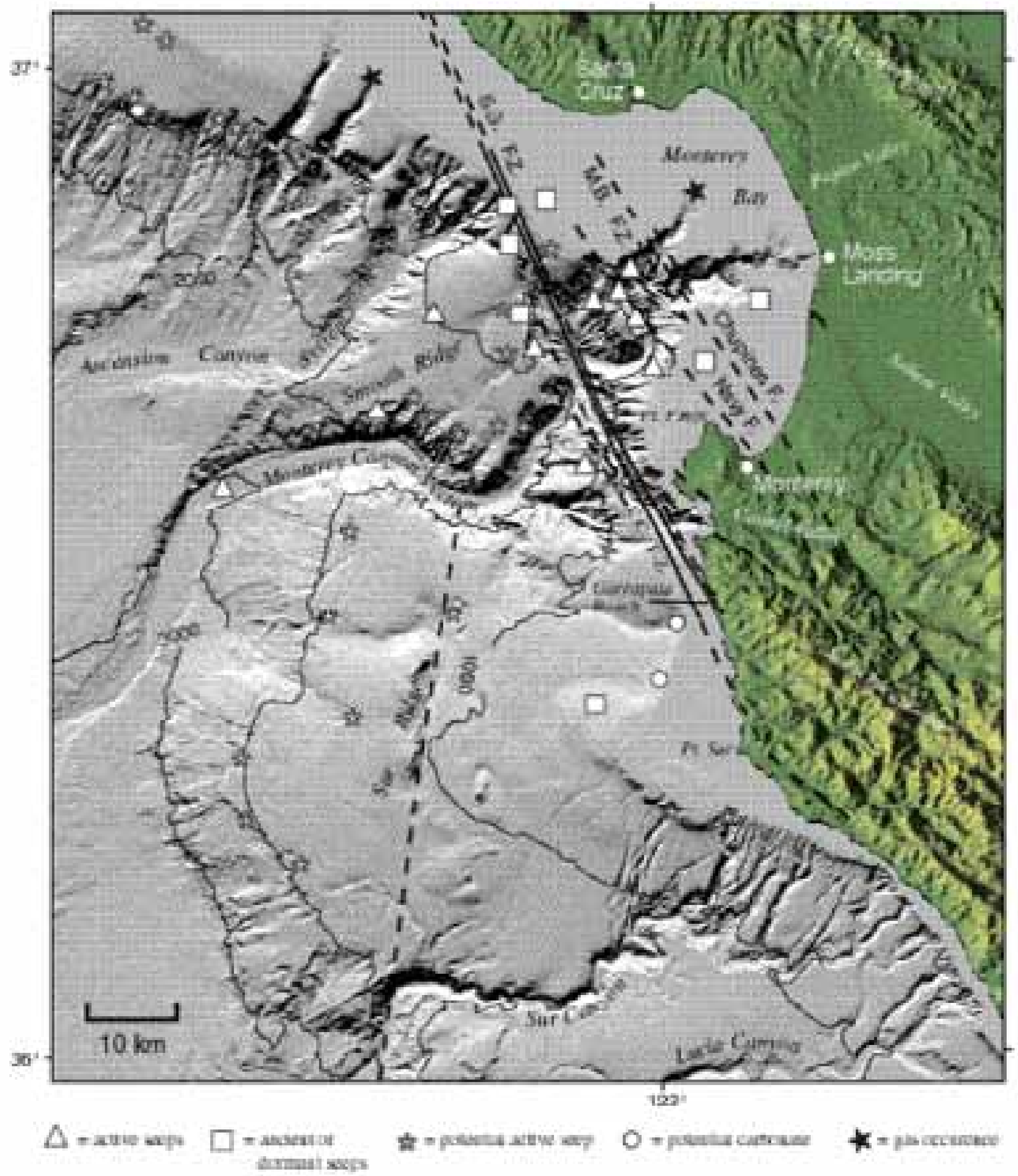


Figure 2. Physiographic map of the Monterey Bay region showing generalized geologic structure and sites of past, present and potential fluid flow and gas concentration on and in the seafloor. Offshore shaded relief map constructed from Simrad EM300 (30 kHz) multibeam bathymetric data collected by MBARI and the USGS; contour interval is 1000 m. Onshore topography from USGS DEM's. Black lines are active faults: solid lines where well defined and dashed lines where inferred. Long dashed black lines on mid-slope are surface expressions of inactive faults

Cretaceous granitic basement rocks of the Salinian block (Fig. 1) lie adjacent to the Franciscan complex west of the San Andreas fault (Jennings and Burnett, 1961) and are thought to underlie the Tertiary marine and Quaternary continental slope deposits west of the Palo Colorado-San Gregorio fault zone (Greene, 1977, 1990; Mullins and Nagel, 1981; Nagel et al., 1986). Offshore in the Monterey Bay region, approximately 1,790 m of Tertiary strata overlie the Cretaceous basement rocks and about 570 m of Quaternary sediments overlie the Tertiary strata, totaling about 2,360 m of sedimentary rocks overlying basement (Greene, 1977).

East of the Palo Colorado-San Gregorio fault zone in northern Monterey Bay about 550 m of the Monterey Formation unconformably overlie Cretaceous granitic basement rocks (Greene, 1977; 1990). Unconformably overlying Monterey is about 370 m of upper Miocene Santa Margarita sands and 200 m of the Santa Cruz Mudstone, a well layered diatomaceous mudstone of middle Miocene age. Unconformably overlying the Santa Cruz Mudstone is approximately 670 m of the Pliocene Purisima Formation which, in turn, is either exposed on the seafloor or covered by Pleistocene deltaic and alluvial deposits or Holocene shelf deposits that can total up to 670 m thick (Fig. 3).

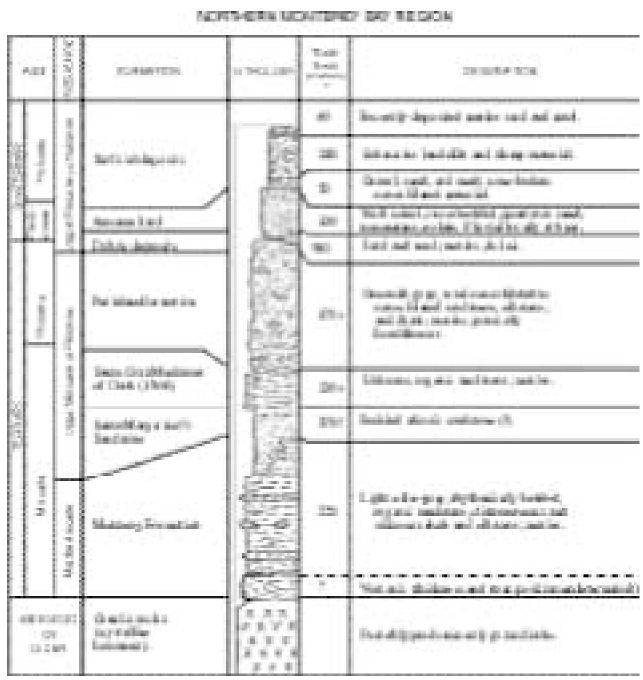


Figure 3. Composite stratigraphic section of the northern Monterey Bay region, east of the Palo Colorado-San Gregorio fault zone. Thickness based on continuous single channel seismic reflection profiler data. Modified after Greene (1977, 1990) and on ROV and submersible observations.

East of the Palo Colorado-San Gregorio fault zone in southern Monterey Bay as much as 850 m of Neogene sedimentary rocks and 630 m of Quaternary sediments are piled an average of 1,480 m above the basement (Fig. 4). The sedimentary units of this sequence total approximately 640 m of the Monterey Formation, a porcelaneous and diatomaceous mudstone sequence of Miocene age rich in hydrocarbons. This formation is either exposed on the seafloor or is unconformably overlain by up to 210 m of the Purisima Formation, a nearshore marine sandstone of Late Miocene to Pliocene age (Fig. 4). Overlying the Purisima Formation are local deposits of Pleistocene deltaic, aeolian, alluvial and Holocene shelf sediments that total more than 630 m.

Figure 4. Composite stratigraphic section of the southern Monterey Bay region, east of the Palo Colorado-San Gregorio fault zone. Thickness based on continuous single channel seismic reflection profiler data. After Greene (1977).

During the summer of 1998, MBARI in conjunction with the USGS undertook an extensive bathymetric survey of the Monterey Bay offshore region using a Simrad EM300 (30 kHz) multibeam system mounted aboard the M/V Ocean Alert. The purpose of this survey was to define the seafloor physiography and geomorphology at a resolution that allows identification and investigation of geologic, biologic and chemical features using MBARI's ROVs Ventana and Tiburon. Over 17,000 km^2 of continental shelf, slope and rise were covered.

Evidence Of Fluid Seeps

In the Monterey Bay region 16 major seafloor sites, many composed of several scattered smaller sites, of fluid seeps have been identified by the presence of chemosynthetic communities primarily composed of chemoautotrophic organisms that are dependent upon thiotrophic symbionts or by carbonate deposition and buildups (Fig. 2). The chemosynthetic communities consist of vesicomyid clams, vestimentiferan worms and free-living bacteria that are dependent upon sulfide-rich fluids for life support and thus indicate present-day seep activity. Carbonate deposits typically represent ancient seeps, although some carbonates were found in the vicinity of current chemosynthetic communities and may be forming today (Orange et al., in press; Stakes et al, in press).

Cold-seeps, both fossil and active are being discovered on a regular basis today along active convergent plate margins. Deep water chemosynthetic communities were first noticed during the discovery of hydrothermal vents along the Galapagos Ridge in 1977 (Corliss et al., 1979). Chemosynthetic communities similar to those found at hydrothermal vents, but associated with "cold" seeps, have been reported offshore of Louisiana (Bright et al., 1980; Kennicutt et al., 1985), along the Florida Escarpment (Paull et al., 1984), within Sagami Bay, Japan (Okutani and Egawa, 1985; Hashimoto et al., 1987, 1989), offshore Oregon (Suess et al., 1985; Kulm et al., 1986; Ritger et al., 1987), and in the Japan Trench (Laubier et al., 1986; Le Pichon et al., 1987, Pautot et al., 1987; Cadet et al., 1987; Ohta and Laubier, 1987), to mention a few studies. Many cold seep communities appear to be associated with dynamic geological processes such as tectonically induced high fluid pressures in compressional regimes (Kulm et al., 1986, 1990), artesian springs (Paull et al., 1984; Robison and Greene, 1992), hydrocarbon or natural biogenic seeps (Brooks et al., 1987; Kennicutt et al., 1989; Hovland and Judd, 1988), or mass wasting (Mayer et al., 1988).

Chemosynthetic Communities – Indicators of Active Seeps

Cold seep communities were discovered in the Monterey Bay region during Alvin dives and bottom-camera tows in Monterey and Ascension Fan Valleys in 1988 (Embley et al., 1990;

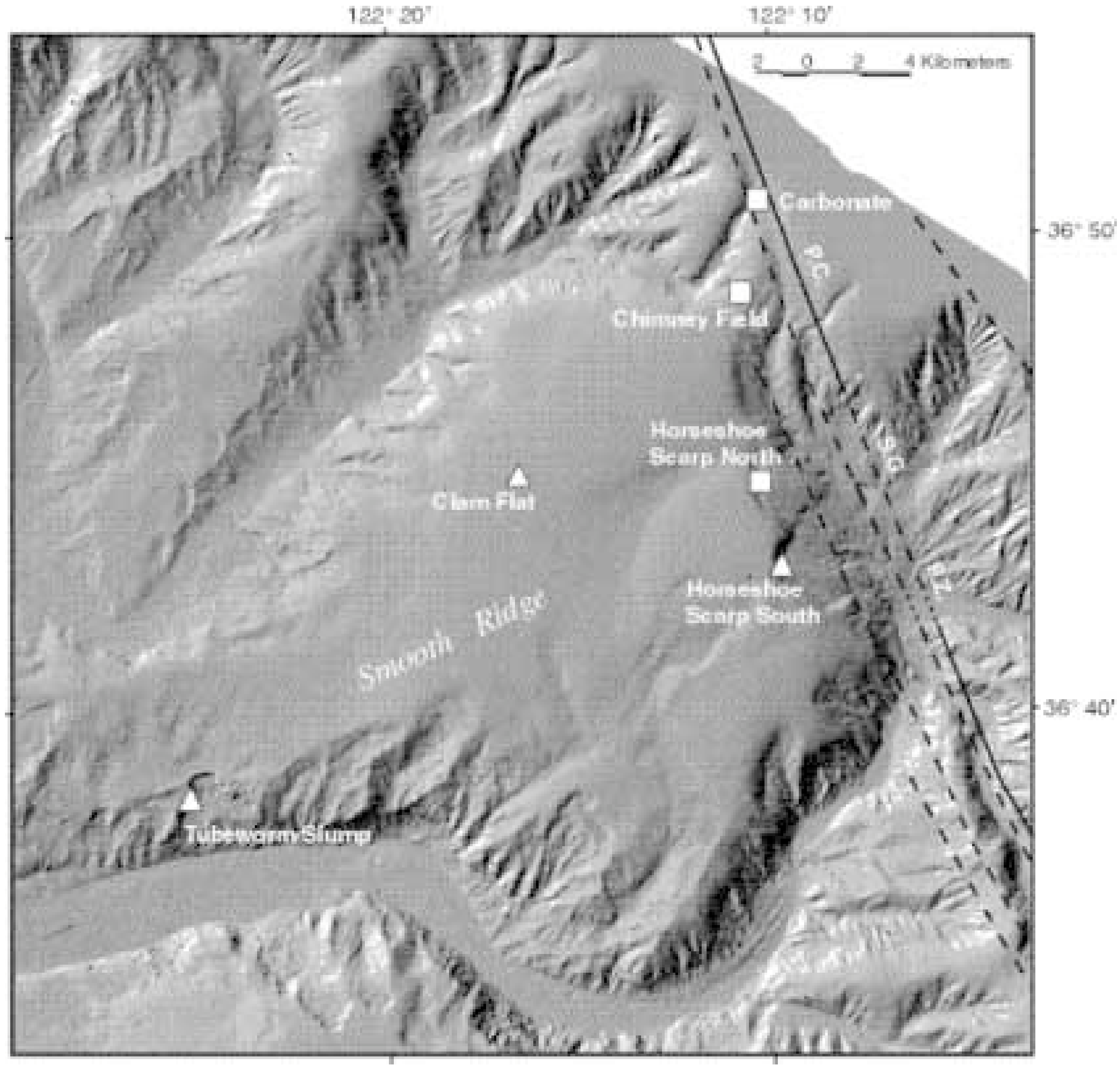


Figure 5. Shaded relief map of Smooth Ridge constructed from MBARI EM300 bathymetry showing seafloor morphology, faults and seep sites. Triangles represent active seeps; squares indicate ancient seeps.

McHugh et al., 1997). Since then several additional cold seep sites have been observed and sampled in Monterey Canyon and along the offshore fault zones and continental slope using the Monterey Bay Aquarium Research Institute's (MBARI) remotely operated vehicle (ROV) Ventana (Barry et al., 1993).

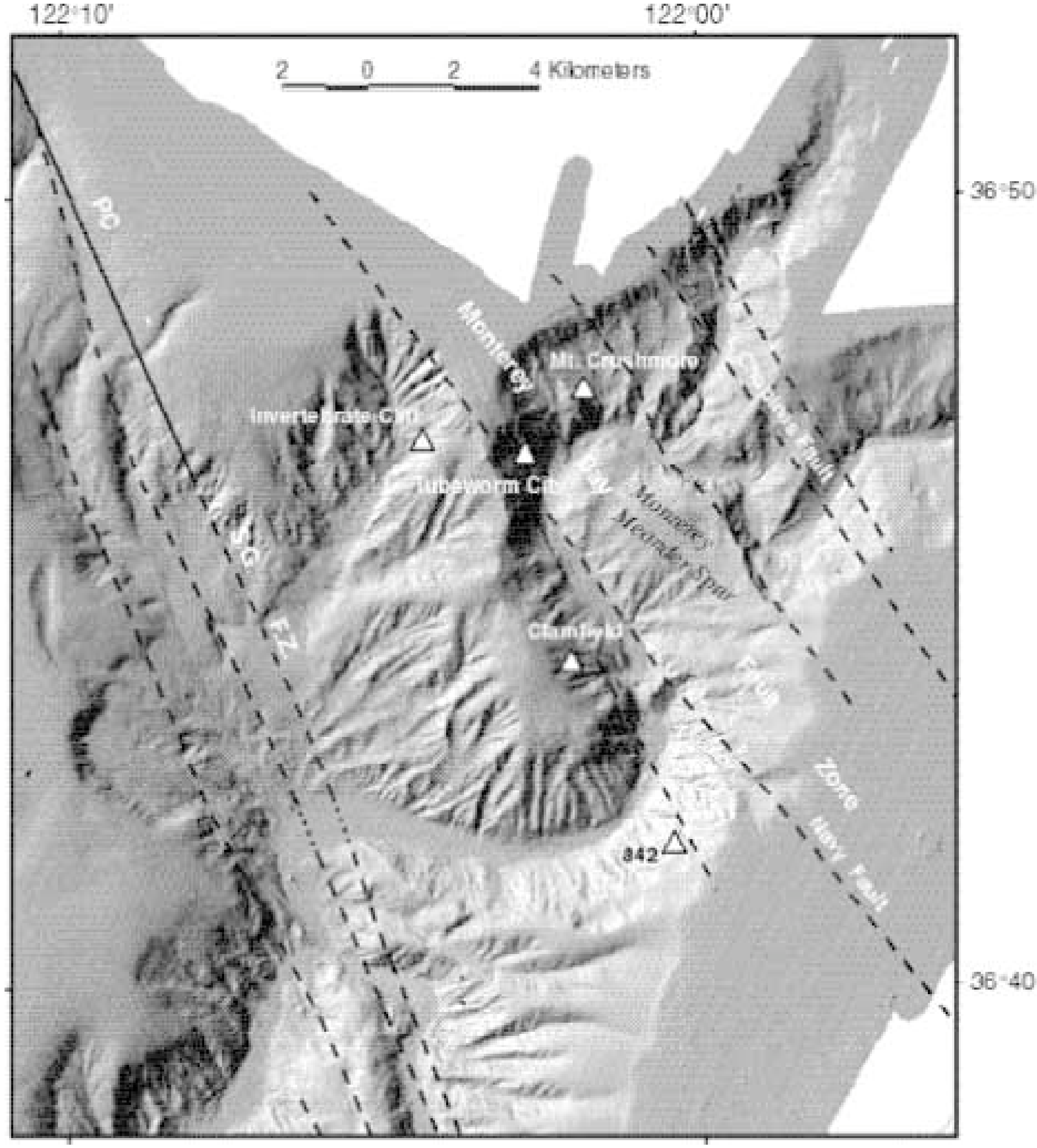


Figure 6. Shaded relief map of the Monterey meander and spur located within the middle part of Monterey Canyon. Seafloor morphology, faults, and active seep sites are shown and labeled. Map constructed from MBARI/USGS EM300 mulltibeam bathymetry.

Barry et al. (1993, 1996, 1997) and Greene et al. (1997) divide the biota inhabiting cold seeps of the Monterey Bay region as including ‘obligate’ species, restricted to sites in direct proximity to fluids rich in sulfide, methane, or perhaps other reduced inorganic compounds (e.g. ammonia; Fisher 1990), and ‘regional’ species that are found at seeps, as well as local non-seep habitats. Obligate species may be chemoautotrophic (e.g. Beggiatoa), or have thiotrophic or methanotrophic symbionts (e.g. vesicomyid clams, mytilid mussels, and vestimentiferan worms), but also may be heterotrophic and rely nearly exclusively on chemosynthetic fauna (e.g. galatheid crabs [Munidopsis? sp.], gastropods [Mitrella sp.], limpets [Pyropelta sp.]). Regional fauna may forage on chemosynthetic biota (e.g. Neptunia amianta, lithode crabs), but range throughout regional benthic environments and are clearly not dependent trophically on chemosynthetic production.

Distribution of Seeps West of the Salinian Block

West of the Salinian block, west of the Palo Colorado-San Gregorio fault zone and within the eastern compressional province, four well defined cold seep sites which support active chemosynthetic communities are known (Fig. 2). The deepest site is located within the proximal Monterey Fan Valley at a water depth of ~3,200 m (Plate 1, A). Here the source of the sulfide-rich fluids that sustain the biota appear to come from either compressional dewatering of sediment under convergent compression or from buried organic sources deposited in channel fill (Embley et al., 1990; Greene et al., 1997).

Three distinct cold seep sites (Clam Flat, Horseshoe Scarp-South, Tubeworm Slump in Fig. 5) that support chemosynthetic communities have been identified on Smooth Ridge (Barry et al., 1993; Greene et al. 1997; Orange et al, in press), a smooth sediment covered ridge that separates the Monterey Canyon system from the Ascension Canyon system and makes up the continental slope immediately west of Moss Landing (Figs. 2 & 5). The site known as “Clam Flat” (Barry et al. 1996, 1997; Greene et al., 1997; Orange et al., in press) is located between 980 and 1,010 m deep along the crest of Smooth Ridge.

Barry et al. (1996) described the vesicomyid clam Calyptogena kilmeri as the dominant obligate taxa at Clam Flat (Plate 1, B). Tectonic compression at this site results in “squeezing” of the sediment package and outflow of CO_2-saturated interstitial fluid according to Barry et al. (1996), Greene et al. (1993), Orange et al. (1993) and Martin et al. (1997). Apparently fluid expulsion in this area promotes surficial carbonate precipitation and the release of sulfide and methane-rich fluids at the sediment-water interface, in close proximity to where aggregations of thousands of live clams are located (Barry et al., 1996)

Pore water analyses of push core sediment samples taken on Smooth Ridge at Clam Flat showed elevated levels of sulfide and methane (Orange et al., in press). Isotopic analyses of authogenic carbonate precipitates by Stakes et al. (in press) from carbonate samples indicate the presence of methane and report isotopic values of –48.8 ‰ to -52.6 ‰ (PDB) for ^{13}C and of +4.05 ‰ to +5.19 ‰ (PDB) for ^{18}O whereas oxygen isotopes indicate precipitation at or near ambient seafloor temperatures. Martin et al. (1997) interprets the presence of the fluids at Smooth Ridge as being derived from both shallow and deep sources based on the presence of higher order hydrocarbons. These authors state that pore fluids outside the Clam Flat seeps include thermogenic methane and within the seeps fluids are of a mixed biogenic-thermogenic origin.

The two other active cold seep sites located west of the Palo Colorado-San Gregorio fault zone lie along the eastern and southern flank of Smooth Ridge (Fig. 5; Orange et al., in press). One of these two sites is known as “Horseshoe Scarp-South” and is located near the upper eastern edge of the ridge at about 800 m deep along an area faulted and deformed by the Palo Colorado-San Gregorio fault zone. At this locality, Orange et al. (in press) reports cold seep chemosynthetic clams and surface parallel authigenic carbonate deposits. The second seep site is located in the secondary head scarp of a recent slump near the lower southern flank of Smooth Ridge in 2,310 m of water and is known as “Tubeworm Slump” (Fig. 5). Here the existence of Vestimentiferan tubeworms and authogenic barite deposits indicate an active cold seep (Naehr et al., 1998).

All of the active seep sites on Smooth Ridge appear to result from dewatering of accretionary-like sedimentary units squeezed against the Salinian block by motion of the Pacific Plate (Figs. 2 & 5; Nagel and Mullins, 1983; Greene et al, 1990; Orange et al., 1994, in press; Barry et al, 1996). A combination of uplift and compression leading to dewatering appears to be responsible for fluid-induced mass wasting along the flanks of Smooth Ridge.

Distribution of Seeps on Salinia

East of the Palo Colorado-San Gregorio fault zone distinct evidence of fluid seepage along faults of the Monterey Bay fault zone and bedding planes of the Purisima Formation exposed along the northern wall of Monterey Canyon consists of sites where metal oxidizing bacterial mats and/or chemosynthetic communities occur (Figs. 2 & 6). Greene (1997) and Orange et al. (in press) proposed that these fluids could be sulfide-rich aquifer waters in the Purisima Formation that originate in the Santa Cruz Mountains northeast of Monterey Canyon and/or fluids that circulate through the hydrocarbon-rich Monterey Formation. Oxygen isotopic analyses of carbonate deposits sampled at some of these seeps do not indicate fresh water flow (Stakes et al., in press). They conclude that hydraulic connectivity to fresh water aquifers does not force fluid flow at the seeps and that the carbon isotopic values indicate that the carbon source is sedimentary, and that lateral transport of particulate organic carbon dominates fluid flow at the canyon head sites.

Of the five confirmed active seep sites found on the Salinian block, three (Mt. Crushmore, Tubeworm City, Clam Field; Fig. 6) are located along the northern wall of Monterey Canyon within Monterey meander and opposite the Monterey meander spur, within the Monterey Bay fault zone (Fig. 6). The fourth site (Invertebrate Cliff) is located within the extensive mass wasting field and canyon complex that has formed between the Monterey Bay and Palo Colorado-San Gregorio fault zones (Fig. 2).

The shallowest seep site is at a depth of 550-700 m and is located at the confluence of Monterey and Soquel submarine canyons, in a region of intense deformation associated with movement along faults within the Monterey Bay fault zone (Greene et al., 1997; Barry et al., 1996). The site is known as “Mount Crushmore”, a name that reflects the shatter ridge-like structure that has been produced from cross-faulting and thrusting within the fault zone. Here bacterial mats and clams buried deeply within black hydrogen sulfide-bearing mud form 0.25-3 m diameter patches of seep communities that stretch for approximately 1 km along the NW-SE trend of the faults in this location (Plate 1, C). Gray bacterial crusts or authigenic carbonate precipitates are common to all seep patches (Barry et al., 1996). The vesicomyid clam Calyptogena pacifica and bacterial mats are the most conspicuous biota found at this site (Barry et al., 1996) (Plate 1, D). Stakes et al. (in press) and Orange et al. (in press) report that pore waters contain moderate sulfide and extremely low methane concentrations.

The second site is known as "Tubeworm City," named after Vestimetifera tubeworms found there. This site is structurally similar to the Mount Crushmore site and is located in water depths of 610 to 810 m along the outer western wall of the Monterey meander. Barry et al. (1996), Greene et al. (1997) and Orange et al. (in press) show that active cold seeps are scattered within crevices and fault gullies in the Monterey Canyon walls that ring the apex of the Monterey meander (Fig. 6). This is an area where several faults of the Monterey Bay fault zone, including the Navy and Chupines faults, cut through the walls of the canyon.

Two other active seep sites exist on the outer western wall of the Monterey meander and are aligned along the trend of the Navy fault within the Monterey Bay fault zone (Fig. 6). The third site is known as "Clamfield" and is located along the outer wall of the Monterey meander in 875-920 m of water, centered at 896 m, is 2 m wide and 150 m long trending E-W. This site lies along the Navy fault trend and is composed of a dense aggregation of Calyptogena sp. clams concentrated in muds overlying the Monterey Formation (Barry et al., 1996). At Clamfield the communities may depend upon a sulfide source within the Miocene Monterey Formation. Here Ferioli (1997) found that the fluids are salt water derived.

The fourth site is called "Invertebrate Cliff" named after clams found there. This site lies in water depths of approximately 900 to 1,100 m (Fig. 6). Because the site has just recently been discovered, no detailed descriptions have been reported. We interpret the community to be sustained by fluids seeping out along the offshore extension of the Navy fault.

The fifth seep site (842 in Fig. 6) is located along the southern wall of Monterey Canyon, just south of the eastern flank of the Monterey meander spur. Stakes et al. (in press) report that faulted granitic rocks exposed along the southern wall of Monterey Canyon in this area is occasionally covered with bacterial mats.

Ancient Carbonate Deposits - Indicators of Past Fluid Flow

Seven major fossil or dormant seep sites have been identified based on the existence of carbonate deposits or buildups. Five of these sites either lie on, or in close proximity to, the western margin of the Salinian block, along the Palo Colorado-San Gregorio fault zone, or on Smooth Ridge and the upper flank of Sur slope (Fig. 2). Two other sites are located on the Salinian block, on the shelf of southern Monterey Bay.

West of Salinia

Using side scan sonar data along with *in situ* observations and sampling from MBARI's ROV Ventana, three major areas of fluid-produced carbonate deposits have been identified near the head of Smooth Ridge (Fig. 5; McHugh et al., 1997; Orange et al., in press; Stakes et al., in press). These deposits occur along the trend of the offshore extension of the San Gregroio fault zone, both east and west of the main fault strands. Although many areas are devoid of living chemosynthetic biota, they are underlain by carbonate cemented sediment. Orange et al. (in press) describe carbonate layers on the seafloor along the western margin of the San Gregorio fault zone and large (5 m x 2 m x 1 m thick) rectangular blocks of carbonates along the eastern margin of the fault zone that are randomly scattered and oriented.

In other areas along the Palo Colorado-San Gregorio fault zone (Fig. 5), on the outer continental

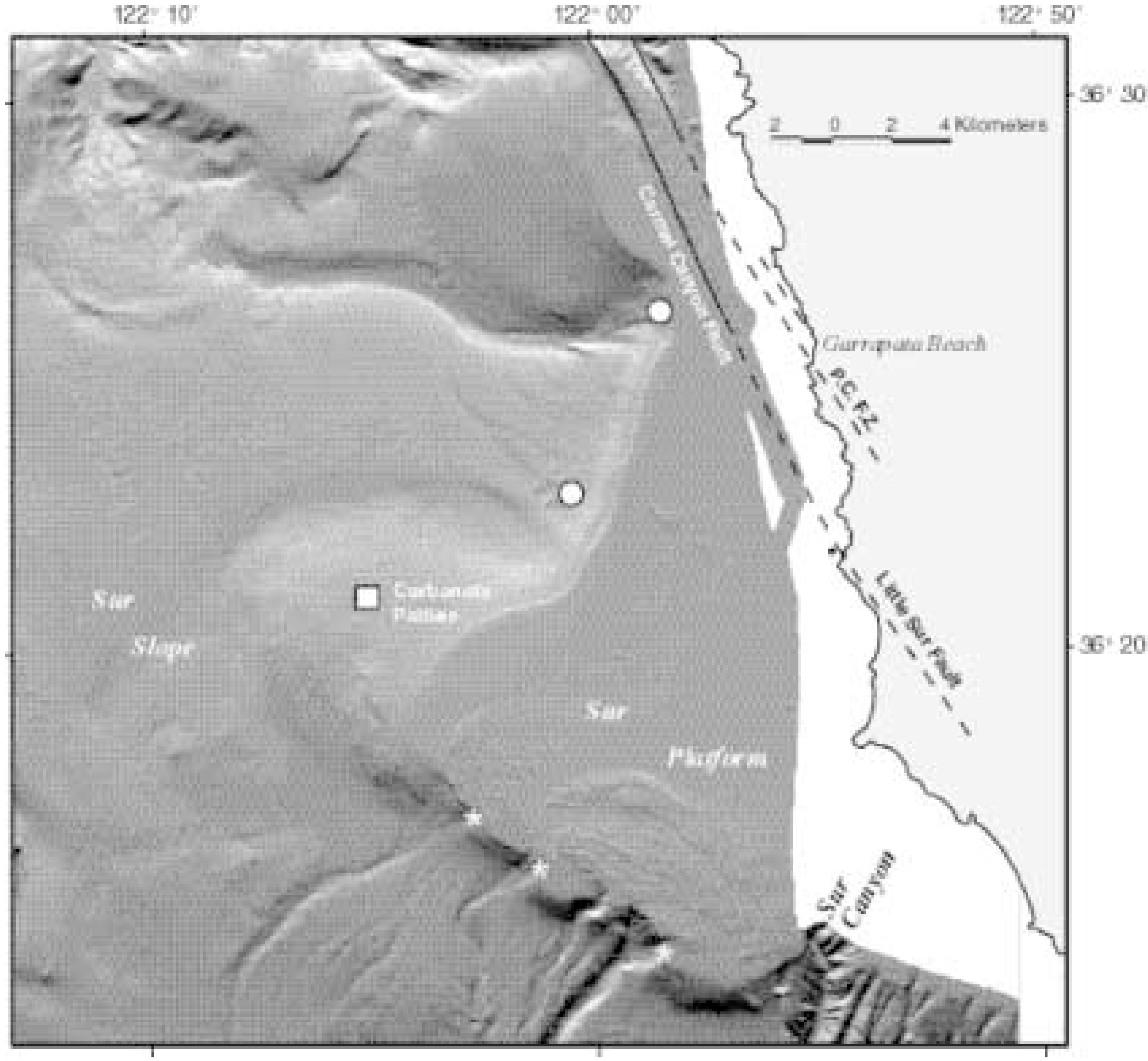


Figure 7. Shaded relief map of the Sur Ridge area showing seafloor geomorphology and seep sites. Image constructed from MBARI/USGS EM300 multibeam bathymetry. Ancient seep sites indicated by squares, potential seep sites by astricks and possible carbonate deposits by circles.

shelf NE of Smooth Ridge, Orange et al. (in press) describe en echelon carbonate ridges a few centimeters wide and high and about 10 m long and trending N-S. Brachiopods are often attached to the carbonate deposits. At sites where no carbonate deposits crop out on the seafloor yet extensive patches of brachiopods occur, we found hard carbonate substrate about 8-10 cm beneath the seafloor. Petrographic analyses reported by Orange et al. (in press) indicate that the carbonates in this area are composed in part of micritic to sparitic calcite and brachiopod shell hash with framboids of sulfide and inclusions of hydrocarbons. Push cores obtained with the ROV Ventana contained minor amounts of hydrocarbons. Orange et al. (in press) concluded that methane seepage is probably dormant, although earlier methane seeps did produce the carbonate deposits.

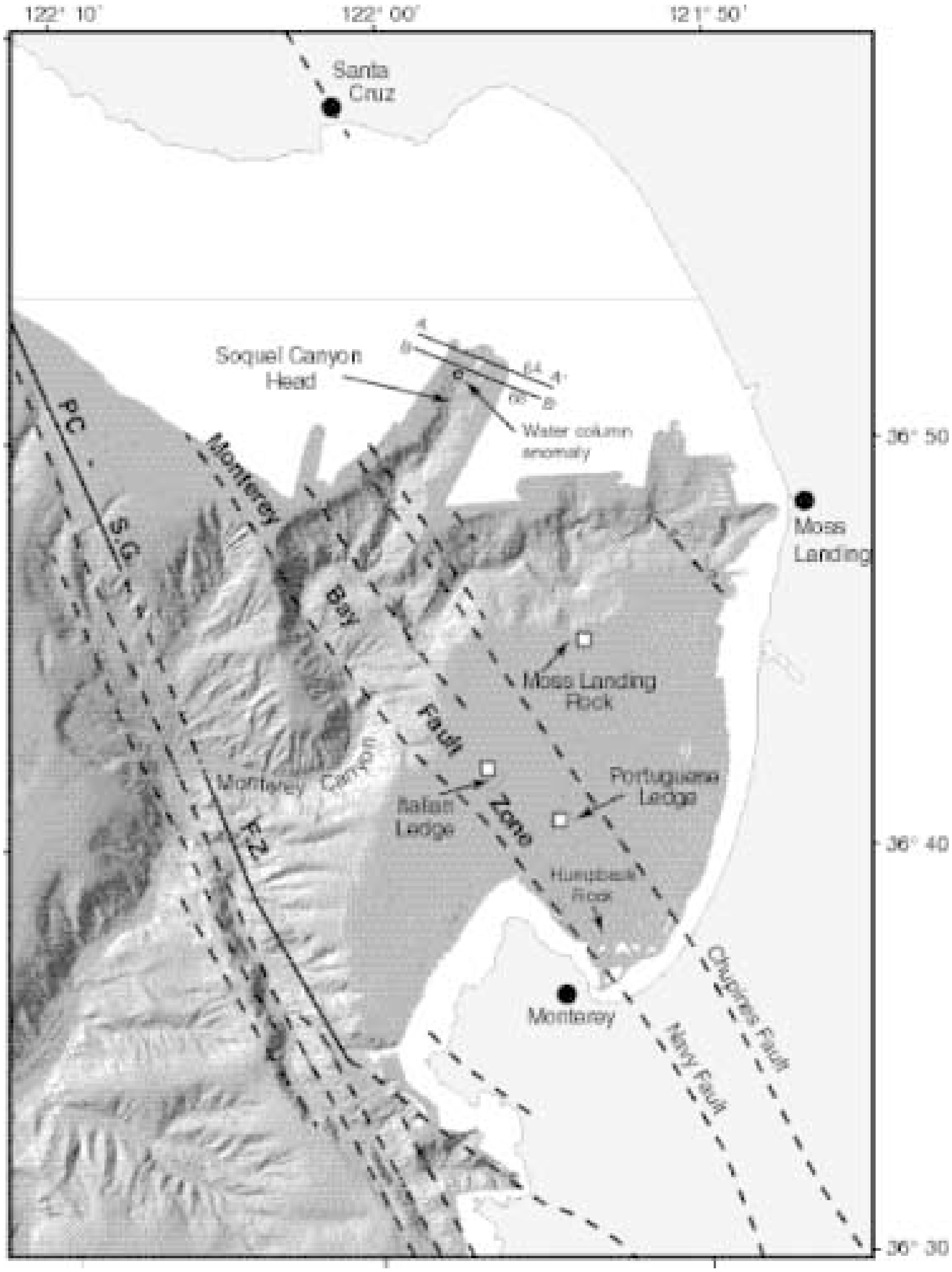


Figure 8. Shaded relief map of the headward part of Monterey Canyon and the Monterey Bay shelf showing seafloor geomorphology, faults and locations of carbonate deposits (squares). Map constructed from USGS EM1000 and MBARI/USGS EM300 multibeam bathymetry.

Two other areas of past fluid seepage were identified on Smooth Ridge. One site, known as "Chimney Field", is located on the upper northern flank of the ridge, at the base of a slump head scarp (Fig. 5). Broken carbonate chimneys (as large as 1.5 m long x 0.6 m in diameter and in the form of doughnut-like features) lying on their sides are concentrated in this area. Orange et al. (in press) and Stakes et al. (in press) report that the isotopic composition of the carbonates range from -55.9 ‰ to -11.8 ‰ (PDB) for ^{13}C and +3.44 ‰ to +6.82 ‰ (PDB) for ^{18}O. Oxygen isotopic analyses indicate that precipitation took place at near ambient seafloor temperatures.

The other site is known as “Horseshoe Scarp-North” and is located along the eastern margin of Smooth Ridge, a fault truncated boundary (Fig. 5). Authigenic slope parallel carbonate slabs are found near the base of the head scarp of the slump here. No biologic communities indicative of present-day fluid flow were found (Orange et al., in press).

A Fourth site is located in about 400 m of water along the upper northern flank of Sur slope (Figs. 2 & 7). Carbonate “patties” (Plate 1, E) are scattered about the slope in this locality and suggest that past fluid flow has occurred in this area (Waldo W. Wakefield, pers. Commun. 1998).

On the Salinian Block

Three major sites of past fluid flow are located on the Salinian block and two are found on the southern Monterey Bay shelf (Fig. 2). One of the three sites lies within the Monterey Bay fault zone, between the offshore extensions of the Navy and Chupines faults (Fig. 8). Side scan sonar and seismic reflection profile data, as well as submersible diving observations and sampling, indicate that a carbonate mound (80 m x 40 m x 4 m high), that incorporates Pleistocene gravels, formed on top of faulted and tilted beds of the Monterey Formation since the last rise in sea level (Plate 1, F). This mound is located in a major fishing ground known as Portuguese Ledge in water depths of 90 m. Simrad EM1000 swath bathymetry data collected by the U.S. Geological Survey (Ettreim et al., 1997; Edwards et al., 1997) indicate that Portuguese Ledge and nearby Italian Ledge, are partially composed of carbonate mounds and angular blocks forming “hard ground” critical to rockfish habitat (Fig. 8).

Oxygen and carbon isotopic analyses of the carbonate cement sampled from the mound at Portuguese Ledge yielded ^{18}O values of -6.01 ‰ to -6.06 ‰ (PDB) and ^{13}C values of -9.77 ‰ to -10.04 ‰ (PDB) (K.C. Lohman, Univ. of Michigan, Written Commun., 1996). Stakes et al. (in press) obtained similar values from a sample collected in the same area, which range from values of -5.81 ‰ to -5.68 ‰ (PDB) for ^{18}O and values of -10.01 ‰ to 10.21 ‰ (PDB) for ^{13}C. These data suggest meteoric water sources and based on this, along with interpretation of geophysical data and *in situ* seafloor observations, we speculate that fresh water fluids flowed offshore along a fault and then along fault-tilted bedding planes to the seafloor where the carbonate mound formed. Because the carbonate mounds found at this location contain Pleistocene gravel, we speculate that seeping occurred before or shortly after the last transgression started, ca 7000 BP.

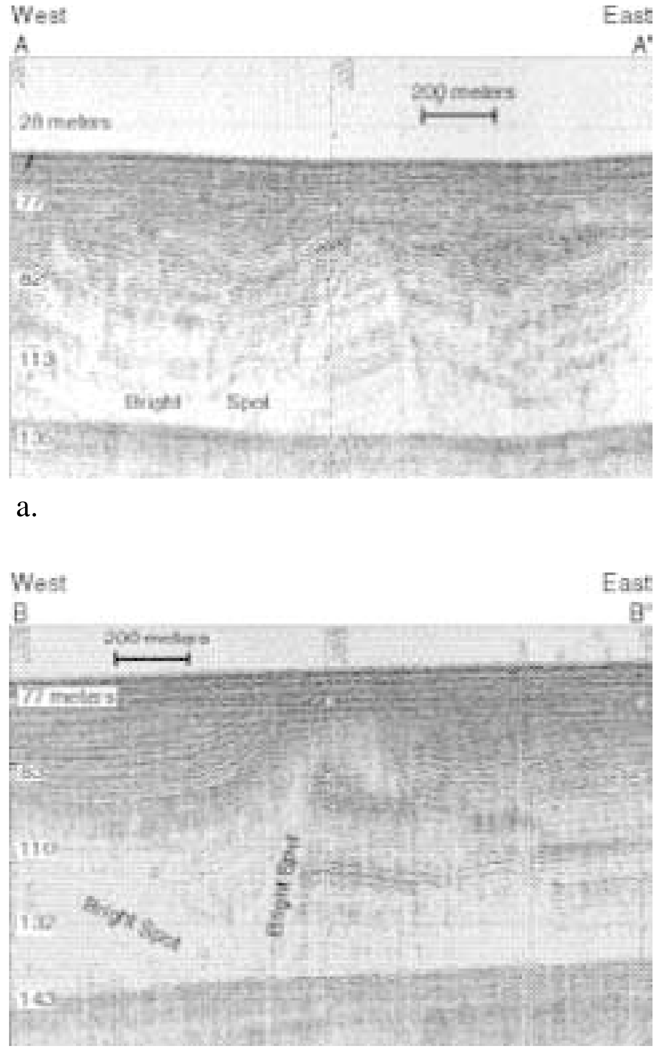
The second site is located along the shelf break at the top of a slump head scarp, at the top of the southern headward wall of Monterey Canyon (Fig. 8). The EM300 multibeam bathymetry data show several rounded mounds that stand about 4 m above an otherwise flat seafloor 90-100 m deep (Fig. 8). In addition, 100 kHz side scan sonar data show a high reflectivity bottom composed of

concentric reflectors that dip away from a gently uplifted center indicating that the seafloor here is domed and composed of thin sheets of hard ground. Dredge haul samples of well lithified gravel cemented by spary calcite (Robert E. Garrison, Pers. Commun., 1998) were collected from this locality. Based on the exposures of fresh water aquifers (180 foot and 400 foot aquifers in the Aromas Red Sands and the deep aquifer in the Purisma Formation) exposed along the slump scarp, we suspect that the carbonate precipitation resulted from the flow of fresh water. Also, just below the shelf break in the slump head scarp, side scan sonar and EM 300 bathymetric data show a series of linear reflectors and ROV observations show that these reflectors correspond with extensive flat lying tabular beds of $CaCO_3$ exposed in the upper wall of the canyon. These beds form overhangs and ledges.

Stakes et al. (in press) described an area (site 842 in Fig. 6) in northern Monterey Bay, along the western edge of the Monterey Bay fault zone, where crusts of $CaCO_3$ were identified. These authors also noted that sometimes bacterial mats are found here as well and that several other minor associated sites in this area contain carbonates that were not occupied by chemosynthetic communities and, therefore may represent past fluid flow.

EVIDENCE OF GAS EXPULSION

In the Monterey Bay region only two gas sites have been identified, and these are found in Tertiary sedimentary rocks at the heads of submarine canyons (Fig. 2). One site is located on the Salinian block east of the Palo Colorado-San Gregorio fault zone, at the head of Soquel Canyon which incises the northern Monterey Bay shelf. The canyon cuts the Purisima Formation and seismic reflection profiles collected across the shelf just north of the canyon head exhibit acoustic anomalies or “bright spots” indicative of gas charged sediments (Figs. 8 & 9; Sullivan, 1994).



a.

b.

Figure 9. Geopulse seismic reflection profiles (a., line 64 and b., line 68) across the shelf immediately north of the head of Soquel Canyon showing acoustic anomalies (bright spots) characteristic of gas charged sediments. See Figure 8 for location. After Sullivan (1994).

Sullivan (1994) reported finding water column anomalies which she interpreted as gas. We speculate that the block glides and other slump deposits found in the head of Soquel Canyon (Sullivan, 1994) result from elevated pore pressures associated with periodic venting of gas in the headwalls of the canyon.

A second gas site lies along the shelf at the head of Año Nuevo Canyon (Fig. 10). Data collected from a single channel 1 kJ sparker and a 300 J Uniboom seismic reflection profiling systems along the Año Nuevo Point to Santa Cruz shelf defined an area of acoustic anomalies (“bright spots”) on the shelf immediately adjacent to the canyon head (Mullins and Nagel, 1982; Nagel et

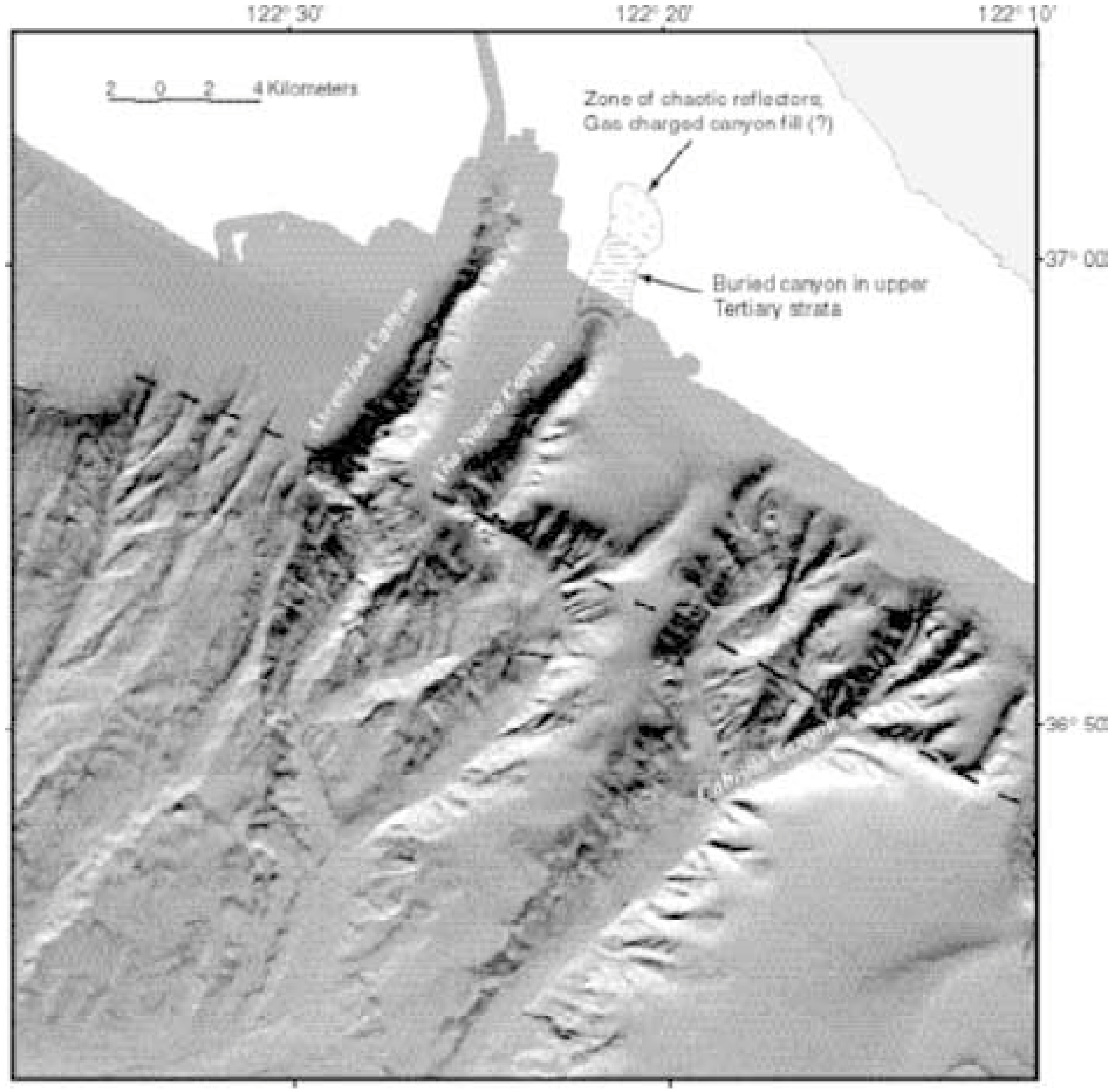


Figure 10. Shaded relief map of Ascension Canyon slope showing inferred gas induced canyon head collapse at Año Nuevo Canyon. Dashed line represents inferred structural lineament, possibly a fault or lithologic contact. Map constructed from MBARI EM300 multibeam bathymetry. Slashes and dashed symbols indicate the location of interpreted gas occurrences near the head of Año Nuevo Canyon by Mullins and Nagel (1982).

al., 1986). Similar to Soquel Canyon, Año Nuevo Canyon notches the continental shelf and has eroded Pliocene sandstones equivalent in age and lithologies to the Purisima Formation. Mullins and Nagel (1982) also reported finding several water column anomalies that they interpreted as gas venting from the seafloor. The recently collected MBARI EM300 swath bathymetry shows Año Nuevo Canyon to have a crecentic to circular collapsed head (Fig. 11). We speculate that this collapse is primarily the results of high pore pressures produced by gas forcing from

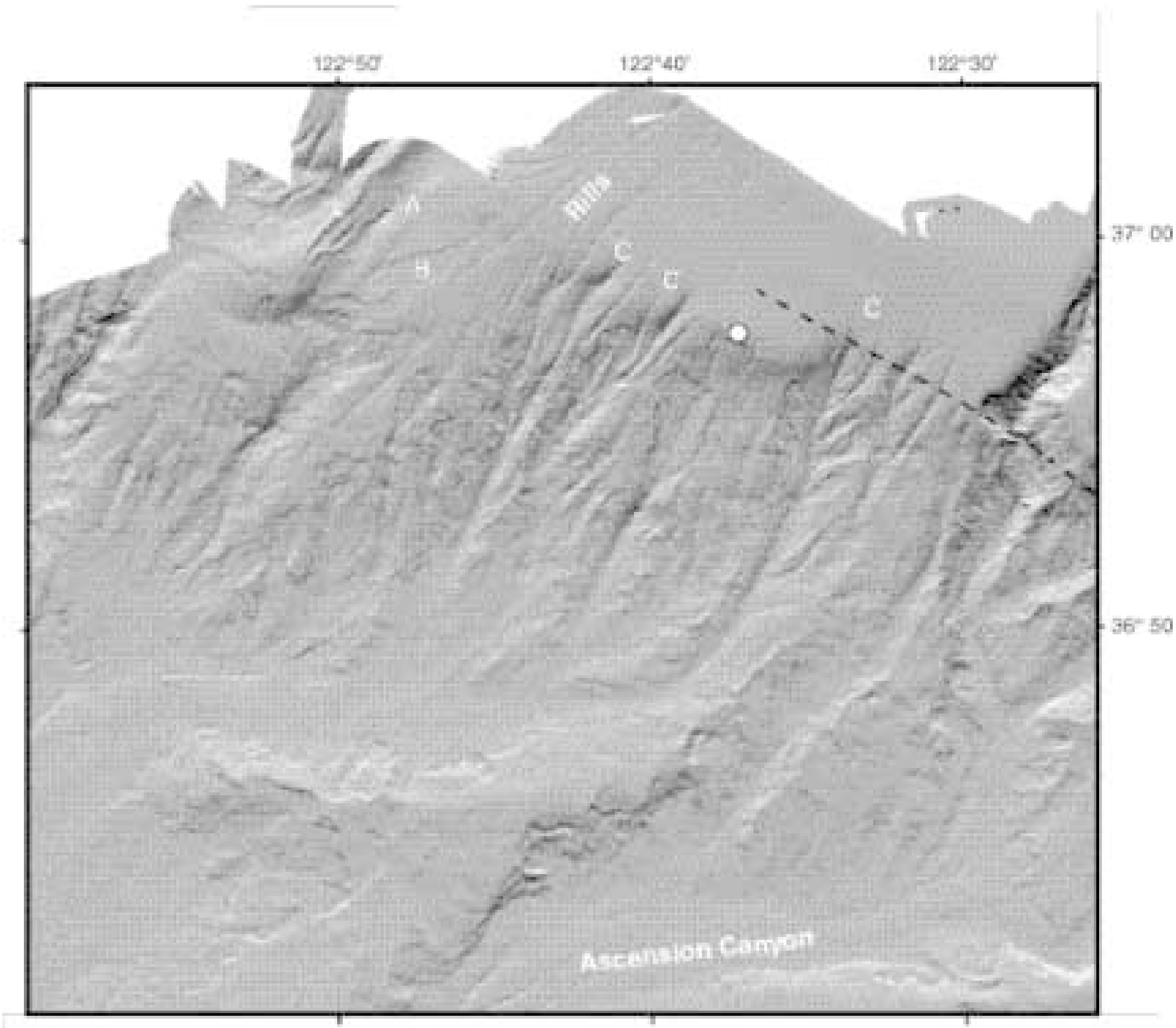


Figure 11. Shaded relief map of the northern Ascension slope showing inferred groundwater geomorphology and seep sites. Map constructed from MBARI EM300 multibeam bathymetry. Circle shows location of possible carbonate mounds. A denotes scallop, B marks thin sediment flow, and C's indicate areas of incipient canyon formation.

hydrocarbon sources at depth with the gas traveling to the headwalls of the canyon where mass wasting and headward encroachment is stimulated

EVIDENCE OF POTENTIAL FLUID SEEPS

The EM300 multibeam data revealed a seafloor morphology that suggests deformation and alteration through transpressional tectonic processes, fluid flow and submarine canyon erosion. Much of the region exhibits fluid induced mass wasting that is especially prominent in the north along the Ascension Canyon slope. Parts of the Sur slope also exhibit a seafloor morphology that may result from fluid induced mass wasting. These two slopes, the Ascension Canyon (including Smooth Ridge) and Sur slopes, are separated by Monterey Canyon and Fan Valley (Fig. 2)

Ascension Canyon Slope and Smooth Ridge

The Ascension Canyon slope (Fig. 11) exhibits features such as rills, pits and gullies associated with piping, fluid induced thin sediment flows, concentric- to circular-shaped small (meters to 10's of meters in diameter) slump scarps we call "scallops" or "cusps" associated with fluid sapping, and fluid induced rotational slumps (Greene et al., 1998; Maher et al., 1998; Naehr et al., 1998). These features are remarkably similar to those described on land by Parker et al. (1990), Jones (1990), Higgins et al. (1990) and Baker et al. (1990). In addition, areas along the distal edge of the shelf and upper slope (100-300 m deep) where rills and pipes terminate correspond to incipient canyon formation (C in Fig. 11). The term pipes as used here refers to narrow conduits through which fluids flow in sedimentary deposits and where granular material is removed forming linear collapsed structures that can be identified as rills and aligned pits on the surface of the seafloor.

Past, and perhaps present, fluid flow is suggested in the EM300 bathymetry by the presence of possible carbonate mounds scattered about the flat shelf floor (Fig. 11). The base of the slope is similar to outwash plains. We speculate that fluid and gas migration from the hydrocarbon source in the Monterey Formation of the Outer Santa Cruz Basin (Hoskins and Griffiths, 1971; McCulloch and Greene, 1990) may be responsible for the shelf and slope morphology. We have identified several geomorphic features along the upper slope and outer shelf where we suspect that fluids and perhaps gases are seeping out into the water column (Figs. 2 and 11).

The EM300 data also shows that the southern flank of Smooth Ridge is shedding its sediment cover, which appears the result of fluid induced mass wasting. We have identified a few of these areas in Figures 2 and 11. Young to incipient cold seep sites aligned N-S along the eastern crest of the ridge, just west of the Horseshoe Scarps, may be forming from compressional squeezing, a result of the buttressing effect the Salinian block creates where the ridge is obliquely converging along the western boundary of the block, along the Palo Colorado-San Gregorio fault zone. This compression is forcing fluid flow.

Sur Slope

Similar to the Ascension Canyon slope and Smooth Ridge, the Sur slope is being tectonically uplifted as indicated by the uplifted terraces in the coastal part of the Santa Lucia Mountains adjacent to Point Sur and the shedding of the sedimentary cover at the base of Sur slope. This uplift has led to the initiation of denudation of the upper slope and the formation of gullies and canyon heads (Fig. 7). Apparent fluid induced mass wasting occurs here as suggested by rills, mounds that may be constructed of carbonates and scallops.

The EM300 data collected along the northern flank of Sur slope shows two possible carbonate sites where mounds have been identified associated with canyon heads on an otherwise smooth area of seafloor (Figs. 2 & 7). One site is located at the head of an unnamed canyon just offshore of Garrapata Beach, in the area where the Palo Colorado fault zone extends offshore to connect with the southern extension of the Carmel Canyon fault zone, the southern extension of the Palo Colorado-San Gregorio fault zone. The other site is to the south of this unnamed canyon on the upper slope and distal outer shelf where distinct mound-like topography is mapped (Figs. 2 & 7).

The entire western base of Sur slope is undergoing mass wasting and, based on the geomorphology, we speculate that many of the landslides in this area are fluid induced. The very large and extensive Sur slide, identified by Hess et al. (1979) and Normark and Gutmacher (1988) is composed of a number of retrogressive slumps (Greene et al., 1989) which probably result from an increase in slope due to tectonic uplift of the Sur slope and platform to the east, and increased fluid flow resulting from compressional squeezing and overburden pressure. The Monterey Formation exists at depth in this area and gas expulsion may also be taking place. The identification of an extensive pockmark field south of the Sur slope, near the lower part of Lucia Canyon, suggests that gas venting occurred in this area in the past (Maher et al., 1998).

We have identified a series of sites along the base of Sur slope that we think are potential fluid seep sites (Figs. 2 & 7). These sites by no means represent the total number of seeps we believe are present, but are identified to indicate symbolically that fluid induced mass wasting is most likely occurring around the base of the lower Sur Ridge.

CONCLUSIONS

At least 16 major active and past fluid seep sites are identified in the Monterey Bay region. Of the 16 identified sites, 9 are confirmed active and 7 are fossilized or dormant. The active seeps are based on the presence of chemosynthethic communities composed of vesicomyid clams, vestimentiferan worms and free-living bacterial mats. The existence of ancient seeps are based on the presence of slabs, pavements, chimneys and other buildups that are composed of authigenic carbonate.

Seeps are generally concentrated along faults, particularly along the Palo Colorado-San Gregorio fault zone that marks the western boundary of the Salinian block in the Monterey Bay region. This boundary locally separates two major tectonic provinces; 1) the eastern fault sheared and slivered allochthonous Salinian block province and 2), the western transpressional accretionary province.

Expelled fluids in the eastern province appears to derive from several different sources. Ancient or dormant seep sites on the southern Monterey Bay shelf may have resulted from the expulsion of aquifer driven meteoric waters. In the Portuguese Ledge and Italian Ledge areas we suggest that these waters traveled along faults within the Monterey Bay fault zone to sites on the seafloor where the water vented.

Along the eastern margin of the western province, west of the Palo Colorado-San Gregorio fault zone and in the area where the faults of the Monterey Bay fault zone merge with the Palo Colorado-San Gregorio fault zone, many active seeps are located. Cold-seep communities of metal oxidizing bacterial mats and chemosynthetic clams (Vesicomya) along the northern wall of Monterey Canyon indicate that sulfide-rich fluids are seeping out of faults in the Monterey Bay fault zone (Barry et al., 1993, 1996, 1997).

The fluid chemistry suggests the mixing of fluids from several sources (Stakes et al., in press; Orange et al., in press). Some fluids may result from advection through the hydrocarbon-rich Monterey Formation whereas other fluids may be transported along fault conduits. Other fluids travel through freshwater aquifers within the Purisima Formation that extend from the Santa Cruz Mountains to Monterey Bay and surface along the walls of Monterey Canyon (Greene et al., 1997). Artesian conditions exist, although flow rates at the faults are not known. At Mount Crushmore the chemosynthetic communities may obtain sulfide-rich fluids from artesian flow of aquifer waters as the biota are all concentrated in black hydrogen-sulfide mud in fault and fractured crevices that cut deeply into the Pliocene Purisima Formation, a shallow water marine sandstone and the best recharged aquifer of the Santa Cruz Mountains (Muir, 1972). Some fluids may be methane-rich resulting from gas overpressures in the Monterey Formation and migration to overlying permeable sandstones such as the Purisima Formation exposed at the heads of Soquel and Año Nuevo canyons.

In the western province expelled fluids originate from several sources and processes. Compression of the sedimentary slope west of the Palo Colorado-San Gregorio fault zone due to transpressional movement may cause dewatering. This dewatering is shown by the existence of cold seep chemosynthetic communities and carbonate crust formation. Carbon and oxygen isotopic analyses indicate several sources for these fluids (Orange et al., in press; Stakes et al., in press). One source is from the hydrocarbon-rich Monterey Formation of Miocene age whereas the other is from carbon buried in Quaternary sediments. The Monterey Bay region is a major upwelling area and high organic production occurs here. Organic-rich sediment accumulates on the slope and produces considerable biogenic methane. Other fluids flow along faults and have a source deep in the sedimentary column.

In Monterey Fan Valley, chemosynthic seeps are reported to be the result of biogenic fluids that originate from buried organic material in filled channels (Greene et al., 1997). No chemical analyses have been made of these seeps so the origin of fluids is still speculative.

The recently collected EM300 multibeam bathymetry data indicates extensive areas of seafloor fluid flow and gas expulsion north and south of Monterey Bay. The Ascension Canyon slope exhibits distinct groundwater geomorpholgy with numerous fluid-induced mass wasting features. Fluid induced rills, grooves, pipes and pits are common in this area. We speculate that these features may be forming from gas and fluid expulsion originating from deep hydrocarbon sources in the Outer Santa Cruz Basin.

EM300 data show that the Sur slope offshore of Point Sur is undergoing similar mass wasting processes. In addition, these data revealed an extensive pockmark field to the south of the Sur slope (Maher et al., 1989) that may be the result of past gas expulsion associated with of gas escaping from the Monterey Formation at depth here, possibly initiated by seismic activity.

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HYDROGEOLOGY OF COASTAL WATERSHEDS: SOUTHERN SANTA CRUZ AND NORTHERN MONTEREY COUNTIES

Nick Johnson

Hydrogeology of Coastal Watersheds: Southern Santa Cruz and Northern Monterey Counties

Nick Johnson

Introduction

Constraints imposed by seasonal and drought scarcities of potable water strongly characterize development patterns in California's past and present. Whereas water imported from the state's north and Sierra Nevada helped alleviate such constraints across large portions of the state, the Central Coast region between San Francisco and San Luis Obispo struggles with its continuing dependency on local supplies. The myriad of problems associated with this struggle include groundwater overdraft, seawater intrusion, depletion of in-stream flows, pressure to construct dams, wanted and unwanted growth, and water quality degradation by agriculture, wastewater, and other aspects of development. Traditional local sources include a few relatively large unconsolidated groundwater basins, scattered bedrock aquifers of primary and/or secondary porosity, direct diversions from large and small streams, and releases from relatively modest reservoirs built prior to the mid-1960s. "New" supplies mostly involve the conjunctive use of surface water, groundwater, reclaimed wastewater, and desalinated water, as well as continued attempts to build new dams and importation pipelines (Table 1).

The streams, aquifers, farms, towns, and relatively native watersheds we pass on our drive from Aptos to Big Sur embody all these issues—from one of the worst cases of seawater intrusion at the mouth of the Salinas Valley, to ongoing fights over water importation into Pajaro Valley; dam construction in Carmel Valley; and residential diversions from small salmonoid streams along the Big Sur Coast.

Highway 1 Rest Stop Between Aptos and Watsonville (0.0 mile)
From this vantage, the Soquel-Aptos groundwater basin extends to our north and the Pajaro groundwater basin lies to our south (Figure 1). Urban water production from the Soquel-Aptos basin is primarily from confined aquifer zones in the semi-consolidated, Pliocene Purisima Formation. Production from the Pajaro basin, mostly for agriculture, is largely from relatively unconfined zones within unconsolidated deposits of Aromas Formation, terrace deposits, and river alluvium.

Soquel-Aptos Basin
The Soquel Creek Water District serves a population of about 50,000 from 17 wells with a total capacity of 17,000 acre-feet per year (ac-ft/yr). Most of these wells draw from confined portions of the Purisima aquifer, although its southern wells are in the Aromas. A building moratorium was imposed in the 1970s in response to a USGS investigator's warning that overdraft and seawater intrusion were imminent. After a District consultant negated these concerns in the 1980s by installing coastal monitoring wells and arguing for a nearly open-ended yield, the area grew substantially and the City of Santa Cruz Water Department began eyeing the Soquel-Aptos basin for itself. Santa Cruz considered an exchange of its stream and river diversions during wet years for Soquel groundwater during dry years, and more recently considered increasing its own Purisima production from along its eastern service area boundary. Meanwhile, far-reaching subsealevel drawdowns propagating through the confined aquifer have renewed overdraft and intrusion concerns.

Evaluating the potential for seawater intrusion depends in part on assumptions about potential pathways and initial conditions. The Purisima outcrops in Monterey Bay, including where cut by the marine canyon. One modeling effort concluded that insufficient time had passed since the Holocene sea level rise to equilibrate the aquifer's freshwater-saltwater interface (Essaid, 1992); i.e., although sea water continues to enter the aquifer through the canyon walls, the interface remains far offshore and pumping has little effective impact. This conceptualization, however, may underestimate downward leakage near shore and communication with intruded portions of the Aromas.

Recent modeling by the Soquel District suggests overdraft of as much as 1,000 ac-ft/yr. Supply augmentation measures being considered include distributing pumping inland and among unconfined zones; offstream storage of Soquel Creek high flows, with injection of same back into the Purisima; and desalination. The City of Santa Cruz is again looking elsewhere for water, including a major desalination facility. In the near term, Santa Cruz will be limited to renewed water conservation and rationing.

Pajaro Basin

As shown in Figure 1, the Purisima dips steeply east and south from Soquel and becomes overlain by many hundreds of feet of unconsolidated Aromas Formation and younger terrace and alluvial deposits beneath the 120-mi^2 Pajaro Valley (Figure 2). Agricultural, urban, and industrial needs are currently met by nearly 70,000 ac-ft/yr of groundwater pumping, mainly from the Aromas aquifer and Pajaro River alluvium. Seawater intrusion into shallow zones near the river mouth and Springfield Terrace to the south was noted as early as the late 1940s. Significant intrusion is now evident in wells along the coast, for example at La Selva Beach immediately west of the scenic overlook at Stop 1.

The Pajaro Valley Water Management Agency (PVWMA) was formed in 1984 to address the overdraft issue. Groundwater modeling for the Agency has estimated 18,000 ac-ft/yr of overdraft, of which a portion is replaced each year by seawater intrusion (Table 2). The Agency's 1993 Basin Management Plan asserted that future water demands could be met without overdraft by eliminating pumping along the coast (thus increasing the "natural" yield by 60 percent), recharging 6,000 ac-ft/yr of local runoff, importing as much as 20,000 ac-ft/yr from outside the basin, and achieving conservation through an aggressive pump tax.

Implementation of the plan began to falter once the pump tax began to hit water users hard and potential growth-inducement from water importation became a stronger environmental issue. With the help of a group called "NOPE" (No Overpriced Pipeline Ever), a halt was put to the pipeline and further increases in the pump tax.

Local recharge projects are going forward, including percolation of river diversions into the basin forebay and percolation of slough diversions into coastal dunes. Logistically, these diversions are fraught with environmental issues of their own, e.g., minimizing disturbances to the streambed and flow conditions. Because extensive clay layers may inhibit deep percolation, new shallow recovery wells are planned along with a pipeline distribution system. Enhancement and use of seasonal storage in College Lake has been delayed pending integration with new Army Corps flood control plans. Finally, a new Basin Plan and EIR are intended to revitalize the importation pipeline, which would bring outside water to the Central Coast for the first time. The pipeline would convey an entitlement from the Bureau of Reclamation's San Felipe Project as well as "water transfers" negotiated on the open market.

Pajaro River to Moss Landing (6.1 to 11.0 miles)
Springfield Terrace and Aromas Sand Hills
After crossing the Pajaro River and leaving Santa Cruz County, we climb out of the flood plain and onto Springfield Terrace, an area of rich farmland cultivated primarily in artichokes. This area and the rolling hills of Aromas Sand to the east are within the overlapping jurisdictions of PVWMA and Monterey County Water Resources Agency (MCWRA). Yet neither agency has any easy answers for dealing with severe groundwater overdraft and seawater intrusion in these areas. As illustrated in Figure 3, Springfield Terrace may be essentially cutoff from inland recharge by a deep clay plug underlying Elkhorn Slough to the south and curving behind to the east. Although the sand hills comprise a highly permeable recharge area, rainfall amounts are low. Furthermore, groundwater quality degradation from fertilizers and septic tanks is particularly acute here. No viable local recharge projects have been advanced. Because houses use less water and introduce less nitrogen than farms, Monterey County has been hard pressed to stem the conversion of agricultural land to residential subdivisions. Ultimately, a prohibition on future development may result from water supply limitations, although curtailing agricultural use remains problematic under California water law.

Moss Landing to just beyond Salinas River (11.0 to 18.0 miles)
Salinas Groundwater Basin
As shown in Figure 4, the long and narrow Salinas Valley floor extends nearly 80 miles inland southeast of Monterey Bay and covers about 470-mi^2. Compared to the rather heterogeneous hydrostratigraphy of the Pajaro Basin, the lower Salinas Basin consists of a series of three relatively distinct aquifer zones defined by confining aquitards (Figures 1, 5, and 6). Drawn by pumping depressions exceeding 100 ft below sea level near and east of Salinas, seawater intrusion in the shallow "180-ft aquifer" extends nearly 7 miles inland, encompassing 30 mi^2 (Figure 7), and nearly 3 miles inland over 15 mi^2 in the "400-ft aquifer." Furthermore, severe nitrate contamination from agriculture and wastewater is prevalent.

Figure 8 summarizes the Salinas Valley groundwater balance. Among its four subareas, groundwater production exceeds 500,000 ac-ft/yr. Since construction of San Antonio and Nacimiento reservoirs in the upper watershed in the 1950s and 1960s, Salinas Valley water supply problems have been mainly a function of distribution rather than available yield. Indeed, when the California Department of Water Resources (DWR) conceptualized these dams in the 1940s, a complementary conveyance system was known to be necessary for a long-term water supply solution. The DWR envisioned using the Upper Valley and Forebay subareas for storage by drawing groundwater levels down, piping the pumped groundwater to the Pressure and East Side subareas, and inducing additional recharge from reservoir releases to replenish upper valley groundwater storage. Because such conveyance facilities were never implemented, the upper (southern) portion of the valley has enjoyed a water surplus and the lower (northern) portion of the valley has experienced severe local overdraft. Due to confining layers and limited local runoff, the lower valley does not receive significant local recharge.

Because water users in the upper basin are apparently unwilling to allow groundwater withdrawals to serve the needs of the lower basin, the current Salinas Valley Water Project intends to use inflatable dams or Ranney collectors to capture excess reservoir releases, hold it in various off-stream storage facilities, and distribute this water for irrigation in the lower valley. This "in-lieu" recharge will reduce groundwater extractions in the lower valley and help the groundwater gradient reverse against seawater intrusion. Reclaimed wastewater is providing an additional source of irrigation water in intruded areas, although planned recharge and recovery of reclaimed water using injection wells in the intruded zone has yet to be permitted.

Salinas River to Monterey (18.0 to 28.0 miles)
Marina/Fort Ord

The City of Marina has assumed responsibility for supplying water to the various new endeavors at Fort Ord. Falling within the Salinas Valley water management zone, it may be assumed that groundwater use by Marina/Fort Ord contributes to existing overdraft and intrusion problems. Marina has gone ahead and constructed a 300 ac-ft/yr desalination project. Because its beach well currently produces brackish water with only 22,000 ppm salinity, wastewater from its treatment plant approaches the salinity of seawater and can be discharged directly to the ocean.

Seaside Basin

Although the Seaside Basin is considered separate from the problems of Salinas Valley, its size and yield are limited. It falls within the jurisdiction of the Monterey Peninsula Water Management District (MPWMD), within which the California-American Water Company (Cal-Am) is the primary water purveyor. With the recent failure to win public approval for a larger dam on the Carmel River, the conjunctive management of surface water and groundwater between Seaside and Carmel Valley has increased. A pilot project now pipes 350 gallons per minute over from the Carmel River when it is flowing to the ocean (thus, about 200 ac-ft/yr) for recharge by injection well into the Seaside Basin. Although approved by regulators, the public also voted down a Seaside desalination project. Nevertheless, the water needs of the Monterey Peninsula may be met by a future water desalinization project and expanded injection and recovery of Carmel River water in the Seaside Basin and perhaps at Fort Ord (i.e., “aquifer storage and recovery,” or ASR).

Rio Road, south end of the City of Carmel (35.0 miles [reset mileage to 0.0 mile])
Carmel River/Carmel Valley

An up-thrown block of granite at the mouth of the Carmel River partially blocks seawater intrusion from entering the 7-mi^2 Carmel Groundwater Basin. However, conflicting water demands and environmental and legal issues have thwarted efforts to optimize the conjunctive use of its surface water and groundwater resources. Presently, the area is under order from the California State Water Resources Control Board (SWRCB) to reduce Carmel Valley water production by 10,000 ac-ft/yr, which may trigger mandatory rationing until other sources and/or projects are developed.

Garrapata Beach (5.5 miles)
Garrapata Creek

Available water supplies become limited in the steep bedrock canyons south of Carmel. Please refer to the attached report prepared for the Garrapata Water Company for an example of water issues in this area. In this case a shallow well beside Garrapata Creek ¼-mile from the coast supplies about 30 nearby homes built since the 1960s. State Fish and Game and the Water Resources Control Board recently challenged the use of this well. At issue is whether the well taps a "subterranean stream." Following a hearing in February 1999, the Board determined that it does.

Andrew Molera State Park (21.3 miles)
Big Sur River Alluvial Fan

The lower reaches of the Big Sur River are likely underlain by a locally significant alluvial aquifer. Perhaps because of its parkland status, it appears to have remained undeveloped.

Selected References

My personal knowledge of water supply conditions and issues along the Central Coast derives from over 20 years of work in the area. However, I am very grateful to my colleague Martin Feeney, a consulting hydrogeologist based in Monterey (831/643-0703; mfeeney@ lx.netcom.com), for the update he provided me on many of these topics immediately prior to the field trip. Furthermore, several of the following references cite only an agency and/or district and its current consultant; titles of many of the most recent and relevant reports were unavailable to me as this guide was prepared.

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PGS Field Trip, May 2000, Aptos to Big Sur – Hydrogeology
summarized by Nick Johnson

Table 1
Summary of Water Supply Sources, Issues, and Proposed Solutions for Central Coast Region

	Traditional Sources				Problems/Issues					Proposed/Pending Solutions											
											Direct Stream Diversion				Reclaimed Wastewater						
Area	Direct Stream Diversion	Reservoir	Unconsolidated Aquifer	Bedrock Aquifer	Shortages	Overdraft	Seawater Intrusion	In-Stream Flows	Degraded Quality	On-Stream Dam	Off-Stream Storage	Percolation Recharge	Injection Recharge	Direct Use ("In-Lieu Recharge")	Direct Use	Groundwater Recharge	Intra-Region Transfers	Importation	Desalination	Mandatory Rationing	Price Structuring
Santa Cruz	●	●		•	●			●	•										?	•	
Soquel-Aptos			•	●		?	?	?			•		•						•		
Pajaro Valley			●			●	●		•		•	•		•				?			•
Springfield Terrace & Aromas Hills			●		•	●	●		●									?		•	
Salinas Valley			●			●	●		●	modify	•			•	•	?	?				
Marina/Fort Ord			●			?	?		•										•		
Seaside, Monterey, Carmel	•	•	•	•	●	?	?	●		?			•		•		•		?	•	
Big Sur Coast	•		•	•	•			●												•	

PGS Field Trip, May 2000, Aptos to Big Sur – Hydrogeology

summarized by Nick Johnson

Table 2
Summary of Pajaro Groundwater Basin 1993 Management Plan
(ac-ft/yr)

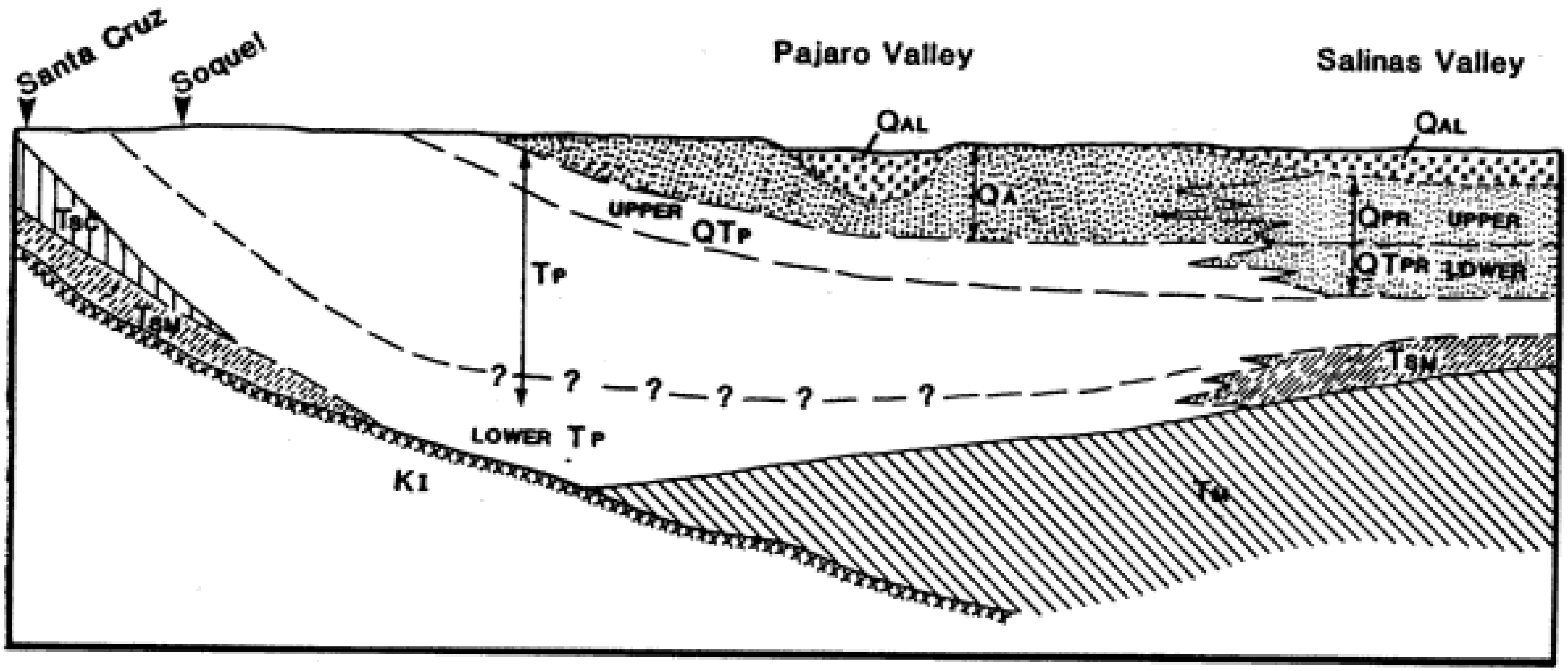
	PRESENT AVERAGE-YEAR	NEEDED TO ELIMINATE PRESENT OVERDRAF	ELIMINATE COASTAL PUMPING		
				PREFERRED ALTERNATIVE YEAR 2040 CONSERVATION?	
			PRESENT	NO	YES
TOTAL WATER DEMAND	66,000	66,000	66,000	78,000	69,000
GROUNDWATER SAFE YIELD	31,000	31,000	50,000	50,000	50,000
CONSERVATION (MUNICIP & AGRIC)	-	-	-	-	9,000
INFLOW AND DIRECT USE					
EXISTING GROUNDWATR RECHARGE	53,000	53,000	53,000	53,000	53,000
ADDITIONAL LOCAL RECHARGE	-	-	-	3,000	3,000
COLLEGE LAKE YIELD	-	-	-	3,000	3,000
SAN FELIPE IMPORT	-	-	-	22,000	13,000
GROUNDWATER OUTFLOW					
PUMPING	66,000	31,000	50,000	50,000	50,000
DISCHARGE TO OCEAN	5,000	23,000/a	4,000/b	4,000	4,000
GROUNDWATER OVERDRAFT					
INTRUSION+DECREASED STORAGE	18,000	1,000/c	1,000	1,000	1,000
SUPPLY SHORTAGE	0	35,000/d	16,000	0	0

a/ Needed discharge to ocean for an acceptable rate of sea water intrusion under present pumping conditions.

b/ Needed discharge to ocean for an acceptable rate of sea water intrusion with coastal pumping eliminated.

c/ Acceptable rate of sea water intrusion.

d/ Note that eliminating overdraft causes a shortage = 2x overdraft.



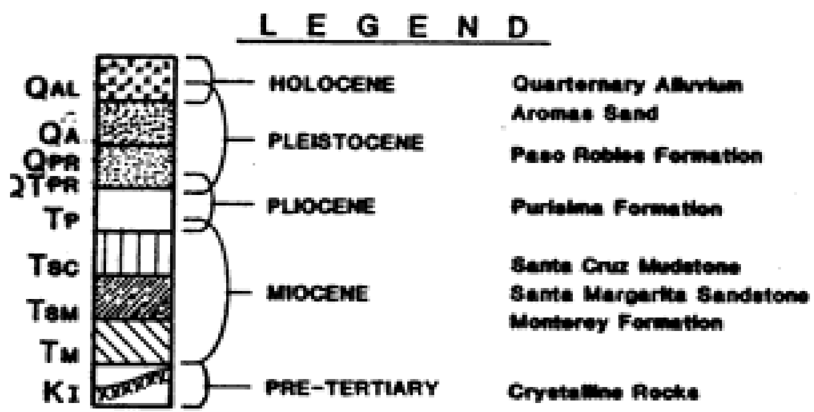
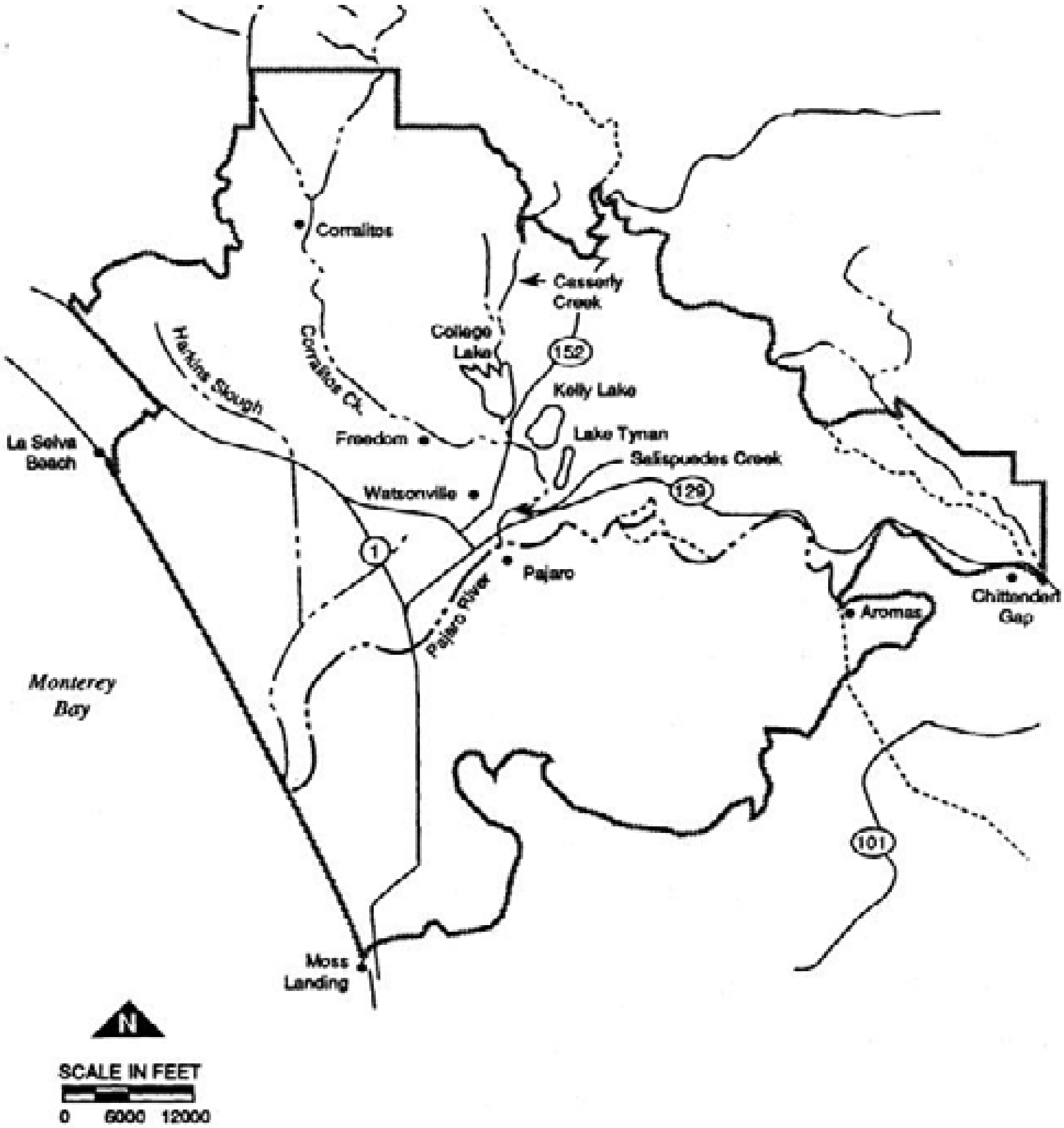


Figure 1
Source: Luhdorf & Scalmanini Consulting Engineers, January 1987

Schematic Stratigraphic Relationships, Monterey Bay Area



PAJARO VALLEY WATER MANAGEMENT AGENCY

PVWMA BOUNDARY MAP

Figure 2

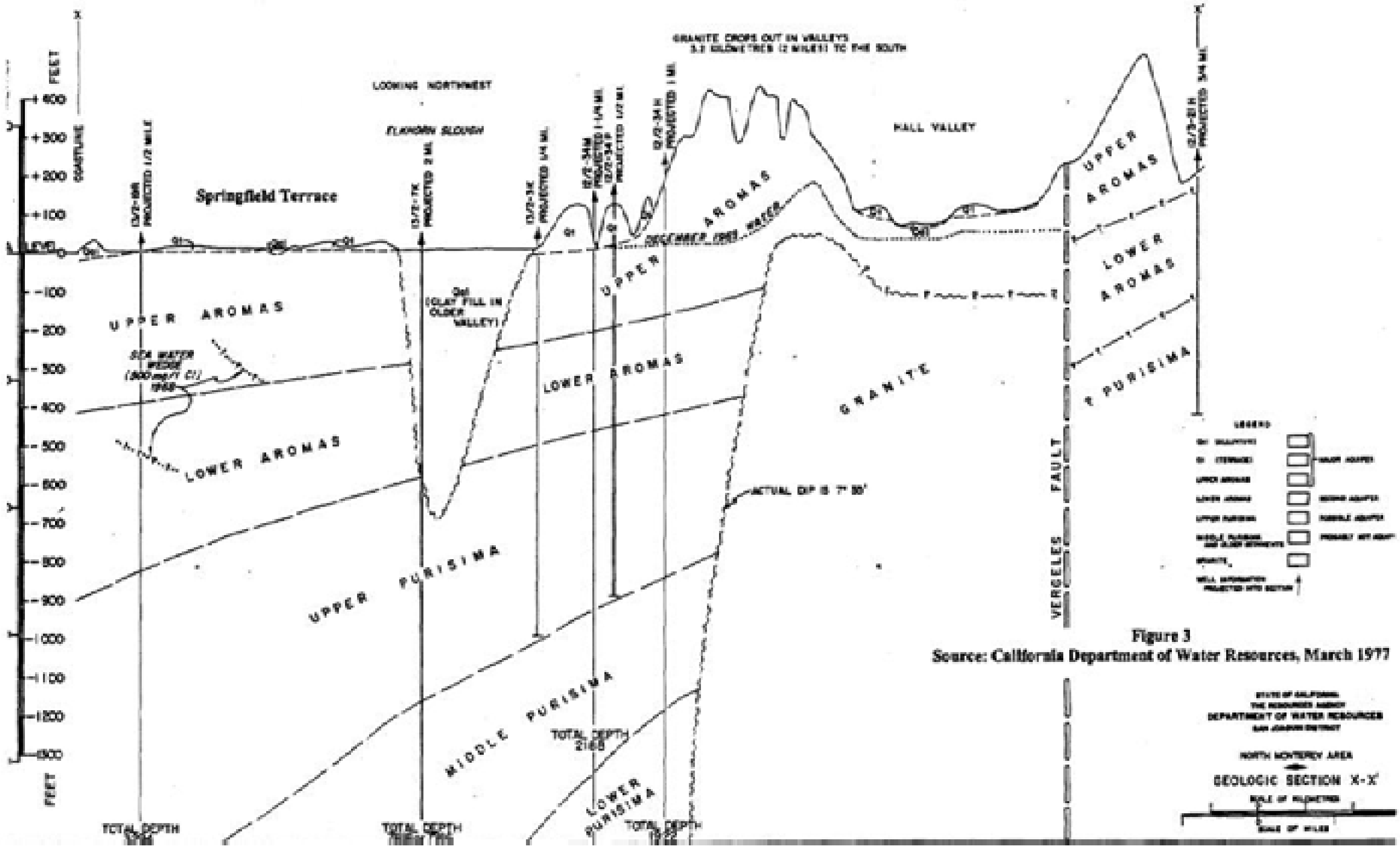
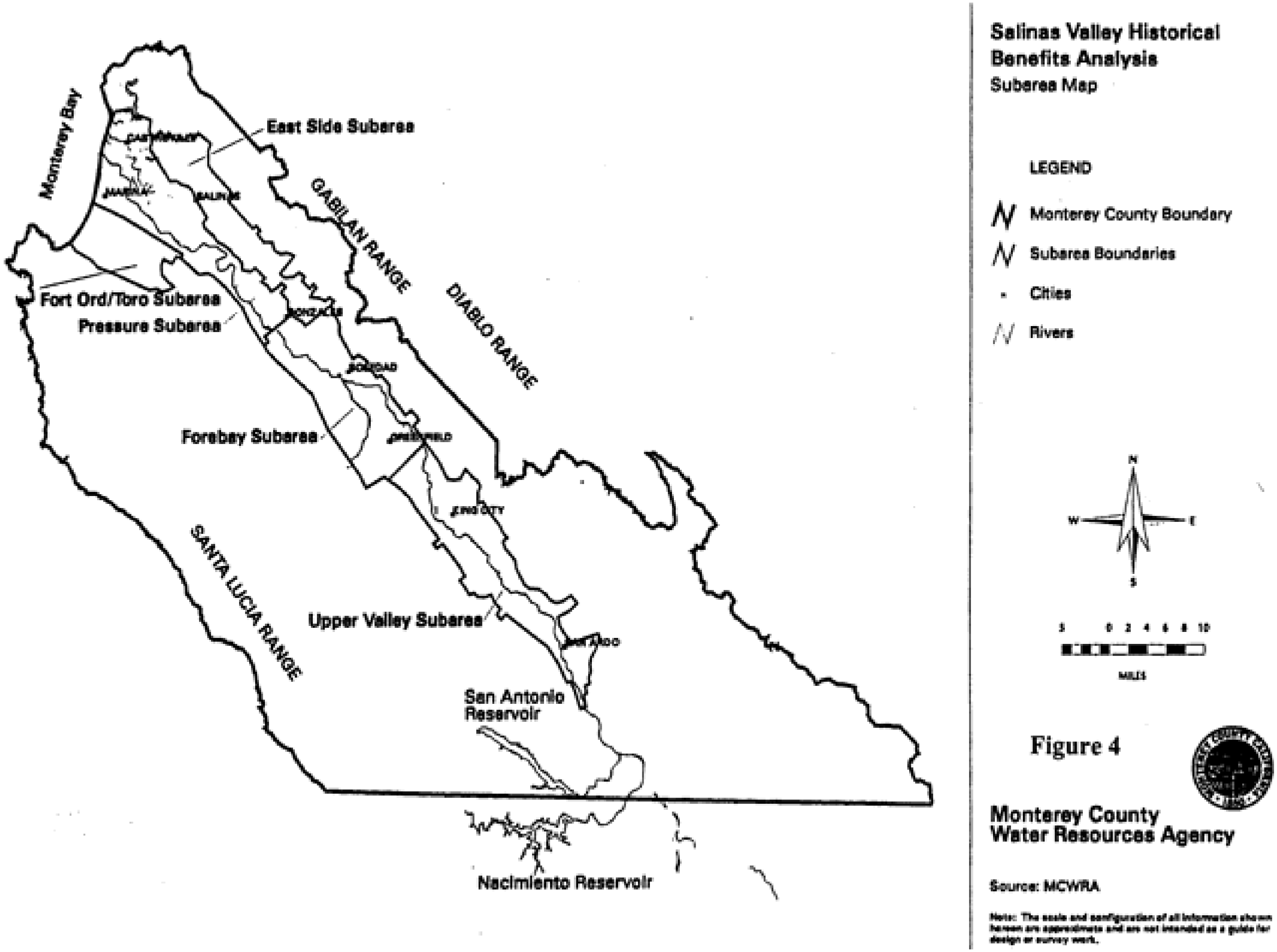
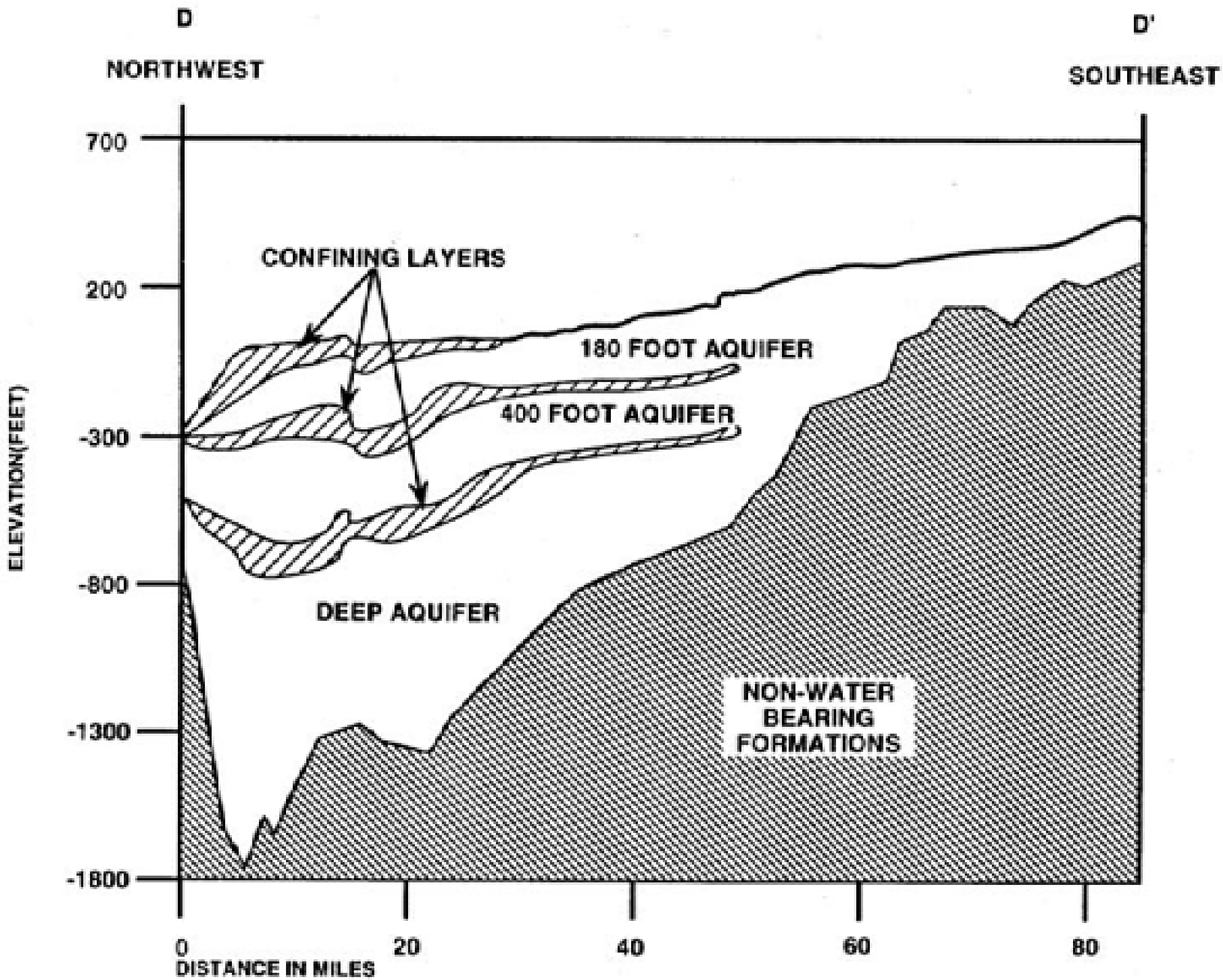


Figure 3
Source: California Department of Water Resources, March 1977



Salinas Valley Historical
Benefits Analysis
Subarea Map
LEGEND
Monterey County Boundary
Subarea Boundaries
Cities
Rivers
N
W
E
S
MILES
Monterey County
Water Resources Agency
Source: MCWRA
Monterey Bay
East Side Subarea
GABILAN RANGE
DIABLO RANGE
Fort Ord/Toro Subarea
Pressure Subarea
Forebay Subarea
SANTA LUCIA RANGE
Upper Valley Subarea
San Antonio
Reservoir
Nacimiento Reservoir
SALINAS
GONZALES
SOLEDAD
KING CITY

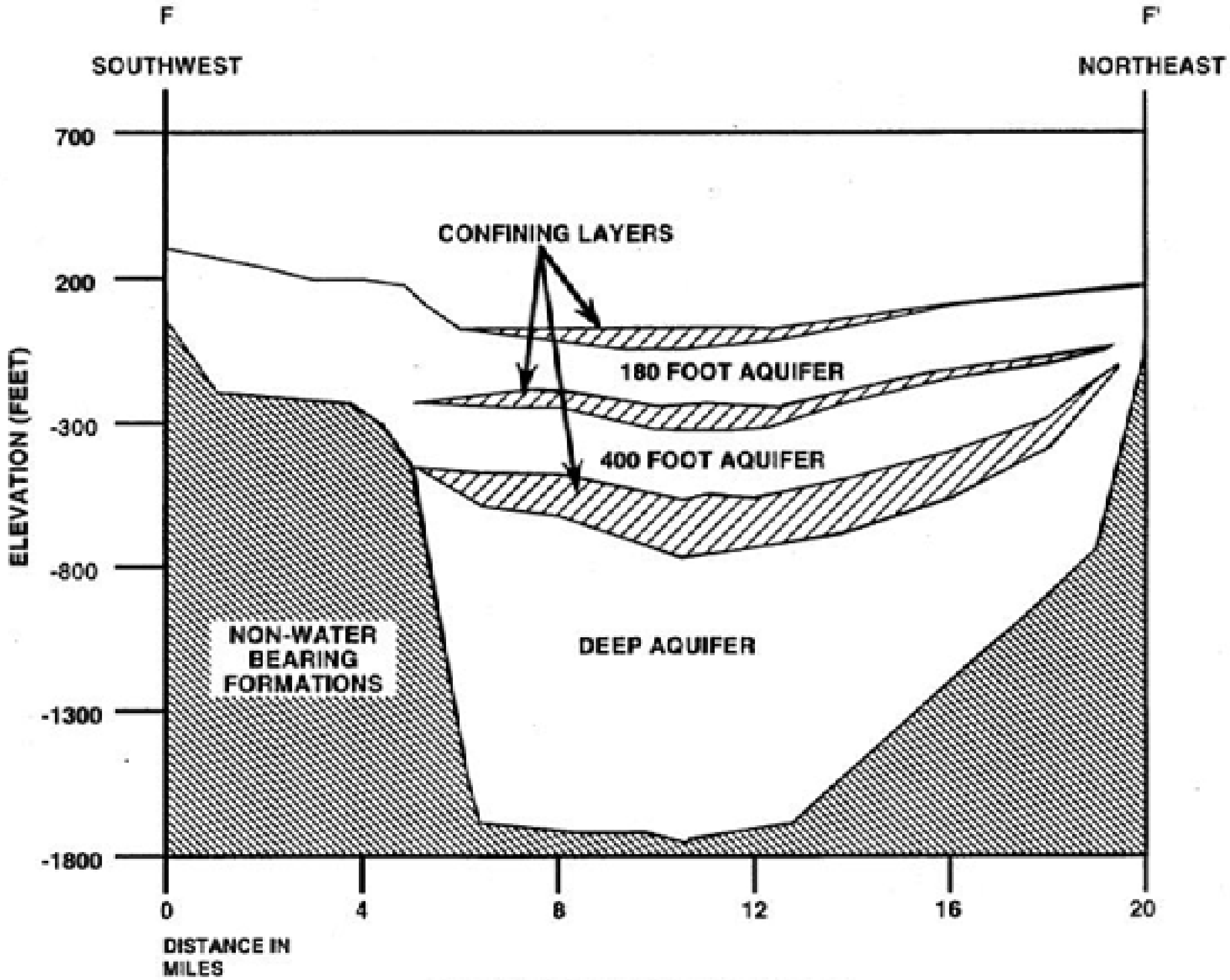
Figure 4



GEOLOGIC CROSS-SECTION D-D'

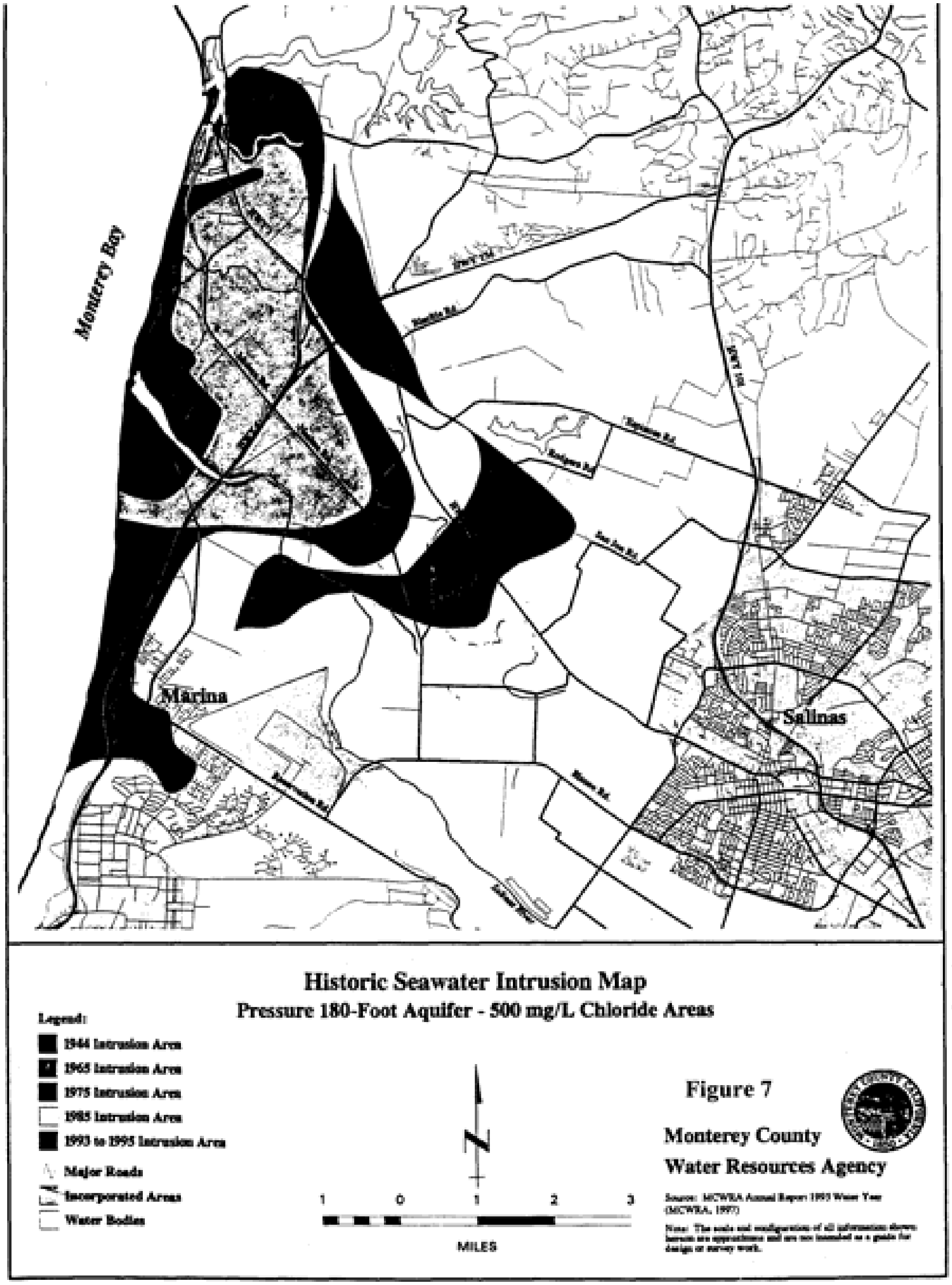
Figure 5

Source: Montgomery Watson, February 1994



GEOLOGIC CROSS-SECTION F-F'

Figure 6
Source: Montgomery Watson, February 1994



Historic Seawater Intrusion Map
Pressure 180-Foot Aquifer - 500 mg/L Chloride Areas

Figure 7

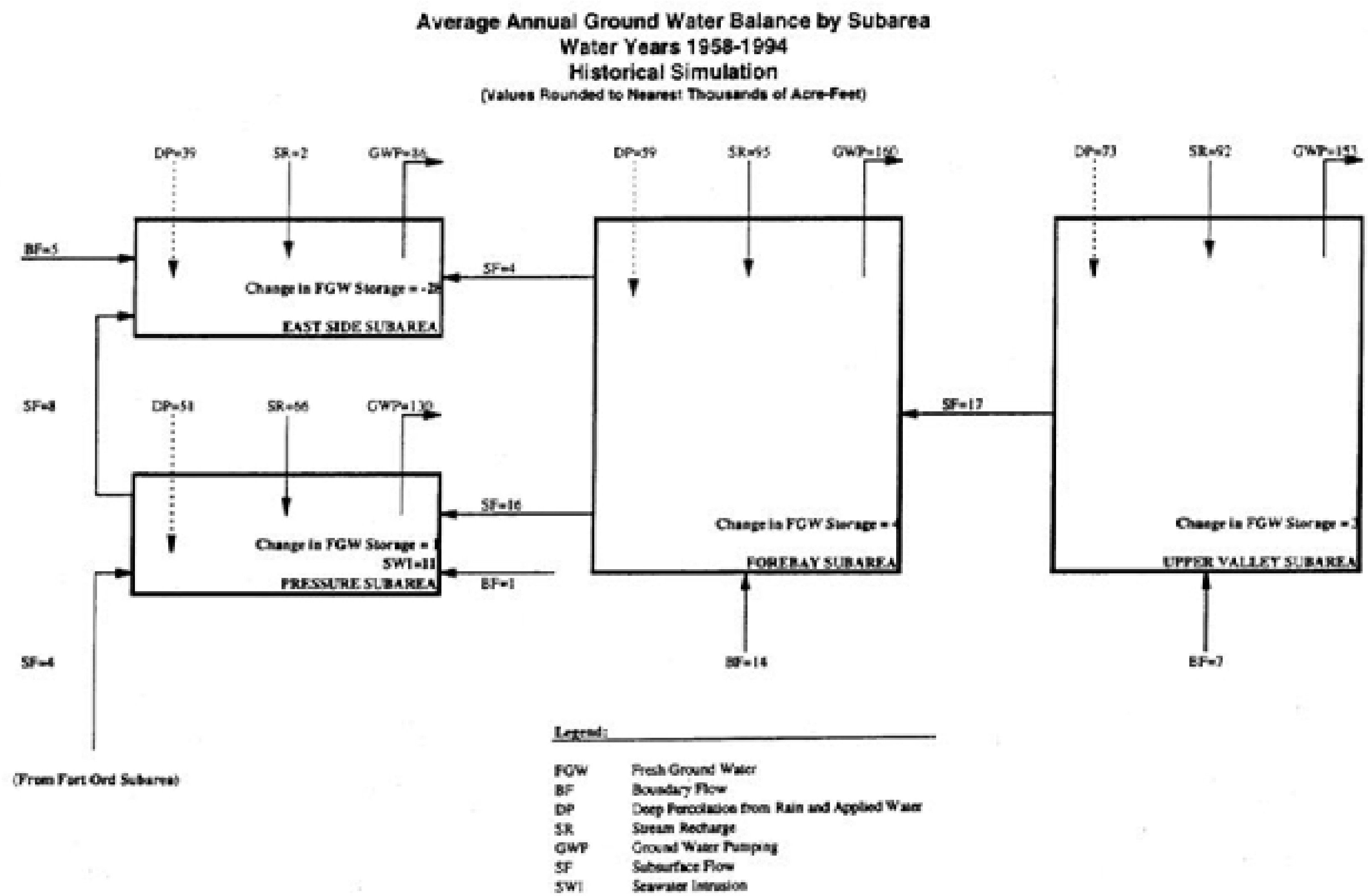


Figure 8
Source: Montgomery Watson, April 1998

Source Evaluation for Groundwater Extracted from Garrapata Water Company Wells

Prepared for

Garrapata Water Company, Inc.

Prepared by

Geomatrix consultants, Inc.
100 Pine Street, 10th Floor
San Francisco, California 94111

December 1998

Source Evaluation for Groundwater Extracted from Garrapata Water Company Wells

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Introduction

Garrapata Water Company (Water Company) supplies water to approximately 35 homes and one restaurant in an area near the Monterey County coast approximately 5 miles south of Carmel Highlands (Figure 1). The water source is from two shallow wells near Garrapata Creek approximately 1500 feet upstream of the coast (Figure 2). Only one of these wells is in regular use.

The Water Company retained Geomatrix Consultants, Inc. (Geomatrix) to evaluate the source of groundwater to its wells. This evaluation relates to whether or not the Division of Water Rights (Division) of the California State Water Resources Control Board (SWRCB) has the jurisdiction to require an appropriative water right for the Water Company's groundwater use.

In California the following definitions are used:

> Groundwater is all subsurface percolating water not flowing in a known and definite channel.
>
> A stream's underflow is a subterranean stream flowing through a known and definite channel having identifiable beds and banks.

As defined, use of underflow requires an appropriative right whereas use of groundwater does not.

Division staff prepared an analysis in May 1997 summarizing a staff field investigation relating to Garrapata Creek water rights issues. This analysis recommended conditions for permitting a Water Company appropriate right to extract groundwater from its wells. A subsequent memorandum by Division staff in October 1997 concluded that the source of water to the Water Company wells is Garrapata Creek underflow.

In this report, Geomatrix evaluates available hydrologic and hydrogeologic information for the Garrapata Creek watershed and nearby region to demonstrate the role of groundwater as a source of water to both stream baseflow and wells.

Watershed Hydrology and Hydrogeology

Garrapata Creek has a watershed area of approximately 10.6 square miles upstream of the Water Company wells. The watershed includes two principal tributaries, Joshua Creek and Wildcat Canyon. The watershed is underlain entirely by granitic bedrock. Alluvial deposits derived from this bedrock underlie Garrapata Creek. One alluviated reach of Garrapata Creek follows a branch of the Palo Colorado fault for a distance of approximately 2½ miles.

Water Balance

Inflow

Watershed average precipitation is approximately 26.4 inches based on a U.S. Geological Survey (USGS) isohyetal map (Figure 3; Rantz, 1969). Average precipitation measured by a resident at an approximate elevation of 1000 feet above mean sea level (ft amsl) in the watershed for water years (WYs) 1982 to 1996 was 29 inches per year (in/yr) (Table A-1). Nearby official precipitation gages include Monterey and Big Sur State Park, where long-term average precipitation is approximately 19 and 42 in/yr, respectively (Figure 4; Tables A-2 and A-3). The Division assumes average watershed precipitation to be 25 in/yr.

Table 1 presents an estimated soil water balance for the Garrapata Creek watershed upstream of the Water Company wells. The soil water balance indicates that actual evapotranspiration is approximately 16.7 in/yr. Thus, approximately 9.7 in/yr, or 5500 acre-feet per year (ac-ft/yr), are available for streamflow and groundwater recharge.

In the May 1997 Division staff report, total watershed runoff was estimated as 35 percent of precipitation, or 4668 ac-ft/yr assuming 25 in/yr of average precipitation. This is reasonably consistent with the above estimate using the soil water balance approach.

Outflow

Meter readings of water produced by the Water Company well between July 12 and September 13, 1997 indicate an extraction rate of approximately 3.6 ac-ft/month during the dry season (27 gpm or 0.06 cfs). This extrapolates to 43 ac-ft/yr, although water use is probably less during other times of the year. The majority of this water is used in nearby areas outside the watershed boundary, and some is recharged by septic tanks and percolated landscape irrigation of Water Company customers within the watershed.

Excluding the Water Company, the Division lists ten diversions of record in the watershed totaling 310 ac-ft/yr of appropriative and claimed water rights (Table 3 of May 1997 staff report). The entire amount of these rights may not be exercised, and of the amount used some returns as applied water and wastewater recharge. Additional water use includes non-recorded diversions and other groundwater extractions. No water use appears to occur downstream of the Water Company wells.

Based on these outflows, a rough, conservative estimate of total watershed outflow to the ocean is 5100 ac-ft/yr. Based on the discussion in the following sections, it is reasonable to assume that most of this reaches the ocean as Garrapata Creek streamflow.

Garrapata Creek Discharge

Garrapata Creek does not have a recording stream gage. The nearest recording gage is operated by the USGS on the Big Sur River. The average discharge of the river's 46.5 square mile gaged watershed is approximately 72,000 ac-ft/yr (Table A-4). Figure 5 provides the river's WY 1951-1997 gaging record in terms of percent average annual discharge. Assuming Garrapata Creek has an average annual flow of approximately 5000 ac-ft/yr near the Water Company well, its average annual flow is equal to approximately 7 percent of that of the Big Sur River.

Available Data

Table 2 summarizes 13 measurements of Garrapata Creek instantaneous discharge reported by various observers during 1976 to 1996. These measurements were taken at various times of the year during both dry and wet years, and range from 0.05 to 22 cubic ft per second (cfs).

The measured instantaneous flows of Garrapata Creek range from about 2 to 11 percent of the corresponding average daily flows of the Big Sur River (Table 2). Creek flows below 1 cfs were roughly 3 percent of corresponding river flows, creek flows from 5 to 10 cfs were about 8 to 11 percent of river flows, and creek flows over 15 cfs ranged from about 5 to 7 percent of river flows. This relation is plotted in Figure 6. The non-linear relation between creek and river flows may be related to various factors, including differences in watershed physiography, geology, precipitation, and vegetation.

Estimate of Average Monthly Flows

Based on the flow relationship in Figure 6, Table 3 provides estimates of the average monthly flows of Garrapata Creek. These total 5000 ac-ft/yr, consistent with the water-balance estimate presented in Section 2.1. Figure 7 is a plot of the estimated average monthly flows of Garrapata Creek expressed in terms of cfs.

In Table 1 of their May 1997 report, Division staff estimate the average monthly flows of Garrapata Creek to equal 35 percent of the estimated volume of average monthly rainfall. Because this approach ignores the contribution of groundwater discharge to streamflow during the dry season, the Division's estimated minimum monthly flow of 0.16 cfs (in July and August) is only about one third of the minimum monthly flow estimated by Geomatrix (in October; Table 3). Indeed, the Division approach for estimating monthly flows is contrary to the following statement by Division staff in the same May 1997 report:

> "Streamflow during the six months [dry season] consists of water that is released from bank and channel storage and water discharged from springs and seeps" (p. 7, 2nd paragraph).

Estimated Baseflows

Similar to other streams in coastal California, Garrapata Creek streamflow consists of two components, runoff and baseflow. The runoff component occurs during and after periods of precipitation. The baseflow component occurs because of the hydraulic head difference between groundwater and the water surface in the creek. During the dry season from May to October, when there is little or no precipitation (Figure 4), the flow is entirely baseflow. All but four of the flow measurements in Table 2 represent such conditions. During the wet season, flows consist of both baseflow and runoff. The rate of baseflow is greatest when the hydraulic gradient between groundwater and stream is greatest. This occurs when groundwater elevations reach their annual peak near the end of the wet season as a result of cumulative recharge.

Figure 7 shows an approximate runoff-baseflow separation for the estimated average annual hydrograph of Garrapata Creek. Peak baseflow is estimated to occur in April at a rate of about 6 cfs. Baseflows of this magnitude were measured during June of 1982 following a winter of above average rainfall. As summarized in Table 3, average annual baseflows are estimated to total about 1900 ac-ft/yr given the runoff-baseflow separation shown in Figure 7.

Groundwater

The Garrapata Creek watershed consists of a dual aquifer system. One aquifer consists of alluvial deposits underlying the valley floor and the other aquifer consists of the weathered and fractured granite exposed across the remainder of the watershed.

Alluvial Deposits

Drillers' logs suggest that alluvial deposits in the vicinity of the Water Company wells are at least 40 to 50 ft thick. The Water Company wells are completed in these deposits and operate at a rate of approximately 50 gallons per minute (gpm). From the Water Company wells upstream to where the creek follows the Palo Colorado fault, the valley floor occupies approximately 42 acres. Another broad portion of the valley floor further upstream occupies another 24 acres. Because the alluvial fill is "V"-shaped in cross section, its average thickness may be about 20 ft. Assuming a porosity of 20 percent, the total amount of groundwater stored in the alluvium may be about 260 ac-ft.

Weathered and Fractured Granitic Bedrock

As described in the October 1997 Division staff memorandum, the granitic bedrock has a moderately to well developed system of joints trending northwest similar to the Palo Colorado fault. Weathering and fracturing associated with the joints and faulting result in a secondary porosity capable of producing significant well yields.

Wells in the granitic bedrock provide groundwater to many residents in the region. For example, a 900-ft deep well drilled in the late 1980s at an elevation of approximately 800 ft amsl on the ridge separating Garrapata Creek and State Route 1 had a yield reportedly sufficient to serve 12 homes (D. Lane, personal communication).

Water Quality

Table 4 gives 7 paired measurements of the water quality of Garrapata Creek and the Water Company well. The electrical conductivity of groundwater averages about 3.5 times greater than the streamflow. The pH and turbidity also are distinctly different. These differences are significant given that groundwater has been extracted continuously at this site for several decades, and indicate that the groundwater pumped from the Water Company well is derived from a source other than Garrapata Creek.

Interpretation

Several lines of evidence indicate that water pumped from the Water Company well is truly groundwater and not underflow, i.e., not a "subterranean stream flowing though a known and definite channel having identifiable beds and banks." These include the following:

- The need for a bedrock aquifer to transmit and sustain baseflows.
- The existence of a bedrock aquifer indicated by the many bedrock wells in the region.
- Significant water quality differences between Garrapata Creek and the groundwater.

It is not possible to transmit the measured and estimated rates of Garrapata Creek baseflow into the stream except through the bedrock aquifer. The volume of water released from "bank and channel storage," as suggested by the Division staff report, could not sustain these volumes of baseflow. Indeed, the alluvial deposits upstream of the Water Company well have an estimated groundwater storage capacity of less than 15 percent of the estimated average annual baseflow. Water released from the banks immediately adjacent to the creek could not provide the additional water needed to sustain baseflow.

The volume of baseflow indicated in Figure 7 and Table 3 requires an average rate of groundwater recharge of 3.5 in/yr across the entire watershed. Effectively transmitting this flow through the colluvium across the entire watershed, as suggested by the October 1997 Division staff memorandum, is highly improbable. Instead, this recharge percolates over the entire watershed to become groundwater within a significantly thick weathered and fractured zone of saturated bedrock. The existence of this bedrock aquifer is known from the many successful wells in granitic bedrock in the region of Garrapata Creek. Aquifers within fractured granitic rock are common throughout the world. The weathering of feldspar minerals into clay, contrary to the Division staff memorandum does not compromise their viability.

The Division staff memorandum states that the "boundary of the zone of [bedrock] fractures and weathering, although not known with exactness" may be inferred to be the "bed and banks of a subterranean stream." Because the granitic bedrock occurs over the entire watershed, and because fractures and weathering are not limited to the bedrock immediately beneath Garrapata Creek, this statement by Division staff may be reasonably interpreted to say that the entire watershed is underlain by a subterranean stream. Geomatrix agrees that the entire watershed is underlain by a bedrock aquifer that transmits recharge to Garrapata Creek, but this clearly should not be described as the underflow of a subterranean stream.

Garrapata Creek occupies the topographic low point of the watershed and is thus the ultimate destination of most groundwater flow through the bedrock aquifer from all points of the watershed. Furthermore, because the hydraulic conductivity of the alluvial deposits is likely greater than that of the fractured and weathered bedrock, groundwater flow paths are directed into the alluvium. The difference in hydraulic head between areas of recharge and the creek cause groundwater entering the alluvium from the bedrock to rise up into the channel. This is particularly true as sea level is approached towards the lower portions of the watershed, such as where the Water Company well is located. Figure 8 illustrates this flow pattern. Whereas this flow system can support the observed baseflows of Garrapata Creek, the flow system described by Division staff cannot.

The water quality differences between the Water Company well and Garrapata Creek are consistent with the interpretation that groundwater flows from the bedrock aquifer across the watershed toward the creek. The groundwater is more mineralized because of its residence time in the bedrock aquifer.

Conclusion

The source of groundwater that both discharges into Garrapata Creek and is pumped from the Water Company well originates from groundwater recharge into the weathered and fractured bedrock aquifer across the entire watershed. This explanation of the watershed hydrology is consistent with rates of observed and estimated baseflow, the existence of wells in the bedrock, and water quality differences between groundwater and the creek. These conditions indicate that percolating groundwater is the source of water to the Water Company well.

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Tables

Table 1

Estimated Soil Water Balance for the Garrapata Creek Watershed Upstream of the Garrapata Water Company Wells[a]

(all values are in inches except T [°F] and I [dimensionless])

Parameter	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
T: Average Air Temperature[b]	50	51	52	54	57	61	63	64	64	62	55	51	57
I: Heat Index[c]	2.86	3.12	3.34	3.86	4.70	5.87	6.49	6.84	6.84	6.21	4.15	3.12	57.4
PE: Adjusted Potential Evapotranspiration[d]	1.23	1.24	1.58	1.95	2.58	3.18	3.26	3.58	3.16	2.64	1.64	1.22	27.3
PPT: Precipitation[e]	5.8	4.1	3.7	2.5	0.5	0.19	0.07	0.11	0.33	1.1	3.2	4.8	26.4
PPT-PE	4.57	2.86	2.12	0.55	-2.08	-2.99	-3.19	-3.47	-2.86	-1.54	1.56	3.58	-0.9
ST: Soil Moisture Storage in Root Zone[f]	5.91	5.91	5.91	5.91	4.12	2.44	1.42	0.79	0.47	0.35	1.93	5.51	
del ST: Change in Storage	0.40	0.0	0.0	0.0	-1.78	-1.69	-1.02	-0.63	-0.32	-0.12	1.58	3.58	
AE: Actual Evapotranspiration[g]	1.23	1.24	1.58	1.95	2.28	1.88	1.09	0.74	0.65	1.22	1.64	1.22	16.7
S: Water Surplus[h]	4.17	2.86	2.12	0.55	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.7

Summary: PPT - AE = SURPLUS = 26.4 - 16.7 = 9.7

Temperature (°F)

Monterey[i] (elev. 385) (1950-1979 normal)	51.4	53.0	53.0	53.9	55.9	58.3	59.5	60.5	62.4	60.7	56.4	52.4	56.5
Pebble Beach[j] (elev. 165) (13-year average)	49.9	52.2	52.2	53.7	55.1	57.1	65.75	58.4	59.7	58.4	55.5	5.24	55.2
Del Monte[j] (elev. 40) (20-year average)	47.5	49.6	52.1	54.5	57.3	59.8	61.2	61.0	60.9	57.1	51.3	48.4	55.1
Carmel Valley[j] (elev. 425) (10-year average)	51.1	52.1	52.0	54.9	56.8	61.3	62.9	63.8	64.3	62.9	55.4	52.6	57.5
Pinnacles[i] (elev. 1307) (1950-1979 normal)	47.2	49.7	51.1	55.0	60.9	67.5	73.5	72.7	69.8	62.6	53.5	48.1	59.3

Notes:

[a] Thornthwaite method adopted from Mather (1978).

[b] Adopted from regional long-term temperature averages (Table 1).

[c] From Table A-2 (Mather, 1978).

[d] Determined from Tables A-3 and A-4 (Mather, 1978).

[e] Adopted from 30-year normal precipitation for Monterey and Big Sur State Park (Figue 4) adjusted to Garrapata Creek watershed average (Figure 3).

[f] From Table A-7 (Mather, 1978) for soils with 150 mm soil moisture retention.

[g] AE = PE when sufficient water is available from rainfall or soil moisture storage. AE = PPT plus absolute value of storage change when PPT<PE and storage change is negative.

[h] S = PPT-PE when soil moisture storage is at capacity; S = (PPT-PE) - ST during month when storage reaches capacity; there is no surplus when storage is not at capacity.

[i] NOAA Cimatological Data for California.

[j] Gilbert, 1973.

Table 2
Instantaneous Discharge Measurements of Garrapata Creek

Gaged Flows						Average Daily Flow of Big Sur R. for Date (cfs)	Garrapata Ck. Flow as % of Big Sur R. Flow for Date	Big Sur R. WY Flow % of Average Flow
Date	Reported Flow (gpm)	(cfs)	Reported Method		Source			
8/76 thru 10/76	188	0.42	none reported; uncertain date within period.		Black & Veatch, 1980	14	2.99%	18%
6/28/1982	-	5.87	Price pygmy current meter; average of 4 measurements; >20 station widths each		HEA, 1982	55	10.66%	183%
7/21/1989	-	0.20	Price pygmy current meter; average of two measurements; >10 station widths each		Nicholas M. Johnson, 1989	5.9	3.31%	27%
10/21/1988	117	0.26	8-inch flume; stage 0.25		John G. Williams, 1977, written communication to Division of Water Rights	8.5	3.06%	24%
8/12/1989	63	0.14	8-inch flume; stage 0.185		"	5.8	2.41%	27%
9/8/1990	22	0.05	2-inch flume; stage 0.225		"	2.8	1.79%	18%
12/14/1991	117	0.26	8-inch flume; stage 0.25		"	9.4	2.77%	50%
9/26/1992	76	0.17	8-inch flume; stage 0.2		"	6.8	2.50%	58%
10/20/1996	233	0.52	none reported		"	18	2.89%	121%
	(m^3/sec)	(cfs)	Prior Rainfall	Reported Method				
3/8/1996	0.617	22	3/3 to 3/5/96	Price pygmy current meter, >20 station widths each	California State University, Monterey Bay, student project, written communication to Division of Water Rights	395	5.52%	121%
3/15/1996	0.5905	21	3/12/1996	" (avg of 2 meas.)	"	342	6.10%	121%
3/22/1996	0.47	17	>month	"	"	224	7.41%	121%
4/12/1996	0.284	10	4/1/1996	"	"	125	8.02%	121%

Tables Table 2 5/15/2000 12:16 PM

Table 3
Estimation of Garrapata Creek Average Monthly Discharge

Stream	Units	Source	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	WY
Big Sur River	ac-ft	Table A-4	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
	cfs		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	
Garrapata Creek	as % of Big Sur R.	Figure 6	3.0%	6.0%	8.0%	7.0%	7.0%	7.0%	8.0%	8.0%	5.0%	4.0%	3.5%	3.0%	#REF!
	cfs		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	
	ac-ft		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
Garrapata Ck. baseflow	cfs	Figure 7	0.52	1.90	2.80	3.70	4.50	5.35	5.80	4.35	1.80	0.92	0.60	0.46	
	ac-ft		32	113	172	228	250	329	345	267	107	57	37	27	1,960

Table 4
Available Paired Water Quality Data for Garrapata Creek and Water Company Well

	Garrapata Creek				Water Company Well Groundwater					
Date	Temp. (°F)	Electrical Conductivity (uS/cm)	pH	Turbidity (NTU)	Temp. (°F)	Electrical Conductivity (uS/cm)	pH	Turbidity (NTU)	Rainfall During Days Prior	Source
6/28/1982	57.2	210	-	-	62.6	445	-	-	trace amounts on 6/22, 6/23, 6/26, and 6/28.	HEA, 1982
1/28/1998	58.9	174	8.63	3.3	58.2	548	7.99	0.2	dry 1/20-1/27, wet 1/28-1/29, very wet 2/1-2/23	Garrapata Water Co.
1/29/1998	59.1	161	8.59	50	60.5	546	7.99	0.15		"
1/30/1998	55.6	156	8.39	13	59.0	540	7.99	0.15		"
2/1/1998	58.3	137	8.72	85	58.0	509	7.98	0.15		"
2/25/1998	58.1	150	8.92	12	59.5	698	7.99	0.1		"
2/26/1998	57.2	150	8.50	7.5	61.9	735	7.99	0.15		"
Average	57.8	163	8.63	28	60.0	574	7.99	0.15		

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Figures

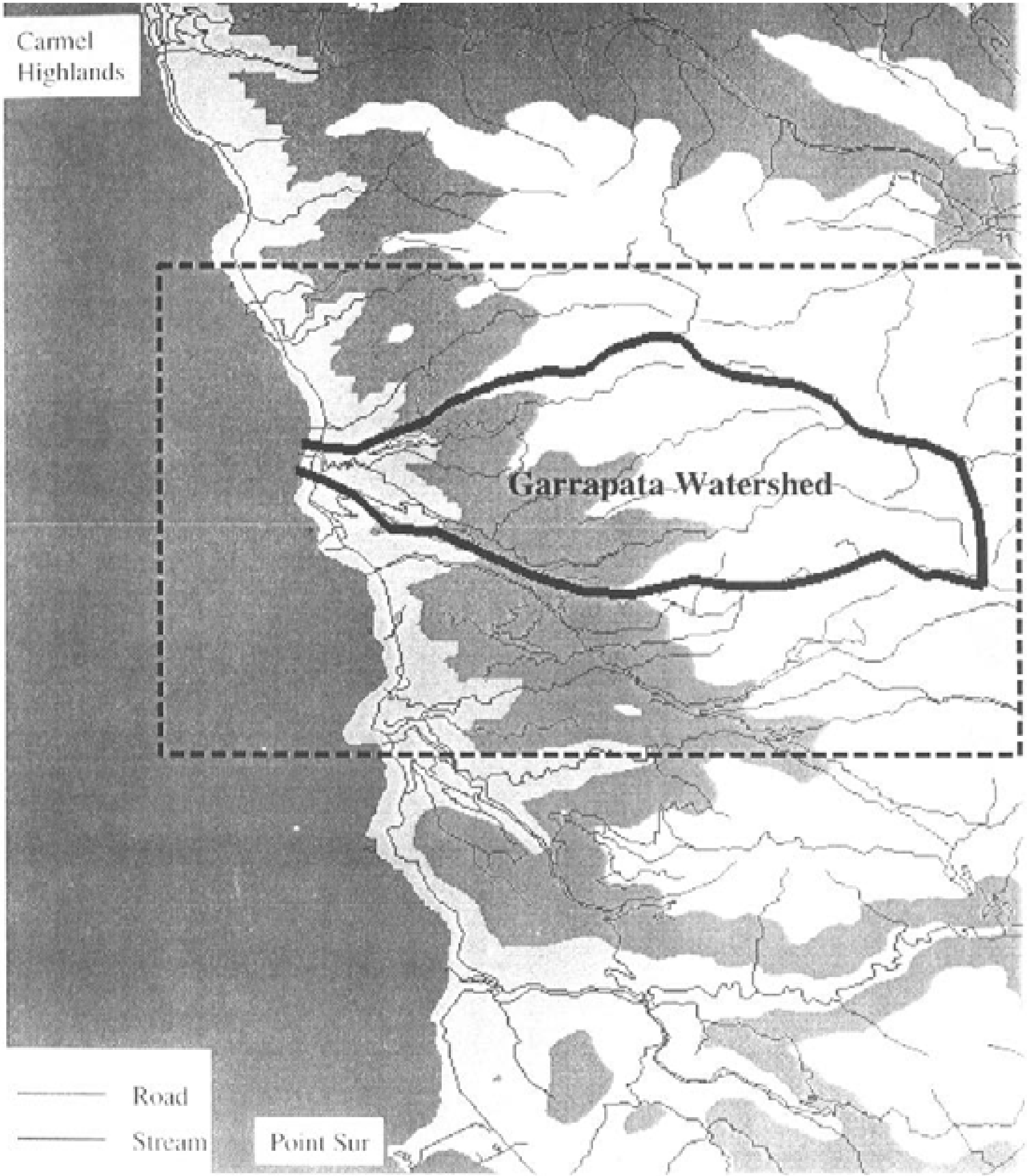

Figure 1

Location Map for Garrapata Creek

Dashed box shows area of Figure 2

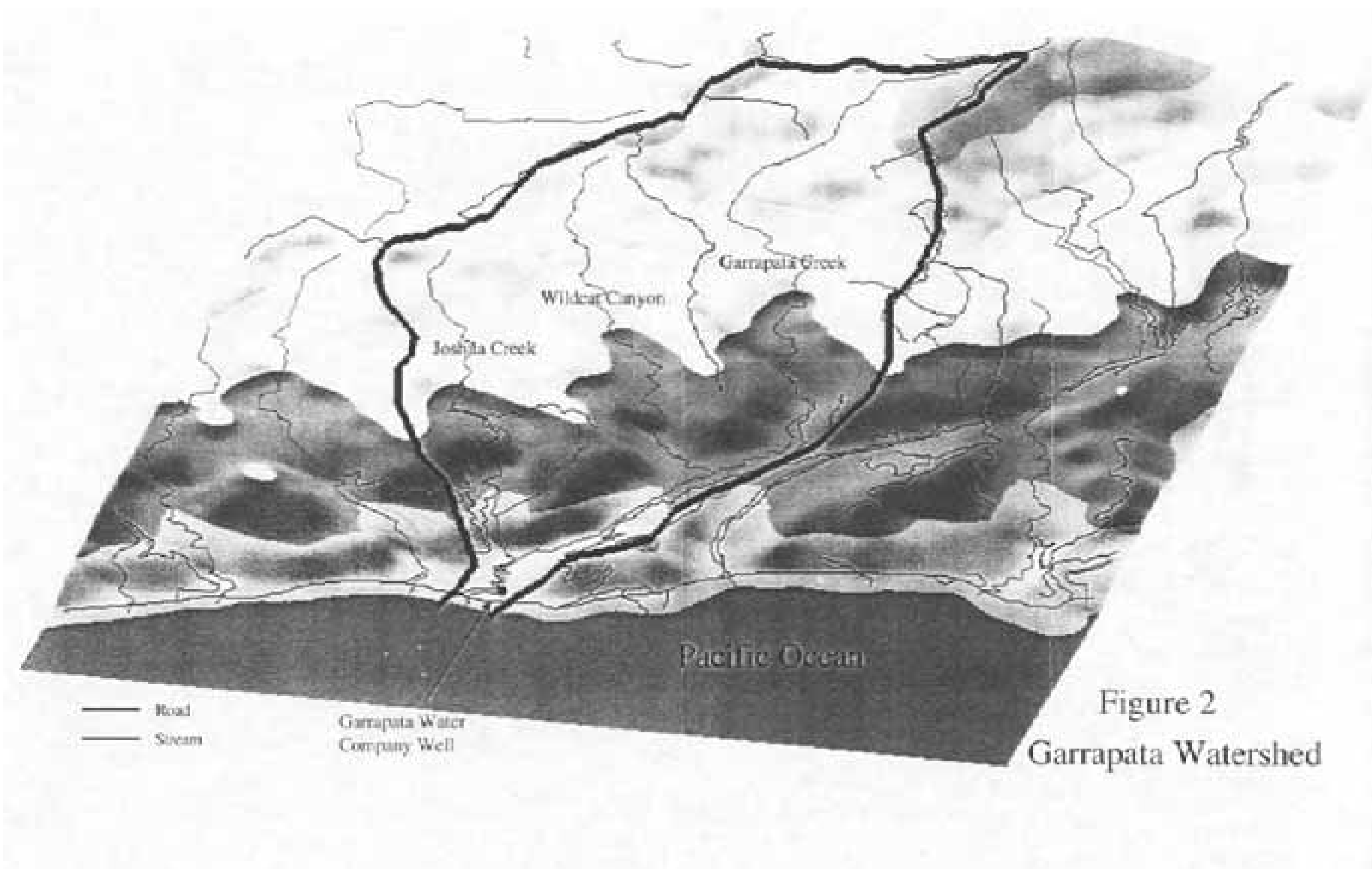

Figure 2
Garrapata Watershed

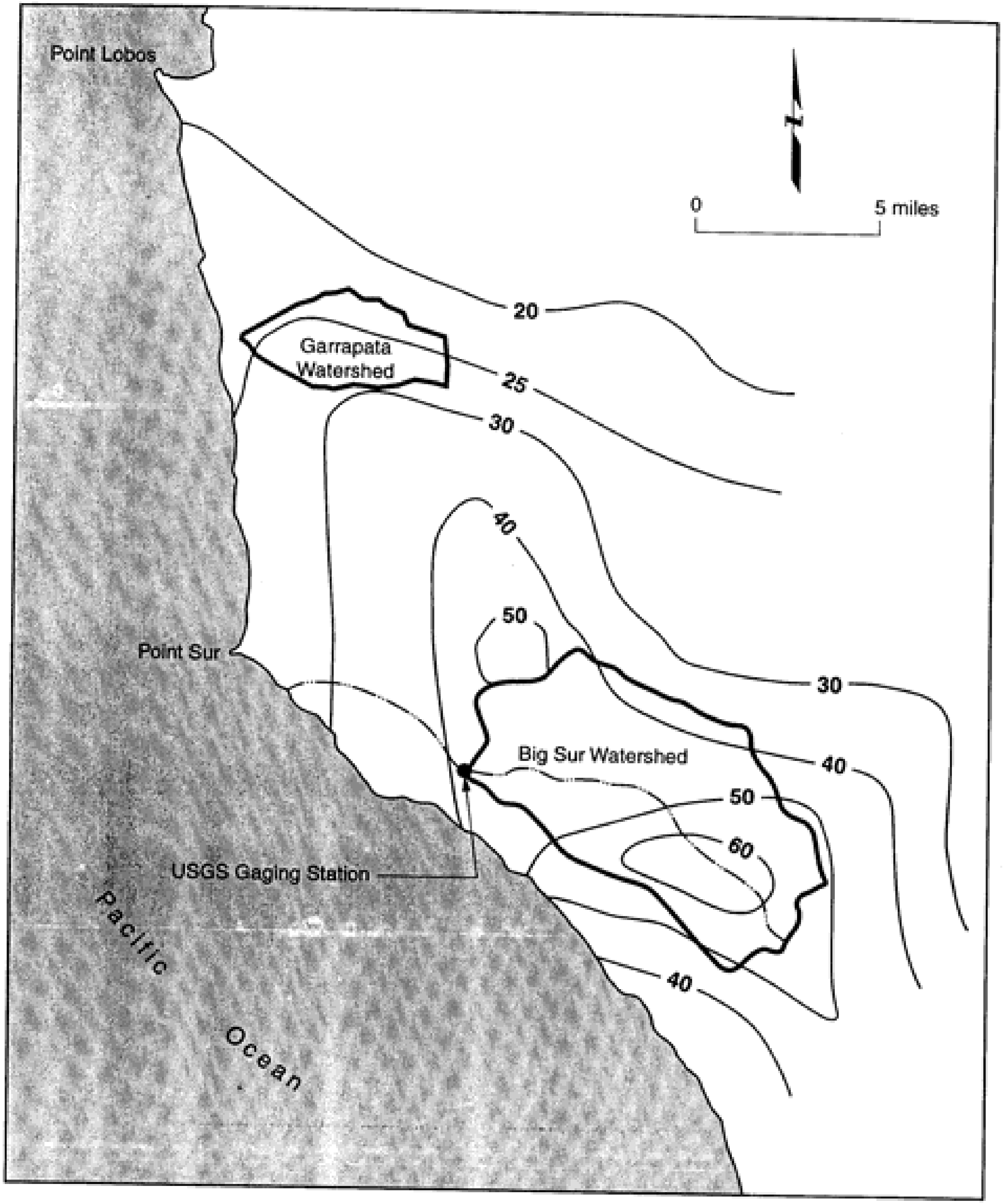

Figure 3
Isohyetal map for Central Monterey County (inches)
(adopted from Rantz, 1969)

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Figure 4
Average Monthly Precipitation at Big Sur State Park and Monterey
(Source: Tables A-2 and A-3)

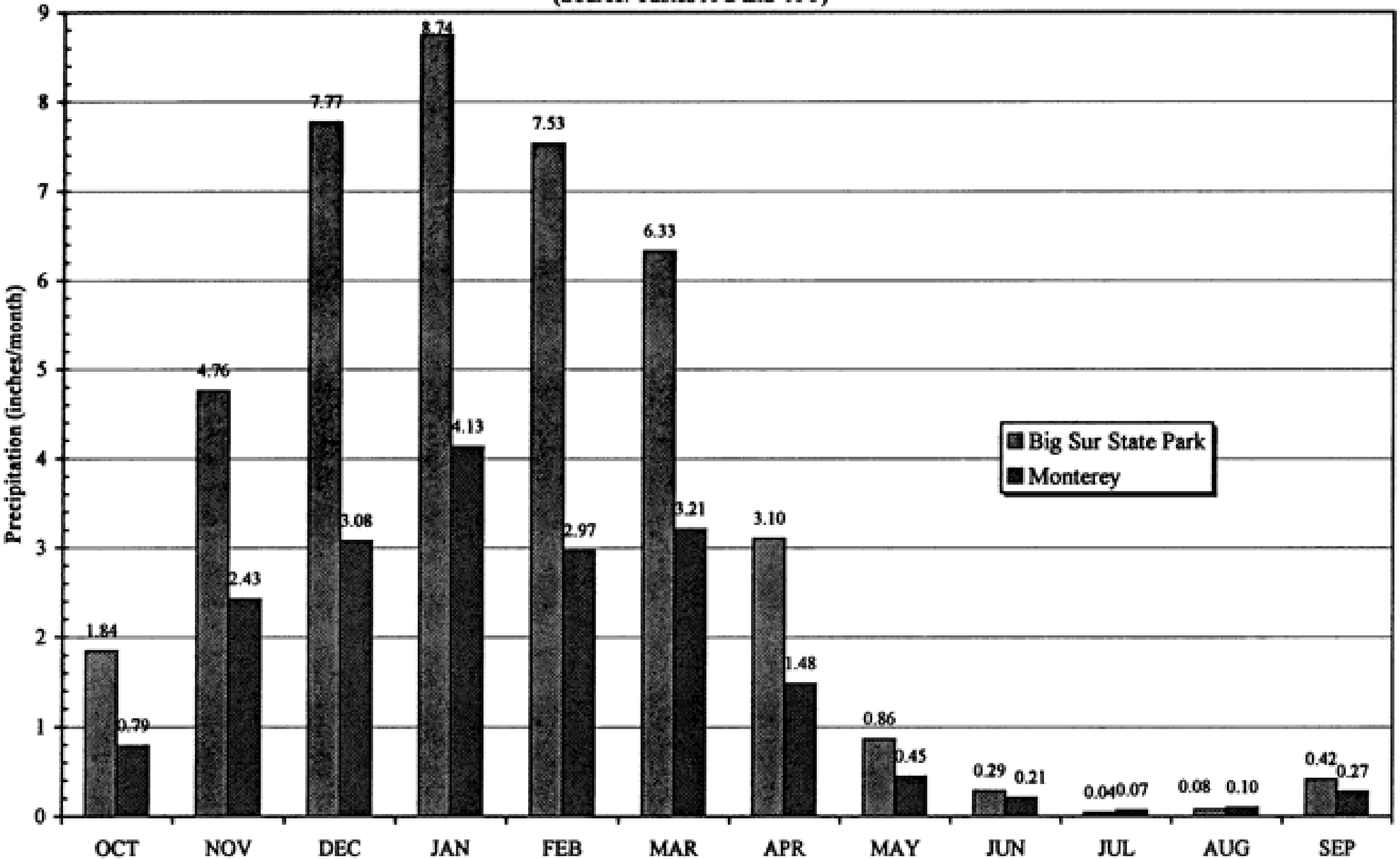

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Figure 5
Annual Discharge of Big Sur River as Percent of 1951-1997 Average Discharge
(Source: Table 4)

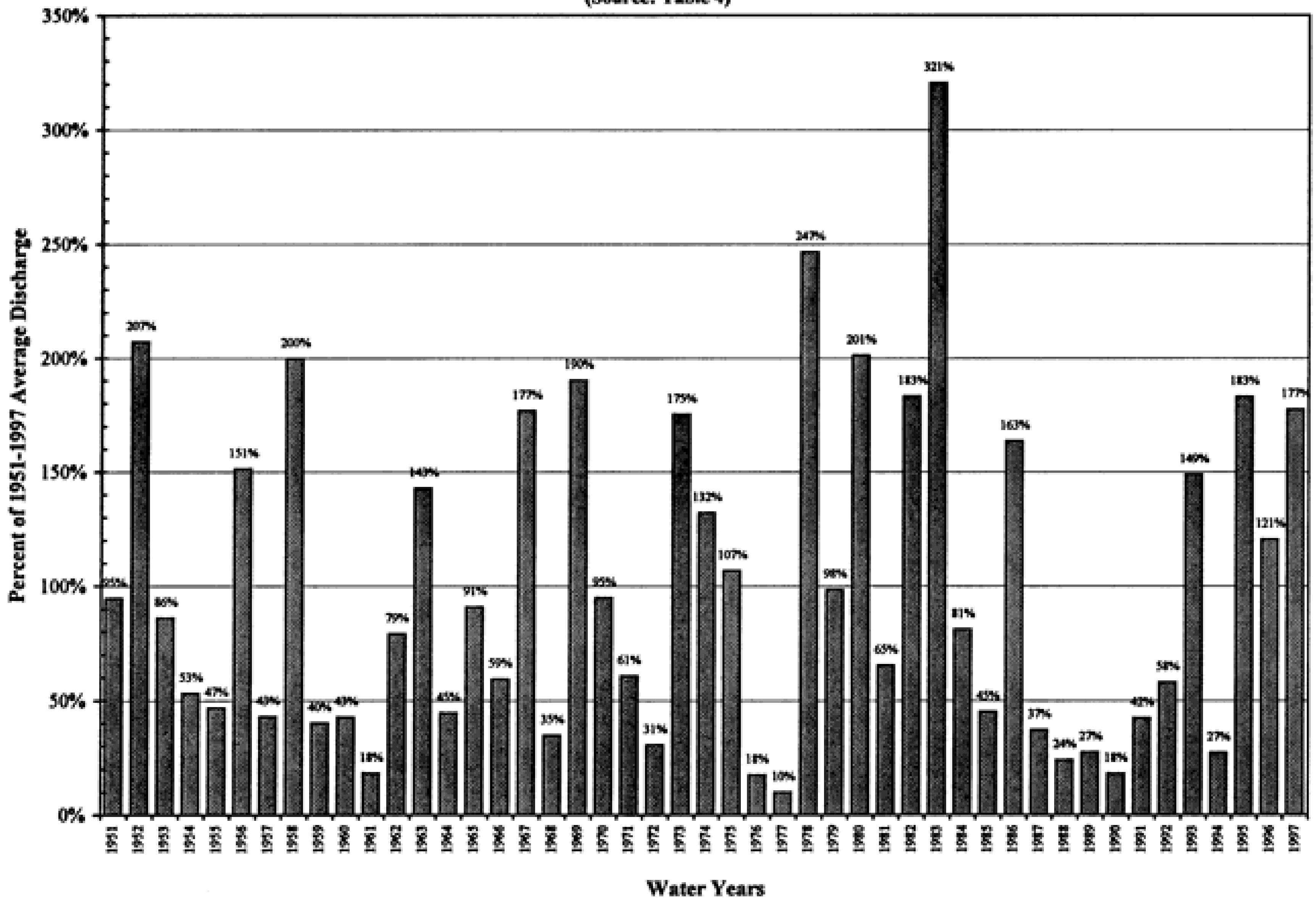

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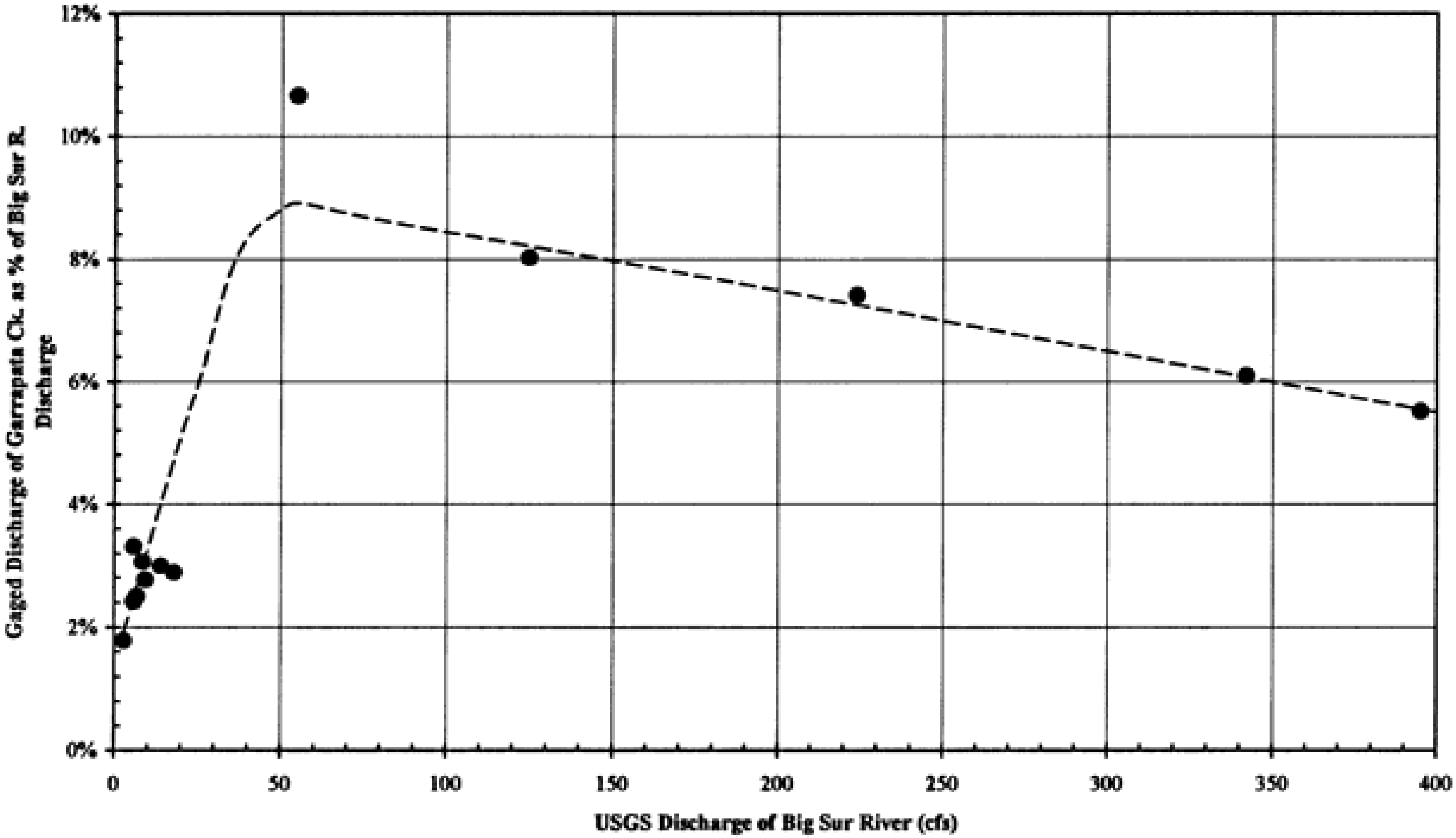
Figure 6
Gaged Instantaneous Discharge of Garrapata Creek as a Percent of Corresponding Big Sur River Average Daily Discharge
(Source: Table 2)



Figures Fig 6 5/15/2000 12:25 PM

Figure 7
Estimated Average Annual Total Discharge and Baseflow of Garrapata Creek

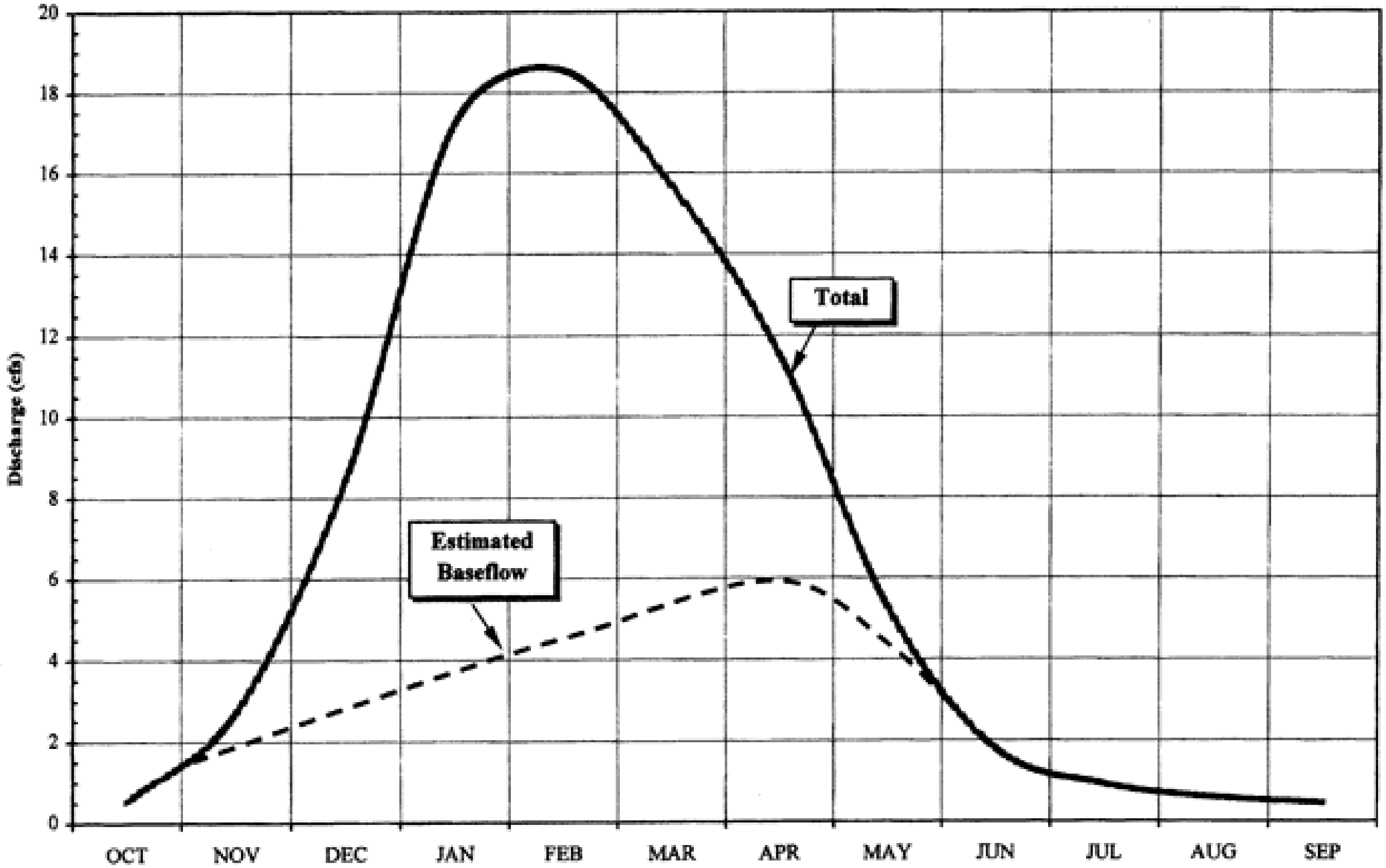
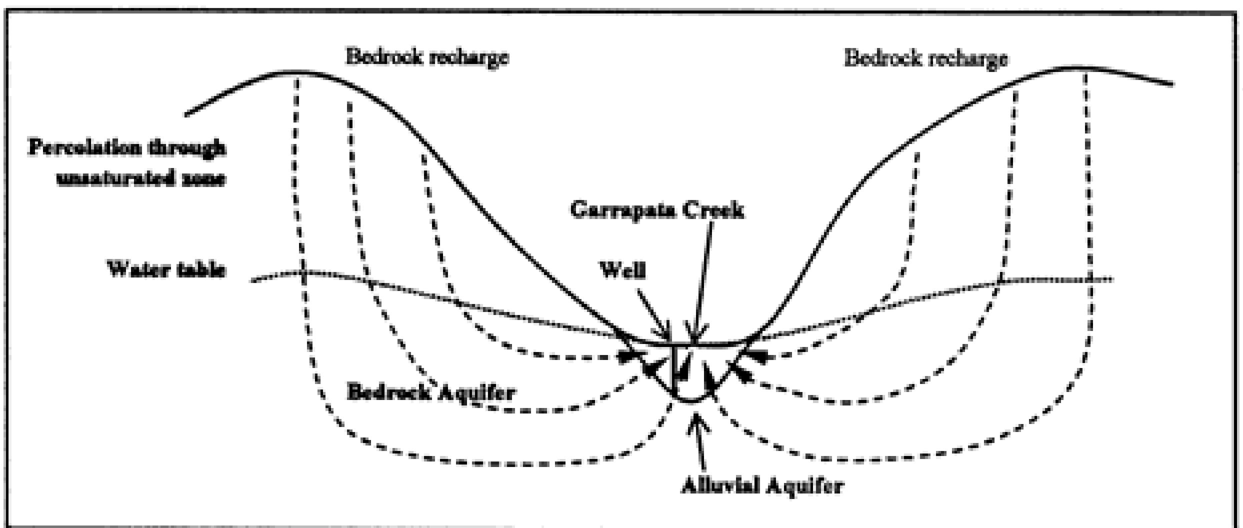


Figure 8
Groundwater Flow Pattern from Bedrock Aquifer Recharge Areas to Alluvial Deposits Beneath Garrapata Creek



View Perpendicular to Valley Axis (not to scale)

Appendix

Table A-1
Precipitation Record of Residence at 1000-Foot Elevation in Garrapata Creek Watershed
(Source: B. Cox, March 1997, written communication to B. Bean/SWRCB)

WY[a]	inches/year
1982	44.95
1983	64.45
1984	25.50
1985	21.56
1986	32.68
1987	17.68
1988	21.42
1989	15.14
1990	15.66
1991	19.21
1992	26.57
1993	38.37
1994	19.39
1995	49.80
1996	29.02
Average	29.43

[a]Reflects July 1 to June 30 water year,; e.g., WY 1982 begins July 1 1981.

Table A-2
Monterey Precipitation Record, WYs 1949-1997
(Source: NOAA)

WY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	% of Avg
1949				****	3.11	5.40	0.13	0.50	0.01	0.04	0.11	0.00	****	
1950	0.02	1.78	1.47	5.11	1.71	2.16	1.65	0.23	0.20	0.00	0.00	0.00	****	****
1951	2.15	****	****	2.63	2.17	****	****	****	0.00	0.12	0.04	0.05	****	****
1952	0.90	2.78	6.88	10.04	2.96	4.41	1.10	0.16	0.24	0.06	0.08	0.08	****	****
1953	0.17	2.19	5.90	2.06	0.04	1.20	1.67	0.49	0.22	0.00	0.11	0.07	14.12	74%
1954	0.38	2.15	0.56	4.26	2.26	4.91	0.85	0.42	0.40	0.00	0.16	0.05	16.40	85%
1955	0.03	2.50	3.13	5.82	1.74	****	1.74	0.87	0.06	0.00	0.00	0.00	15.89	83%
1956	0.08	1.96	9.79	6.09	2.25	0.15	1.67	0.59	0.00	0.07	0.02	0.36	****	****
1957	1.00	0.00	0.84	4.65	3.52	1.92	1.49	2.39	0.20	0.00	0.00	0.23	16.24	85%
1958	1.58	0.93	3.70	3.71	5.66	7.17	4.71	0.56	0.35	0.04	0.00	0.48	28.89	151%
1959	0.04	0.51	0.49	4.85	5.76	0.32	0.29	0.12	0.00	0.00	0.04	3.14	15.56	81%
1960	0.00	0.00	0.59	4.30	4.53	0.84	0.88	0.34	0.00	0.03	0.00	0.13	11.64	61%
1961	0.07	2.06	0.85	1.89	1.17	2.58	1.29	0.72	0.00	0.00	0.14	0.09	10.86	57%
1962	0.04	1.74	1.19	2.64	5.17	2.57	0.30	0.15	0.23	0.00	0.25	0.15	14.43	75%
1963	1.33	0.37	2.21	3.05	2.70	4.14	****	****	****	****	****	****	****	****
1964	1.46	3.77	0.53	3.50	0.42	2.23	0.22	0.86	0.22	0.09	0.35	0.01	13.66	71%
1965	0.78	3.29	6.45	2.56	1.05	2.44	2.26	0.17	0.15	0.05	0.16	0.02	19.38	101%
1966	0.23	6.49	5.56	2.32	1.88	0.43	0.27	0.13	0.12	0.28	0.09	0.32	18.12	94%
1967	0.09	4.74	4.18	5.29	0.45	5.48	7.11	0.40	1.56	0.02	0.06	0.17	29.55	154%
1968	0.38	1.61	2.27	3.10	1.40	3.06	0.79	0.32	0.01	0.06	0.23	0.05	13.28	69%
1969	0.31	3.13	3.27	9.45	7.31	1.31	2.70	0.12	0.42	0.04	0.00	0.12	28.18	147%
1970	0.50	0.72	3.08	5.91	2.04	2.97	0.35	0.05	0.30	0.03	0.06	0.02	16.03	84%
1971	0.59	6.17	4.99	1.08	0.62	1.96	1.19	0.71	0.03	0.07	0.13	0.43	17.97	94%
1972	0.09	1.99	4.76	1.23	1.05	0.03	0.88	0.09	0.15	0.06	0.04	0.10	10.47	55%
1973	2.46	5.95	2.08	6.05	5.88	4.52	0.13	0.06	0.02	0.02	0.05	0.34	27.56	144%
1974	2.20	3.87	4.73	3.73	0.91	4.48	3.40	0.03	0.37	0.25	0.02	0.01	24.00	125%
1975	1.54	0.56	2.48	1.34	3.62	4.06	1.76	0.01	0.17	0.17	0.43	0.02	16.16	84%
1976	1.70	0.52	0.37	0.18	2.97	1.52	1.74	0.07	0.17	0.02	0.97	0.42	10.65	56%
1977	0.60	0.72	2.08	1.74	0.83	1.75	0.04	1.21	0.08	0.03	0.02	0.65	9.75	51%
1978	0.14	0.54	5.85	6.78	4.78	5.24	5.43	0.02	0.08	0.04	0.00	0.29	29.19	152%
1979	0.02	2.13	1.59	4.82	4.52	4.41	0.98	0.29	0.02	0.35	0.09	0.02	18.84	98%
1980	1.80	2.85	3.18	5.95	4.78	2.40	1.77	0.57	0.04	0.73	0.09	0.09	24.25	126%
1981	0.05	0.12	1.72	6.99	2.12	3.98	0.96	0.19	0.00	0.01	0.16	0.07	15.97	83%
1982	2.10	5.66	1.67	4.69	2.37	8.04	3.14	0.07	0.53	0.10	0.06	1.45	29.88	156%
1983	2.31	6.23	3.56	6.90	5.56	9.61	4.42	0.26	0.18	0.00	0.04	1.23	40.30	210%
1984	0.47	5.33	3.70	0.11	2.39	1.24	0.75	0.24	0.18	0.00	0.03	0.02	14.46	75%
1985	2.08	4.82	2.03	1.11	1.37	3.93	0.75	0.32	0.27	0.10	0.00	0.16	16.94	88%
1986	1.61	4.43	1.49	2.12	4.49	5.12	0.42	0.44	0.08	0.00	0.08	0.94	21.22	111%
1987	0.13	0.27	1.68	3.36	3.02	2.83	0.53	0.14	0.00	0.08	0.02	0.00	12.06	63%
1988	1.11	1.84	3.19	2.19	0.73	0.13	1.94	0.63	0.28	0.02	0.03	0.04	12.13	****
1989	0.17	2.74	3.44	1.56	2.20	2.91	0.98	0.33	0.02	0.00	0.03	0.96	15.34	80%
1990	1.68	1.38	0.16	3.54	2.88	1.58	0.88	1.83	0.02	0.04	0.07	0.08	14.14	74%
1991	0.14	0.52	1.66	0.70	2.26	7.52	0.48	0.24	0.03	0.05	0.26	0.02	13.88	72%
1992	1.28	0.14	3.50	2.20	6.30	3.99	0.60	0.01	0.19	0.03	0.10	0.07	17.84	93%
1993	0.65	0.18	6.26	9.66	7.56	3.10	0.92	0.83	0.84	0.04	0.04	0.01	30.09	157%
1994	0.15	1.76	2.20	3.02	4.00	0.46	1.37	0.84	0.02	0.04	0.05	0.05	13.96	73%
1995	0.33	2.78	2.43	10.61	0.73	7.26	2.24	0.58	1.40	0.02	0.03	0.00	28.41	148%
1996	0.03	0.22	2.34	5.02	8.08	2.91	0.92	1.33	0.04	0.05	0.03	0.04	21.01	110%
1997	1.06	2.63	8.01	8.75	0.21	0.18	0.40	0.12	0.08	0.03	0.23	0.04	21.74	113%
1998	0.58	7.48	3.56	****	****	****	****	****	****	****	****	****	****	****
Avg	0.79	2.43	3.08	4.13	2.97	3.21	1.48	0.45	0.21	0.07	0.10	0.27	19.18	

Table A-3

Big Sur State Park Precipitation Record, WYs 1932-1997

(Source: NOAA)

WY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	% of Avg
1931	****	****	****	9.32	2.14	0.79	0.82	2.01	1.33	0.00	0.00	0.00	****	
1932	0.60	4.97	18.21	6.90	9.17	2.36	1.49	0.64	0.05	0.00	0.00	0.00	44.39	106%
1933	0.09	0.69	3.55	9.96	1.64	3.55	0.34	1.61	0.36	0.00	0.00	0.03	21.82	52%
1934	3.30	0.06	12.38	2.61	10.99	0.00	0.88	1.34	2.53	0.00	0.00	0.29	34.38	82%
1935	2.76	6.78	6.07	10.60	2.09	5.90	9.77	0.08	0.00	0.00	0.45	0.00	44.50	107%
1936	3.28	1.55	4.74	11.10	20.67	2.78	3.54	1.30	1.03	0.00	0.00	0.06	50.05	120%
1937	1.62	0.00	8.42	7.15	13.46	12.68	1.58	0.00	0.80	0.00	0.00	0.00	45.71	109%
1938	0.41	2.42	12.43	7.35	13.45	15.01	2.79	0.00	0.00	0.00	0.00	0.00	53.86	129%
1939	1.84	1.41	3.75	5.30	3.83	4.92	0.46	1.21	0.00	0.00	0.00	0.57	23.29	56%
1940	1.31	0.50	4.21	22.11	22.39	4.42	2.25	0.94	0.00	0.03	0.00	0.47	58.63	140%
1941	1.85	0.78	15.70	15.16	18.70	13.39	9.55	1.86	0.04	0.00	0.00	0.00	77.03	184%
1942	1.49	1.58	18.07	10.25	5.10	5.75	6.45	2.06	0.00	0.00	0.00	0.00	50.76	122%
1943	1.09	6.99	4.79	13.78	5.98	10.54	2.31	0.00	0.00	0.00	0.00	0.00	45.48	109%
1944	2.35	0.79	5.57	6.76	14.48	1.96	4.60	1.17	0.18	0.00	0.00	0.00	37.86	91%
1945	3.84	7.44	****	2.95	12.57	7.25	0.63	0.49	0.25	0.00	0.16	0.07	****	****
1946	5.87	4.37	12.96	2.39	4.88	7.07	0.07	0.82	0.00	0.00	0.00	0.03	38.46	92%
1947	0.38	10.99	3.48	1.15	4.90	5.09	0.94	0.93	0.43	0.00	0.00	0.05	28.34	68%
1948	3.57	0.84	2.52	0.21	3.38	9.06	7.77	1.79	0.03	0.00	0.00	0.00	29.17	70%
1949	4.10	0.53	6.83	4.48	5.57	10.02	0.03	0.13	0.00	0.05	0.02	0.01	31.77	76%
1950	0.00	4.67	3.70	10.26	7.93	4.18	1.71	0.48	0.00	0.01	0.00	0.31	33.25	80%
1951	4.90	12.73	7.35	5.09	2.58	2.36	1.78	1.45	0.00	0.00	0.00	0.00	38.24	92%
1952	1.91	4.25	17.44	17.10	2.66	11.34	1.87	0.76	0.08	0.00	0.00	0.07	57.48	138%
1953	0.10	4.72	15.10	9.77	0.00	3.97	6.31	0.31	0.29	0.00	0.07	0.00	40.64	97%
1954	0.32	4.43	1.22	8.69	5.46	8.73	4.01	0.44	0.51	0.00	0.01	0.00	33.82	81%
1955	0.00	7.58	7.05	8.70	2.16	0.32	4.27	1.19	0.12	0.00	0.00	0.00	31.39	75%
1956	0.05	3.29	27.21	11.18	4.52	0.18	4.21	1.27	0.00	0.00	0.00	0.05	51.96	124%
1957	1.72	0.00	0.75	6.70	7.82	2.86	3.62	7.58	0.23	0.00	0.00	0.56	31.84	76%
1958	4.44	1.33	8.66	8.24	14.80	15.41	9.98	0.49	0.11	0.00	0.00	0.47	63.93	153%
1959	0.00	0.41	1.31	12.87	7.41	0.41	1.10	0.02	0.00	0.00	0.04	8.72	32.29	77%
1960	0.00	0.00	0.95	10.66	9.76	3.42	2.28	0.40	0.00	0.00	0.00	0.00	27.47	66%
1961	0.12	6.60	3.09	4.57	1.68	3.84	1.21	0.49	0.09	0.00	0.00	0.12	21.81	52%
1962	0.06	5.05	3.49	3.96	21.88	4.45	0.62	0.26	0.11	0.00	0.00	0.00	39.88	95%
1963	8.15	0.35	6.16	13.89	11.67	7.80	11.08	0.53	0.08	0.00	0.00	0.03	59.74	143%
1964	3.38	10.22	0.41	5.57	0.40	4.63	0.72	2.69	1.02	0.00	0.00	0.36	29.40	70%
1965	2.96	5.87	13.96	8.38	1.78	4.79	4.76	0.13	0.00	0.00	0.07	0.00	42.70	102%
1966	0.24	14.97	8.41	3.54	5.14	0.31	0.89	0.00	0.00	0.12	0.00	0.23	33.85	81%
1967	0.00	9.60	11.89	13.94	1.09	9.34	12.41	0.68	1.14	0.00	0.00	0.18	60.27	144%
1968	0.29	1.83	4.51	8.30	4.23	3.94	1.25	0.50	0.00	0.00	0.21	0.00	25.06	60%
1969	1.80	3.38	8.06	23.50	17.61	2.66	3.90	0.10	0.08	0.00	0.00	0.11	61.20	147%
1970	2.43	2.79	11.46	15.28	4.01	4.47	0.90	0.00	0.55	0.00	****	****	****	****
1971	1.03	12.37	10.35	3.06	1.08	3.93	2.00	0.88	0.00	0.00	0.00	0.21	34.91	84%
1972	0.25	3.66	13.33	1.36	2.94	0.07	1.42	0.10	0.15	0.00	0.00	0.18	23.46	56%
1973	5.20	14.56	2.59	13.76	17.27	6.40	0.25	0.00	0.00	0.00	0.00	0.12	60.15	144%
1974	4.50	9.05	10.82	9.10	1.27	16.12	5.62	0.00	0.84	0.68	0.00	0.00	58.00	139%
1975	2.01	2.40	9.92	1.91	11.30	11.60	2.56	0.00	0.00	0.04	0.20	0.00	41.94	100%
1976	4.64	0.56	0.54	0.20	2.58	3.50	3.05	0.00	0.17	0.00	2.60	1.68	19.52	47%
1977	0.60	1.35	2.40	2.50	1.01	3.39	0.00	1.64	0.03	0.00	0.00	1.80	14.72	35%
1978	0.39	2.95	15.08	15.87	11.38	10.60	8.26	0.10	0.00	0.00	0.00	0.77	65.40	157%
1979	0.00	8.72	2.04	9.22	8.96	7.25	1.40	0.22	0.00	0.25	0.00	0.00	38.06	91%
1980	3.90	6.32	9.19	14.02	10.82	5.13	****	0.99	0.10	0.87	0.00	0.00	****	****
1981	0.00	0.11	3.61	10.11	3.53	10.03	0.60	0.06	0.00	0.00	0.00	0.00	28.05	67%
1982	2.44	13.68	6.68	13.47	5.07	9.41	10.65	0.04	0.68	0.00	0.00	2.10	64.22	154%
1983	2.93	11.60	7.72	15.35	15.44	19.73	8.89	1.37	0.08	0.00	0.00	3.39	86.50	207%
1984	2.63	14.22	7.75	0.35	2.76	2.82	0.75	0.05	0.11	0.04	0.03	0.22	31.73	76%
1985	2.96	8.64	4.02	0.88	3.83	6.83	0.71	****	0.26	0.00	0.00	0.68	****	****
1986	1.34	8.26	5.13	8.79	17.06	11.33	0.56	0.23	****	****	0.00	1.67	****	****
1987	0.00	0.69	5.02	4.94	9.99	9.47	1.41	0.07	0.00	0.00	0.00	0.00	31.59	76%
1988	1.94	3.27	11.31	4.69	1.77	0.61	4.13	1.16	0.42	0.00	0.00	0.00	29.30	70%
1989	0.00	4.61	8.33	2.44	3.09	9.20	1.14	0.16	0.00	0.00	0.00	0.97	29.94	72%
1990	3.69	2.59	0.16	5.53	3.70	2.38	1.06	2.35	0.00	0.00	0.00	0.49	21.95	53%
1991	0.01	0.63	1.84	0.71	4.96	20.72	1.29	0.09	1.91	0.00	0.06	0.00	32.22	77%
1992	2.76	0.72	7.82	2.69	13.00	7.51	0.45	0.00	0.00	0.56	0.02	0.00	35.53	85%
1993	3.17	0.56	12.88	21.04	11.36	2.74	1.46	2.42	0.84	0.00	0.00	0.00	56.47	135%
1994	0.03	4.01	3.38	5.42	9.39	1.34	3.17	1.81	0.00	0.00	0.00	0.32	28.87	69%
1995	1.33	6.75	****	26.47	2.22	15.84	5.35	1.86	1.78	0.23	0.00	0.00	****	****
1996	0.00	0.09	8.45	14.65	18.21	3.99	3.07	3.29	0.00	0.00	0.00	0.00	51.75	124%
1997	2.83	10.48	20.65	17.64	0.39	0.22	0.50	0.02	0.07	0.00	1.38	0.00	54.18	130%
1998	0.40	9.29	8.09											
Avg	1.84	4.76	7.77	8.74	7.53	6.33	3.10	0.86	0.29	0.04	0.08	0.42	41.77	

Table A-4

Discharge Record for Big Sur River, Water Years 1951-1997 (ac-ft)

WY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	WY	% of Avg
1951	993	17,980	16,935	9,418	5,482	6,651	3,529	3,340	2,047	1,285	780	744	68,190	95%
1952	954	1,922	17,508	60,639	16,681	27,731	10,451	5,300	3,239	2,075	1,619	1,297	149,415	207%
1953	1,111	1,412	10,112	20,557	4,610	6,635	5,548	5,024	2,834	1,722	1,359	1,105	62,027	86%
1954	885	1,987	1,327	3,888	7,809	7,970	6,821	3,358	1,981	1,275	823	670	38,394	53%
1955	699	1,619	5,185	6,524	4,465	3,558	3,435	3,392	1,817	1,250	980	626	33,749	47%
1956	814	1,142	27,614	33,062	19,712	9,933	5,818	5,022	2,551	1,611	1,160	695	109,134	151%
1957	799	670	942	2,348	6,430	4,411	3,074	6,284	2,789	1,400	948	873	30,970	43%
1958	1,252	1,180	4,122	9,435	28,124	34,159	50,134	7,115	3,481	2,342	1,476	1,186	144,006	200%
1959	970	823	968	4,056	10,350	3,943	2,091	1,535	1,012	614	539	2,119	29,020	40%
1960	811	758	853	4,548	13,456	3,342	2,438	1,908	1,053	736	550	478	30,931	43%
1961	561	1,139	2,382	1,597	1,987	1,783	1,303	946	556	356	324	269	13,205	18%
1962	344	609	2,200	1,712	28,602	13,051	4,090	2,432	1,474	1,051	721	657	56,941	79%
1963	5,340	1,460	2,852	11,470	28,054	10,231	23,988	9,606	4,268	2,721	1,716	1,258	102,964	143%
1964	1,482	6,688	2,602	7,862	3,523	2,777	2,220	1,488	1,180	928	662	617	32,229	45%
1965	614	2,537	11,308	21,937	4,707	4,153	9,937	4,171	2,388	1,561	1,142	1,027	65,484	91%
1966	966	5,704	7,210	8,152	8,902	4,126	2,592	1,878	1,142	841	714	634	42,862	59%
1967	563	2,196	20,824	19,817	13,357	19,979	29,734	11,393	4,463	2,519	1,537	1,196	127,578	177%
1968	1,365	1,339	2,271	3,745	5,411	4,504	2,261	1,543	950	690	617	488	25,184	35%
1969	677	873	2,739	46,965	41,913	23,766	8,805	4,620	3,068	1,817	1,041	855	137,138	190%
1970	1,168	1,161	5,798	24,301	8,265	15,302	4,715	2,997	1,857	1,222	845	819	68,390	95%
1971	897	6,214	13,160	6,897	3,154	4,106	3,180	2,251	1,507	960	740	696	43,761	61%
1972	623	1,010	6,974	3,114	3,973	1,847	1,905	986	611	547	437	471	22,097	31%
1973	1,607	10,711	3,499	20,219	41,855	28,784	8,773	4,380	2,521	1,694	1,214	1,045	126,302	175%
1974	1,275	3,792	7,125	16,213	4,923	27,632	20,154	5,935	3,304	2,261	1,470	1,057	95,141	132%
1975	1,450	1,369	3,644	2,263	22,219	24,163	9,842	4,982	2,690	1,680	1,509	1,162	76,973	107%
1976	1,624	1,271	1,254	978	1,129	1,726	1,741	938	684	406	457	467	12,675	18%
1977	480	552	839	1,351	630	1,031	545	535	367	304	233	384	7,251	10%
1978	421	623	8,945	46,671	50,051	35,966	15,864	7,983	4,477	2,989	2,051	1,734	177,775	247%
1979	1,367	2,975	2,190	7,888	17,724	15,398	10,717	4,497	2,785	2,089	2,166	1,103	70,897	98%
1980	1,472	2,344	7,900	45,112	38,932	24,351	10,040	5,222	3,574	2,715	1,920	1,388	144,972	201%
1981	1,410	1,291	1,763	8,039	4,711	14,646	6,946	3,060	1,851	1,448	1,071	893	47,129	65%
1982	1,293	7,751	5,784	23,399	11,217	18,097	45,338	8,521	4,151	2,785	2,190	1,652	132,139	183%
1983	1,551	7,008	19,396	35,064	52,307	59,280	22,990	20,448	5,401	3,293	2,485	2,346	231,068	321%
1984	1,910	9,064	20,013	9,045	4,901	4,165	2,850	2,176	1,543	1,113	897	807	58,485	81%
1985	1,085	3,435	4,072	2,140	5,847	6,171	4,217	2,275	1,208	793	698	702	32,644	45%
1986	902	2,612	4,792	6,385	45,237	38,733	8,907	4,106	2,384	1,718	1,212	1,261	117,850	163%
1987	1,244	1,117	1,511	2,313	7,037	6,855	2,364	1,349	895	746	709	670	26,808	37%
1988	482	988	2,955	4,994	1,734	1,323	1,505	1,133	752	416	547	599	17,429	24%
1989	507	814	2,514	2,283	1,908	6,228	2,458	1,117	694	417	374	467	19,781	27%
1990	818	1,053	722	1,940	3,646	1,688	924	771	484	366	263	321	12,998	18%
1991	312	296	463	509	937	18,956	4,842	1,815	938	660	471	366	30,563	42%
1992	550	587	2,006	2,672	15,901	10,758	4,044	1,980	1,214	960	675	456	41,803	58%
1993	696	720	5,639	43,210	24,347	15,261	6,077	3,915	2,977	1,918	1,347	1,135	107,242	149%
1994	1,168	1,248	1,785	1,579	6,252	2,463	1,722	1,317	714	602	472	356	19,677	27%
1995	528	833	1,517	42,900	11,264	44,273	12,032	8,281	4,181	2,822	1,993	1,375	132,001	183%
1996	1,162	1,049	3,049	8,180	32,573	19,761	8,108	5,397	3,074	2,071	1,440	1,073	86,937	121%
1997	1,206	4,268	25,956	64,360	16,001	6,188	3,620	2,039	1,432	924	968	942	127,904	177%
Average	1,073	2,718	6,494	15,143	14,727	13,784	8,585	4,067	2,140	1,419	1,055	905	72,088	100%

DROUGHT, FIRE AND GEOLOGY: KEY WATERSHED INFLUENCES IN THE NORTHERN SANTA LUCIA MOUNTAINS

Barry Hecht

Sediment Yield Variations in the Northern Santa Lucia Mountains

Barry Hecht[1]

Sediment yields in the northern Santa Lucia Mountains affect channel stability and flood inundation levels along the larger streams, riparian vegetation and aquatic habitat associated with the streams, beach sand supply, and the supply of sand available for transport into the deepsea canyon network just offshore. Sediment yields vary considerably over space and time in this region. Understanding this variability is one key to usefully reconstructing events of the recent past and anticipating channel, beach, and offshore dynamics likely to occur in the near future.

Knowledge of sediment yields and transport rates are based on a limited number of measurements of sediment transport (c.f., Matthews, 1989; Hecht and Napolitano, 1995); on progressive measurements of sedimentation rates in three reservoirs (see Figure 1, from Woyshner and Hecht, 2000); and on miscellaneous observations observations developed by biologists and engineers in the course of evaluating instream habitat and channel stability or flooding potential. Until recently, absence of data and analysis would have precluded developing even initial assessments of sediment yields.

Sediment originating in the northern Santa Lucia Mountains is transported subequally as suspended and bedload sediment (Kondolf, 1982), in contrast to other many other Central Coast streams, where bedload is frequently 10 percent or less of the material delivered from large watersheds. The predominantly granitic or crystalline-metamorphic parent rock often weathers to relatively coarse sands, normally transported by rolling or saltating along the bed. One recent analysis of portions of the sediment retained in San Clemente Reservoir on the Carmel River (Moffatt and Nichol, 1996) indicates that about 95 percent of the material is sand, primarily coarser than 0.25 millimeters.

Spatial Variability

Data to date show much more temporal variability, which masks sub-regional or basin-by-basin tendencies. In keeping with patterns observed elsewhere in the world, the sub-arid portion of the region, where mean annual rainfall is less than 20 inches (600 mm.), appears to yield more sediment per unit area than the sub-humid areas (20 to 40 inches of mean annual precipitation) based on the limited information presently available. One important mechanism for the

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[1]1 Balance Hydrologics
Principal
900 Modoc St., Berkeley, CA 94707
(510) 527-0727(ph)
(510) 527-8531 (fx)
bhecht@balancehydro.com

apparently higher rates in the drier areas is mobilization of sediment stored in valley fills by incision of the larger streams into the adjoining alluvium (Williams and Matthews, 1983; Hampson, 1997). Higher local relief in the wetter areas also contributes to yields from the headwaters. It is difficult to distinguish the effects of climate from those of grazing or other land-use practices, which tend to affect the drier areas to a greater degree.

Underlying geologic materials strongly affect the mechanisms—and presumably the rates—of erosion. About one-quarter of the northern Santa Lucia Mountains are underlain by Tertiary sandstones and shales (including Monterey Shales), or by Mesozoic Franciscan and Great Valley Assemblages. Since little is known directly about yields from these substrates (Hampson, 1997; Matthews, 1989), rates and processes may be best inferred from adjoining areas with similar erosional influences (Brown, 1973, Hecht and Enkeboll, 1981, Hecht and Kittleson, 1997 for the Tertiary sediments; Brown and Jackson, 1973; Knott, 1976; Hecht, 1983 for the older rocks).

Short-Term Variability

Both rates and processes of sediment delivery vary episodically in the northern Santa Lucia Mountains. Sediment yields following large wildfires, in particular, can abruptly alter sediment yields and result in fundamental changes in the processes which move sediment (c.f., Cleveland, 1973, 1977; Jackson, 1977; Hecht, 1993). Sedimentation in Los Padres Reservoir during the winter following the Marble-Cone fire of 1977 effectively doubled the long-term rate of reservoir filling (Hecht, 1981). Following the same fire, Arroyo Seco aggraded nine feet at the Green Bridge upstream of Greenfield, with the bed gradually being exhumed during the following 4 to 6 years (Roberts and others, 1984); farther downstream, non-cohesive banks of the Salinas River were destabilized during the following 10 years. The pulse of suspended sediment generated by this fire was several times larger than that moved by the record storms of January and February 1969, two of the regional floods of record. Smaller—but still geomorphically significant—episodic events generating large volumes of sediment have been attributed to large regional storms, landsliding associated (Fig. 1) with large-scale grading and channel incision and instability (Kondolf, 1982; Williams and Matthews, 1983; Matthews, 1989; Hampson, 1997; Woyshner and Hecht, 2000).

It is difficult to evaluate sediment yields (or sediment storage) in the streams of the northern Santa Lucia Mountains without knowing the recent local history of fire, floods and other episodes. For example, the March 1995 storm fundamentally altered sediment delivery and channel stability on several regional streams, such as Cachagua Creek (Kondolf, 1995), while incision events which altered the entire Carmel River corridor downstream occurred on Tularcitos Creek during 1983 and 1998. At Big Sur, debris flows following fires have complemented overbank flooding during 1995, which left atypical vegetation washed in from the watershed growing on the floodplain downstream from the mountain front (Jeff Norman, pers. comm.).

Episodic variability is sometimes caused and extended by two or more discrete unusual events occurring concurrently, or nearly so. The high rates of sediment yield following the Marble-Cone fire are likely related to a very large buildup in fuel loadings caused by a record snowstorm in January 1974 (Griffith, 1978). The numerous hardwood limbs which broke off during this event had been thoroughly dried in time for the July and August 1977 fire by a hard drought during 1976 and 1977—at Big Sur, the driest and third-driest years in a century of measuring rainfall. The winter 1978 fire/fill episode resulted from the sequential occurrence of snow, then drought, then lightning.

Whether eroded during isolated or compound episodes, sediment can be rapidly removed from source areas and delivered to the lower alluvial reaches of the master stream or to the near-shore environment following episodic events. Factors promoting quick recovery of the sedimentary system and related instream and riparian habitat values are rapid curtailment of the source of sediment (such as after a fire by regrowth) and/or maintenance of terrestrial channel stability downstream. Soft, non-cohesive banks may retreat during the rapid delivery of sediment, adding substantial volumes from bank or bed storage to the event-related yields from far upstream. The additive yields of sediment from these primary and secondary sources can result in large accumulations of sediment in the lower alluvial reaches or on the adjoining continental shelf over a period of a few years, potentially generating density currents in the marine environment. It may be that depositional sequences in the offshore canyons or abyssal plain are most likely to be generated or preserved following episodic events in the high-relief setting of the northern Santa Lucia Mountains.

Valley-Filling Events

The geological evidence points to a number of periods of valley-filling aggradation throughout the northern Santa Lucia Mountains. Multiple river terraces are visible at heights of 1000 feet (300 m) or more along the larger streams, such as the Carmel and Big and Little Sur Rivers. The terraces appear to be remnants of once-continuous and presumably coeval surfaces, now discontinuous and partially buried beneath cones or slopes of colluvial deposition.

Kondolf (1982) shows that the flood of 1911, perhaps in combination with a smaller event in 1914, left deposits which now form much of the floor of Carmel Valley. The flood(s) resulted in sedimentation of typically 2 to 20 feet thick over much of the eastern half of the valley. No subsequent events have even approached the level, magnitude, or extent of deposition. The river terraces visible high above the present-day valley floors may be eroded relics of comparable depositional epicycles in the past.

River terraces and alluvial benches or fans are often ascribed to climatic change, typically to the drying stages of the fluctuations prevailing throughout the Quaternary. Conventional thinking is that the higher rates of erosion prevailing in drier climate lead to accelerated erosion of the weathering which occurred during the wetter stade. This mechanism may or may not play a significant role in the incidence of valley-filling events. It might be held that this epicycle followed a period of protracted drying from the preceding glacial maximum, circa 15000 bp, when the Monterey Bay region was clearly colder and wetter, locally supporting Sitka spruce woodlands (c.f., Adams, 1975). It is also possible that the valley-filling epicycles are associated simply with peaks in sediment supply. Such peaks might be created by discrete events (such as massive erosion following fires, or failures during earthquakes). They may also be an artifact of the rapid rise of the mountains. Very large sediment loads might be generated by temporary obstructions of the main channel (such as the debris flows described by Cleveland in 1973), rapid erosion of large point bars or the previous generation(s) of terraces as the rivers erode beneath the riparian trees which hold such features in place in less tectonically-dynamic settings, or by large failures of soils and regolith as the river undercuts metastabale slopes not previously-attacked for many years (c.f., Kondolf, 1995).

Many homes and extensive public improvements have been built on deposits of the 1911/1914 floods in Carmel Valley. The scale of such valley-filling epicycles should be better known, if only in deference to their public safety implications. They also have a significant, little-understood role in the regional sediment budget when considered at the geologic time scale. Although perhaps better known from Southern California or the Wasatch Front, the causes and implications of valley-filling events in a rapidly-uplifting areas merit consideration and evaluation in many aspects of local geological investigations.

Conclusions

Sediment yields in the northern Santa Lucia Mountains are variable spatially, with underlying geology, rainfall and relief as significant influences. Sediment yields in this region vary even more over both the short term and geologic time frame. The sedimentary record preserved in reservoirs and Quaternary stream terraces helps in understanding accumulation in the lower valleys and near-offshore environments during the recent geologic past. The episodes which generate sediment yields in this high-relief setting may aid in understanding (and be better understood through) the turbidites and other high-energy deposits recorded in the Jurassic and Cretaceous rock record preserved along this coast.

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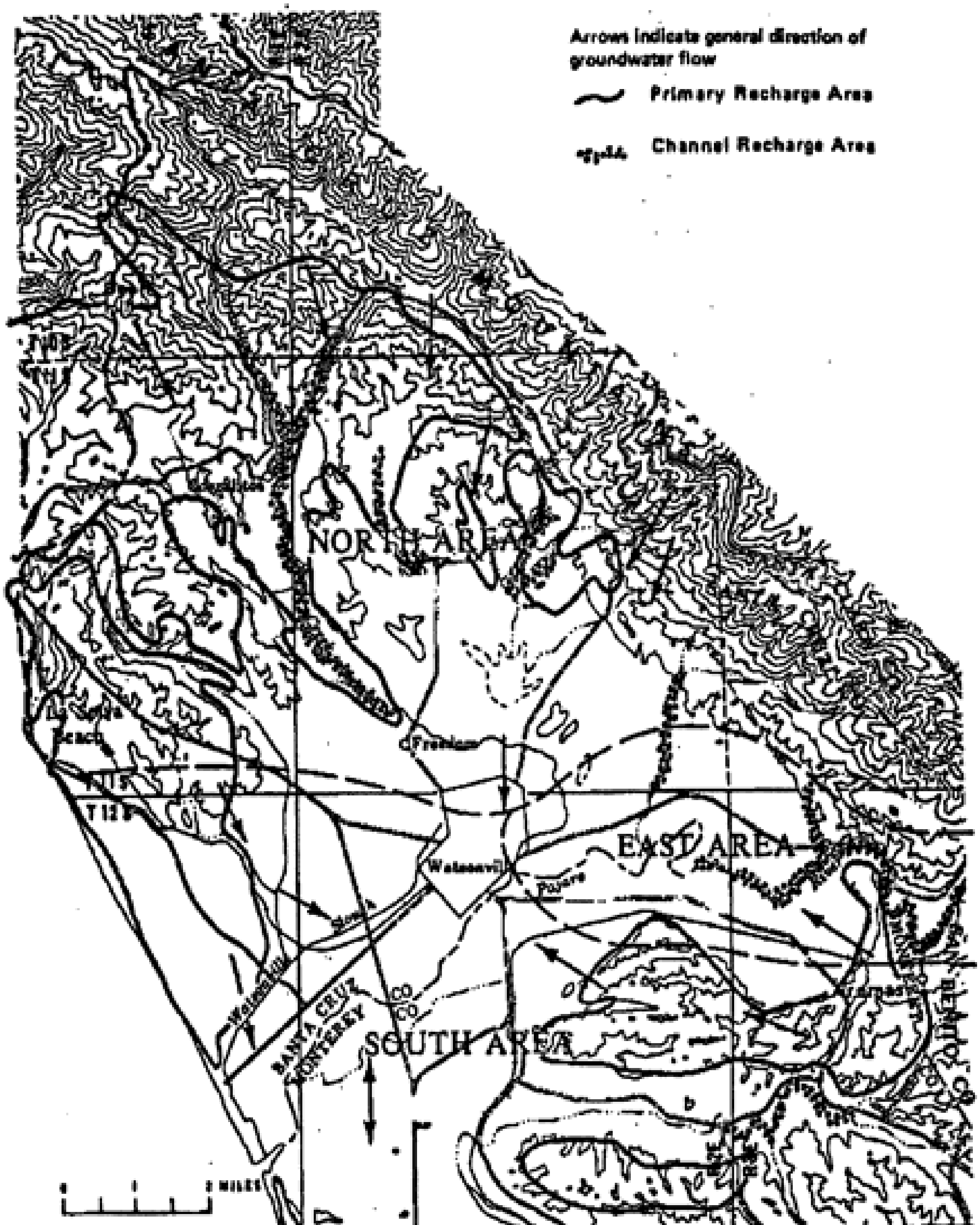

FIGURE 3-4. PRIMARY AND CHANNEL RECHARGE AREAS IN THE PAJARO VALLEY

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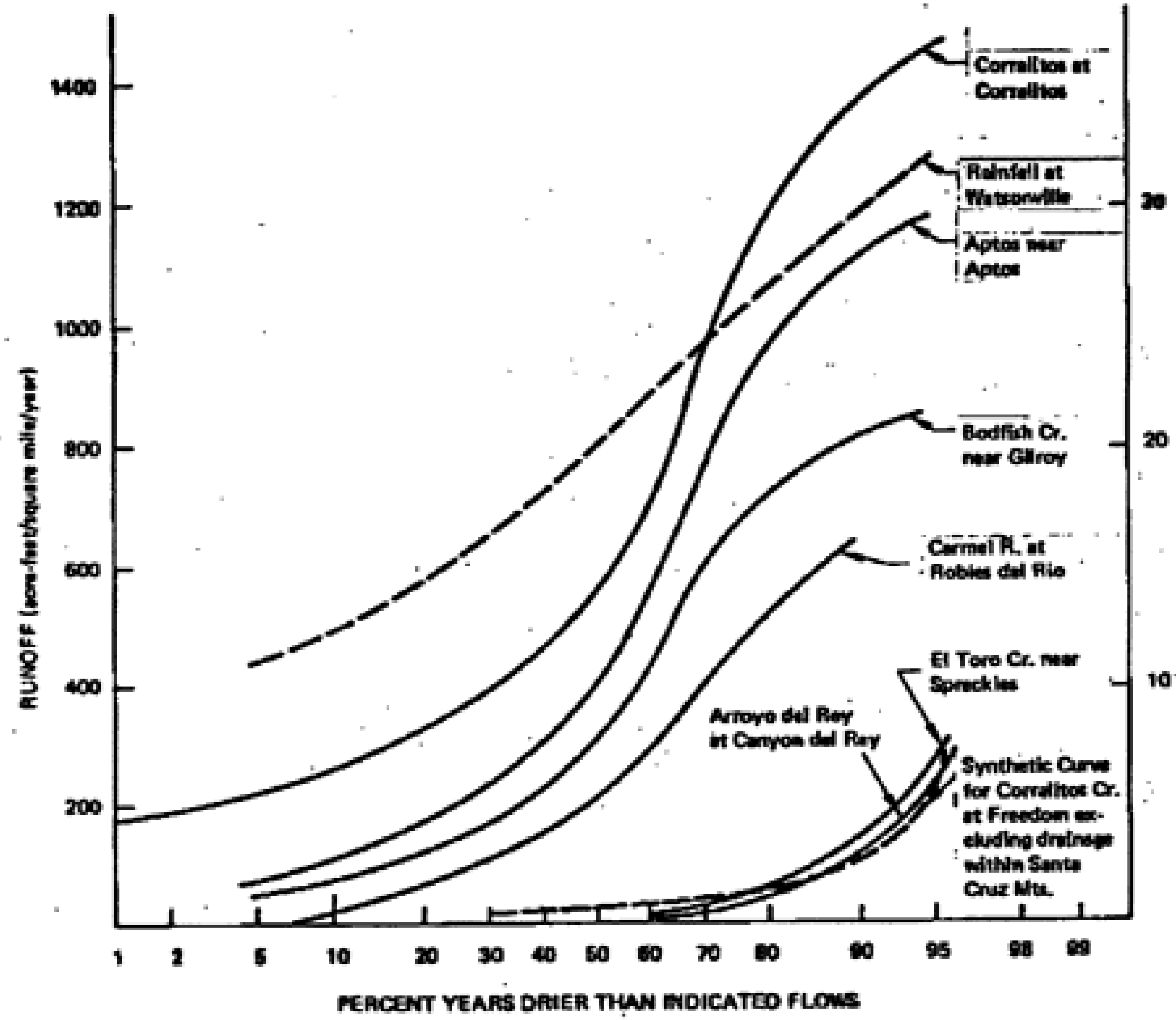

FIGURE 3 - 5. RAINFALL AND ANNUAL RUNOFF RECURRENCE CURVES FOR STREAMS IN THE PAJARO VALLEY AND NEARBY AREAS

South of the Spotted Owl: Restoration Strategies for Episodic Channels and Riparian Corridors in Central California

Barry Hecht

Balance Hydrologics, Inc.
1760 Solano Ave., Ste 209
Berkeley, CA 94707

Abstract: *Episodic change at the scale of decades may be the distinguishing characteristic of riparian environments in semi-arid central and southern California. In episodic corridors, substrate and community structure are rejuvenated abruptly at intervals shorter than those needed for a mature woodland to develop. Disruption caused by fires, floods, pulses of sediment, or drought is extensive but not complete. Communities are often adapted to regenerate from undisturbed areas in the corridor. Post-event increases in sediment transport and decreases in evapotranspiration accelerate re-establishment, particularly for aquatic components of the riparian systems. Ecological and hydrological professionals need to develop understandable, implementable paradigms for the functions, processes, and values of episodic corridors upon which to base meaningful criteria and planning for restoration success. If based on processes inherent to this region, they can ultimately serve as a basis for floodplain management, community planning, and public-works design within the riparian corridors. Without a clear understanding of the roles and effects of episodic events, riparian systems which do not develop mature woodlands or ancient forests are likely to be undervalued and awkwardly regulated using inappropriate concepts borrowed from other regions.*

While change is intrinsic to most channel and riparian corridors, episodic change may be the distinguishing characteristic and hallmark of riparian environments in semi-arid central and southern California. Naturally-occurring episodic events periodically establish new bed conditions and vegetation patterns along many streams in this region and in many other areas where old-growth valley-floor vegetation have not been sustained in the past. Disturbance at intervals shorter than maturation of a riparian woodland, followed by a period of gradual re-establishment, is a repeating pattern both in a given corridor and for corridors within a region. A typical sequence of disturbances of varying magnitudes and recurrences is shown in Figure 1.

Definitions and Influences

An episodic corridor is one where the substrate is renewed or rejuvenated abruptly, at intervals shorter than that typically needed for a mature woodland to develop. Floods, wildfires, sudden pulses of sediment, or droughts are typical of natural disrupting events. Disrupting processes can be erosion, deposition or changes in grade. Disruption is extensive, but usually not complete. Pre-existing communities are generally re-established by propagation from remnant populations. Dominant species in episodic corridors are seemingly adapted to exploit the changed hydrologic conditions following episodic events, such that their regeneration is abetted and (in the cases of numerous woody species) their regeneration abets the restoration of normal or chronic conditions. Additionally, during periods of disruption,

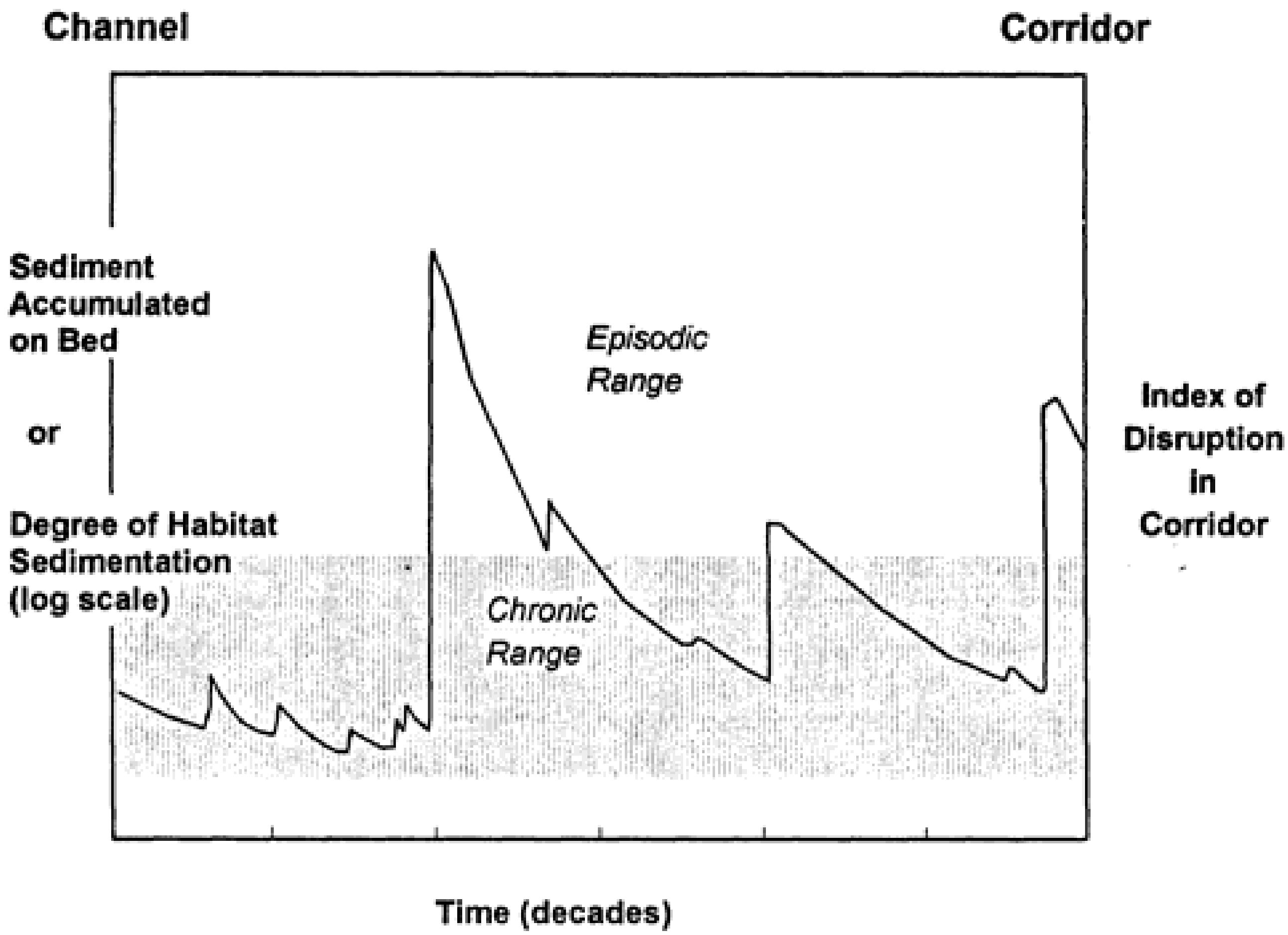

Figure 1. Schematic representation of episodic variations in bed sedimentation and/or disturbance in riparian alluvial-scrub corridors of centra or southernl California streams.

changes in hydrologic or geomorphic processes occur which tend to be exploited by the aquatic or riparian organisms which are most persistent in that corridor. Variability in the processes and rates of growth in biological communities (Vogel 1980) and field manifestations (Faber et al 1989) have been previously discussed in the ecological and restoration literature.

The focus of this paper is upon corridors with streams that are minimally affected by regulation of flows. In central and southern California, the principal mechanisms of flow regulation are the changes in flows and sediment supply caused by dams, summer diversions, increased dry-season flows composed of treated effluent or of irrigation tailwaters, or changes in flows associated with pumping from alluvial aquifers. Each can substantially change the episodic character of the corridor downstream. While the number of unregulated streams in the region is diminishing, most watersheds still have large sub-basins which are substantially unregulated, or reaches which are not predominantly affected by upstream regulation. Once the effects of episodicity on these unregulated channels and reaches is better understood, recommendations for emulating (or devising nonemulative) patterns of disturbance can be more easily substantiated.

For the purposes of this paper, corridors include the full width of a valley which may be occupied by the existing stream during an extreme episodic event. Corridors may extend somewhat beyond the outer ecotone of riparian vegetation or alluvial scrub into the lowermost depositional aprons at the bases of slopes, which are occasionally eroded by flood flows.

Intervals which typically are shorter than needed for development of a mature woodland are central to the concept of episodic event used in this paper, as are abruptness and associated sediment influxes and/or channel instability. Longer-term geomorphic effects, such as regional channel incision, tectonic changes in base level, or climatic fluctuations result in semi-permanent (relative to successional or human time frames) or epicyclical modifications in the valley corridor.

Findings from Field Studies

A partial digest of insights developed from field studies can provide initial directions in understanding episodicity in such systems, and applying this understanding in management and restoration. Individual corridors discussed in the text are shown in Figure 2.

Changes During Episodes

Most episodes result in a sudden influx of sediment and organic debris into a corridor. The influx may come predominantly from the slopes or upper watershed, as following a large wildfire or landslide. It may come predominantly from the channel and adjoining valley flat, as during the first floods after severe drought has overstressed a riparian woodland. With major floods, the influx may come from slopes, the channel corridor and other sources throughout the watershed. Multiple events during a brief period can magnify the sediment pulse. Figure 3 shows the dominance of two events, a major 1966 wildfire and the storms of 1969, on sediment loading for the Sisquoc River, a large unregulated stream near Santa Maria, California.

Debris is stored in the channel and corridor, filling pools and overbank areas. Stored debris is depleted by subsequent flows. Depletion is rapid at first, and then progressively slows, as normal or chronic conditions are attained. Sprouting woody vegetation stabilizes some of the deposited sediment, a process which begins slowly and becomes progressively more effective during the first few years.

Communities re-establish from sheltered, minimally-disturbed areas or patches within the corridor, as well as by seed and by propagation from vegetative debris scattered by floodwaters throughout the riparian zone. These *refugia* can be portions of the channel protected by bedrock outcrops or large boulders or thickets, and abandoned channels or tributaries not substantially affected by the episodic events.

Events which disrupt the corridor, rather than solely the channel, yield much greater amounts of organic matter and large woody debris. Dispersal of this debris can affect not only riparian and aquatic community structure, but also water quality, public works and public safety. Current engineering practice and federal flood-protection regulations do not generally encourage considering hazards posed by woody debris, nor do they recognize that certain types of events are likely to produce debris of varying amounts and sizes.

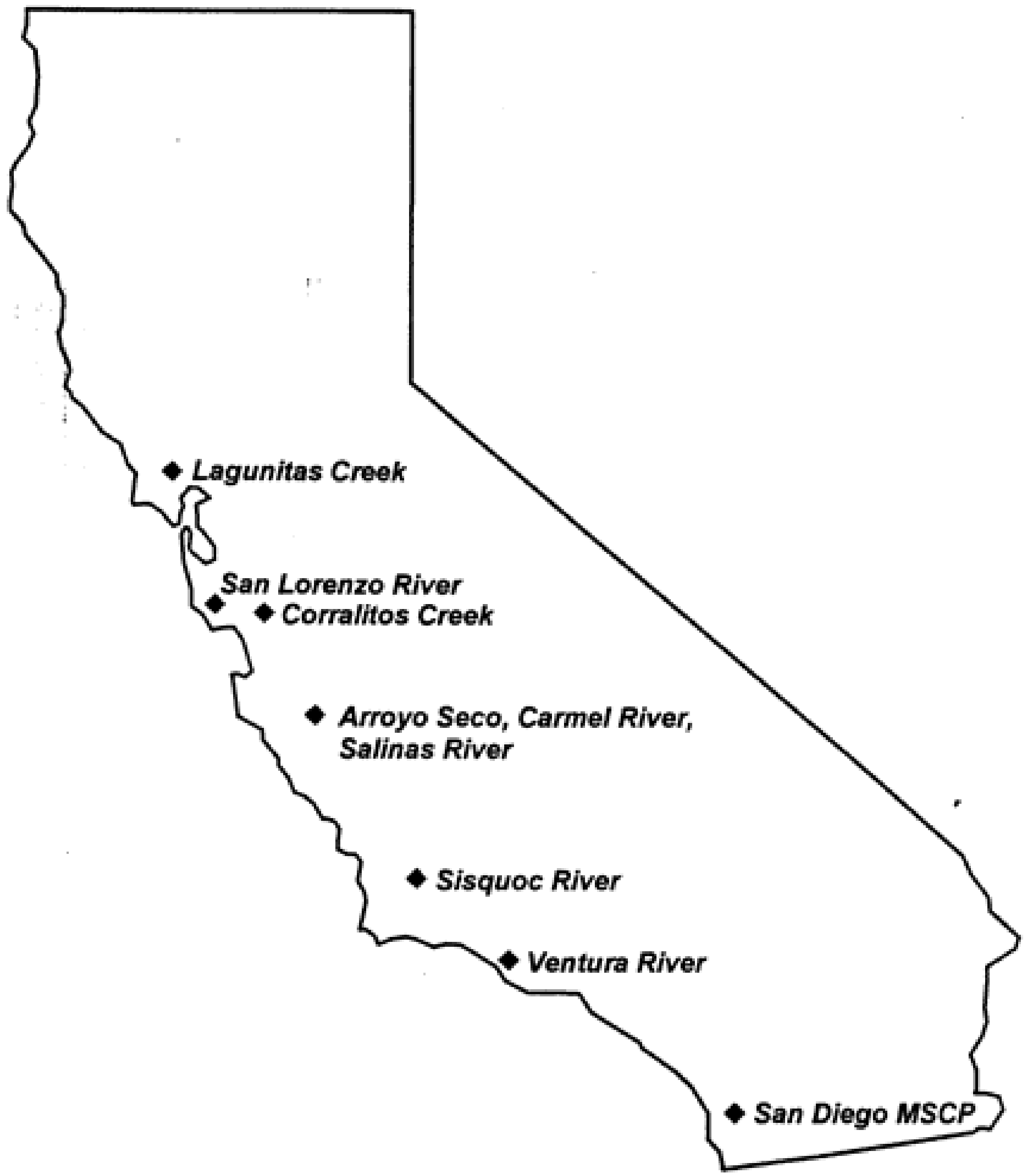

Figure 2. Locations of corridors discussed in text.

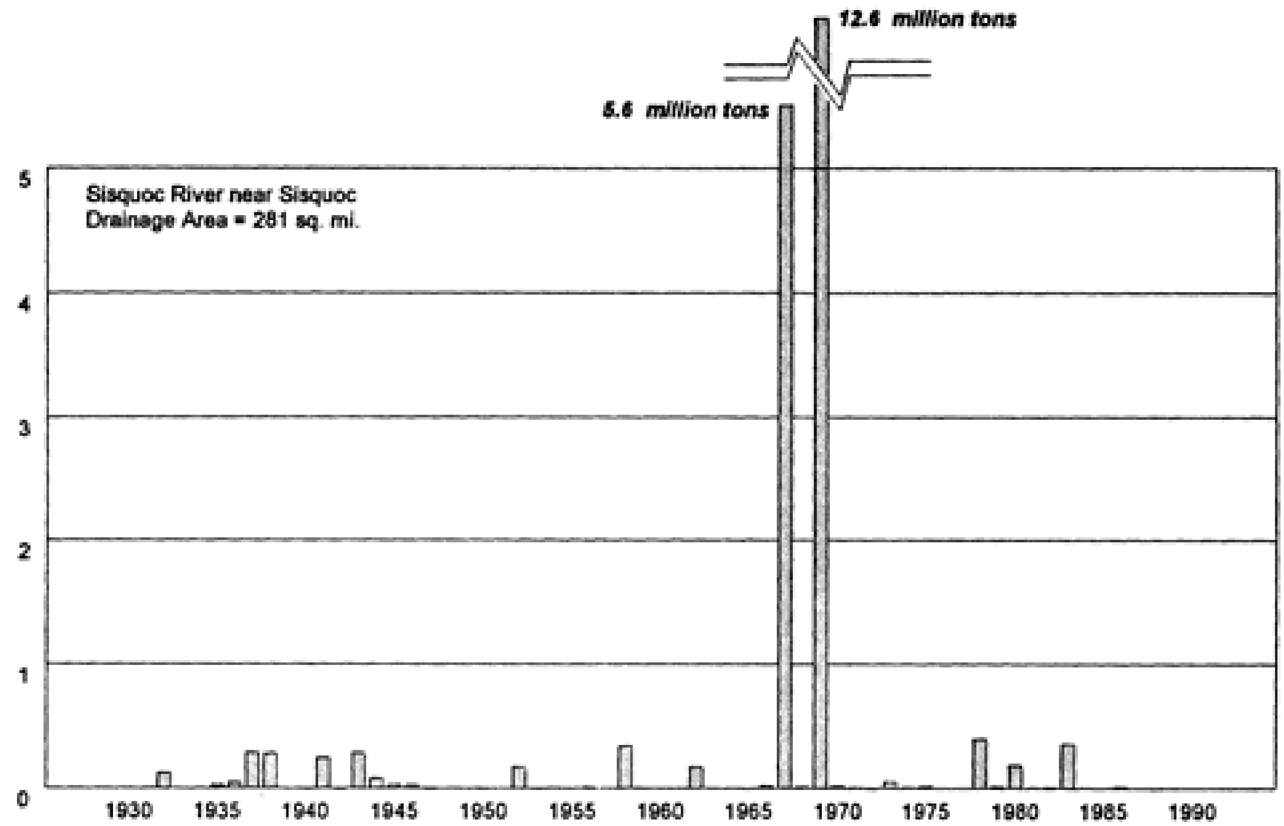

Figure 3. Simulated long-term record of bedload sediment transport in an unregulated episodic stream-- the Sisquoc River, near Santa Maria, California. More than half of the bedload (coarse) sediment transported by the river during the 60 years was probably associated with two events -- the Wellman fire (1966), which burned approximately 35 percent of the watershed, and high-recurrence storms of January and February 1969. Source: Knudsen et al. (1992).

Duration of Episodes

In most stable episodic systems, the supply of eroded material rapidly attenuates following the event(s) which has produced the sediment pulse. Diminishing sediment delivery is attributable both to geomorphic adjustment and to vegetative stabilization. Following large landslides or fires, the initial sudden pulse of sediment is followed by smaller and secondary slips or mudflows, and by rilling and gullying of the bare fresh surface. Once the new network of hillslope channels has developed, rates of erosion tend to decrease rapidly, unless the new surface continues to be disturbed. Regrowth further reduces erosion, particularly following fires. In stable systems, most hillslope debris associated with typical episodic events will have been eroded during the first one or two rainy seasons.

A broadly-similar sequence may be observed as a stream erodes or undercuts a valley flat, such as may occur following a severe drought or other cause of sudden riparian dieback. Initial rapid bank retreat and sloughing is often followed by geomorphic adjustment and vegetative regrowth (Kondolf and Curry 1986).

Event-generated sediment frequently passes through stable episodic corridors over a period of several years. In many streams, measurements of reservoir sedimentation trace progressive declines to pre-event sedimentation rates within two to five years after a discrete event (Ritter and Brown 1972, Wells 1982, Hecht 1983, Glysson 1983, Hecht 1984). Detailed repetitive surveys of bed conditions affecting aquatic habitat also indicate that many key descriptors return to pre-event ranges within a few seasons when the source of sediment is self-curtailing (California Department of Water Resources 1958, Hecht 1984, Hecht and Woyshner 1991). Not all natural aspects of the corridor will be re-established within this period. However, the general structure of the channel and of the vegetative mosaic will often have done so.

Larger events can in some instances fundamentally de-stabilize slopes (Kelsey 1980) or valley flats such that erosion continues well after the event, and original channel patterns and riparian corridors may not be re-established within several decades. Near the mouths of coastal streams or other low-gradient reaches, sediment and debris may also be stored in the corridor for tens of years, affecting both aquatic habitat conditions and channel form (Madej 1987).

Variability of Episodic Change Along A Channel

At the larger scale, both the extent and frequency of disturbance vary longitudinally along the corridor. More frequent, and generally more extensive, disturbance tends to occur immediately downstream of tributary confluences (Hecht 1991), bedrock constrictions in the corridor (Lisle 1986) or recurrent large landslides. Reaches in which the longitudinal slope of the corridor decreases rapidly in the downstream direction also tend to be affected more frequently and to a greater degree following episodic events. Other reaches and segments are often affected less frequently or to lesser degrees. Expected down-valley trends in the frequency, and generally the magnitude, of disturbance are shown in Figure 4.

Much of the downvalley or cross-corridor variability of importance to restoration planning occurs at the scale of individual channel segments (such as pools, bends, riffles, major bars and crossovers), or at the scale of individual large bed elements (such as debris jams, flood-resistant thickets, bedrock ledges, or in the lees of large boulders fallen from adjacent slopes). Restoration planning can usefully consider both reach and segment (a pool, riffle, or bar) scales. Aerial or ground photographs of the corridor following prior events can be particularly helpful in identifying reaches or areas subject to greater or lesser disturbance.

Self-Adjustment Ameliorates Effects On Populations

A number of changes in processes and physical conditions occur following the peaks of episodes which ameliorate effects on remnant populations, and on habitat values in general. Representative examples include:

- transient increases in the rate of sediment transport, allowing for accelerated depletion of sediment entering the corridor and stored within it;
- transient decreases in riparian evapotranspirative rates during droughts, as water

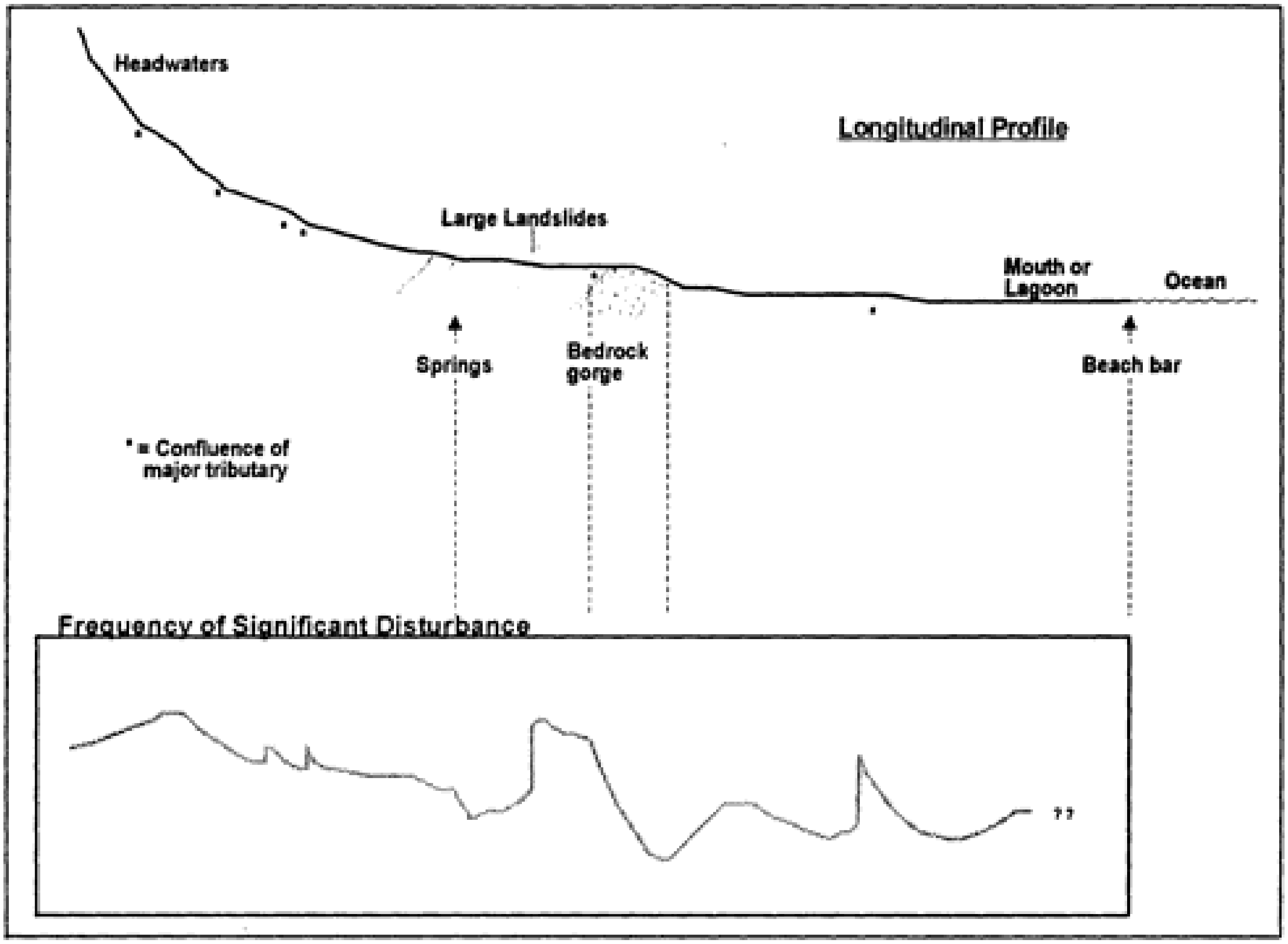

Figure 4. Schematic longitudinal variability in the frequency of episodic disturbance in a representative central California corridor. Reaches immediately downstream from channel confluences and other point sources of sediment are more susceptible to frequent disturbances; reaches with gorges or perennial springs tend to be more resilient to the same disturbances. Frequency diminishes from upstream to downstream, but relative severity or extent of disturbance does not.

levels decline in the channel and underlying alluvium;

- temporary increases in dry-season flows, where fires or other events have reduced vegetative cover (see Figure 5).

The corridor scientist should recognize these and other changes, which tend to buffer the expected effects on individual reaches of stream, or particular organisms and communities. Concepts and models of functions and processes within a corridor can benefit from incorporating factors which promote persistence of species, communities, or channel form. Upper limits for the severity, extent, or frequency of disturbance likely exist for key species, beyond which the ameliorating changes no longer will aid in maintaining historical patterns or populations. These limits may be reached earlier in the aquatic communities of perennial or near-perennial reaches than in riparian or scrub communities. A reasonable case may be made, for example, that the increasing frequency, magnitude, and extent of channel disturbance during the past 50 to 100 years may be a major contributor to the near-extirpation of coho salmon from the streams of central coastal California.

Applying Episodicity

Initial directions

The role of episodic events in corridor management and restoration can be used to modify existing programs or practices through:

- exploring how these programs or practices would function during the types of episodes known to have occurred in the past (see Capelli and Keller 1993 for a useful application to the lower Ventura River);
- using criteria based on acceptable responses of the corridor to a natural episode, such as restricting withdrawals from an alluvial well to those creating a certain percent of the water-level decline observed during a design drought, and
- revising programs or practices which do not appropriately consider conditions or processes prevailing during episodes, such as seeking revisions in a bridge design which meets FEMA criteria but is unlikely to pass the dislodged riparian vegetation being conveyed through the corridor during certain types of events.

Planning for the episodes which may be anticipated in a particular corridor can also serve as a cornerstone in developing new policies and programs for valued corridors. First, if a clear goal is established to maintain an ecologically-sound level of disturbance (either emulating inferred natural patterns, or using other specified magnitudes and frequencies), implicit biases favoring development of a mature woodland may be redirected toward a more realistic mosaic of vegetative types and stages of development. Policies valuing the natural dynamism of the corridor lead to do-able programs for habitat and species conservation as well as meeting public safety and recreation needs. Second, estimates of likely frequencies and/or durations of episodic effects can provide the bases for framing (or evaluating) management plans for the corridor for key sensitive or valued species. In a given region, the types of habitat-affecting events can vary considerably over short distances, depending upon geologic setting and vegetation. Figures 6 and 7 portray results of an analysis of this type, developed primarily for a steelhead recovery and enhancement program. Finally, a focus on episodes can help embed the habitat manager or restorationist in regional water-resource and watershed-management planning. Many watershed or engineering professionals understand the importance of episodes to habitat values, and will work with the corridor scientist to build the episodes into management or operations models. Portions of all three approaches are being used in the cooperative multi-species conservation plan currently being developed in the San Diego area.

Discussion: Guidelines

Several guidelines can be offered for incorporating episodic change in evaluation and planning of riparian and channel corridors.

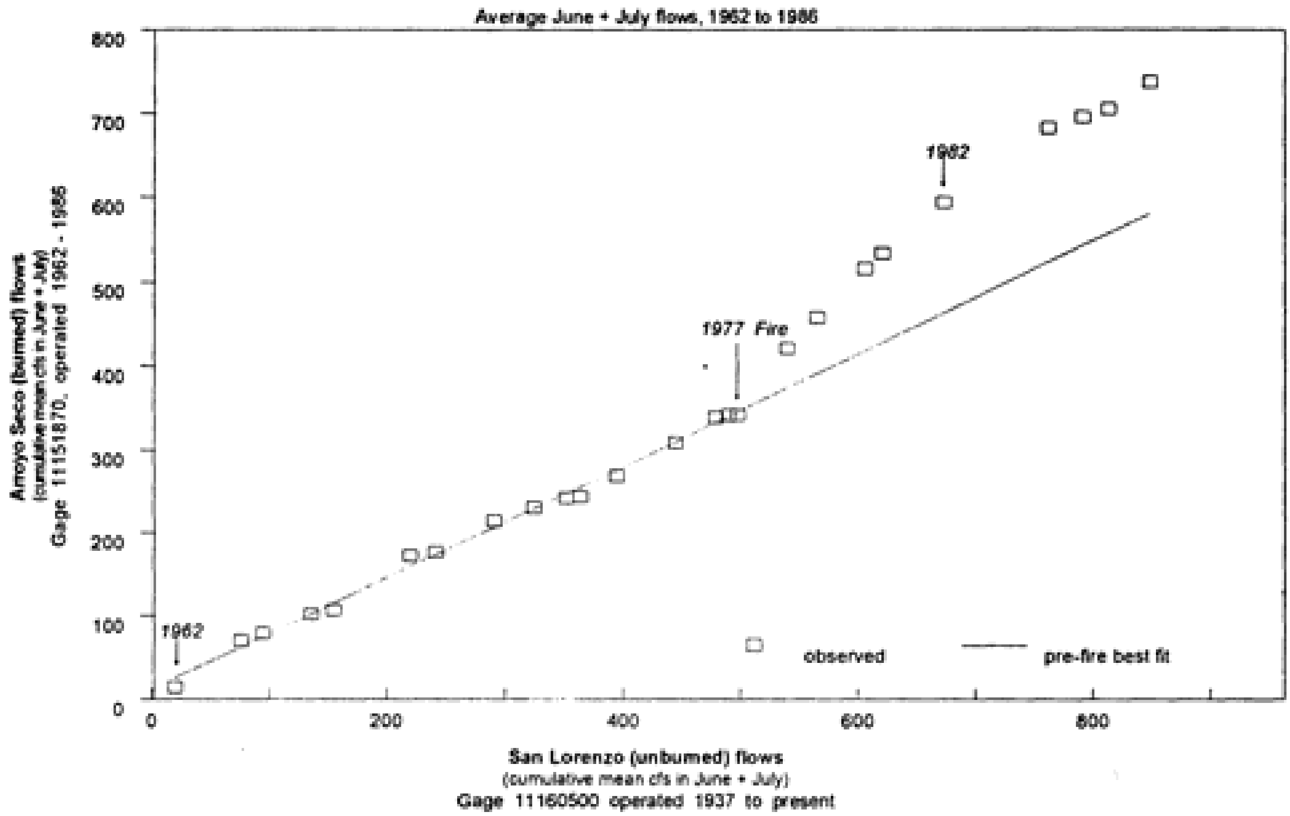

Figure 5. Increased summer streamflows following the Marble-Cone fire (1977) helped sustain aquatic and near-channel habitat in Arroyo Seco and adjoining streams, which were initially heavily sedimented by post-fire runoff. From 1978 through 1982 or 1983, summer flows in Arroyo Seco were nearly twice values expected based on long-term correlation with the San Lorenzo River (unburned watershed), offsetting some of sediment water-quality and temperature effects on aquatic biota. The double-mass curve shows that the pre-fire relation for June and July flows between Arroyo Seco and the San Lorenzo River resumed after 1982 or 1983.

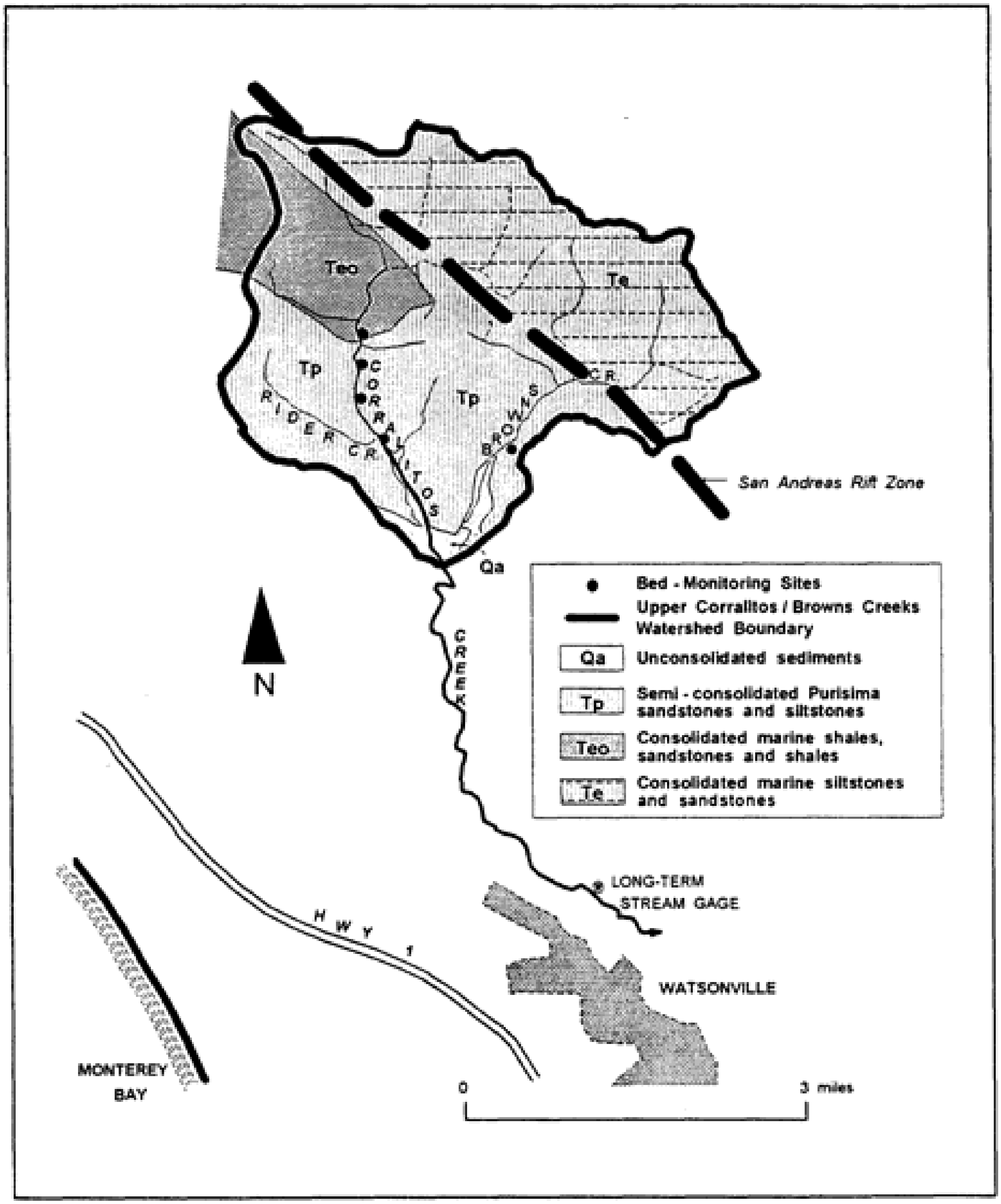

Figure 6. Location and geologic influences, Corralitos and Browns Creeks.

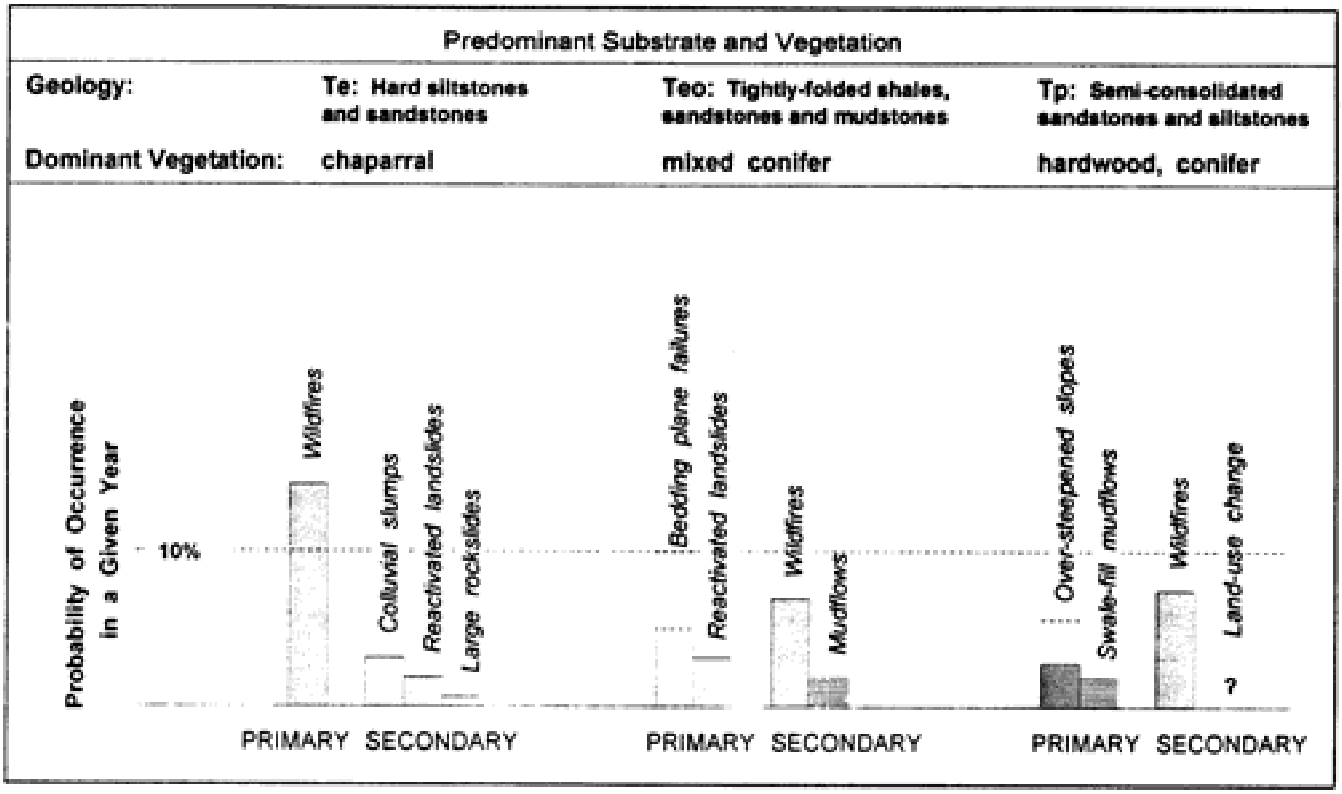

Figure 7. Estimated probability of significant sedimentation of steelhead habitat caused by episodic events, in three geologic/vegetative regimes, Corralitos Creek watershed. Probabilities based on estimated or observed frequencies and projected durations of bed sedimentation. Primary disturbances warrant site assessments by knowledgeable specialists and may merit temporary management measures. Secondary influences are more localized or less severe than primary. Source: Hecht and Woyshner (1991).

1. *Applying episodicity requires abrupt gradualism.*

The episodic paradigm is not based upon development of equilibrium channels and mature habitats or communities. Change that is abrupt, recurring, and progressively more gradual following events becomes the underlying and fundamental tenet for understanding the corridor. Familiar concepts or tools, such as bankfull geometry, vegetation mapping, or a standard base condition for flood simulations, acquire different, and generally less-central, meanings.

2. *Past episodes are the key to the future.*

Planners, scientists, and engineers proposing plans or works in episodic corridors should become familiar with the major events and episodes. The ability to withstand or adapt to the range of past episodes is a basic test of reasonableness for programs or projects proposed in the corridor.

3. *Habitat instability may usefully drive corridor management.*

Episodic corridors are ones where successful management of the baseflows, floodplain values, and water quality may ultimately be based upon concepts of a corridor integrally related to habitats and communities.

4. *Restorational success requires successional restoration.*

Generally, criteria for success in managing or restoring habitats are most likely to be useful if they are based on process or on communities, rather than on form or individuals or conditions during a base period.

5. *Bad episodic planning will drive out the good.*

Useful, valid analyses should logically be based upon the processes which prevail and the distribution of habitats likely to be achieved, both over time and spatially within the corridor. Simply adding a contingency or an engineering risk factor to a model which does not recognize changing processes or conditions may lead to fundamental errors in planning. Similarly, efforts to portray significant construction activity or changes in land use as just another episode are usually incorrect, misdirected, and inappropriate. By extending sedimentation or other effects through non-episodic periods, these activities tend to diminish the stability, robustness, and resilience of a corridor to disturbance during natural episodes. Readers may wish to speculate on whether such land-use increments may be more usefully considered epicyclical (see above) or permanent.

6. *Hydrologic responses may be self-mitigating.*

Hydrologic and geomorphic processes in episodic corridors tend to change after events in ways which protect remnant populations and may promote eventual re-establishment of a community similar to that prevailing prior to the event. As one example, increased flows and more efficient transport of habitat-impairing sediment immediately following major fires or storms help sustain pockets of viable aquatic habitat, albeit under considerable stress. Hydrologic models or plans should recognize that different processes and physical relations may apply during the event and recovery period. Those which do incorporate these differences will provide more useful results, with a considerably greater likelihood of resulting in a successful management and restoration program.

7. *Do codes meet episodes?*

If restoration of past episodic patterns is to be a management goal, regulatory approaches may need to explicitly recognize that:

a. mature and stable habitats and habitat values may not necessarily be useful or appropriate objectives;

b. approaches used *everywhere-else-in-the-country* may not work suitably in episodic corridors, particularly with respect to flood simulations;

c. it may be more beneficial and emulative to plan restoration within a reach, rather than necessarily on a particular parcel;

d. stable functions and values within a corridor may require objectives and criteria which vary over time, and between reaches, and consider episodic events and responses particular to that corridor;

e. ecological professionals, either as planners or preserve managers, need to be embedded in regional water, watershed, and floodplain management if natural patterns of disruption are to sought or emulated.

Conclusions

It behooves the technical communities of ecological and hydrological professionals to develop understandable, implementable paradigms for the functions, processes, and values of episodic streams and corridors, such as those in central or southern California and similar areas. If a goal of restoration is to emulate a near-natural (or other specified) pattern of disruption, useful types of strategies include:

- reach-by-reach management, including restoration of nearby off-site locations to exploit longitudinal and cross-channel variability;
- widening or modifying the corridor to promote variability;
- using sites both along the main corridor and in suitable nearby tributaries;
- curtailing chronic sediment sources;
- inducing or re-creating hydrologic conditions which emulate natural patterns (both spatial and temporal) of disruption.

Establishing restoration goals which clearly and rationally incorporate effects of episodic events can lead to sound habitat management and meaningful criteria for success of restoration, based on processes inherent to this region. Without a clear understanding of the roles and effects of these events, we can expect riparian systems which do not develop either mature woodlands or ancient forests to be undervalued, and to continue to awkwardly respond using regulatory guidelines, standards, and criteria which are more applicable in regions where mature riparian systems are a legitimate goal.

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FIRE + RAIN = MUDFLOWS

BIG SUR

1972

by George B. Cleveland, geologist
California Division of Mines and Geology

Rainwater rushes down barren hillslopes, converges in narrow canyons, and bursts out onto broad valley floors that contain the main conduits along which streams flow to lower elevations. The water slices through brush and timber, increasing in density as it picks up loose soil and plant and rock fragments along the drainage courses. At times it may slow, piling up against natural dams of debris or rising up onto protecting hillslopes. But when unopposed, it gathers speed and sound — the debris fragments clack and rumble as they are beaten together in the churning flow. The muddy torrent may slash into a community, pluck cars from the roads, rush around houses and punch through windows, spilling destruction within. Eventually it slows and stops, its energy mostly dissipated in the ruin created along its path. This is a mudflow.

Although mudflows occur over wide areas of California each year, most of them slip by unnoticed. Only when they block a road or sweep through a community is much attention given to anything as mundane as mud. Yet mudflows are potentially more dangerous than other types of landslides because they can form with dramatic suddenness and move, at times, with astonishing velocity. Some have been clocked at over 50 miles per hour. Because of their greater density, mudflows have a relatively higher destructive capability than do floodwaters, and, unlike flood waters, the mud doesn't recede after a storm has passed but may become a relatively permanent feature of the landscape.

A mudflow is more than just mud that flows. Fine grained particles usually make up the largest percentage of the solid material, but the balance can be all manner of rock fragments and plant debris. It is the fine grained component of the mix, with water, that gives the flow its mobility. Each grain or aggregate of grains is encased in a film of water which insulates it from any hard knocks by its neighbors. This leads to reduced friction and increased mobility. Mixtures with the highest ratio of solid to liquid may move so slowly as to be classified as creep or slope wash deposits. As the amount of water increases the material may begin to slide as a discrete unit along a defined slip plane. This type of movement is called a mudslide or an earthslide. The mudflow phase is reached when the water content is sufficient for the mass to actually flow. Depending upon the nature of the solid material, the amount of water can range from 10 to 60 percent. As the ratio of solids to water changes, the density and viscosity change, and depending upon the gradient of the slope, the velocity and carrying capacity change as well. Relatively dense mudflows, some of which reach a density nearly two and a half times that of water, can support and transport exceptionally large rocks. One mudflow 4 feet thick transported a rock 9 by 13 by 16 feet; thicker flows have moved blocks 20 by 30 by 40 feet. If the rock debris in the flow is mainly coarse fragments such as cobbles and boulders, it may be called a debris flow. Depending upon the volume and properties of a mudflow, the gradient of the slope, and the topography, mudflows can travel a few feet to several miles. In 1941 a mudflow at Wrightwood, in the San Gabriel Mountains near Los Angeles, traveled about 15 miles. Mudflows, the product of the amount of solid material and water available at any one site, also range widely in volume from a few cubic yards to millions of cubic yards. The mudflows at Wrightwood originate from a debris source estimated at 5 million cubic yards and individual flows have exceeded a million cubic yards.

Mudflows may be associated with volcanic eruptions when great volumes of water from melting snow fields and glaciers or steam derived from the volcanic vent are introduced rapidly into poorly consolidated deposits of volcanic ash or other volcanic debris. But most frequently mudflows occur during intense rainfall. In climatic zones where the rainfall is frequently intense there are two places where mudflows commonly originate: at the bases of steep slopes, and at the mouths of major canyons. During periods of normal stream flow it is at these locations, where stream gradients become gentle, that weathered rock and soil tend to accumulate. After they become saturated, these thick blankets of debris become the main source materials for mudflows when sufficient stream energy becomes available to move them.

MUDFLOWS AT BIG SUR

Take one burned over forest slope, add intense rainfall, and stand back — instant mudflow. This recipe is well known and the events are predictable, yet precise causes of the mudflow phenomenon are not well understood. One example of mudflow evolution occurred recently at Big Sur, Monterey County, California, when nearby hills and canyons shed their skin of loose debris during a series of early season rainstorms. The geographic setting and the nature and sequence of events at Big Sur illustrate some of the conditions that can lead to the development of mudflows.

The Setting

The sea, the mountains, and the forest dominate the Big Sur coast. Even its thousands of visitors, and those who live scattered along the lower reaches of the Big Sur River or adhering to the steep hillslopes facing the sea, are lost in significance in comparison with the greater dimension of the natural setting.

The Sur fault intercepts the Big Sur River as it flows westward out of the higher reaches of the Santa Lucia Range (see map). The river then trends northwest and follows the fault zone, cutting a sinuous defile in the more easily eroded rocks of the fault zone before it empties into the sea near Point Sur. Along this 5 mile stretch of the river is the Big Sur area. In contrast to the more gentle slopes and lower elevations on the southwest of the fault zone, to the northeast, Big Sur is crowded against a mountain front which rises abruptly to more than 3500 feet. Slope angles range from about 15 degrees to 90 degrees with most slopes between 25 and 40 degrees.[10] Off this rock wall flow several minor tributaries to the Big Sur River, and on three of these tributaries damaging mudflows originated in 1972.

The Sur fault zone separates the dissimilar rocks of the ancient Sur Series on the northeast, from the younger Franciscian Formation on the southwest.[12] The Sur Series in this area is comprised of hard metamorphic rocks, largely gneiss, quartzite, and limestone; the rocks of the Franciscian Formation are mainly sandstone and shale. A narrow belt of fine- to coarse-grained sandstones, and

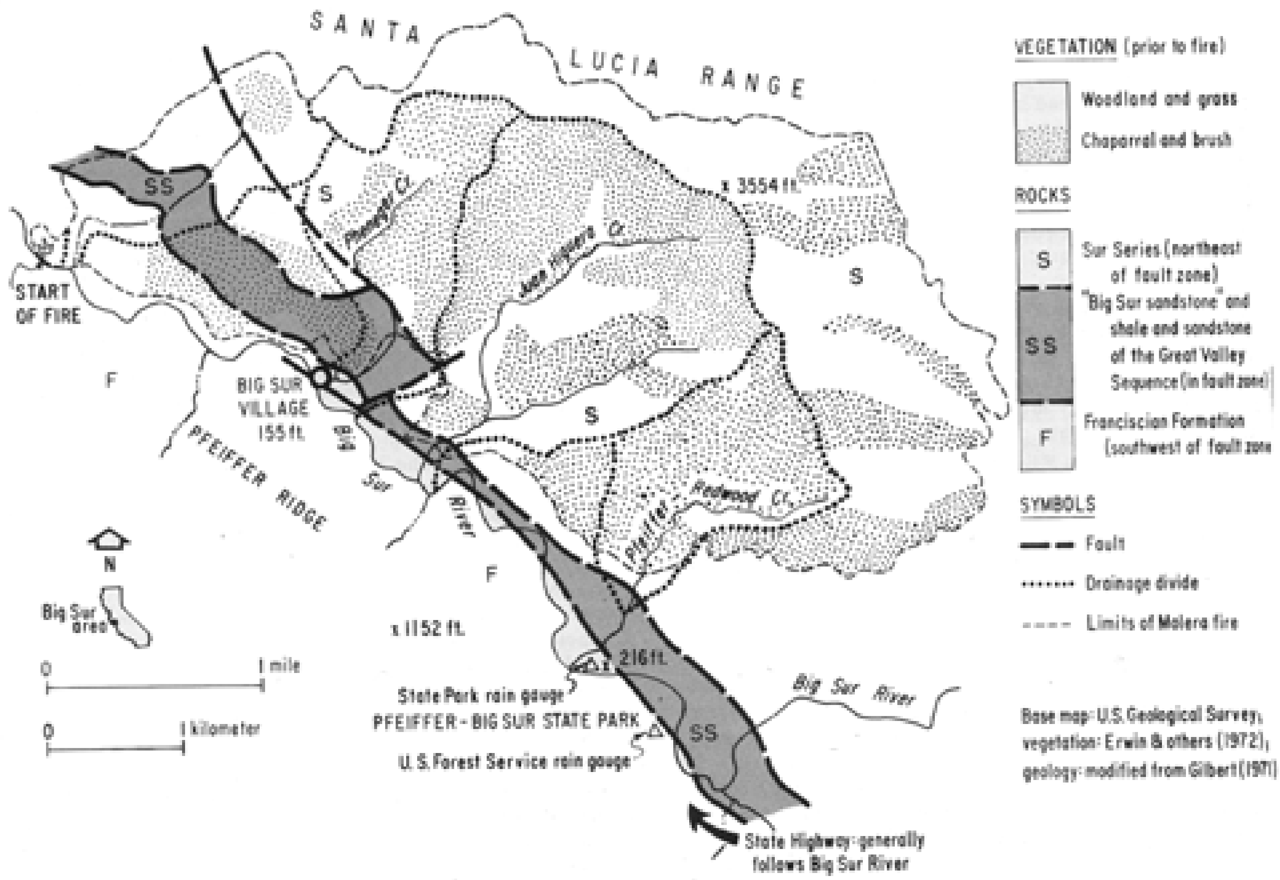

Figure 1. Geologic and geographic sketch map of Big Sur area, California.

Figure 2. Molera fire which occurred in early August 1972 left baked slopes above Big Sur. View north.

conglomerate and shale is sandwiched between the other two rock units and forms the core of the fault zone. The rocks in the fault zone are part of the Great Valley Sequence and the "Big Sur Sandstone" (see map).[12] They form a weak foundation along the base of the hillslopes northeast of the Big Sur River and are more easily weathered and eroded than those of the Sur Series that are stacked above them. The weathered debris from the Great Valley Sequence and the "Big Sur Sandstone" is mainly sand and clay; debris from the Sur Series is coarse angular blocks of gneiss. These and other rock materials have been classified into several soil types.[10] The soil types are all generally similar — coarse grained, shallow, and moderately erodable. Erosion rates vary widely, however, and depend upon local conditions within each drainage basin. The thin soil cover and the impermeable bedrock below leads to rapid runoff.

Big Sur, lying near sea level, receives about 40 inches of rainfall annually giving it a somewhat humid climate and a vegetation cover to match.[6] Higher elevations nearby drain toward Big Sur and receive an annual rainfall of from 50 to 60 inches.[10] But these annual rainfall figures reveal little with respect to the extremes of weather, especially in terms of rates of rainfall and runoff.

Both short and long duration rainfall totals are related to the landslide process, but short duration high intensity rainfall appears to be most closely related to mudflow activity. Less intense rainfall of longer duration mainly influences massive soil and bedrock landslides.

The rainfall intensity figures for the Big Sur area, when compared with those from other parts of California, show that short term rainfall is relatively high in the Big Sur region. Rainfall commonly will reach intensities equivalent to 0.8 inches per hour. Much higher rates per hour are reached for shorter durations.[17] Only local areas in the Transverse Ranges in the southern part of the state, and the Santa Cruz Mountains to the north, can normally expect slightly higher *intensity* rainfall than that of coastal Monterey and San Luis Obispo Counties.

In contrast to both intensity and total annual rainfall, single-storm rainfall totals around Big Sur are generally lower than single-storm totals for most of the rest of the California coast. But compared to many interior parts of the state and for the western states generally, storm totals in the Big Sur region are significantly higher.[13]

The Big Sur River drains a relatively small region of about 46 square miles, but storm rainfall totals within the region vary widely. It is common for the lower reaches of the river to flood. Weather records indicate that the Big Sur River drainage basin has a mean annual rainfall of about 51 inches, of which roughly half runs off. This amounts to a mean runoff of about 63,000 acre-feet. During 7 non-consecutive years of severe storms and resultant flooding between 1931 and 1960, runoff was very high, reaching a high of 177,500 acre-feet in 1941. The lowest runoff was in 1931 when only 8100 acre-feet were recorded.[1] Thus, it may be inferred that the capacity of the stream courses will not accommodate the runoff without flooding during peak years of high rainfall.

The influence of rainfall on the formation of mudflows is dependent upon other conditions as well. The character and density of the vegetation has a profound influence on regulating the way in which the rainfall is dissipated. The plants prevent the falling raindrops from hitting the soil at a high velocity, allowing a greater amount of the moisture to enter the soil rather than to run off over the surface and erode away the soil. Once the moisture is absorbed by the soil, part of it is taken up by the plant which returns most of it to the atmosphere by transpiration. Plants also impart strength to the soil through their interlocking roots which help to prevent the soil from moving down slope. Other conditions being the same, this root mat tends to allow steeper slopes to be maintained than where the vegetation is either more sparse or absent. The influence of the vegetation is further dependent upon the kinds of plants represented. Different plant types, because of their physiology, will utilize and dissipate the ground moisture in various ways. The nature of their root structure also will bear on the gross strength of the soil.

In the Big Sur area the slopes are mantled mainly with chaparral and grass, but stands of timber grow locally in the canyon bottoms. Chaparral is a collective term for a group of similar shrubs and small trees which make up the dull grayish green, velvet-like cover on much of the coastal ranges of California. The composition of the chaparral community is not everywhere the same, but changes in concert with local soil and climatic conditions. At Big Sur it is composed of coast live oak, laurel, tanoak, chamise, ceanothus, toyon, and manzanita among other plants. Trees in the canyon bottoms are the coast redwood, sycamore, madrone, cottonwood, maple, alder, and willow. Chaparral comprises about 65 percent of the plant cover with trees and grass comprising the remainder in about equal amounts.

The Events

If the vegetation did not normally protect the steep slopes from the effects of winter rainfall, the mountains above Big Sur would regularly shed tremendous amounts of runoff. Even so, vegetative cover is not always sufficient to completely offset periodic high intensity rainfall.

Molera Fire

On 1 August 1972, the tenuous equilibrium between the rainfall and the vegetation, soil, and slope that existed on the mountainsides was almost completely destroyed when a wildfire developed west of Highway 1, north of Big Sur Village. It swept northeastward to the crest of the main ridge above Big Sur and southward along the east side of Big Sur Canyon. It was contained at a cost of about $850,000 on 6 August after burning 4300 acres of chaparral, grass, and timber (figures 1 and 2). The natural beauty of the canyon floor with its vegetation escaped destruction, but it lay below a baked and largely destroyed landscape to the east. The fire burned through four basins tributary to and northeast of the lower Big Sur River — Pfeiffer Redwood Creek, which flows through the State Park, Juan Higuera Creek, Pheneger Creek, and an unnamed creek a mile northwest of Big Sur Village.

The intensity of the heat from the fire, especially where it was fueled by dense thickets of low growing chaparral, baked the surface of the soil to a bright red and brown crust. Trees burned vigorously in some side canyons, but elsewhere they were left only slightly charred with their leaves prematurely turned to autumn colors.

Rain

Next came the rain. In a series of storms beginning in mid-October and lasting for several days, and then again in mid-November (tables 1 and 2), both storm periods brought flooding and mudflow activity. The second period was the more destructive.

The first storm yielded 4.67 inches of rain from 10 October through 17 October. The major drainages were flooded during this period, but mudflows occurred only on 17 and 18 October, during intense, short-duration rainfall. The mudflow on 17 October followed 0.52 inches of rain, most of which fell within an hour, but on 18 October it followed rainfall of 0.73 inches which was recorded between 0500 and 0900 of that day.

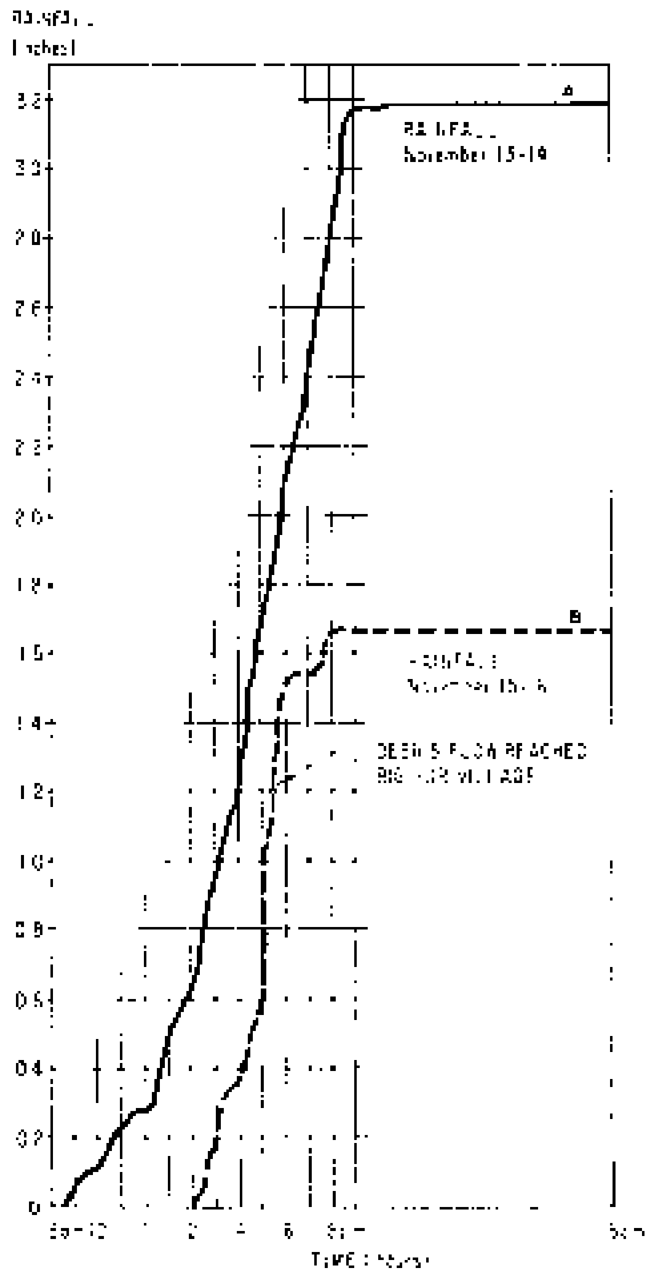

Figure 3. Graph showing the cumulative rainfall for 13-14, 15-16 November at Big Sur, California, as measured by a recording rain gauge. The total rainfall shown does not represent the total amount of rain for the 24 hour period. See Table 2 for correct totals. Differences are caused by the inaccuracies introduced by the recording rain gauge apparatus. The accuracy of this apparatus decreases with increased rainfall. Courtesy of U.S. Forest Service weather station, Big Sur.

TABLE 1: RAINFALL, OCTOBER STORM, BIG SUR, CALIFORNIA - 1972

Weather station at Pfeiffer-Big Sur State Park; rainfall recorded daily at 0800 for previous 24 hour period.

Date	Rainfall	Remarks
Prior to 10 October	0.18 inches	
10 October	0.32	
11	0.01	
12	0.82	Most fell during a short period around 0700.
13	0.05	
14	0.93	
15	1.02	0.73 inches fell between 0800 and 0900.
16	0.82	
17	1.10	
Storm total	5.07 inches	

Data from: California Department of Parks and Recreation, Pfeiffer-Big Sur State Park

The rainfall during the November storm was measured on a continuous recording rain gauge installed after the October storm by the U.S. Forest Service. This record gives more precise data in terms of critical rates of rainfall and the beginning of the mudflows, although it less accurately records total amount of rainfall. Figure 3, curve A shows the rate of rainfall for the 24 hour period between 0800 hours 13 November and 0800 14 November. Although total rainfall was high (4.98 inches as measured by standard, non-recording, cumulative rainfall gauge), the short term hourly rate was not as great as for the period 15-16 November when a 24-hour total of 1.79 inches fell (figure 3, curve B). The 13-14 November curve shows a steady heavy rainfall beginning at 0830 and ending about 2100; no mudflows reached Big Sur during this period. The curve for 15-16 November indicates heavy rainfall began in the early afternoon and reached its highest intensity beginning at 1700 when 0.44 inches fell in 15 minutes. After this surge, it took another 15 minutes for the runoff to accumulate and mix with debris and race down Pheneger Creek, for at 1730 on 15 November a debris flow, estimated at several thousand cubic yards, struck Big Sur Village.

The rain gauges were not in the drainage basins from which the mudflows originated, but were along the Big Sur River. Furthermore, because of the high mountains to the northeast, rainfall intensities at higher elevations may have been significantly greater. Stream flow measurements would be more meaningful if they were available.

TABLE 2: RAINFALL, NOVEMBER STORM, BIG SUR, CALIFORNIA - 1972

Weather station at Pfeiffer-Big Sur State Park and U.S. Forest Service, Big Sur; rainfall recorded daily at 0800 for previous 24 hour period at both locations.

Date	Rainfall			Remarks
	State Park	Forest Service	Recording Gauge	
10 November	0.88 inches	0.80 inches		
11	1.27	1.15		
12	0.28	0.27		
13	tr	0.0		
14	4.70	4.98	3.18	Flooding only on 13-14 November
15	2.47	2.38	1.65	Destructive debris flow occurred at 1730 15 Nov. after 0.44 inches of rain fell in 15 minutes
16	1.83	1.79		
17	0.15	—		
18	0.01	—		
Storm total	11.59 inches			

Data From: California Department of Parks and Recreation, Pfeiffer-Big Sur State Park; and U.S. Forest Service, Big Sur

Figure 4. Mudflows repeatedly closed Highway 1 at Pfeiffer-Big Sur State Park during storms of October and November 1972. Mudflows jumped the bed of Pfeiffer-Redwood Creek and crossed the highway to the Big Sur River (out of sight to the right). View southeast.

Mudflows

During the storm periods of late 1972 three of the four creeks draining into the Big Sur River at Big Sur would at one time yield relatively clear water and at another time a mudflow or debris flow. Generally, Pfeiffer-Redwood Creek carried fine grained materials and only mudflows occurred along this drainage course (figure 4). The size of the debris fragments was greater on the creeks to the north and at Pheneger Creek, blocks of rock 8 feet in greatest dimension and trees 4 feet in diameter were carried along, within, or riding atop the flows (figure 5). Juan Higuera Creek carried relatively smaller volume mudflows than did the other two creeks.

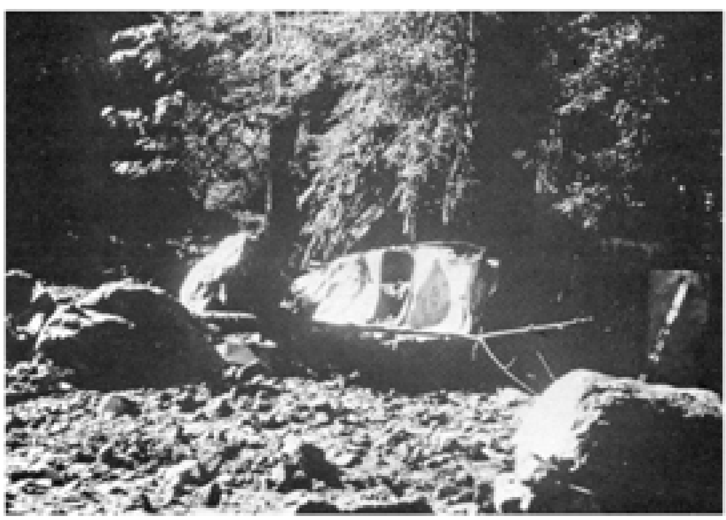

Figure 5. Large boulders, some 8 feet in greatest dimension, rode atop the debris flow that struck Big Sur Village on 15 November, 1972. Debris shown here came to rest in the Post Office parking lot. An automobile was crushed between a large boulder and a tree. Fifteen other vehicles met a similar fate and four were known to have been washed into the Big Sur River.

The notable difference in grain size between the flows that originated on Pfeiffer-Redwood Creek and those farther north is difficult to explain; compare figures 4 and 5. The available source materials for all the flows is debris that accumulates near the mouths of the tributaries to the Big Sur River and the blanket of soil that mantles the hillslopes. These materials are derived from the face of the massif behind Big Sur which is mainly crystalline rocks and younger sedimentary rocks. The sedimentary rocks are of the Great Valley Sequence north of the cross fault near Pheneger Creek, and "Big Sur Sandstone", to the south. Although both units are mainly sandstones, some shale occurs with sand in the section to the south. This difference in lithology, the erosion of soil left unprotected after the fire, or the possibility that Pfeiffer-Redwood Creek failed to develop enough energy to move larger clasts, may account for the finer grained flows along this creek.

The volume of some of the flows was estimated to be on the order of 10,000 cubic yards. The estimates were difficult to make because succeeding flows overrode previously deposited flows, masking their original dimensions. Moreover, the ratio of solids to liquid ranged widely and after a flow stablized it "deflated" as the water drained away.

Some of the flows apparently moved at high velocity and generally in one or a few distinct pulses. Although no estimates are available, eyewitnesses could hear the flows approaching and were forced to run from their paths. Probably these flows traveled a few tens of miles per hour. The mudflow at the State Park on 12 October, however, moved relatively more slowly judging from the observations of State Park personnel. They noted that this flow moved about half a mile in 10 minutes, or about 3 miles per hour.

The mudflows and debris flows reached the inhabited sections of Big Sur several times during the October and November storms. The state highway was blocked by flows

Figure 6. Debris flow of 15 November 1972 inundated the Big Sur Village, damaged buildings, and swept vehicles ahead of it toward the Big Sur River, beyond the trees.

and numerous homes and business buildings were inundated by mud and water. The most devastating events occurred when the flows were diverted by previously deposited debris or when they jumped the drainage channels and moved into habited areas along unexpected routes.

On 15 November a debris flow was crowded out of the channel of Pheneger Creek at Big Sur Village and flowed toward the north and west cutting across the business area to the Big Sur River. It blocked the highway with a train of debris 6 feet thick, plowed through a cement block building, climbed up and around the lower story of the two story building that houses the post office, and farther beyond dropped a tow truck onto a house trailer. In all it smashed a dozen cars or more into trees and rocks and into each other, then rafted four of them to the river where one of them was washed downstream 2 miles from the village (figures 6 and 7).

Of the numerous ways in which mudflows originate, those associated with the "fire-flood sequence" have been studied in most detail. Although much remains to be learned, one of the most notable aspects of the events at Big Sur, is that they were predicted with uncanny accuracy well before they took place. A team of hydrologists, foresters, and pedologists, from the U.S. Forest Service, the U.S. Soil Conservation Service, and the California Division of Forestry, began an investigation of the area after the August 1972 fire and prepared a Forest Service report that gives a detailed chronology of what was to come.[10] Their conclusions were reached by measuring how the bedrock, soil, vegetation, and slope would react to expected weather conditions based on the climatic pattern of the region. From these data estimates were made of the amounts of debris available for transport by the stream, erosion and runoff rates, and what remedial measures could be taken to reduce the danger from flooding and mudflows.

Figure 7. Ironically, this establishment at Big Sur Village lived up to its name when some of the flow from Pheneger Creek chose to cut through a parking lot on its way to the Big Sur River.

The Reasons

The cause of the mudflows at Big Sur may be traced to properties of the rocks and soils, and to the pattern of the rainfall during short time periods. The evidence suggests that the changes brought on by the fire set the stage for later mudflow and debris flow events.

During the October storm when mudflows were occurring at Big Sur, no other drainage courses from Big Sur south to the San Luis Obispo County line showed either mudflow activity or excessive runoff at the shoreline, even though rainfall appeared to be general all along the coast.

Three drainage basins within the fire area yielded mud or debris flows—the fourth only flooded. Mudflow activity or flooding was not observed in drainage basins in which the vegetation was unaffected by the fire, even though the unburned basins lay adjacent to the fire zone. Moreover, as far back as 1920, local residents cannot recall any large mudflows, although the Big Sur area has been flooded several times during that period.

The already steep and largely impervious slopes were probably sensitized by the fire through changes in the physical and chemical regimen of the soil at, and just below, the ground surface. This could have occurred when the protective canopy of vegetation was destroyed and certain organic compounds were redistributed in the soil.

The loss of the plant cover exposes the ground to direct impact of the raindrops which reduces the infiltration capacity and increases runoff.[4] Without the plants to intercept the rainfall, the soil absorbs a smaller amount of moisture. The rainfall does not collect and run off along established depressions on the slope, but is dissipated rapidly as sheet flow.

Some evidence suggests that another mechanism may have conditioned the ground surface and increased the runoff at Big Sur. After a heavy rainfall during the October storm period, members of the U.S. Forest Service examined the slopes above Big Sur in the fire area. The ground surface was moist, but by kicking into the soil a dry zone a few inches below the surface was uncovered. This indicated that, at least locally, a recently recognized phenomenon known as nonwettable or hydrophobic soil may have developed.[5] Hydrophobic soils are a particular product of fires in chaparral terrain.

Under a chaparral cover aluminum hydroxide and other organically derived compounds accumulate in the soil. These compounds contribute to the hydrophobic character of the soil. They are more concentrated below plants such as chamise (*Adenostoma fasciculatum*), but they also occur below other plants of the chaparral community: mountain mahogany, scrub oak and certain species of *Ceanothus*, among others.[5] When these plants burn, intense heat is generated. Above the ground surface, the temperature can reach 2000 degrees Fahrenheit. At the ground surface it can reach 1200 degrees, but because of the low heat conductivity of soil, the temperature drops off to 350 to 550 degrees F about 1-2 inches below the soil surface.

Laboratory experiments indicate that at high temperatures hydrophobic compounds are vaporized and part of the vapor condenses in a zone of concentration a few inches below the ground surface, forming an impervious layer. In these experiments, slightly non-wettable soils were heated above 400 degrees F for 5 to 20 minutes, whereupon their hydrophobic properties increased. But when the temperature reached 500 to 550 degrees F, the hydrophobicity was destroyed.

The implications of these relationships with regard to the origin of mudflows are far reaching. If a slope is burned over by a fire of intense heat, the near surface zone is purged of hydrophobic compounds. The vaporized compounds condense in a cooler zone just below the surface. Rainfall would then penetrate the surface layer and reduce its shear strength. Any excess water would migrate downslope, just above the impervious layer, carrying away the weakened material as a mudflow. All or part of this mechanism may have been important in forming the mudflows at Big Sur.

With the physical properties of the ground favoring rapid run-off, the prolonged, and at times, high intensity rainfall of October and November reached critical levels with respect to debris transport. On some days, steady rainfall of relatively high total volume, apparently drained over or through the debris stored in the stream courses without much of the debris being transported (figures 1 and 2). The principal mudflow and debris flow activity occurred during or just after short periods of intense precipitation following a previous longer period of relatively steady, but not intense rainfall. The periods of intense rainfall yielded a volume of water flow that could not filter through the debris fast enough to be dissipated simply as flood water.

Because of the range of conditions that control runoff and subsequent debris transport in each of the drainage basins, no quantitative measure of rainfall intensity can be cited as being critical with respect to the formation of mudflows. Mudflows followed periods of rainfall with intensities of about 0.82 inches per hour, 0.75 inches per hour, and the destructive mudflow after 0.70 inches per hour.

Table 3 shows average hourly rates of rainfall of similar nature for the time periods on the curves in figure 3. Average hourly rates for the two total rainfall periods are comparable, but the high intensity of the rainfall on 18 November was nearly three times the intensity of the rainfall on 15 November, even though it was of much shorter duration. The highest intensity rainfall on 18 November, just prior to the major mudslide, lasted for only 15 minutes. No quarter hour intensity rates on 15 November ever came close to the intensity recorded on 18 November. These data suggest that mudflow activity may depend less on total daily rainfall and more on relatively higher hourly rates followed by shorter bursts of precipitation. But antecedent rainfall of several hours or days undoubtedly primes the terrain in terms of lowering its infiltration capacity by saturating the ground. Thus, less of any subsequent short duration, higher intensity rainfall infiltrates into the ground, leading to greater rates of runoff and subsequent mudflow activity.

TABLE 3: AVERAGE HOURLY RAINFALL INTENSITY NOVEMBER STORM, 1972, U.S. FOREST SERVICE BIG SUR, CALIFORNIA

Date	Duration	Time Period	Average Rainfall
13 November			
Total rainfall period[1]	12.25 hrs.	0830 - 2045 hrs.	0.40 inches/hr.
High intensity rainfall period[2]	8.5 hrs.	1215 - 2045 hrs.	0.33 inches/hr.
15 November		1400 - 1800;	
Total rainfall period[1]	5.0 hrs.	1900 - 2000 hrs.	0.36 inches/hr.
High intensity rainfall period[2,3]	1.0 hr.	1700 - 1800 hrs.	0.90 inches/hr.

[1]Based on record of standard cumulative rainfall guage.

[2]Based on record of recording cumulative rainfall gauge, figure 3.

[3]During the period 1700 - 1715 hours, 0.44 inches of rain fell, or nearly half of that for the full one hour period.

The recent history at Big Sur may be only the beginning of a period of flood and mudflow activity that could continue for the next several years. The danger will be greatest during the early part of this period while the vegetation is recovering and the ground is healing. Much of the loose debris available to form mudflows, originally estimated at 29,600 cubic yards per square mile,[10] still lies waiting above Big Sur.

ACKNOWLEDGMENTS

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DATING AND RECURRENCE FREQUENCY OF PREHISTORIC MUDFLOWS NEAR BIG SUR, MONTEREY COUNTY, CALIFORNIA

By LIONEL E. JACKSON, Jr., Menlo Park, Calif.

Abstract.—Botanical evidence based on the dendrochronology and root horizons of redwoods (*Sequoia sempervirens*) and radiocarbon dating were used to date prehistoric mudflows near Big Sur, Calif. At least three periods of mudflow activity were delineated for the approximate prehistoric period 1370–1800. Two historic periods of mudflow activity have occurred, 1906–10 and 1972–73. The documentation of mudflows as characteristic surficial processes in the Santa Lucia Range indicates a hazard to development on recent mudflow deposits in this region.

From mid-October 1972 through mid-February 1973, mudflows from the rugged Santa Lucia Range repeatedly invaded the community of Big Sur, Calif. (figs. 1, 2). The flows were generated by intense winter rains falling on the steep slopes of the Santa Lucias which had been denuded by the Molera fire in August 1972. Damage from mudflows and floodwater was predominantly confined to areas marginal to the lower courses of Pheneger, Juan Higuera, and Pfeiffer-Redwood Creeks (fig. 2). Within these areas California State Highway 1 was blocked by mud, boulders, and vegetational debris; structures were partly buried, heavily damaged, or leveled; automobiles were swept into the Big Sur River; and private and public recreational areas were littered with bouldery debris. One life was lost as a result of the mudflow activity.

A reconnaissance of the mudflow-afflicted areas of Big Sur following the first flows in October 1972 showed that the structures and roads damaged by mudflows and attendant floodwater were generally on alluvial fans deposited by Pheneger, Juan Higuera, and Pfeiffer-Redwood Creeks. Older mudflow deposits, almost identical to those freshly deposited, were well exposed along stream channels in these fans.

The alluvial fans of these three streams are dominantly covered with forests of redwood (*Sequoia sempervirens*). Subsequent investigation of the fans indicated that the root systems of the redwoods have, over the years, acted as bedding markers along the tops and bottoms of the older mudflow deposits. Thus, by dating root layers, a chronology and recurrence frequency of mudflow activity could be established. Such a recurrence frequency is useful in evaluating

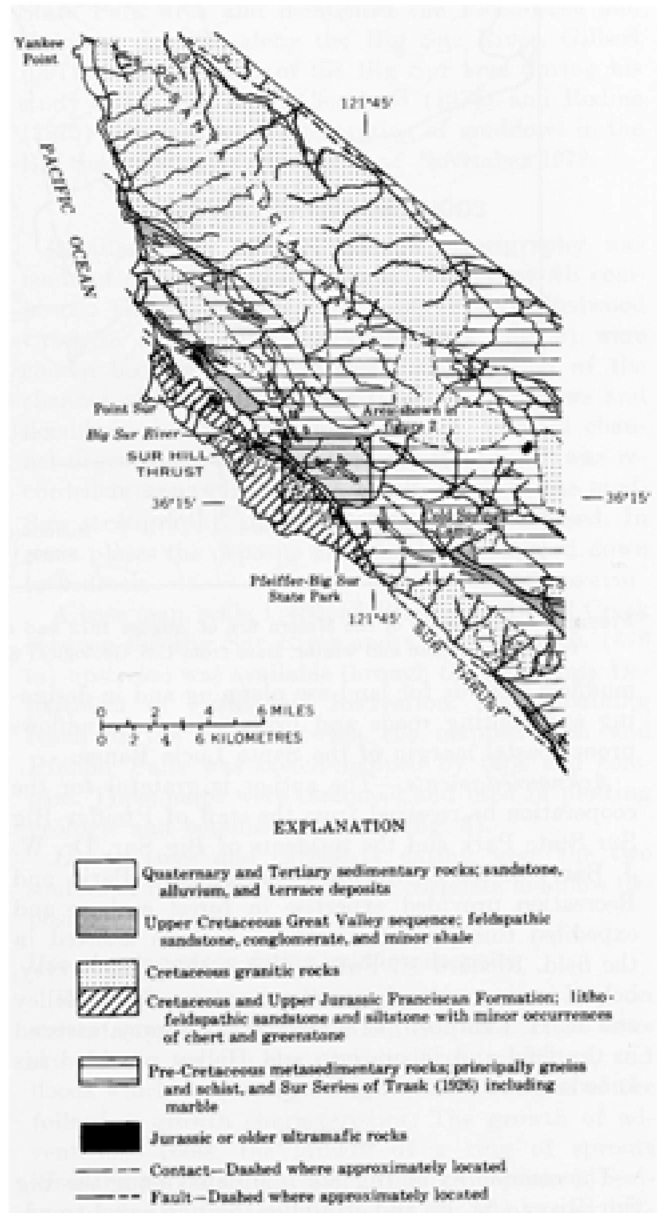


FIGURE 1.—Generalized geology of the Big Sur area, Calif. Base from U.S. Geological Survey Santa Cruz map, scale 1:250,000, 1965. Geology modified from Jennings and Strand (1958) and Gilbert (1971).

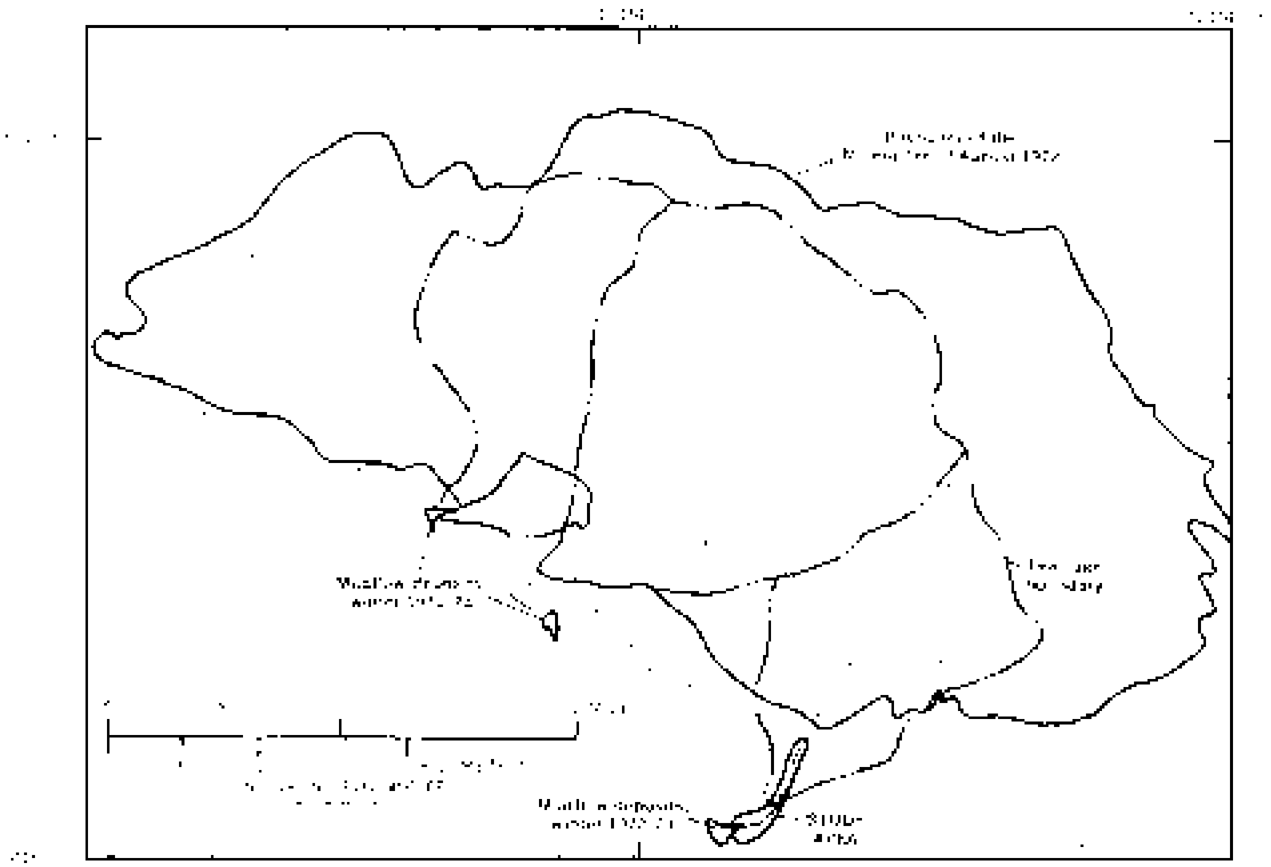


FIGURE 2.—Boundaries of the Molera fire of August 1972 and of the three major drainages that produced mudflows during the following autumn and winter. Base from U.S. Geological Survey Big Sur topographic quadrangle, scale 1:24,000, 1956.

mudflow hazards for land-use planning and in designing and routing roads and bridges on the mudflow-prone coastal margin of the Santa Lucia Range.

Acknowledgments.—The author is grateful for the cooperation he received from the staff of Pfeiffer-Big Sur State Park and the residents of Big Sur. Dr. W. J. Barry of the California Department of Parks and Recreation provided expertise in forest ecology and expedited this project. Carol N. Jackson assisted in the field. Richard H. Fuller, U.S. Geological Survey, helped in clay mineralogy determinations. E. J. Helley and R. H. Campbell, U.S. Geological Survey, assisted in the field and laboratory, and Helley provided his knowledge of dendrochronology.

SETTING

The community of Big Sur is situated along the Big Sur River (fig. 2) and straddles the northwest-trending Sur thrust, a major structural boundary of the Santa Lucia Range in this area. East of the thrust are Cretaceous granitic intrusive rocks and the pre-Cretaceous metamorphic rocks of the Sur Series of Trask (1926) which compose the core of the range. West of the thrust are the complex eugeosynclinal rocks of the Cretaceous and Upper Jurassic Franciscan Formation which form the basement west of the fault (Gilbert, 1971). The Sur thrust bifurcates into two parallel faults in the Big Sur area (fig. 1): the Sur Hill thrust on the east and the Sur thrust on the west. Sandwiched between these two faults is a narrow wedge of Tertiary sandstone (Oakeshott, 1951). Pleistocene and Holocene deposits discontinuously mask the bedrock geology along the Big Sur River.

The topography and drainage of the area generally parallel the regional northwest-trending structure. Relief is rugged east of the Sur thrust. For example, the altitude ranges from 120 feet (37 metres) at the mouth of the Juan Higuera Creek to 3,550 ft (1,080 m) atop Cabezo Prieto less than 2 miles (3 kilometres) to the east (fig. 2). Slopes are commonly 45° or greater on the granitic and metamorphic terrain east of Big Sur, but they are generally less precipitous on the Franciscan terrain west of the Sur thrust.

The climate of the area is Mediterranean with almost all rainfall occurring between October and April. Mean annual precipitation at Pfeiffer–Big Sur State Park averages about 41 inches (1,040 millimetres) per year; however, extremes in mean annual precipitation as low as 21 in (530 mm) and as high as 80 in (2,000 mm) have been recorded. Summer advection fogs, which are common in the area, supplement mean annual precipitation through drip from forest trees. Mean annual precipitation increases with altitude in the Big Sur area. For example, 80 in (2,000 mm) of rain was recorded at Pfeiffer–Big Sur State Park during the winter 1940–41; Cold Springs Camp, 7 mi (12 km) south of the park, received 160 in (4,060 mm) of rain (Pearson and others, 1967, p. B-51). The altitude of Pfeiffer Big Sur State Park averages 216 ft (65.8 m), and that of Cold Springs Camp, 1,350 ft (410 m).

The distribution of vegetation is controlled primarily by exposure and topography. Coastal chaparral dominates on very steep or south-facing slopes. North-facing slopes, deep narrow canyons, and valley bottoms are mantled by conifers and hardwoods. Redwood is the dominant tree in these forests.

The upper parts of the drainage basins of Pheneger, Juan Higuera, and Pfeiffer-Redwood Creeks and several adjacent unnamed basins were denuded of their vegetation by the Molera fire in August 1972 (fig. 2). The combination of the steep fire-denuded slopes and intense rains of the autumn and winter 1972–73 helped to generate the mudflows in the Big Sur area (Cleveland, 1973). The only other mudflows recorded in these basins since the area was settled in 1860 occurred during the winters 1908, 1909, and 1910. The flows followed a 1907 forest fire which burned the vegetation in the three basins (L. R. Helm, written commun., 1973).

The most extensive mudflow deposits in the Big Sur area are along the lower courses of Pheneger, Juan Higuera, and Pfeiffer-Redwood Creeks. In these areas, alluvial fans and valley fills have been deposited primarily from mudflow activity. The fans grade upstream into valley fills which are constricted by steep-sided canyon walls cut from river and older mudflow deposits and bedrock. The valley fills are generally bounded upstream by an abrupt increase in channel gradient which usually coincides with the change in lithology at the Sur Hill thrust. The downstream fans abruptly flare at the mouths of the canyons near their confluence with the Big Sur River. Gradients on the fans and upstream valley fills range from 6 to 10 percent. The mudflow deposits are typically not well sorted and are composed of particles that range in size from clay to boulders greater than 10 ft (3 m) in length. Minor lenses of fluvial deposits occur within the mudflow deposits. These deposits probably represent fluvial reworking following deposition of the mudflows.

PREVIOUS INVESTIGATIONS

Most geologic investigations in the Big Sur area have been concerned primarily with bedrock geology. Trask (1926) first mapped the Point Sur 15' quadrangle, Oakeshott (1951) mapped the Pfeiffer–Big Sur State Park area and mentioned the Pleistocene and Holocene deposits along the Big Sur River. Gilbert (1971) mapped parts of the Big Sur area during his study of the Sur fault. Cleveland (1973) and Rodine (1975) investigated the generation of mudflows in the Big Sur area during October and November 1972.

INVESTIGATIVE METHODS

Detailed study of the mudflow stratigraphy was made of one of the three alluvial fan valley fill complexes. The mudflow deposits along Pfeiffer Redwood Creek in Pfeiffer–Big Sur State Park (fig. 2) were chosen because of the extensive degradation of the channel of Pfeiffer-Redwood Creek by mudflows and floodflows during the winter 1972–73. Vertical channel degradation of as much as 6.0 ft (1.8 m) was recorded in some places. As a result, much of the mudflow stratigraphy along the creek is well exposed. In some places the deposits are completely exposed down to bedrock.

A base map, scale 1:480, of Pfeiffer-Redwood Creek between the Big Sur River and a point 1,240 ft (378 m) upstream was available through the California Department of Parks and Recreation. The remaining reach of the creek between the mapped area and Pfeiffer Falls was sketch-mapped by tape and compass. These maps were combined and used in plotting geologic and botanical features (fig. 3).

Living trees and carbon-14 dating were the two sources of data used to date and correlate mudflow deposits.

Use of redwoods in dating mudflow deposits

Redwoods grow abundantly in the canyons and on north-facing hillsides of the Big Sur area. These trees are able to survive the periodic fires, mudflows, and floods which frequent the Big Sur area because of the following growth characteristics: The growth of adventitious roots, the growth of a ring of sprouts around a parent stump (fairy ring development), healing of fire or impact injuries to the trunk, and buttress ring growth following tilting of the trunk. These responses to injury or burial provide evidence for the dating of past catastrophic events.

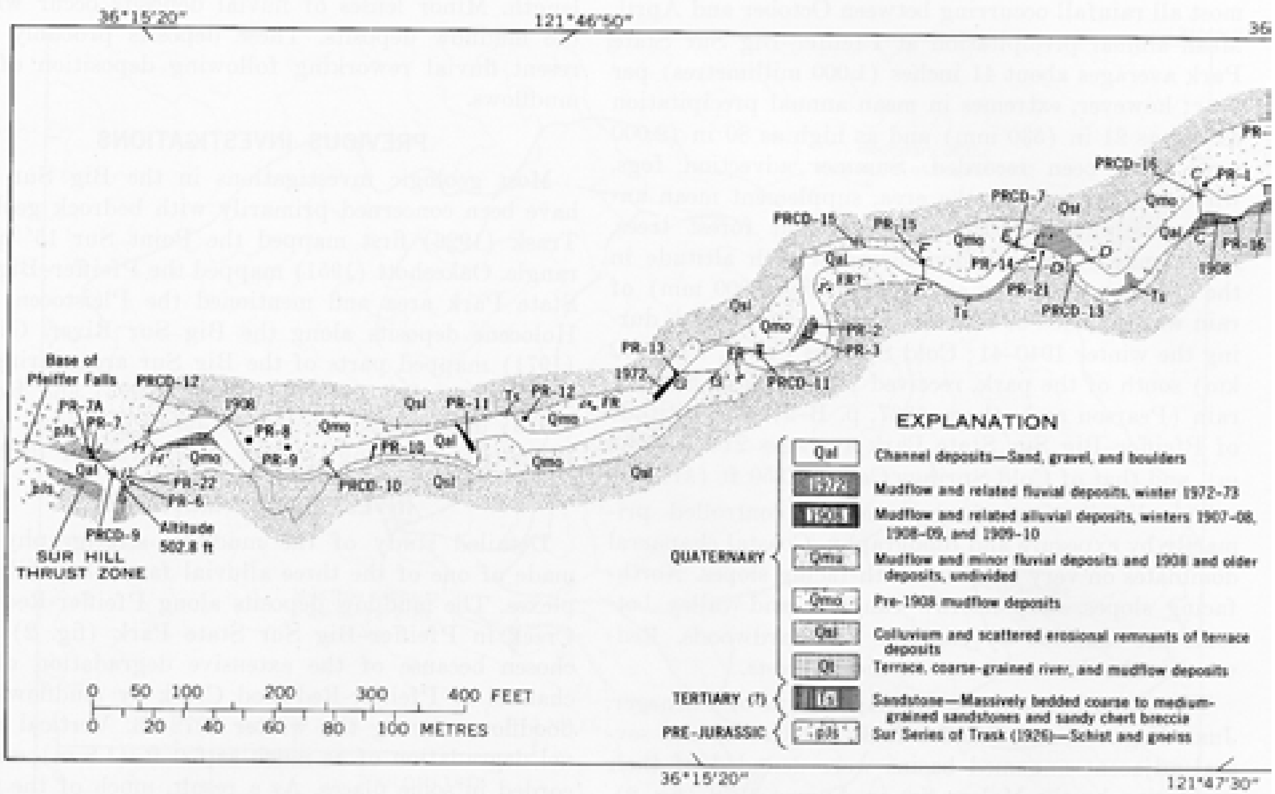
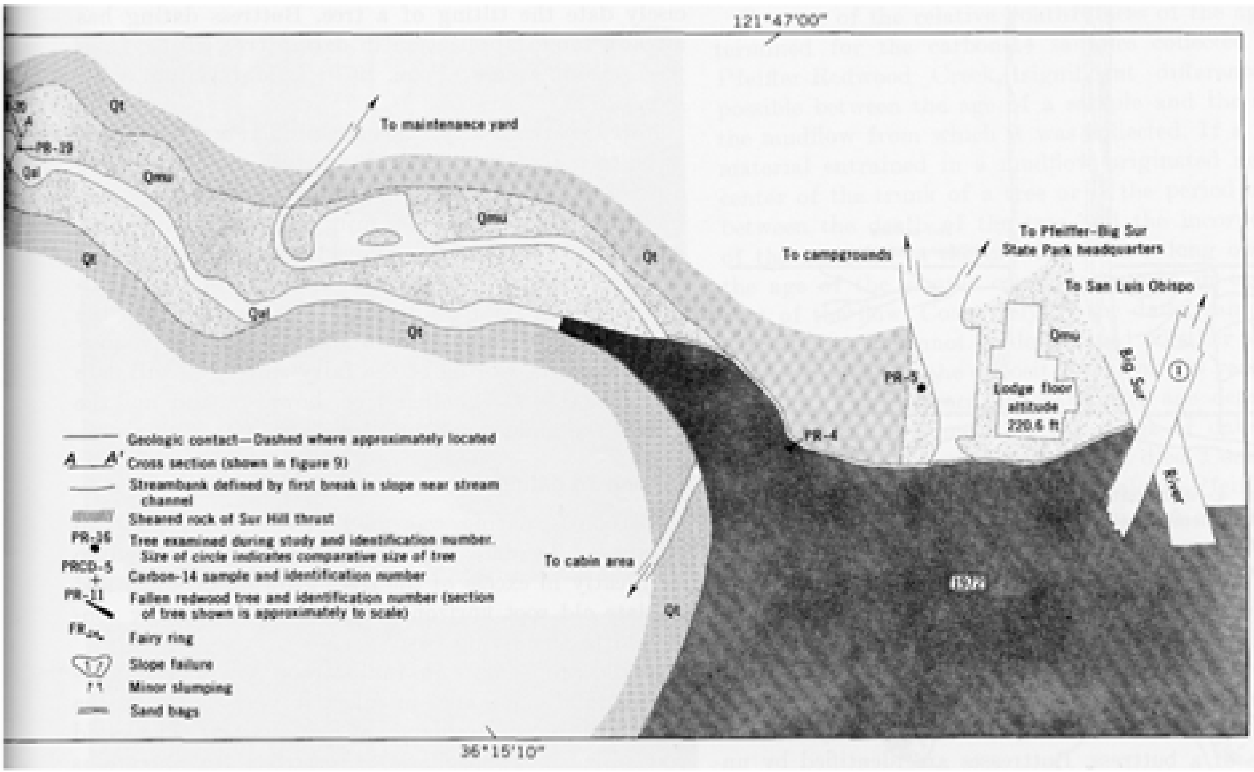


FIGURE 3.—Geology and selected botanical features along

Fundamental to all uses of the redwood to date past catastrophic natural events is its long lifespan. Individual specimens in the 500- to 1,000-year-old range have been identified in the Big Sur area.

Root system.—Redwoods lack tap roots (Fritz, 1934). Instead they develop extensive, relatively thin root horizons that, in the study area, never exceeded 4 ft (1.2 m) in thickness. Redwoods are able to withstand periodic burial by mudflows or flood-deposited sediment because of their propensity for negative geotrophic root growth (roots growing toward the surface following burial) and subsequent development of a new and shallower root system (Stone and Vasey, 1968). Negative geotrophic root growth restores the flow of water and nutrients into the tree which would otherwise be inhibited by the newly deposited sediments (Stone and Vasey, 1968). The vertical roots are eventually supplanted by horizontal shallower root systems developed from adventitious buds on the buried stem (fig. 4). A schematic cross section of the root horizons of old redwoods that have experienced several mudflows during their lifetimes is shown in figure 5, trees 2 and 3. Each root horizon marks the top of the underlying mudflow and the bottom of the overlying deposit. Furthermore, the presence of a buried root horizon indicates a significant hiatus between successive mudflows. Without such an indicator it is impossible to determine whether two successive mudflows were deposited during the same winter or 100 years apart. Figure 6 shows examples of the appearance of some of these adventitious roots in the field.

The relations between root horizons and mudflow deposits used to date past mudflow events in this study are illustrated in figure 5. Tree 1 in figure 5 has only a single root system. Cores were taken from trees with a single root horizon. The annual rings in the cores were counted in the laboratory in an attempt to find the oldest trees. The ages of the oldest trees sampled are the minimum ages of the deposits underlying the trees. Ages of trees with several root systems (fig. 5; trees 2, 3) are the minimum ages of the deposits below the lowest and original root system. Counting the root horizons above the original root system determines the number of mudflows which buried the tree deeply enough to cause it to develop new root systems. If the number of root zones is divided into the age of the tree, then the result is the average recurrence interval (in years) for mudflows at that site and of a character capable of causing development of a new root zone. Thus, the division of the number of subsequent



edwood Creek between Pfeiffer Falls and the Big Sur River.

root horizons into the age of the tree produces the minimum average mudflow recurrence interval. Where trees with different numbers of multiple roots were located in close proximity, minimum and maximum ages were established for the mudflows. Table 1 describes tree cores examined during this study.

Mudflow recurrence frequencies determined by root-horizon studies must be regarded as minimum values owing to the complex history of streams such as Pfeiffer-Redwood Creek. Constant channel migration and attendant cutting and filling complicate the stratigraphy of deposits adjacent to the channel. For example, the mudflow deposits of 1972–73 are only sporadically deposited along the upper part of the Pfeiffer-Redwood Creek (fig. 3).

Trunks.—Redwood trunks may record mudflow events in several ways. The pounding of mudflows or floodwater-driven bedload against the upstream side of the trees strips away the bark and phloem and scars the underlying xylem. For example, scars from the mudflows of 1908–10 are still visible on some trees along both Pfeiffer-Redwood and Pheneger Creeks. If no subsequent flows attack these trees, the scars will eventually be healed by peripheral growth around the scar, which can be identified in annual-growth-ring studies (see section "Field and Laboratory Procedures"). When such a scar is identified, the year of the responsible flow may be estimated by dating the first complete annual growth ring on the outside of the scar (Sigafoos, 1964).

Forest fire scars are recorded in the redwood in a similar manner. Fire scars are significant because, on the basis of the past 113 years of recorded history, mudflow-producing winters (1907–10 and 1972–73) have been preceded by fire, suggesting a direct relation between the two phenomena. At any rate, fires seem to have been frequent events near Pfeiffer-Redwood, Juan Higuera, and Pheneger Creeks. Many of the redwoods along these streams are burned out inside or have multiple fire scars by the time they are 200 or 300 years old. This situation can be partly accounted for by the fact that the stands of usually fire-resistant redwoods, which grow in the bottoms and on the sides of narrow valleys, end abruptly, and the flammable chaparral vegetation on the surrounding slopes begins. When the chaparral burns, the intense fire overcomes the natural resistance of the redwoods and causes damage.

The only other trees growing with the redwoods in

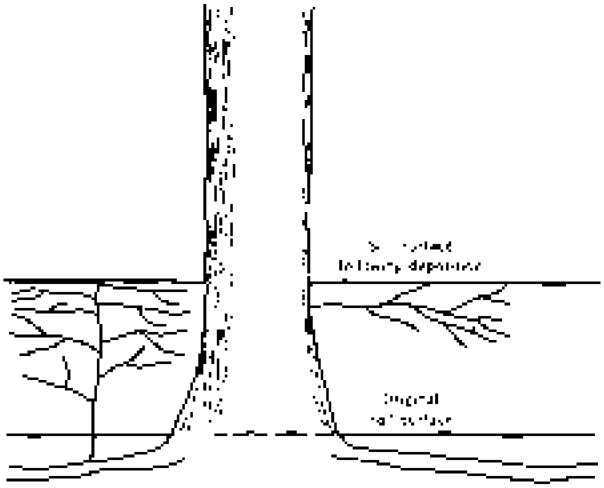


FIGURE 4.—Schematic representation of a new redwood root system developing after burial of old root system by flood or mudflow deposits. (Modified from Stone and Vasey, 1968.)

these valleys are hardwoods which can rapidly re-sprout after fires.

Any tilting of the ground surface resulting from marginal slumping, or any injury to the redwood which causes the tree to tilt, is recorded by the formation of a buttress. Buttresses are identified by unusually wide growth rings which develop in the direction of tilt. The buttress mechanically compensates for the tree's unbalanced weight distribution (Fritz, 1934). The initiation of buttress-ring growth can precisely date the tilting of a tree. Buttress dating has already found application in dating tree tilting from past seismic events (Page, 1970; LaMarche and Wallace, 1972).

Fairy rings.—Fairy rings are circular stands of redwood trees that have a common origin as sprouts from a preexisting parent tree (fig. 7). The sprouting takes place as a response to an injury to the mother tree, usually by fire (Stone and Vasey, 1968). The presence of a fairy ring growing on mudflow deposits, especially where only one root horizon is present beneath the fairy ring, indicates relative antiquity for the underlying deposits. Coring of the fairy-ring trees will date the injury to the mother tree, however, and not the age of the underlying mudflow deposits.

Carbon-14 dating

Carbon-14 dating was used in this study for two purposes: To date deposits whose ages appeared to be greatly in excess of the trees growing on them and to date old root horizons which were not visibly connected to any living tree.

Radiocarbon ages in radiocarbon years were corrected to absolute ages in calendar years by using the bristlecone pine chronology of Suess (1970). The rapid variations in atmospheric radiocarbon concentrations during the past several hundred years caused four of the radiocarbon samples to have two or three possible calendar ages. Table 2 is a compilation of these dates. The locations of the samples are shown in figure 5.

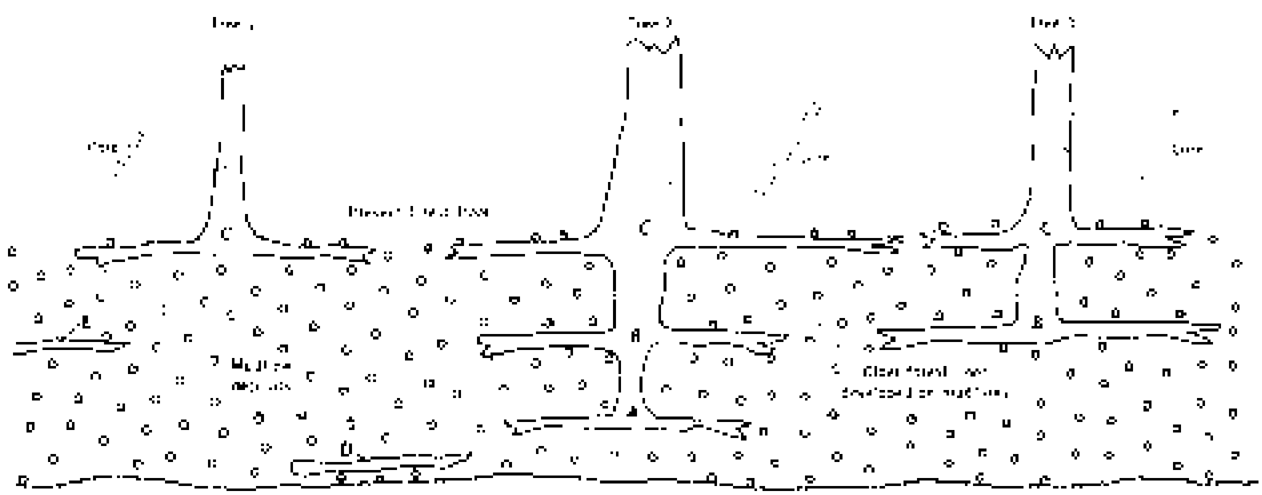


FIGURE 5.—Cores taken from trees 1, 2, and 3 and rings counted to determine minimum age of tree. For tree 1, with one root horizon, this dated top mudflow. For trees 2 and 3, which had experienced several mudflows, ring counting dated minimum age of lowest and original root system. Division of number of root horizons (A, B, and C) into this minimum age gave a minimum recurrence interval of mudflows. Samples from old root horizons not apparently connected to any living tree (D and E) were dated by carbon-14 methods to determine ages of mudflow deposits.

FIGURE 6.—Examples of redwood-root horizons along Pfeiffer-Redwood Creek. *A*, Two young redwoods, PR–2 in the foreground and PR–3 in the background, with single root horizons growing in the deposits of the mudflows of the winter 1907–08. Both trees, PR–2 and PR–3, dated the deposits within 1–5 years. The large underlying log is part of the underlying deposit. The stadia rod is 8 ft (2.2 m) in length. *B*, Root horizons below 472-year-old tree PR–1. Five root horizons including the present forest floor are present below this tree; however, only the upper two root horizons and the second root horizon from the bottom belong to this tree. The youngest deposits may predate the mudflows of 1908–10. The stadia rod is 11 ft (3.4 m) in length. Note the large size of some of the channel-sediment clasts and the height of the mud splatter marks on tree PR–1 (indicated by the arrow).

Because of the relative youthfulness of the ages determined for the carbon-14 samples collected along Pfeiffer-Redwood Creek, significant differences are possible between the age of a sample and the age of the mudflow from which it was collected. If a woody material entrained in a mudflow originated near the center of the trunk of a tree or if the period of time between the death of the tree and the incorporation of the material in the mudflow was a long one, then the age of the sample could be greatly in excess of that of the flow. Conversely, if the dated sample was a root, then it cannot be determined whether the root began growing in the deposit 1 year or 100 years after the flow. Furthermore, the carbon-14 age determined for a sample is a mean of the range of dates when each of the woody cells composing it died. Consequently, the carbon-14 dates obtained along Pfeiffer-Redwood Creek were regarded as minimum or maximum limits of the ages of the mudflows from which they were collected.

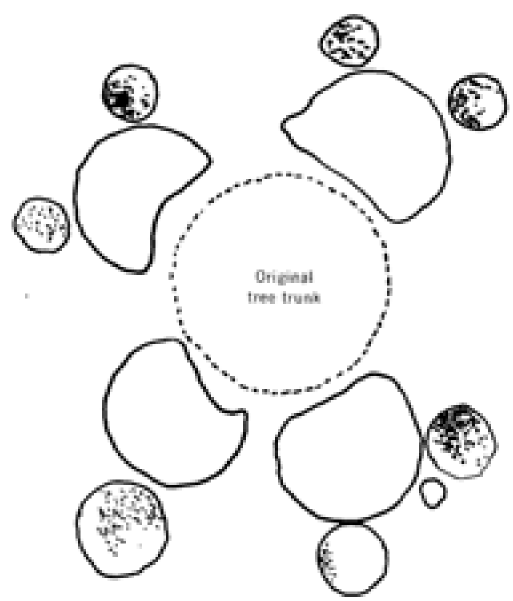


FIGURE 7.—Schematic representation of the development of a fairy ring. The fairy ring is shown as the shaded trunks. Repeated fires during several hundred years critically injured the original tree in the center. In response to this injury, sprouts began growing from its base. Of these sprouts only three or four survived. The others, along with the critically injured mother tree, were killed and consumed by successive fires. As this sequence is repeated, the fairy ring enlarges until it finally loses its identity among the surrounding trees. (Modified from Stone and Vasey, 1968.)

TABLE 1.—Description of [illegible]

[illegible]

See footnotes at end of table

TABLE 1.—*Description of trees dated*[1]—Continued

Tree number	[illegible]	Root structure	State of preservation	Stratigraphic significance	[illegible]	[illegible]	[illegible]	[illegible]	Total age (years)	Remarks
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]			[illegible]	

[illegible]

[illegible]

[illegible]

Field and laboratory procedures

Significant geological and botanical features of the study area were mapped (fig. 3). Cores were taken from 13 redwood trees by using a power tree borer developed by the Geological Survey of Canada (Parker, 1970) which cuts a 19.0-mm core and a Swedish increment borer which cuts a 4.50-mm core. One complete section of a fallen redwood was cut (fig. 8), and the annual rings of the samples were counted in the laboratory. Fire scars, impact injuries, periods of buttress growth, and the general condition and quality of the core were noted during counting and are listed in table 1.

Stream cross sections were plotted (figs. 3, 9) and photographs were taken (fig. 6) of the mudflow and redwood root horizons adjacent to locations along Pfeiffer-Redwood Creek where trees were cored or carbon samples were collected. These photographs and cross sections were used to document the locations of carbon-14 samples and root horizons.

Sources of error in annual ring studies

Some counting error must be assumed for highly fragmented cores where rings may have been destroyed during the coring operation or unknowingly counted twice. Error from this source is probably less than 5 percent of the total age of even the most fragmented cores examined. Discontinuous rings, which are common in redwoods (Fritz, 1940) and do not completely encircle the tree (fig. 8), are another source of error. Errors in tree ages owing to discontinuous rings cannot be estimated unless several cores are taken per tree. The ring count on tree PR–10, which was a complete redwood cross section (fig. 8*B*), ranged from a maximum of 151 rings to a minimum of 148 rings over the three radii that were counted, a maximum error of 2 percent. It is hoped that the age error owing to missing rings of the cores counted is as small, although larger errors are possible.

DATA AND FIELD OBSERVATION ANALYSES FOR DEVELOPING MUDFLOW CHRONOLOGY

Data for tree cores and carbon-14 samples taken near each cross section (fig. 9) were compared with field observations to determine which data were reliable and should be used to define periods of mudflow activity. Discussion of two cross sections (*C–C′* and *E–E′*) will show how partial or questionable data were evaluated and how the data and field observations were used to determine dates of mudflow activity.

Cross section C–C′.—The left bank of Pfeiffer-Redwood Creek at this site shows more root horizons than any other individual section exposed along the creek. Tree PR–1 (fig. 3), which yielded an age of 472 years, and the root stratigraphies underlying it are pictured in figure 6*B*. This section was exposed by the scouring and undermining of mudflows and torrential surges of floodwaters that almost caused the tree to topple. Only

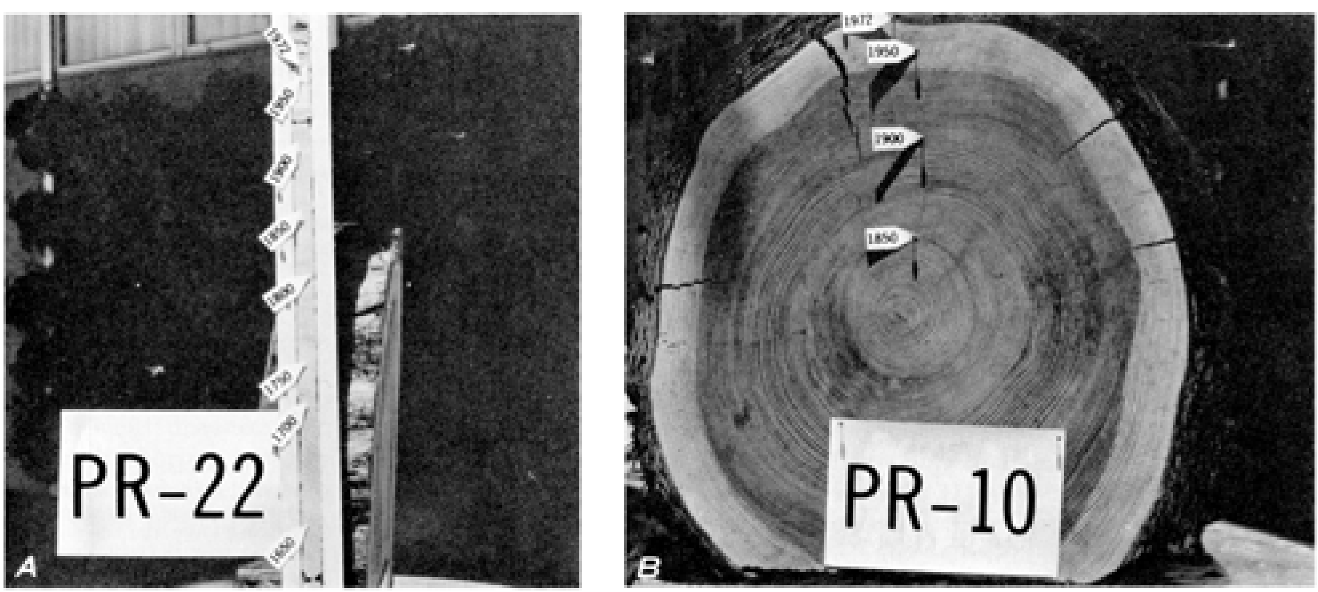


FIGURE 8.—Examples of core and slab samples prepared for annual-growth-ring studies. *A*, A part of the core taken from tree PR–22. The core was oriented for ring counting, bonded to the pregrooved mounting board, and sanded flush with the mount. *B*, A slab from fallen redwood PR–10. Note that the ring widths vary and that some of the rings are discontinuous. The cards are 5 by 8 in (130 by 200 mm).

TABLE 2. — *Data for carbon-14 samples*[1]

[Location of sampling sites shown in figure 3. B.P., before present; [illegible]]

Sample	Age (including tree-ring correction) Years B.P.	Year	Tree-ring correction[2]	Description	Comments
PRCD 1	<150	--	--	Sampled from the first old root layer below present root system of tree PR 20 (fig. 9, cross section B-B').	Sample age indicates deposition of the overlying mudflow deposits between [illegible] and 1776, which is 150 years older [illegible]. Sample assigns a minimum age to the underlying mudflow.
PRCD 5	320±80	1630	150	Sample from the second and oldest root system below the present root system of tree PR 20 (fig. 9, cross section B-B').	Sample assigns a maximum age limit for the overlying mudflow deposits and a minimum age for the underlying deposits.
PRCD 6	<150	---	--	Sample from the lowest root horizon on the left side of the bank of Pfeiffer-Redwood Creek (fig. 9, cross section C-C'). This root horizon is not visibly connected to any living tree.	Older age of the overlying root horizon indicates that this sample is anomalously young and should be discounted.
PRCD 7	310±80	1640	-165	Sample from roots of possibly a younger root horizon overlying PRCD 6 in the left bank (fig. 9, cross section C-C').	Sample assigns a maximum age to overlying mudflow deposits and a minimum age to underlying deposits.
PRCD 9	300±80 450±80	1650 1500	180 220	Sample taken from the lowest root horizon in the left bank (fig. 9, cross section C-C').	Sample assigns a maximum age to overlying and a minimum age to underlying deposits.
PRCD 10	1110±80	840	0	Sample is part of a trunk or large branch entrapped in clay-rich mudflow deposits. Mudflow either rests on or is close to bedrock.	Sample assigns a maximum age to overlying deposits and a minimum age to underlying deposits, if present.
PRCD 11	310±80 410±80 450±80	1640 1540 1500	-150 -190 220	Sample from an old and discontinuous root layer 5 ft upstream from tree PR 3.	The youngest of the three possible dates assigns a minimum age to the underlying deposit, and the oldest of the three possible dates assigns a maximum age to the overlying deposits.
PRCD 12	350±80 420±80	1600 1530	70 -270	Sample from a plant in a [illegible] mudflow deposit on the left bank (fig. 9, cross section [illegible]). Deposit directly overlies bedrock.	Sample assigns a maximum age to overlying deposits.
PRCD 13 ...	510±80	1440	135	Sample is a log fragment collected in a mudflow deposit near bedrock in the right bank (fig. 9, cross section [illegible]). Sample is stratigraphically below the root horizons from which PRCD 6 and PRCD 7 were sampled.	Sample assigns a maximum age to overlying deposits.
PRCD 15 ...	730±80	1220	0	Sample is from a log in a mudflow unit correlative to the lowest unit in figure 9, cross section [illegible] about 45 ft upstream from tree PR 15 (fig. 3).	Sample assigns maximum age to overlying and a minimum age to underlying deposits.
PRCD 16 ...	310±80 430±80 450±80	1640 1520 1500	150 190 220	Stratigraphically lowest root layer below tree PR 1 (fig. 9, cross section C-C').	Sample date should be discounted because of several possible calendar ages for carbon-14 age and the possibility that the late root sample grew into the section after the overlying deposit or deposits were laid down.

[1] Samples analyzed by [illegible]. Samples were [illegible] for the removal of [illegible].
[2] Corrections for [illegible] chronology of [illegible].
[3] [illegible] indicates that [illegible] the sample's age.

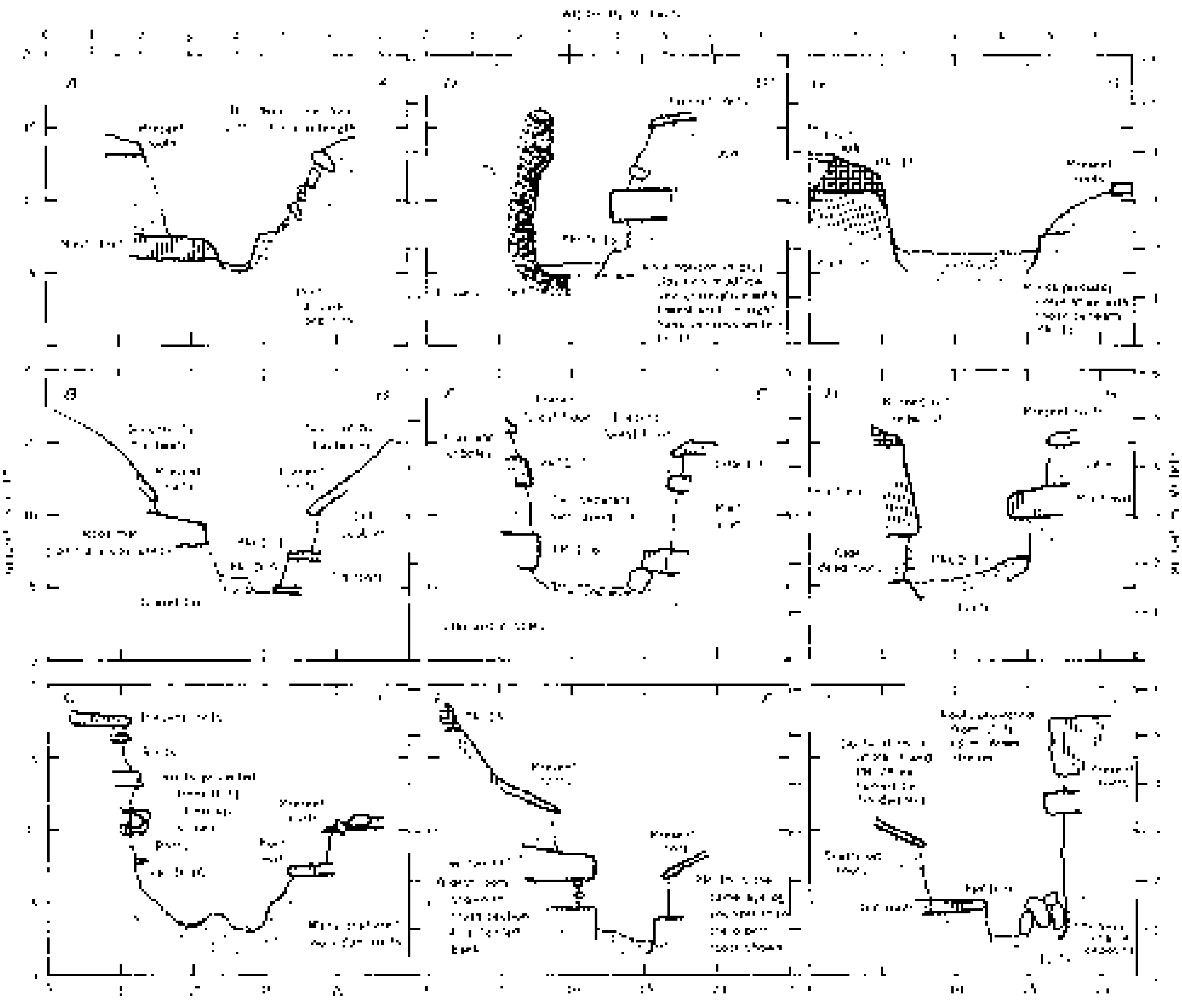


FIGURE 8.—Cross sections of mudflow deposits and exhumed root horizons along Little Redwood Creek. The cross sections illustrate key stratigraphic relations which were useful in identifying individual mudflow events. All views are looking downstream.

the second lowest and the two upper root horizons are physically connected to tree PR 1. The third root horizon from the top of cross section C-C' is projected from a short distance upstream (fig. 8B). The main root in this horizon tapers in the direction of tree PR 1, and the root does not appear to have been connected to this tree in the past. Carbon-14 sample PRCD 16 was collected from the lowest root layer below tree PR 1. This root layer was not visibly connected to PR 1. Owing to past variations in atmospheric carbon, the uncorrected age, 190 radiocarbon years before present, could be corrected to three possible calendar ages by the bristlecone pine calibration curve: 310, 190, and 150 years before present. All dates are younger than the PR 1 tree. This apparent reversal in stratigraphy probably results from contamination of the sample by fine younger rootlets which were growing pervasively through the sample. Although only visibly uncontaminated fragments of the sample were submitted for analysis, enough young carbon-14 was apparently present to render the sample useless.

Ring 228 (from the outside of the tree) of the core obtained from tree PR 1 terminates against a scar which appears to have been the result of an impact injury or abrasion. This may be significant because it could date a mudflow event of about 320 years before present.

Two distinct root horizons, which are present on the opposite side of cross section C–C', are connected to tree PR–16. PR–16 yielded an age of 104 years, indicating that the upper set of roots dates from the 1908 mudflows and that the lower set suggests the underlying deposits are older than 104 years. Correlation of these underlying deposits with those on the opposite side of the stream is not clear. The 1908 deposits are fresh in appearance and do not seem to correlate with the youngest deposits on the left side of the cross section C–C'.

Taken together, the two sides of this cross section indicate that as many as four or as few as two periods of mudflow activity have occurred between about 1580 and 1908. This count would depend upon whether three root horizons or one root horizon below tree PR-1 was assumed to mark mudflow events since the tree began growing. The lowest root horizon below PR-1, without further evidence, would have to be regarded as predating PR–1 and cannot be included in this total. The abrasion scar noted in the core of PR-1 dates one of these flows at about 320 years (1655).

Cross section E–E'.—Two carbon samples were collected from the root horizon on the left side of the channel. Carbon-14 sample PRCD-6 was from the lower part of a very thick root horizon, and PRCD-7 was from the upper part of this thick root horizon. PRCD–6 dated at less than 180 years, and PRCD-7 yielded a corrected age of 510 years before present (1440). The most apparent explanation for this reverse stratigraphy is that PRCD–6 was sampled from a much younger root which grew into the mat at a later date; PRCD-6 date should be discounted. The age 510 years before present for PRCD-7 is the same as that yielded by PRCD-13, indicating the two are very close in carbon-14 age and probably mark the same mudflow period. No age was determined for the mudflow deposit overlying this root horizon. The lowest root horizon on the right bank of *E–E'* is the same horizon that overlies PRCD-13 and is probably correlative to the root horizon across the channel from which PRCD-6 and PRCD–7 were sampled. The next shallowest root horizon on the right side of cross section *E–E'* contains the lowest roots of the multiple-rooted trees PR-11 and PR-21; these trees yielded tree-ring ages of 377 years and 285 years, respectively. The deposits overlying this root horizon may date from the 1908 mudflow event. In summary, this cross section provides evidence for two mudflow events prior to the beginning of the historical record in 1860. The older occurred about 1440, and the younger between 1599 and 1688.

DISCUSSION AND CONCLUSIONS

Figure 10 is a diagrammatic compilation of all the usable data collected along Pfeiffer-Redwood Creek during this study. The ages are plotted in a downstream direction from left to right. Radiocarbon dates with more than one possible calendar date have not been incorporated in this figure. The data represented in this figure indicate that at least three mudflow events have occurred along Pfeiffer-Redwood Creek between about 1370 and the beginning of recorded history of the area in 1860. The shaded bands bounded by dashed lines in the figure indicate the apparent minimum and maximum age ranges of these mudflow events. The breadth of the time-span between these boundaries represents dating error due to core breakage, missing rings, minimum and maximum age relations of trees and radiocarbon dates to deposits, imprecision in carbon dating, imprecision in the conversion of radiocarbon years to calendar years, or the possibility of more than one mudflow period within a shaded band. The last mentioned is highly possible. For example, the mudflows of 1918–19 and 1972–73 left only scattered evidence of their occurrence along Pfeiffer-Redwood Creek. Because of the possibility of similar past events, the three prehistoric mudflow events delineated in figure 10 must be regarded as a minimum number.

If carbon-14 sample PRCD-10 (fig. 10) dates the mudflow deposit that contains it, then the mudflow deposit is the oldest preserved along the lower course of Pfeiffer-Redwood Creek. Because PRCD-10 is the only absolute age control for this mudflow deposit, however, the relation of this mudflow deposit to others both upstream and downstream must remain uncertain.

If the age of this mudflow unit is about 1,100 years before present as indicated by PRCD-10, the 20 ft (6.0 m) of mudflow deposits above it indicate frequent and (or) massive mudflow activity during the past millennium. If the mudflow deposit dated by PRCD-10 is significantly younger than 1,100 years, then inferred past mudflow activity becomes even more certain.

The oldest mudflow deposits that can be dated with certainty were deposited between 1370 and 1440 (fig. 10). Part of the deposits of this flow are well marked by a buried root horizon that can be clearly traced from the vicinity of the collection point of sample PRCD-13 to the collection point of PRCD-15 (fig. 5). All usable carbon-14 dates determined for this

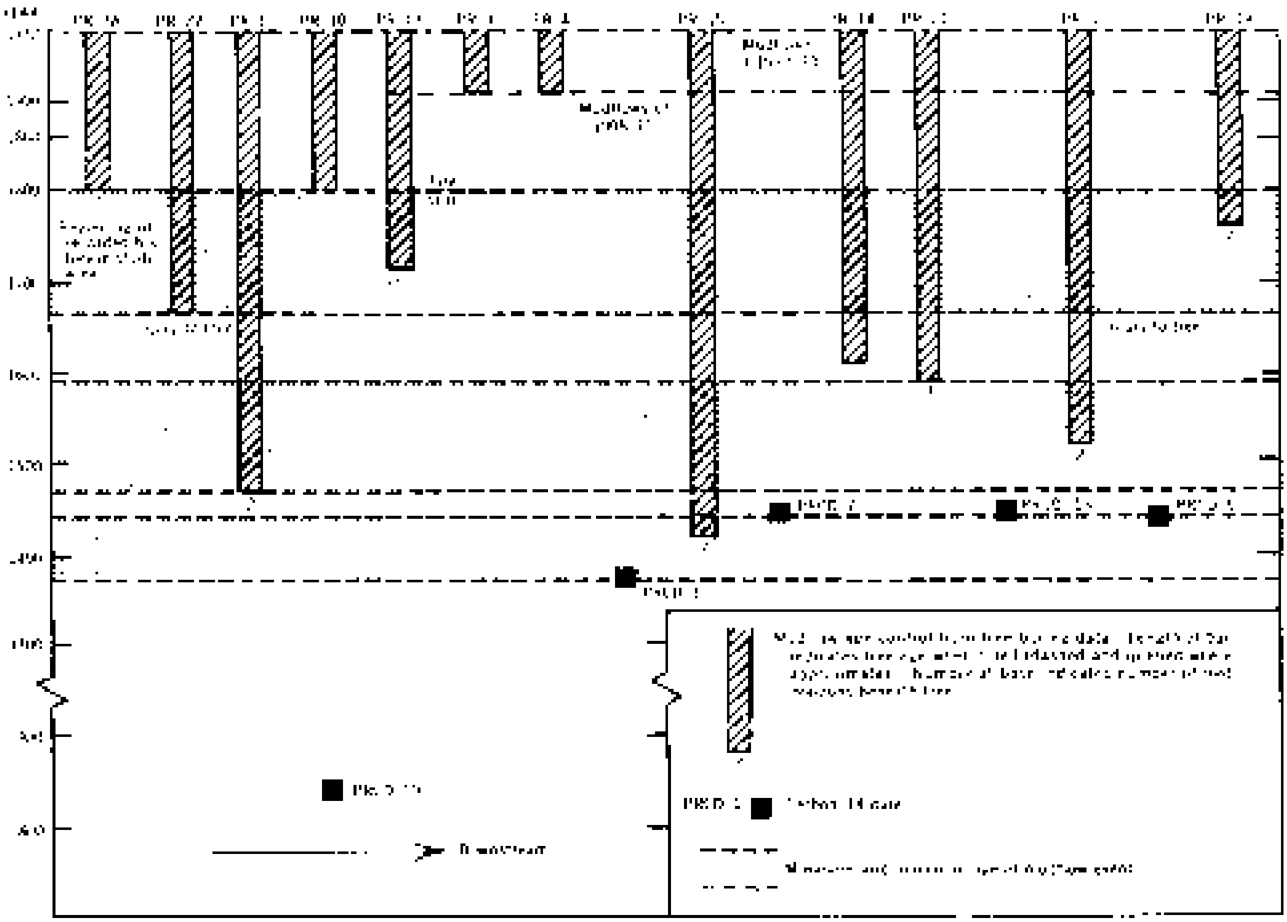


FIGURE 10. Three prehistoric periods of mudflow activity along Pfeiffer Redwood Creek as determined from geologic, botanic, and radiometric carbon-14 dating data. Prehistoric mudflow periods are shown as shaded bands bounded by broken lines. Three periods of mudflow activity during the past 600 years should be regarded as a minimum figure.

root horizon range from 1370 to 1440. The minimum age of the lowest roots of tree PR 6 is about 550 years (1425). This absolute age agrees well with the range of carbon-14 dates obtained from entrained material within the deposits.

Carbon-14 sample PRCD-5, which was sampled from the lowest root horizon below tree PR 28, yielded a corrected date of 1430. This date falls within the 1370–1440 range; however, it could not be determined if this root horizon marks the same mudflow event.

Many of the deposits in the 1370–1440 age range are relatively clay rich compared to younger deposits. Unfortunately, the clay mineralogy is the same within mudflow deposits of all ages along Pfeiffer-Redwood Creek and could not be used to distinguish between periods of mudflow activity.

The second oldest event shown in figure 10 is defined primarily by cross section E–E'. This event probably occurred sometime between the end of the 1400's and the end of the 1500's. Trees PR-14 and PR-22 assign a minimum age of about 385 years (1588) to the deposits underlying them. These deposits overlie the deposits of the 1370–1440 mudflow event. The oldest roots of tree PR-1 date within the 1500–1600 period, as does the root horizon from which sample PRCD-9 was taken. However, other than for the determined ages, direct or indirect relations between these two pieces of data and the mudflow event defined by trees PR-14 and PR-22 are not apparent.

The youngest prehistoric mudflow event or events probably occurred sometime between the mid-1600's and the late 1700's. Evidence for mudflow activity during this period is based on the minimum-maximum relation of tree PR-7A and carbon-14 sample PRCD-9, a fire scar in tree PR-13, apparent injuries to trees PR-1 and PR-22, and the minimum age relation of tree PR-10 to its underlying deposits. The tree injuries recorded by trees PR-1 and PR-22 in the middle 1600's and the fire recorded by tree PR-13 near the middle 1700's suggest the possibility of two separate mudflow events rather than one during this period.

Radiometric and dendrochronological evidence seems to indicate that no mudflow activity occurred between the early and middle 1600's and between about 1830 and 1860.

The dating and study of mudflow deposits along Pfeiffer-Redwood Creek indicate that mudflows have been periodic natural phenomena in the Big Sur area for at least the last 600 years and probably for as long as there have been heavy and intense rainfall and steep slopes mantled by chaparral vegetation in the Santa Lucia Range. Mudflow deposits in terraces along the lower course of Pfeiffer-Redwood Creek indicate that these conditions have prevailed for many thousands of years.

Redwood dendrochronology, radiocarbon stratigraphies, and radiocarbon data indicate that a minimum of three periods of mudflow activity occurred under pristine conditions along the lower course of Pfeiffer-Redwood Creek between about 1370 and 1800. This yields an approximate recurrence frequency of about once every 110 years; however, this recurrence frequency should be considered a minimum figure because other mudflows may have passed through the lower course of Pfeiffer-Redwood Creek without leaving a detectable record.

Judging by the past 115 years of recorded history of the Big Sur area, fire plays an important role in the generation of mudflows. The two recorded periods of mudflow activity in the area of the community of Big Sur (the winters 1909-10 and 1972-73) followed fires that denuded the steep drainage basins to the east. Whatever the actual past recurrence frequency of mudflow events might have been in the Big Sur area and elsewhere in the Santa Lucia Range where similar conditions prevail, it has probably been modified by Man's activities in starting or suppressing fires.

The documentation of mudflows as a characteristic erosional process in the Santa Lucia Range indicates that a hazard exists to lives and property where mudflow-deposited fans are inhabited. Mudflow-deposited fans along the lower courses of steep, chaparral-covered drainage basins similar to Pfeiffer-Redwood Creek occur over much of the Santa Lucia Range. Development in these areas courts the possibility that a catastrophe like the Big Sur mudflows of the winter 1972-73 will occur again.

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MARBLE CONE FIRE

......EFFECT ON EROSION

By

GEORGE B. CLEVELAND, Geologist
California Division of Mines and Geology

The Marble Cone fire of August 1977 is the third largest fire in California history. It consumed vegetation in a large part of the Ventana Wilderness area, destroying valuable watershed in four major drainage basins in the northernmost part of the Santa Lucia Mountains, Monterey County, California (see map; front cover; photos 1–3).

The data in this survey of erosion conditions within the Big Sur drainage basin were rapidly assembled and interpreted because of the serious hazards that may develop during this winter. The area was examined briefly on the ground, but the analysis is based mainly on air photographic interpretation of geologic features, vegetation, and geomorphology. I am indebted to the personnel of the U.S. Forest Service for valuable discussion of the erosion problems and for the loan of air photographs and unpublished maps.

PHYSICAL SETTING

The Big Sur drainage basin covers an area of about 38,000 acres, with about 30,000 acres situated in the upper basin. About 28,000 acres in the upper basin were burned over during the fire (see map).

Geology

The details of the geology and mineral resources of the area have been reported on by Pearson and others (1967). The basin is underlain mainly by strong crystalline rocks which reflect their resistance to erosion by forming steep slopes. Below the steep slopes, highly irregular drainage courses have developed.

The Sur Series, a sequence of metamorphic rocks, is the principal rock unit in the basin. A soil mantle supporting sparse to heavy vegetation has developed on these rocks. The vegetation on the upper slopes is composed mainly of hardwoods and dense chaparral. Conifers, including some redwoods, are primarily found along the drainage courses. The extensive root mat of the plant cover tends to hold the slopes in place by protecting the ground from direct impact of precipitation and reducing ground moisture through evapo-transpiration. Locally, landslides in areas underlain by the metamorphic rocks occur along the principal drainage courses where the slopes have been undercut by stream erosion.

Granitic rocks occur mainly in two large masses in the eastern part of the basin and locally elsewhere. These rocks regularly shed their weathered products and only relatively thin rocky soils cover the slopes. These rocky soils are thinly covered by vegetation.

Minor bodies of sedimentary rocks occur in the southwest part of the area. These rocks are primarily sandstones and conglomerates and are generally covered by relatively dense vegetation.

Rainfall Patterns

The Big Sur region lies in a climatic zone of high annual rainfall and short duration high-intensity rainfall. The annual rainfall over the basin averages from 50 to 60 inches, but reaches 100 inches along the coast ridge. At Cold Spring Camp (elevation 1,350 feet) during the period July 1940 to June 1941, 161 inches of rain fell — the greatest recorded in California (Pearson and others, 1967). During the winter of 1972–1973 high-intensity rainfalls caused floods, debris flows, and mudflows. At Cold Spring Camp, 0.86 of an inch of rain fell in 18 minutes (U. S. Forest Service). Within 15 minutes, 0.44 of an inch of rain was recorded at an elevation of 216 feet on the lower Big Sur River (Cleveland, 1973). A review of projected rainfall intensities over the Big Sur basin indicates a pattern of precipitation that increases steadily from the coastline up to the southwestern edge of the basin, then rises abruptly to a maximum in the northeastern part of the basin (Miller and others, 1973).

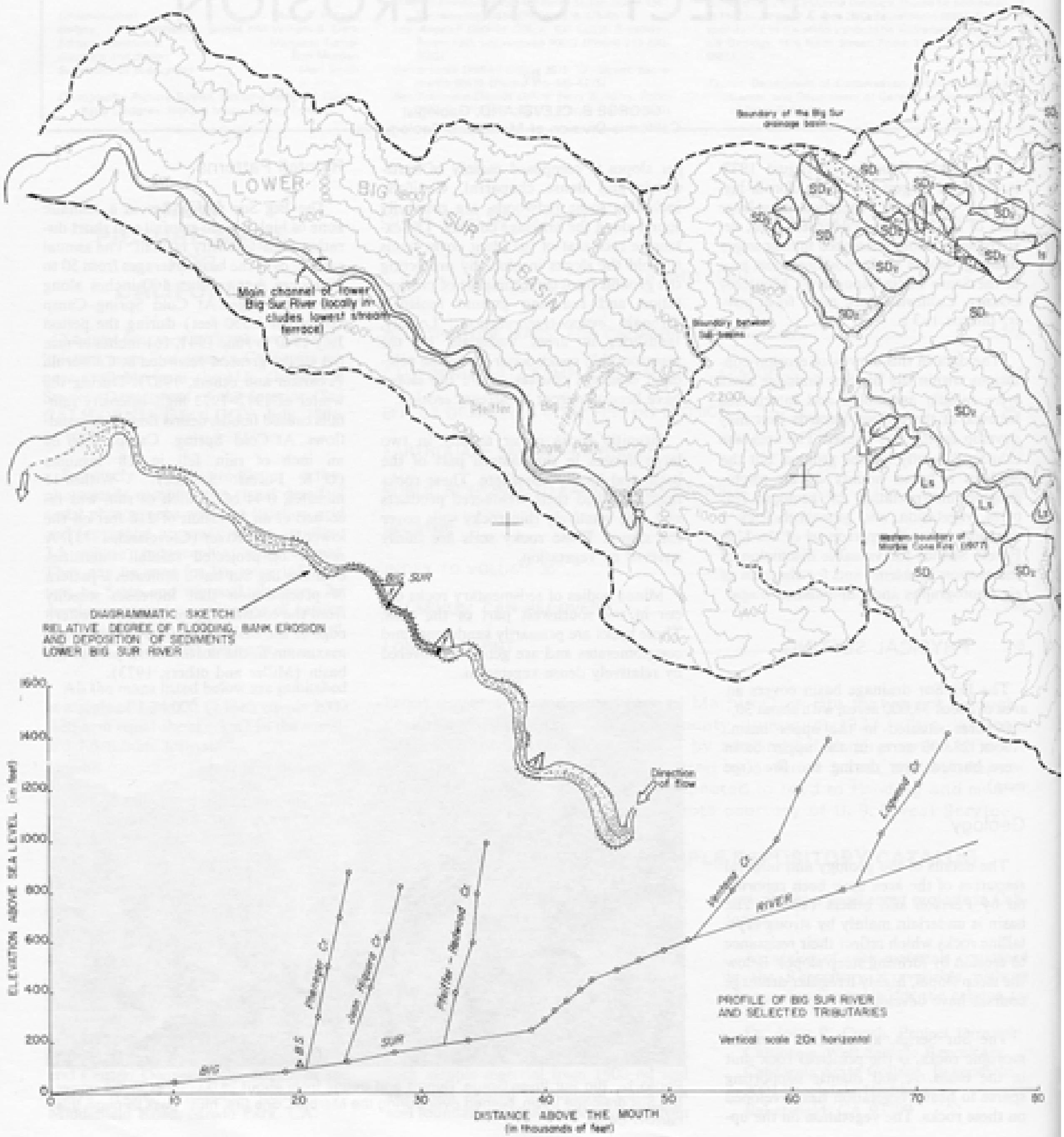
Photo 1. Big Sur River Gorge. Runoff and debris from about 28,000 acres in the upper Big Sur drainage basin, burned over during the Marble Cone fire, must pass through this narrow defile.

L E G

GEOLOGIC UNITS

SURFICIAL ROCKS

SLOPE DEPOSITS Soil and weathered bedrock	SD_1	*Relatively thick deposits, anchored and protected from erosion by vegetation cover*	LANDSLIDE DEPOSITS Bedrock slope failures	Ls	Massive rock failures *Debris at surface anchored and protected from erosion by cover of vegetation*
	SD_2	*Relatively thin deposits in areas of rapid sheet erosion on relatively steep slopes with sparse cover of vegetation*		ls	Massive rock failures *Debris deeply eroded and sparsely covered with vegetation; locally includes debris flows*



E N D

BEDROCK

CRETACEOUS and TERTIARY — Sedimentary rocks. *Mainly sandstone and conglomerate*

JURASSIC (?) and CRETACEOUS (?) — Intrusive rocks. *Mainly quartz diorite and granodiorite*

PRE-CRETACEOUS — Metamorphic rocks. *Mainly gneiss and schist of the Sur Series*

EROSION PROPENSITY FOLLOWING MARBLE CONE FIRE, BIG SUR BASIN, MONTEREY COUNTY, CALIFORNIA

G. B. CLEVELAND
August 1977

GEOLOGIC PROCESSES AND PRODUCTS[2]

UPPER BIG SUR BASIN

AREAL EROSION

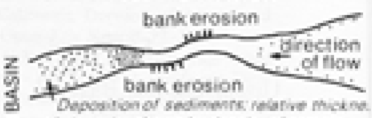
SD1 — *Areas where loss of vegetation will release significant amounts of slope debris to Big Sur River system; probably, in part, in the form of mudslides and debris flows.*

SD2, ls — *Areas where loss of vegetation will release moderate amounts of slope debris to Big Sur River system*

Ls — *Bedrock landslides where loss of vegetation will lead to accelerated erosion of near-surface materials and possible reactivation of large landslide masses due to undercutting of slopes by channel erosion*

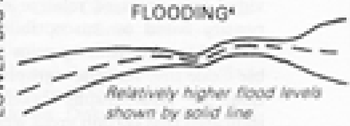
LOWER BIG SUR BASIN

CHANNEL EROSION AND SEDIMENTATION[3]



Deposition of sediments; relative thickness of deposits shown by density of pattern

FLOODING[4]



Relatively higher flood levels shown by solid line

DEBRIS BLOCKAGE OR RESTRICTION OF STREAM FLOW[5]

Partial restriction or damming of stream flow by landslide debris, fanglomerate or by channel debris (rock and vegetation) stalled and jammed by riparian vegetation

NOTES

1. Shown only in area of Marble Cone fire (1977); bedrock units shown beneath surficial units; bedrock units modified from Pearson and others (1967).
2. Effects of normal or above-normal precipitation on terrain due to loss of vegetation following Marble Cone fire; influence of fire will diminish as vegetation recovers, probably within a few years.
3. Channel erosion will be minimal where strong bedrock comprises river bank; zones of deposition shown are ephemeral, sediments subject to transportation and redeposition downstream depending on nature of runoff.
4. Flood levels determined by channel volume (cross section) – local restrictions of the channel such as crowding of the stream by alluvial fan development from tributary drainages and by stream flowing on top of previously deposited rock debris.
5. Location and number of possible dams along channel (speculative).

Photo 2. Burned over area along Logwood Creek in upper Big Sur drainage basin; view east from Coast Ridge Road.

EROSION

Upper Big Sur Basin

The upper Big Sur basin has been divided into areas of relative erosion propensity based on susceptibility to sheet erosion and landsliding prior to the Marble Cone fire. Air photographic examination, of photographs taken in 1968, indicated that certain areas were undergoing relatively more rapid erosion than other areas. These areas (SD_2 on the map) are generally in steep terrain, unprotected by an adeqaute cover of stabilizing vegetation, and are not prone to landsliding except locally where debris flows have occurred. A relatively thin layer of weathered rock and soil covers the slopes, but some stream channels below the slopes are choked with significant amounts of weathered debris. This indicates that these slopes were supplying much of the sediment load carried by the Big Sur drainage system. The cumulative extent of these areas amounts to about 40% of the upper basin and is probably the main source of the 22 acre feet of sediment produced yearly (U.S. Forest Service, 1977).

The balance of the basin (SD_1 on map) was characterized by relatively stable slope materials on gentle to steep terrain, anchored and protected from rainfall and runoff by a relatively dense cover of vegetation. Thick accumulations of soil and weathered rock debris cover these slopes. Bedrock landslides occur along the channels of the major drainages. These landslides, which were mantled with a dense and mature forest cover, appeared to be relatively stable under the prevailing conditions in 1968. Although part of the basin was burned over in 1924, most of the debris on the slopes has been accumulating since the last major fire-flood sequence in the upper basin. This sequence began with a fire in 1907 and was followed by floods in 1907–1908; 1908–1909; and 1909–1910 (Jackson, 1977). Therefore, in 60% of the basin a large new source of erodable debris is available to be transported in the Big Sur drainage system.

Coupled with this volume of debris will be a moderate increase in sediment yield originating from the areas of normally active erosion (SD_2) prior to the fire. Moreover, channel deposits have been accumulating below these slopes for more than 50 years and these materials will be an additional source of sediment.

Lower Big Sur Basin

The last 8 miles of the Big Sur River occupies a relatively wide channel and flows down a gentle gradient to the sea. It was in this subbasin that the Molera fire and destructive debris flows occurred in 1972 (Cleveland, 1973). This reach of the river represents the conduit, through which all the water and sediment from the upper basin must pass to reach the sea. Most of the manmade development in the Big Sur area also is concentrated here.

Relation of Molera Fire to Marble Cone Fire

The Molera fire of 1972 occurred in the lower Big Sur basin. The debris flows of 1972 occurred in the steep tributary drainages off the mountain front east of Big Sur. Much of the energy developed to mobilize the debris was dependent on the steep gradients of the channels. The gradients of Pheneger, Juan Higuera and Pfeiffer–Redwood Creek, where the debris flows occurred, are shown on the map drawn to the same scale as that of the Big Sur River. In the 5 years since the Molera fire much of the vegetation has recovered and future runoff rates would not approach those that were associated with the storms of 1972.

The Marble Cone fire burned through 94% of the vegetation cover in the upper Big Sur drainage basin and upset the equilibrium between established terrain features and the climate. The destruction of the greater part of the vegetation in the basin will prevent normal rainfall infiltration and reduce evapo-transpiration. This will lead to rapid runoff from an area of

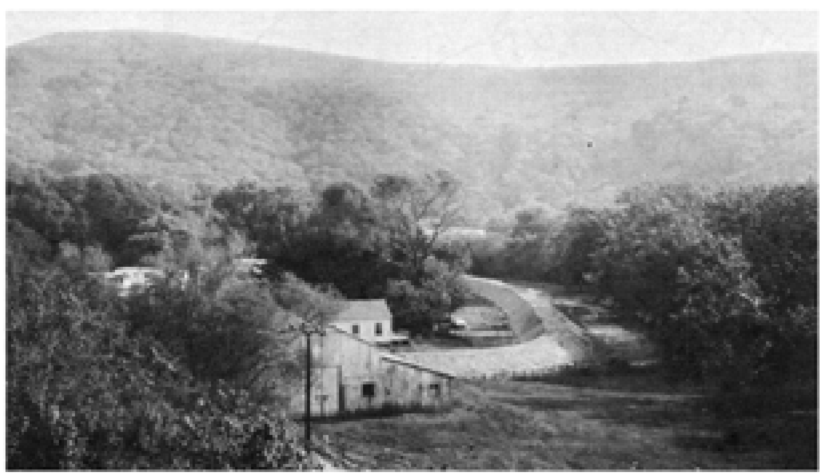


Photo 3. Dikes around structures near mouth of lower Big Sur River. Dikes were constructed to provide protection from floodwaters.

44 square miles. If the rate of rainfall approaches some of the high values already recorded, sufficient stream energy will be created to mobilize a major part of the debris in the basin. Present conditions indicate that the volume of debris will be at least several orders of magnitude greater than normal.

PROJECTED EFFECTS IN LOWER BIG SUR RIVER BASIN

Debris Flows

Although major terrain features have been significantly changed by the fire, the nature of future weather conditions will establish the degree to which these changes will affect the physical environment of the lower Big Sur basin. The total rainfall and the pattern in which it is delivered will determine the amount of stream energy available for erosion at any one time. Several sets of conditions can be postulated; among these the most likely are:

(1) Normal rainfall spread out rather evenly over the rainy season would lead to above average runoff and the deposition locally of significant amounts of mainly fine-grained sediments. Bank erosion would be minimal and flooding moderate except along the narrowest reaches of the channel. Occasional high-intensity rainfall of small total amount could probably be absorbed within the upper basin. Slope debris would be transported short distances, but only moderate amounts of debris would reach the lower basin.

(2) Above average rainfall delivered in a series of widely spaced heavy storms spread over the rainy season would lead to short term rapid runoff and the transportation of large amounts of fine to coarse sediments off the slopes and into the channels. A large part of this debris would reach the lower basin. Much of the coarse debris would accumulate at the upstream end of the lower basin. Heavy flooding and local bank erosion would be expected.

(3) A period of light but steady precipitation would infiltrate and moisten the soil. This event, followed within a few weeks by record high rainfall from a series of closely spaced storms, would lead to the mobilization of large volumes of weathered rock and vegetation debris throughout the drainage system. Some of the inactive landslides would become reactivated, contributing coarse debris and locally damming the trunk drainage courses. New bedrock landslides would locally occur due to the undercutting of the channel banks, but the main failures would be mudflows and debris flows. However, most of the rock debris would be carried off the steep slopes and into the channels by sheet flow. Unburned or partially burned stands of riparian vegetation would be undercut and transported along with weathered rock, soil and other vegetation. This material would stall locally in narrow reaches of the channels of the upper basin and at the junction of tributaries with main trunk drainages. The subsequent dams formed by the debris would eventually be overtopped or would fail and lead to surging in the flood waters downstream.

In the lower basin where the gradient of the river is relatively gentle, the floodplain would be deeply mantled with coarse debris (see diagrammatic sketch on map). As stream velocity lessens, the size of coarse sediment, floating trees, and other vegetation would form jams among the trees growing in the floodplain, restricting or damming the stream flow.

Flooding

The depth of the flood waters would be highest where the channel is normally narrow, or where it has been restricted by the building of alluvial fans across the channel out from tributary drainages (see map). These fans occur mainly at the junction of Pheneger, Juan Higuera and Pfeiffer-Redwood Creeks with the lower Big Sur River. Elsewhere, water levels will rise relatively higher where the river flows on top of sediments deposited during previous stages of the flood. Such a veneer of sediment, in effect, reduces the normal volume of the channel. During a one hour storm in El Dorado Canyon, Nevada, 12 feet of sedimentary debris was deposited and subsequent flood waters flowed on top of these sediments (Cleveland, 1973). Bank erosion would be common along the same reaches of the river as those of maximum flooding but also on the outside curve of the river where it normally makes broad bends within its channel.

FLOOD HAZARDS

Conditions in the lower Big Sur basin pose a significant threat to life and property. Rainfall runoff that has collected over a total of 46 square miles must pass through a narrow funnel — in places only a few hundred feet across. Rainfall may be moderate in the lower basin, while record runoff is collecting above. Even during periods of obvious flooding the river can be deceptive. Upstream the flow may be temporarily dammed by debris, lowering the flood levels along the lower reaches. If the debris gives way abruptly, a large volume of water may be suddenly forced through the lower channel. The channel area should not be occupied until a storm is known to have completely passed through the region and conditions in the upper basin have been evaluated.

This report was released by CDMG as Open-File Report 77-12 LA "Analysis of erosion following the Marble Cone fire, Big Sur, Monterey County, California" by George B. Cleveland, August 1977, 13 pages, 1 plate (scale 1:24,000). Arrangements for copies of the original map can be made through a bonded blue print or reproduction service; reproducible master available in Los Angeles office only.

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In August 1977, fire burned 178,000 acres in Los Padres National Forest. Photographs by the author except where indicated.

THE MARBLE-CONE FIRE TEN MONTHS LATER

by James R. Griffin

For three weeks in August 1977 I watched the Marble-Cone fire char 178,000 acres of the Los Padres National Forest in Monterey County. Although smaller than the record-setting 219,000 acre Matilija fire of 1932 in total size and rate of spread, the Marble-Cone burn set new California records in the size of control efforts. Some 6,000 people, vast fleets of equipment, and more than $13,000,000 were involved. The Marble-Cone fire also prompted record levels of public alarm over damage to vegetation, wildlife, and watersheds as well as concern over fire management problems in wilderness regions.

Why So Large?

Despite media reports to the contrary, the Los Padres National Forest was not prohibited from using mechanized equipment in suppressing the fire within the Ventana Wilderness. However, wilderness and roadless areas inherently limit quick access of fire fighters and equipment, and the steep rugged terrain and dense vegetation of the Santa Lucias limited the operation of the sixty-one bulldozers mustered for the fire. The hazardous topography and cover conditions also made it impossible for the crews to work in many places after they had hiked or been airlifted to the fire. In addition, atmospheric conditions kept the advancing fire under an unusually dense smoke screen that hampered air operations. But perhaps the major factor in the spread of this fire was the extreme accumulation of dead brush and other material to feed the fire.

Only small portions of the Marble-Cone area had been burned during the past thirty years, and the majority of the land had not been burned for over forty or fifty years. Some portions of the area had been piling up fuel for at least seventy-six years.

But the single most important factor in the abundance of fuel was a wet, sticky snowfall on January 3, 1974 which crushed the crowns of the evergreen trees and shrubs. In many areas the branches broken by this storm in one night added more fuel than had accumulated in more than thirty years of fire control. On tens of thousands of acres at least ten tons per acre of dead fuel were lying on the ground or hanging in the trees. In the worst spots fifty tons per acre of broken branches were present. Then this dead wood was dried during two seasons of drought. Thus, the stage was set for the fury that erupted when lightning set four fires in the Ventana Wilderness on August 1, 1977. One strike was on Marble Peak; another was on South Ventana Cone. After these two lightning-caused fires merged the resulting conflagration was named the "Marble-Cone" fire.

Fire Frequency in the Past

After blaming fire control for causing an "unnatural" fuel level, what can we say about "natural" fire frequency in the Santa Lucias? In this Marble-Cone area almost nothing is known about either lightning- or Indian-caused fires prior to the arrival of the Spanish in 1769. During the Spanish and Mexican eras there were many reports of fires being set by Costanoan and Salinan Indians, particularly in valley or coastal grasslands. But none of these reports specifically is related to the Marble-Cone area. The Esselen Indians, who inhabited most of the Marble-Cone area, were gone before any observations were made of their use of fire. Undoubtedly the Esselens engaged in intentional burning and also caused some accidental fires, but we don't know any details.

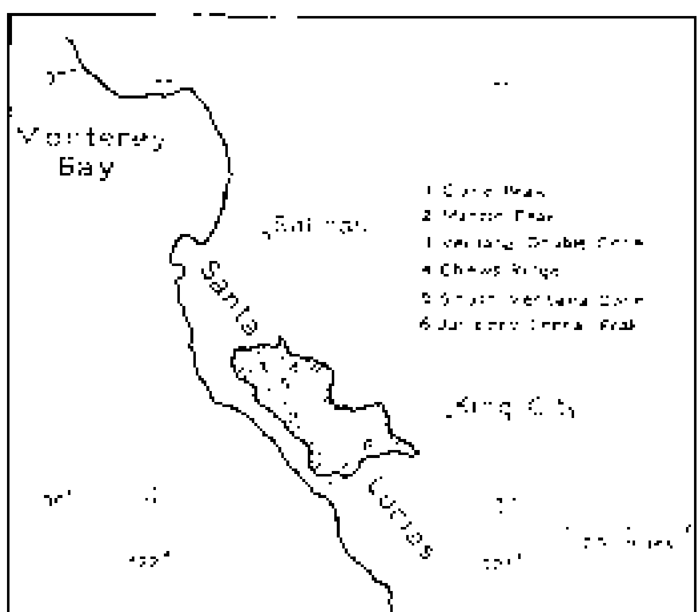
There is no question, however, about the indiscriminate burning of the forests by American prospectors, hunters, and ranchers. By the late 1800s tales of huge fires in the Santa Lucias were common in newspapers and government reports. Federal surveyors seeking lands to become "Forest Reserves" were appalled by the extent of burning and the serious damage to timber and watersheds. One report mentioned that a large region of the central Santa Lucias embracing the upper watersheds of all major streams burned for weeks in 1894. Another report told of a fire which started from an untended campfire near Chews Ridge in July 1903. During the following months the fire burned a strip over six miles wide all the way to the coast. In October 1906 newspapers reported a fire of some 150,000 acres in the Santa Lucias. All these fires burned large portions of the Marble-Cone area. After 1907, when the U.S. Forest Service started to manage the land, the frequency and extent of the fires declined.

Chaparral

Chaparral was a major vegetation type in the area of the burn. South-facing slopes and ridges, densely clothed with tall evergreen shrubs or scrubby live oaks, burned more intensely and more uniformly than other plant communities. One early and striking post-fire response in the chaparral was the unseasonal blooming of Spanish bayonet (*Yucca whipplei*). Apparently scattered plants which had not bloomed in the spring of 1977 were induced to flower by the heat. Within weeks huge panicles of ivory flowers rose above the scorched rosettes. Since the special moths required for pollination would not have been present at this odd season, I assume these flowers produced no seeds.

The scrubby interior live oaks (*Quercus wislizenii*) and canyon live oaks (*Q. chrysolepis*) were seldom completely consumed by the chaparral crown fires; they usually remained as charred trunks, perhaps five to ten feet tall, standing above the ashes. Within a month these oaks and other scrubs, such as coffee berry (*Rhamnus californica*), sprouted vigorously from the base. By the time freezing weather arrived in November many of these burnt shrubs had shoots several feet tall.

The burl-forming shrubs — chamise (*Adenostoma fasciculatum*) and Eastwood manzanita (*Arctostaphylos glandulosa* and its varieties) — often



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burned to ground level. In portions of the burn where I observed these shrubs, they were slower to sprout than the oaks. Few burls sprouted within the first three months. Perhaps drought stress delayed response, but some of the burls probably were killed. One measure of the heat produced at ground level was the melting of bottles and aluminum cans which had been present in the chaparral litter.

Knobcone pine (*Pinus attenuata*) is found in some places in the chaparral in the Santa Lucias, and about half the Monterey County range of this pine was within the burn. From an airplane I observed that knobcone pine groves had been largely destroyed in the chaparral crown fires, but it is unlikely that all the seeds in the vast store of "closed" cones would have been consumed.

Two rare Santa Lucia endemics grow in the chaparral. Almost the entire range occupied by the Arroyo Seco bush-mallow (*Malacothamnus palmeri* var. *lucianus*) and Hickman sidalcea (*Sidalcea hickmanii* subsp. *hickmanii*) was burned. Both species are on the CNPS rare and endangered list. I would expect that such plants growing in the chaparral would be well adapted to fire; in garden situations the bush-mallow spreads vigorously by runners; but there must be weak points in their reproductive potential, or they would not be so rare. About half the known sidalcea localities were on a ridge below Pinyon Peak that received massive bulldozer scraping. In this case only time will tell whether the sidalcea was extirpated from the ridge or rejuvenated in the new "open" habitat. Many disjunct or otherwise interesting herbs occurred in the chaparral regions of the burned area, mostly concentrated around Hanging Valley. It is to be hoped that most of these herbs will reappear.

The severely burned chaparral slopes suffered heavy soil erosion during the January-to-March storms in 1978. On slopes steeper than forty percent, most of the ashes, charred litter, and the upper inch or so of soil were washed off by sheet erosion by late January. A network of rills and small gullies was later cut into these steep slopes; at the top of some slopes the rills are now many inches deep and at the bottom channels were scoured several feet deep. The erosion and rapid run-off from such slopes had a disastrous effect on the riparian communities downstream. Probably the most significant habitat alterations resulting from the fire occurred in the streams.

As part of the rehabilitation effort 500 tons of annual rye grass (*Lolium multiflorum*) were aerially seeded over the burn. In areas where this grass has produced a thick cover the native herbs have severe competition. On other areas where the grass did not germinate or is sparse there are many fire-following herbs developing (*Fremontia* January 1977), but at the time of writing the herbs were not mature enough to identify readily. On limited

Within weeks after the fire *Yucca whipplei* produced out-of-season flowers.

Chamise and manzanita shrubs burned to the ground but still standing are charred trunks of oaks and one Coulter pine.

areas, particularly ridge tops, no grass or native herbs have started and only a few shrub sprouts or seedlings are present yet.

Mixed Hardwood Forests

Hardwood forests are another major vegetation type in the burned area. These forests, which are concentrated on north slopes and canyon bottoms, were damaged in various patterns. Some stands had severe crown fires, many had a ground fire which scorched the crowns, and some had a light ground fire that did little damage.

At lower elevations coast live oaks (*Quercus agrifolia*) and madrones (*Arbutus menziesii*) dominate the mixture. At higher elevations canyon live oak (*Q. chrysolepis*) is the most widespread tree, but tan-oak (*Lithocarpus densiflorus*) and interior live oak (*Q. wislizenii*) are locally abundant. All these trees sprout readily from the base when the crown is destroyed, but vulnerability of their crowns to fire varies widely. Canyon live oak has a sensitive crown. The thin dry bark is flammable and seems to invite self-destruction. Under some conditions canyon live oak crowns may carry a crown fire when there is not enough litter on the ground to burn. In contrast coast live oak has thick, wet bark which is extremely fire retardant. Hopeless-looking charred branches can produce new crowns.

Some very small areas in the Marble-Cone region seem to have been free of damaging fire for many centuries. The oaks and madrones in such spots are massive, their trunks often well over sixty inches in diameter. In some cases the Marble-Cone fire was too much for these veterans, but in the bottom of Miller Canyon the largest canyon live oak that I know of in the Santa Lucias (ninety inches in diameter) survived without damage. Such trees are not large because the habitat is especially favorable for tree growth; they are large because fuel and topographic conditions preclude all but minor ground fires.

These unburned areas pose an interesting question. Are forests of large single-stemmed trees which started from seeds more "natural" than forests of smaller multiple-stemmed trees from sprouts? Both conditions exist in the Santa Lucias, but fires such as the Marble-Cone burn certainly reduce the proportion of large single-stemmed trees. Several such fires would convert virtually all the hardwood forests into thickets of multiple-stemmed sprout clumps. Whether light fires occur infrequently or severe fires occur more often these hardwoods will survive. The form of the stand will change, but the species will remain on the site in either case.

In the Santa Lucias Coulter pines (*Pinus coulteri*) are widely scattered within the mixed hardwood forest, but they seldom form extensive pure stands.

Two months after fire new sprouts surround the charred trunk of interior live oak, *Quercus wizlizenii*.

The Coulter pine thicket which started after the 1928 fire on Chews Ridge was killed by crown fire.

Old-growth Coulter pines which survived the 1928 fire on Chews Ridge were destroyed in 1977.

The Santa Lucia firs (*Abies bracteata*) grow, as here on Cone Peak, on steep and rocky slopes. Photograph by Wayne Roderick.

Where fire or other disturbance opens the hardwood canopy, seedlings of Coulter pines may come up abundantly in the openings. Ultimately the base-sprouting hardwoods will recover dominance, and the pines will survive only where there are gaps in the canopy.

After the 1928 fire on Chews Ridge many of the large Coulter pines, which germinated in the 1890s, survived and produced abundant seedlings. By 1977 these seedlings had become thickets of trees over fifty feet tall with an alarming amount of litter on the ground. Many of these pine thickets carried crown fires that left no adult trees to produce seeds. Elsewhere in the burned area surviving Coulter pines should produce seedlings within a few years, but areas such as the crowned groves on Chews Ridge will have only hardwood sprouts in the near future.

Santa Lucia Fir

Another conifer associated with the hardwood forest, particularly in the canyon live oak community, is the Santa Lucia fir (*Abies bracteata*). Almost every fir grove north of the Cone Peak region — more than two-thirds of the total distribution of this endemic — was within the burn. However, the bulk of the fir colonies grow on steep rocky terrain, and they were not seriously burned. The largest Santa Lucia fir (fifty-one inches in trunk diameter) survived the fire with no damage. This fir is in the bottom of Miller Canyon not far from the huge canyon live oak mentioned above. These firs survive not because of fire resistance; the species is rather sensitive to heat damage. They survive because they can grow on steep barren slopes that will not support strong fires.

Ground fires did burn into many of the fir colonies, and some trees on the fringes of the groves were killed. But the majority of the trees in the groves I have seen still have healthy looking crowns. Perhaps some latent heat damage will show up when the trees come under moisture stress this summer, but I suspect that insect damage may finally kill more firs than the fire. Two fir groves within the large 1970 Buckeye fire that were studied by Dr. Steven Talley displayed this pattern. Both groves lost only a small number of trees as a direct effect of the fire but seemed to have more mortality from insect damage. My general impression of the Marble-Cone burn area is that some firs were killed, some additional trees will die, but the species and even individual stands are in no way doomed. The firs had a heavy cone crop in 1977, and if the seeds are viable (they are often damaged by insects), there might be a good crop of seedlings to replace the tree losses.

One CNPS rare and endangered species, Muir's raillardella (*Raillardella muirii*), which is disjunct from the southern Sierra Nevada, has a tiny out-

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post in the fir region on the summit of Ventana Double Cone. Several other interesting montane disjuncts which are common on rock outcrops at Cone Peak are scattered on the rocks at Ventana Double Cone. The fire burned slowly over this ridge without any complications by bulldozers or suppression efforts, and these plants were probably not seriously damaged.

Mixed Conifer Forest

Several conifers which grow in the Sierra Nevada montane forest also grow in the Santa Lucias: ponderosa pine (*Pinus ponderosa*), sugar pine (*P. lambertiana*), and incense-cedar (*Calocedrus decurrens*). These conifers are not closely associated with each other; the sugar pine and ponderosa pine ranges usually do not meet. In all stands the old pines have vigorous hardwood understories. At least a dozen Sierran shrubs and herbs — including Sierra gooseberry (*Ribes roezlii*), creambush (*Holodiscus microphyllus*), pipsissiwa (*Chimaphila menziesii*), and a sedge (*Carex multicaulis*) — grow in the Santa Lucia forests but are not found elsewhere in the south Coast Ranges.

The best old-growth ponderosa pine forests in the Santa Lucias (Big Pines, Little Pines, Pine Valley, Pine Ridge) all burned in varying degrees. The stand that I have looked at most carefully is on the summit of Pine Ridge. This area last burned in August 1916 when lightning fires spread over several thousand acres there. By 1977 the fuel load on Pine Ridge was excessive, and the flames from the nearby South Ventana Cone lightning strike destroyed much of the cover on the southern portion of the summit. In this case the fuel hazard was strictly a function of the long period between fires; there was no snow breakage at this elevation.

The heat forced most of the 1977 ponderosa pine cones to open, but these seeds were not fully mature by August. Seeds exposed on the ashes, ripe or not, were quickly eaten by the surviving blue jays and chipmunks. Some mature ponderosa pines survive on the summit, but the seed supply will be limited in the next few years — the period when sprouts from the hardwood forest and chaparral species fill in the area. The extent of pine forest on the summit has probably been reduced.

The Marble-Cone fire burned only one minor outpost of the Cone Peak sugar pine population, but the entire Junipero Serra Peak sugar pine region was within the burn. Only isolated sugar pines on rock bluffs escaped unharmed. On the summit and adjacent slopes the damage was locally heavy. Both sugar pine and Coulter pine trees of seed-producing size remain on the summit, and it will be interesting to see which pine regenerates better.

A steep slope photographed in March shows surface erosion and many gullies over a foot deep.

A small drainage channel has been scoured to a depth of five feet, exposing oak and madrone roots.

Dr. Steven Talley recently studied fire scars on sugar pines on Junipero Serra Peak, and he con-

An eroded slope has been seeded with rye grass dense enough to compete with native seedlings.

cluded that at least six fires had burned the summit forest between 1790 and 1901. Those fires had scarred some of the sugar pine trunks but had not killed mature trees. Last year's fire after a seventy-six year lapse killed many sugar pine veterans which had been on the peak long before the Spanish came.

Incense-cedar also occurs on Junipero Serra Peak in the deeper canyons, growing there because these canyons provide cooler, moister habitats, but also because the canyon bottoms do not burn as intensely as the ridges, and this partial fire protection helps preserve the Sierran conifers. Viewed from the air the topographic pattern of fire damage in the forest is striking, with the least-damaged sugar pine stands and the only incense-cedar stands in deep canyons. Undoubtedly incense-cedars were more widespread here in the past. A few more fires of this intensity will not only restrict incense-cedars to smaller portions of the canyons but might eliminate them from the peak.

Two CNPS rare and endangered species, Santa Lucia bedstraw, (*Galium clementis*) and Santa Lucia lupine, (*Lupinus cervinus*) are scattered on Junipero Serra Peak. The bedstraw tended to be in rocky spots within the forest that did not burn heavily. The lupine grew in openings in the forest that did have significant ground fires. Both should survive although perhaps reduced in numbers. The most attractive and restricted flower on the peak is the montane disjunct *Cycladenia humilis* var. *venusta*. Its one small stand on Junipero Serra Peak is near the lookout tower on the summit. Part of this area was badly scraped by bulldozers; part had a moderate ground fire; part between bulldozer trails did not burn. The other Santa Lucia population of the cycladenia near Cone Peak was unaffected by the fire.

Redwood Forest

Coast redwoods (*Sequoia sempervirens*) are reputedly among the most fire resistant conifers, and some redwood groves along the Big Sur River canyons received a severe test. Within a month many of these charred redwoods were sprouting from the base, and some were sprouting all along the trunk. Probably the recovery of the redwoods which had their crowns destroyed in the Marble-Cone fire will follow the same pattern as those burned in the 1970 Buckeye fire, which was further south in the Santa Lucias. Thickets of basal sprouts ten feet or more in height are common now in the redwood groves of the Buckeye fire area. The trees which had trunk sprouts there now look like giant bottle brushes with dead branches poking through the tall column of green sprouts. A few redwood groves at higher elevations in the Big Sur drainage may have been killed outright. At least they showed no sign of sprouting when last viewed before the winter storms closed the area to any prudent observer.

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SEQUENTIAL CHANGES IN BED HABITAT CONDITIONS IN THE UPPER CARMEL RIVER FOLLOWING THE MARBLE-CONE FIRE OF AUGUST, 1977[1]

Barry Hecht[2]

Abstract.--Runoff following a major fire filled the upper Carmel River with sediment. Repeated measurements of four habitat descriptors were made in riffles during the three years after the fire. Habitat values were largely restored by the end of the first winter, with virtually complete recovery after three years.

INTRODUCTION

The importance of episodic or unusual events in the management of riparian systems in montane areas is increasingly being recognized. Wildfires are one of the major recurring disturbances affecting biologic and geomorphic processes in these watersheds. This is especially true in basins with significant areas of steep, chaparral-covered slopes.

Many resource managers consider the canyon bottoms--the channels, riparian zones, and valley flats--as the most biologically-significant zones in these watersheds. The bottomlands commonly remain unburned during fires which otherwise affect much of the drainage area. The primary physical changes in these corridors are frequently those associated with erosion, deposition, and channel instabilities induced by post-fire storm runoff. While numerous studies of fire-related increases in runoff and debris load have been made, relatively little is known of their effects on habitat values.

This report is a preliminary summary of an ongoing study addressing one aspect of the larger management problem--the indirect effects of fires on bed conditions affecting aquatic habitat values. The upper Carmel watershed in Los Padres National Forest, Monterey County, California was chosen for this study for three reasons. First, the drainage is used primarily for recreational, habitat, and watershed purposes; the alluvial corridor is central to all three uses. Second, direct human disruption of soil and vegetation in the basin is minimal, limited primarily to ridgetops far removed from the channels. Third, the watershed is in the size range of the smaller basins capable of sustaining an anadromous fishery, which in the central coastal area of California is commonly considered to be from about 10 to 100 km.^{2} (4 to 40 mi.^{2}).

There were two significant limitations on this study imposed by choice of the upper Carmel watershed. First, there are no stream gages in the basin. Synthesis of a flow-record for each site will be required to establish the relationship of the observed sequential changes to runoff. Data needed to develop the synthetic flow-record are presently not fully available. Secondly, access to the sites required a hike of about 8 km. (5 mi.) over damaged trails with backpacks and survey gear, limiting both the equipment which could be used and the number of sites which could be monitored during a given weekend.

REGIONAL SETTING

The Carmel River drains the northern slopes of the Santa Lucia Mountains. The upper portion of the basin is a rugged area of approximately 161 km.^{2} (62 mi.^{2}) above Los Padres Dam, a municipal water-supply source for the Monterey Peninsula urban area about 50 km. (30 mi.) to the north.

The watershed is underlain by faulted crystalline rocks, primarily schists, gneisses, and metasomatic granitic rocks ranging in composition from granodiorite to gabbro (Wiebe 1970). Weathering of these rocks produces a large amount of medium-grained sand, and a disproportionately small percentage of fine gravel. The courses of the main channels are structurally-controlled, primarily by faults and fractures. The channels are unusually steep for watersheds of comparable size in the region.

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[1]Paper presented at the California Riparian Systems Conference. [University of California, Davis, September 17-19, 1981].

[2]Barry Hecht is Senior Hydrologist, HEA, a Division of J.H. Kleinfelder and Associates, Berkeley, California.

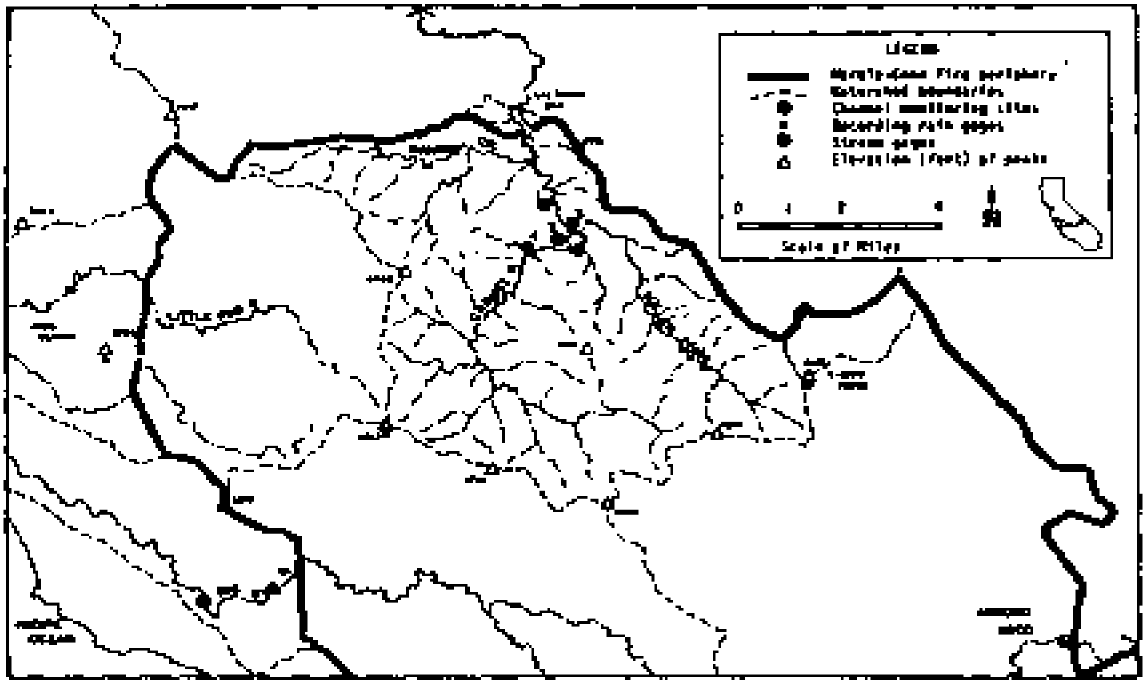

Figure 1.—Upper Carmel watershed and vicinity. Monitoring sites on the Carmel River are at Bluff Camp (1), Carmel Camp (2), below Bruce Fork (3), at Sulphur Springs Camp (4) and on Miller Fork above its mouth (5).

Rainfall ranges from an average of 610 mm. (24 in.) per year at Los Padres Dam to an estimated 1150 to 1270 mm. (45 to 50 in.) at the drainage divide with the Big Sur watershed. This supports a vegetative mosaic with chamise/chaparral on steeper exposed slopes, an oak/madrone woodland community on more protected slopes and terraces, and a mixed hardwood/coniferous forest at the highest elevations.

The Marble-Cone Fire

The Marble-Cone Fire burned approximately 72000 ha. (178000 ac.) in the Santa Lucia Mountains during August, 1977. Virtually all of the Carmel watershed above Los Padres Reservoir was affected by the fire. The USDA Forest Service staff[1] estimated remaining canopy cover to be less than 10% in 62% of the upper Carmel basin, 11-50% over an additional 20% of the watershed, and more than 51% over the remaining 18% of the area. No extensive fires had occurred in the watershed during the previous 50 years. Much of the basin had remained unburned for 74 years or more (Griffin 1978).

Two unusual occurrences contributed to the severity of the burn, and particularly to its impact on the canyon floor areas. Fuel levels were abnormally high due to an extreme amount of limb breakage sustained during a wet and sticky snowfall on January 3, 1974. The effect on fuel loadings was especially large in the riparian zone, on the terraces, and lower slopes, areas seldom affected by snowfall. Secondly, conditions were also unusually dry following the severe drought of 1976 and 1977. Rainfall at Big Sur, the nearest long-term station, during each of these years was less than that measured for any of the previous 38 years.

Post-Fire Runoff

Rainfall during the 1977-78 and 1979-80 winter seasons was 40-50% above normal at many stations in the region; rainfall during 1978-79 was generally slightly below average. Reflecting both the above-average rainfall and the altered runoff characteristics, runoff in the Carmel and nearby watersheds was markedly above normal during this 3-year period (table 1). The duration of high flows was also much above normal. One measure of this duration is the number of days that flow exceeded bankfull conditions. In the Monterey Bay area (as in many other regions), this corresponds roughly to the flood with a recurrence of 1.5 years. The Big Sur River is the nearest gaged

[1]USDA Forest Service. Undated. Marble-Cone Fire: Remaining vegetative cover. Unpublished staff report. Los Padres National Forest.

stream, and is considered most representative of the upper Carmel River. The 1.5-year flood discharge on the Big Sur River is approximately 1600 cubic feet per second (cfs). Based on preliminary records, this discharge was exceeded for a total of about 10 days in 1978 and about 6 days in 1980, compared with an annual average of 1.1 days for the period prior to the fire.

More specific data are available on the effects of the fire on sediment yields of the upper Carmel watershed (table 2). Deposition in Los Padres Reservoir during the 3 years following the fire was about equal to that occurring during the previous 30 years. In addition, a large but undetermined amount of debris has accumulated in the channels of the Carmel River and Danish Creek above the spillway elevation[4].

Table 1.--Post-fire runoff at gages in vicinity of the upper Carmel watershed.

USGS gage no.		11143000	11143200	11151870
Stream		Big Sur R.	Carmel R.	Arroyo Seco
Location		Big Sur	Robles del Rio	nr. Greenfield
Period of record		1950–pres.	1957–pres.	1962–pres.
Drainage area (sq. mi.)		46.5	193	113
Mean annual runoff (cfs)		89.4	71.3	121
Runoff				
1978	(cfs)	344	306	378
	(% of mean[1])	375	385	312
1979	(cfs)	43.6	43.5	163
	(% of mean[1])	109	49	135
1980	(cfs)	305	183	295
	(% of mean[1])	333	259	243

[1]Mean annual runoff through Sept. 30, 1977, excluding period of post-fire runoff.

SEQUENTIAL CHANGES IN BED HABITAT CONDITIONS

Habitat in the streams of the upper Carmel system is generally evaluated by its suitability for salmonid production. The local resource includes both steelhead and resident trout. Availabilities of suitable spawning and rearing habitats are considered factors limiting both populations, a common situation in streams of central California.

In riffles of boulder-bedded streams such as the upper Carmel River, both spawning and rearing occur in spaces or openings between the larger bed-forming rocks. Spawning occurs in bars and accumulations of gravels which form between the boulders or in their lees, locations partially protected from scour.

[4]Lloyd, R.H. Letter of March 18, 1981 to Robert F. Blecker, hydrologist for Los Padres National Forest, which summarizes U. S. Geological Survey studies of post-fire sedimentation in Los Padres Reservoir.

Table 2.—Sequential sediment accumulation in Los Padres Reservoir[1].

Survey date	Reservoir capacity[2] (acre feet)	Loss in capacity (acre ft.)	Annual rate of capacity loss (acre ft.)
Nov 1947[3]	3200	–	–
Nov 1977	2592.7	607.3	20.2
Sep 1978	2037.6	555	555
Oct 1980	1996.3	41.3	20.6

[1]Source: R. H. Lloyd[4]

[2]Below spillway elevation of 317.3 m. (1040.8 ft.) above mean sea level.

[3]From pre-construction capacity curves developed by California Water and Telephone Company.

The epicycle of massive fill and scour following fires in this environment temporarily buries most of the limited habitat with finer material, largely sand. For this reconnaissance study, descriptors chosen to define the extent of burial and subsequent uncovering of habitat include:

1. net fill and scour, as measured by level-surveys following each major group of storms;
2. particle-size distribution of the bed surface, measured by censusing particles at the intersections of a grid;
3. percentage of bed area occupied by sand and finer material, also sampled on a grid; and
4. percent of the bed covered by material of sizes suitable for spawning, determined as above.

Net Fill and Scour

Minimal spawning or rearing habitat was available in the upper Carmel channels during the period of maximum fill. Habitat availability increased as the stored sediment was gradually scoured. A useful measure of these sequential changes is net mean fill or scour, determined from the change in mean bed elevation of the channel during each storm period. This change was quantified using repeated level-surveys of monumented cross-sections.

The sequence of fill and scour was recorded at 6 cross-sections in 3 riffles. The riffles were chosen shortly after the fire on the basis of observable habitat values for both spawning and rearing, their general alluvial character, absence of major unusual hydraulic properties, and presence in a long and straight reach. The last three criteria were necessary to meet the hydraulic requirement of the indirect discharge measurements used to determine the peak flows during each storm period. The sections were established in early November, 1977, following the fire but prior to

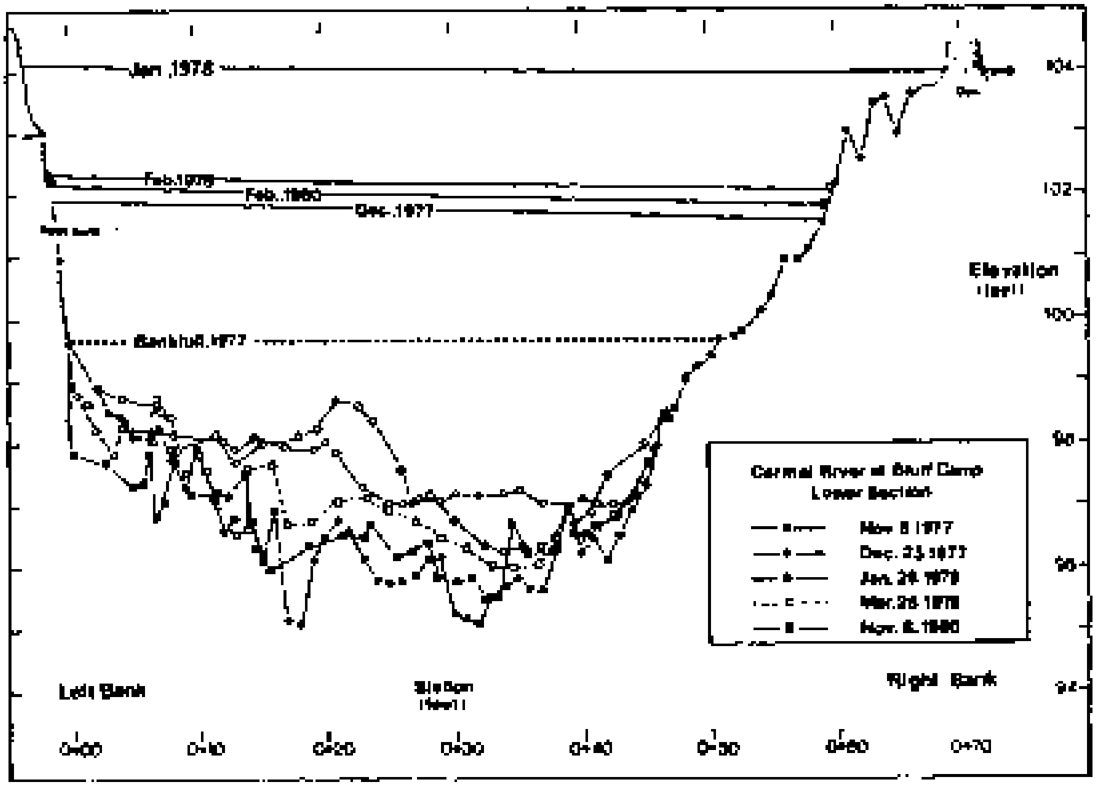

Figure 2.-- Bed configuration and high-water marks during the fill and scour cycle following the Marble-Cone fire. View downstream. Some high-water profiles slope toward the right bank, discussed below in the text.

any measurable runoff. Cross-sections were resurveyed after each significant flood event during the winter of 1977-78, and again following the wet season of 1979-80. An example of data collected at one section to describe the sequential changes in elevation and configuration of the bed is presented in figure 2.

The fill and scour cycle observed at each riffle is summarized in table 3. Fill occurred immediately after the first storms in December, 1977, and continued at some sections through the major storm period in January, 1978. By the end of the first winter, the bed was being scoured at all six sections, a process which continued through the second and third rainy seasons. The final column in the table traces the proportion of maximum net fill removed during each period.[1] By the end of the first season, 57-102% of the maximum observed net fill had been scoured. "Recovery percentages" of 80-151% were recorded by the end of the third year. At four of the six sections, 80-90% of the maximum observed fill had been removed by the end of the third year. Mean scour exceeding the mean maximum fill was limited to the riffle at Carmel Camp, where about half of the mean scour is attributable to lateral erosion of the lower bank area on one side of the channel.

[1]Maximum fills may have been greater during one of the storm periods. Ephemeral bed conditions during storm events may not have great importance in defining spawning or rearing habitat value; thus the methodology is appropriate for the purposes of this study. The reader is cautioned that recovery percentages in table 3 may under-estimate the removal of within-storm fill maxima.

Size Distribution of Bed Material

The particle-size distribution of bed material is commonly quantified in the course of habitat assessments, either by a visual estimate or by a grid-by-number census. The latter approach was used in this study.

Particle-size distributions of bed-surface material were determined by measurement made at the same five riffles in the early fall months of each year, prior to the onset of rains. This is the season in which rearing habitat is most likely to be constrained by sediment. An area-stratified random sample of the entire riffle bed was drawn by stretching cloth measuring tapes between rows of 5 to 10 iron pins at the top and base of each riffle. Lengths of intermediate axes of particles immediately beneath pre-selected points on the tapes were measured and grouped in standard size-classes. This procedure is an adaption for use in boulder-bed channels of Wolman's (1954) non-standard methodology. A sample of 50 to 100 rocks is generally considered sufficient to describe bed-surface populations; larger samples were drawn following the 1978 storms as a wider range of size-classes was observed.

Sequential changes in the size distribution of bed material are shown in table 4. Sizes at the key descriptive percentiles generally decreased following the fire, then subsequently have

Table 3.—Sequential changes in net fill and scour.

		Mean Bed Elevation (ft.)	Net fill(+) or Scour(-) (ft.)	Percent[1] Recovery
Carmel River at [illegible]				
Lower Section	11/25/77	96.83	–	–
	12/31/77	94.73[2]	+0.90	–
	01/23/78	93.83	-2.11	0
	03/24/78	93.45	-0.38	17
	11/20/80	94.93	-0.52	89
Upper Section	11/24/77	99.86[2]	–	–
	12/31/77	100.48	+1.01	0
	01/24/78	98.86	-0.80	39
	03/24/78	98.64	-0.21	80
	11/20/80	98.64	0.00	86
Carmel River at Carmel Camp				
Lower Section	11/26/77	93.82	–	–
	12/28/77	94.23[2]	+0.41	0
	01/24/78	94.00	-0.23	56
	03/24/78	93.86	-0.39	103
	11/09/80	93.62	-0.20	131
Upper Section	11/26/77	95.24	–	–
	12/28/77	95.48[2]	+0.24	0
	01/24/78	95.40	-0.08	33
	03/24/78	95.30	-0.10	35
	11/09/80	95.15	-0.15	110
Miller Fork above Carmel R.				
Lower Section	12/04/77	95.50	–	–
	12/24/77	95.56[2]	+0.06	0
	01/24/78	95.56[2]	0.00	0
	03/24/78	95.52	-0.04	67
	11/09/80	95.51	-0.01	83
Upper Section	12/04/77	94.18	–	–
	12/26/77	94.39	+0.21	–
	01/24/78	94.53[2]	+0.14	0
	03/24/78	94.23	-0.36	14
	11/09/80	94.22	-0.01	86

[1] Defined as whole channel change in mean bed elevation (MBE) by the relation 100[(MBE_a−MBE_c)/(MBE_b−MBE_c)], with subscripts a, b, and c identifying maximum net fill, measured, and original post-fire elevations, respectively.
[2] [illegible]

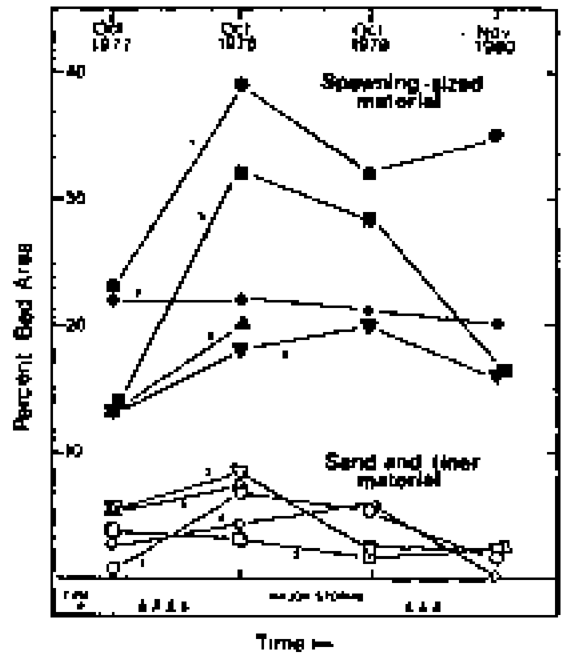

Figure 3.—Sequential changes in bed area occupied by spawning-sized material and sand-and-finer debris following the Marble-Cone fire. Run-off events substantially exceeding bankfull discharge are considered major storms. Sites are numbered as on figure 1 and table 4.

increased. Relative changes are more pronounced at the 16th and 50th percentiles than in the larger material, as might be expected.

Much and probably most, of the change in particle-size distribution occurred during the first year following the fire. It was not feasible to re-measure the bed between storms in the unusually high flows of the winter of 1978. In most cases, the minimum sizes probably were associated with the December, 1977 or January, 1978 storm periods. Had no more storms occurred during the winter of 1978, a much greater effect on habitat conditions would have been observed during the summer and fall of 1978.

Sand-Covered Bed Areas

Aquatic biologists have often identified percent bed area covered by sand (or finer material) as a significant influence on the distribution of species in the channel, and as a factor affecting salmonid egg viability. The distribution of sand and finer material on the bed of mountain stream riffles appears to be controlled by different geomorphic processes than those governing the coarser sizes. In this study, sand is considered as a separate population, but whose variability is also best described by the percentage of the riffle bed

Table 4.--Sequential changes in particle-size distribution of bed material, upper Carmel Watershed

Site no.		1				2				3				4				5	
Stream		Carmel River				Carmel River				Carmel River				Carmel River				Miller Fork	
Location		at Bluff Camp				at Carmel Camp				below Bruce Fork				at Sulphur Springs Camp				above mouth	
Month/year		10/77	10/78	10/79	11/80	10/77	10/78	10/79	11/80	10/77	10/78	10/79	11/80	10/77	10/78	10/79	11/80	10/77	10/78
Lower limit of size class																			
Boulders	2048 mm	1	1	1	1														
	1450	1	2	1	5		7		1	1	1	1	5						1
	1024	3	7	1	8	4	5	1	1	3	8	1	3		2		2	2	1
	725	8	2	13	9	10	4	2	5	6	5	2	8	4	5	1	5	8	8
	512	6	5	17	9	19	17	18	15	8	9	12	11	1	14	15	8	6	7
	360	1	9	14	17	39	13	13	13	6	7	56	17	8	15	33	17	3	3
	256	63	7	12	36	36	16	16	37	8	15	35	48	35	19	58	11	16	7
Cobbles	180	1	7	24	9	9	13	15	36	7	17	57	36	3	16	35	30	12	17
	128	6	10	18	8	3	7	19	37	6	9	53	36	50	34	56	15	17	9
	90	5	9	18	11	1	1	13	14	5	3	56	11	7	17	35	19	9	7
	64	1	7	43	27	2	4	13	9	3	9	3	7	5	30	4	12	3	8
Pebbles	45	3	7	13	15	7	5	3	3	-	9	3	4	-	7	8	7	3	4
	32	3	6	15	8	1	5	7	7	1	5	8	3	1	3	9	4	2	3
	22.6	1	8	4	7	1	3	3	7	-	3	4	1	1	3	1	1	-	5
	16	3	4	3	5	2	1	3	3	1	3	2	3	8	1	3	1	7	1
[illegible]	11.3	4	1	3	7	1	-	3	7	7	8	3	1	1	1	1	-	8	3
	8	3	1	5	1	1	-	3	1	1	1	-	1	1	-	3	-	2	-
	5.6	1	3	1	-	1	1	8	1	-	-	1	-	1	1	1	1	-	1
	4	1	7	3	-	-	-	-	-	-	1	-	-	-	1	-	-	8	1
	<4 mm.[1]	1	4	9	3	5	9	3	3	2	3	3	3	3	5	7	0	5	6
Totals[2]		99+1	88+6	107+9	130+7	81+5	94+9	135+5	131+3	94+2	88+6	112+7	118+3	60+3	118+5	158+7	115+0	82+5	88+4
Percentile size (mm.)[3]																			
d_{84}		310	476	404	763	351	476	511	510	584	462	490	658	599	503	588	482	541	587
d_{50}		213	218	156	184	295	296	225	264	306	188	281	297	315	306	356	317	252	314
d_{16}		99	27	40	65	151	44	74	88	47	48	65	91	97	89	54	86	98	60
Fines abundance[4] (% bed area)		1.4	4.6	5.1	1.5	5.8	8.4	3.4	8.6	3.8	3.0	1.8	7.3	4.8	4.1	5.8	6.0	2.7	4.3
Spawning material abundance[5] (% bed area)		21	19	52	35	21	18	30	56	34	17	78	28	74	27	73	30	13	22

[1] 4 mm. is considered the lower limit for size class discrimination under field conditions. Division between sand and gravel usually given at 2 mm.

[2] Expressed as total rocks + total sand and finer material (<4 mm.).

[3] Size, in millimeters, of material, coarser than 84, 50, and 16 percent of the sample.

[4] Percentage of bed area covered by material finer than 4 mm.; in the upper Carmel basin, this is mainly medium sand.

[5] Percentage of bed area occupied by material of 4 - 90 mm. (see text).

[6] Bed-surface distribution clearly altered by large limb from diseased oak which fell into channel during 1979. Monitoring discontinued.

which it covers. In this study, the sand-and-finer percentage of the bed surface was determined in the course of the particle-size measurements. Intermediate axial lengths of particles smaller than 4 mm. could not be readily measured under field conditions; these were grouped in a single class informally labelled as "fines."[4]

Sequential changes in the sand-covered proportion of the bed are shown in figure 3. The fines abundance increased markedly with the first storms after the fire. At the Bluff Camp riffle, the percentage of bed area covered by sand or finer debris on December 25, 1977, was visually estimated to be 40% in the riffle and 95% in the pool beneath it. By the end of the first year, the fines abundance at the five sites averaged only very slightly greater than at the time of the fire. As with the particle-size changes, the sequential variations in fines abundance were greatly accelerated by the unusually high runoff conditions of the 1978 water year.

[4]Most standard classifications divide sands and gravels at 2 mm. In the upper Carmel environment, deficient in very fine gravels, any interpretive difficulty introduced by including 2-4 mm. material with the sands is minor.

Availability of Spawning-Sized Material

Salmonid spawning habitat in the upper Carmel watershed may be limited by the availability of material of suitable sizes in riffles. The relative abundance of this material can be quantified for the Carmel channels as the percentage of the bed surface occupied by rocks within the range of suitable sizes, as no appreciable armoring of the bed was observed. For this study, it is assumed that the range of 4-90 mm. defines the bulk of material found in and above freshly-constructed redds in streams of comparable size, slope, and underlying rock types (e.g., Orcutt et al. 1968, Platts et al. 1979).[7]

The availability of spawning-sized material increased markedly at 4 of the 5 riffles in the first year after the fire. The percentage of the bed occupied by this size-range has remained slightly elevated, although depletion has probably occurred since 1978, particularly in the smaller sizes. To an appreciable degree, the increase has been manifested as expanded bars in the lees of large boulders, a location preferentially used for spawning in boulder-bedded channels. The role of fires in the supply of gravels in high-gradient streams merits study.

SUPPLEMENTAL OBSERVATIONS

Other processes related to post-fire sedimentation also affected the channels and riparian corridors. These were observed in a more general way.

1. The fill and scour cycle in pools and in glides (or "runs") was greater in absolute magnitude than in riffles. Several traditional swimming holes were completely filled during the December and January storms following the fire. The relative rates of recovery in pools and glides seemed to be similar or slightly slower than those occuring in the riffles of this boulder-bedded channel.

This study was limited to describing sequential changes in riffles, where indirect discharge estimates and bed-material census are customarily made. Equally important in this decision was the historical emphasis on riffles by aquatic biologists. Subsequent research has clarified and quantified the importance of rearing habitat within pools and glides in salmonid production (e.g., Bjornn et al. 1977; Kelley and Dettman 1979). Future studies of post-fire changes in habitat should include pools and glides.

2. Few secondary slope instabilities were induced by the fire. Landslide-related sediment delivery to the main channels was probably of negligible magnitude, probably contributing to the rapid rate of sediment depletion in the channels. The relative stability of the slopes is considered to be primarily a function of bedrock type.

3. Interception of sediment on the lowermost terrace was widespread, particularly at the mouths of ravines, chutes, and small tributaries. Much of this material is of gravel or pebble size. Relative to the volume of coarse material deposited in and above Los Padres Reservoir since the fire, the volume of debris intercepted on the terrace was small, perhaps 1 to 3%. This proportion is smaller, but of a similar order of magnitude, to the fire-related sediment still stored in the main channels at least above the tailwater areas of Los Padres Reservoir. Delayed delivery of coarse material stored in these debris cones may be a factor in maintaining the supply of spawning-sized material during extended periods between major fires and floods.

4. Floods following the fire removed much of the organic matter which had accumulated in the channel. Most fallen trunks and limbs on or spanning the bed were dislodged, then either washed through to Los Padres Reservoir or wedged between the trunks of the larger riparian trees distributed along the banks. These small debris jams generated significant eddies during flood periods. As an example, the high-water marks of the December, 1977, February, 1978 and February, 1980 floods indicate that the water-surface profile sloped toward the right bank, the result of a small debris jam 12 m. (40 ft.) upstream. Nearly continuous lines of broken twigs and other fine organic matter accumulated in the eddies during each storm. Each line contained an appreciable amount of material, generally 0.5 to 5 cm. in thickness. Partial incorporation of this material into the soil was clearly visible by November, 1980. Post fire addition of organic material to soils at or slightly above the active flood plain may be an appreciable factor in the development of soils in the riparian zone.

CONCLUSIONS

1. Sequential changes in riffle conditions in the upper Carmel watershed following the Marble-Cone fire were observed using 4 physical descriptors of salmonid habitat:
   a. mean fill and scour;
   b. particle-size distribution of the bed surface;
   c. percent of the bed surface covered by sand and finer debris;
   d. percent of the bed surface occupied by material of sizes suitable for spawning.

2. Riffles in the master channels of the upper Carmel watershed filled up to 1 foot during the first storms following the Marble-Cone fire, primarily with sand. By the end of the first year, most of the fill had been scoured; much of what remained was of pebble and cobble size. By the end of the third year, all descriptors had returned to within 20% (relative to the maximum measured disruption) of their pre-fire conditions. Other on-going watershed processes were probably more important than residual effects of the fire as

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[7] Percentages of bed area occupied by material of other ranges may be computed from table 4 by those who would prefer to consider different sizes.

influences on habitat conditions by the end of the third year.

3. Effects of the fire on runs and pools were not measured. Maximum mean channel fill was generally observed to be several times greater than in riffles. Recovery of habitat values appear to occur at relative rates that were similar to or slightly slower than those in the riffles.

4. A substantial volume of sediment, primarily gravels and cobbles, was intercepted in the riparian and terrace areas. Delayed delivery to main channels is likely to be an important factor in maintaining the availability of spawning-sized material between major disruptive events.

ACKNOWLEDGEMENTS

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BOTANY

Jeff Norman

Along the central coast, Monterey pine (*Pinus radiata*) forests grace the stairstep marine terraces rising above the contemporary shoreline. Photograph by Linda L. Smith.

CALIFORNIA'S NATIVE MONTEREY PINE FOREST: CAN IT BE SAVED?

by Mary Ann Mathews and Nicole Nedeff

WHILE THE MONTEREY pine (*Pinus radiata*) is the most widely planted timber tree in the world, its three remaining native central coast stands are endangered and are faced with multiple threats stemming from an increasing population along its natural range. We can easily propagate a Monterey pine, and we can grow a stand of these pines in a plantation, but we do not understand the requirements for maintaining a Monterey pine forest with all its associated species. In the 1994 CNPS *Inventory of Rare and Endangered Plants* the Monterey pine is listed as endangered (CNPS List 1B). How did a tree that is so widely grown reach the point where it could be considered at risk?

It is not change itself, but the human-accelerated pace of change that puts the Monterey pine at risk. After all, these native forests have survived massive environmental changes over the last twelve million years, expanding and contracting their distributional range in response to changing climatic conditions. During the Pleistocene epoch they covered extensive areas in coastal California. As the climate became warmer and drier following the last glacial period, pine populations contracted to three small mainland locations—Año Nuevo, Cambria, and the Monterey Peninsula—a total of about 16,000 acres. The Monterey population, extending along the coast from Carmel Highlands on the south to Pacific Grove and Monterey on the north and inland about six miles, is the largest, the most diverse, and arguably the most endangered native forest. Only about 4,500 of the original 11,000 to 12,000 acres can be considered natural forest, in contrast to manicured urban forests, which have been subdivided and fragmented and thus have lost much of their ecological value.

Red-legged frogs are found in ponds and streams in pine forests in Northern California. *Amanita muscaria* (below), a relatively common hallucinogenic mushroom, grows in the Monterey pine forest on Jackson Peak. Photographs by Deborah Hillyard.

The Monterey pine belongs to the group of closed-cone conifers that appear to depend on fire or high temperatures for reproduction. On the Monterey Peninsula two other members of this closed-cone group, Bishop pine (*Pinus muricata*) and Gowen cypress (*Cupressus govenii*), occupy highly acidic hardpan soils on Huckleberry Hill and above Point Lobos in small stands surrounded by Monterey pines. Nearby is Monterey cypress (*C. macrocarpa*), which survives in a natural state only on the rocky headlands of the peninsula and Point Lobos, although it too has been widely and successfully grown in planted landscapes. The Monterey Peninsula is the only place in the world where these trees grow together with a unique assemblage of understory shrubs, herbs, and grasses.

The Monterey pine is a distinctive tree with stout, spreading branches forming an irregular round-topped canopy. Mature trees average eighty feet in height and two to three feet in diameter, with thick, deeply furrowed, red-brown bark. The average life span is eighty to a hundred years, although specimens have been documented at over 160 years old, over 150 feet tall, and with diameters over four feet. The bright, rich green needles, in bundles of three, rarely two, are four to six inches long, usually living about three years. The asymmetrical cones, three to six inches long and clustered, mature in the second season and may shed seeds in the absence of fire, but prolific seedling regeneration takes place only after a fire. With the continued absence of fire or an acceptable substitute management technique, questions are raised concerning the long-term sustainability of existing natural forests.

Understory vegetation in a Monterey pine forest has been shown to average about thirty-five percent cover. An early study concluded that this vegetation is critical in insulating shallow pine roots from heat and desiccation and that, where cover is removed, trees decline rapidly. Fog drip is considered the major factor in limiting the range of Monterey pine. The understory appears to increase the amount of moisture captured from frequent heavy summer fogs, decreasing the threat of wildfire except under unusually hot and dry conditions.

Common understory plants in Monterey pine forest include blackberry (*Rubus ursinus*), snowberry (*Symphoricarpus mollis*), huckleberry (*Vaccinium ovatum*), sticky monkeyflower (*Mimulus aurantiacus*), blue-blossom (*Ceanothus thyrsiflorus*), shaggy-bark manzanita (*Arctostaphylos tomentosa*), poison-oak (*Toxicodendron diversilobum*), and blue wildrye (*Elymus glaucus*). The understory varies considerably, depending on soil, with hard-leaved manzanitas and ceanothus replacing soft-leaved shrubs on more shallow and sterile soils.

Because of their limited and shrinking range, a Monterey pine forest harbors a remarkable number of rare and endemic species, including Eastwood's golden fleece (*Ericameria fasciculata*), Monterey manzanita (*Arctostaphylos hookeri*), sandmat manzanita (*A. pumila*), Yadon's rein orchid (*Piperia yadonii*), Hickman's cinquefoil (*Potentilla hickmanii*), Hickman's onion (*Allium hickmanii*), Pacific Grove clover (*Trifolium polyodon*), Monterey spineflower (*Chorizanthe pungens*), and Monterey ceanothus (*Ceanothus rigidus*). Several rare or disjunct plants flourish only after fires, such as bear grass (*Xerophyllum tenax*) and Monterey clover (*Trifolium trichocalyx*).

In 1994 the status of the Monterey pine forest was the subject of two major conferences and dozens of newspaper articles. Valuable new information was presented on pine forest associations that have developed on ancient marine terraces. The forest has been discovered to be an ecological staircase ecosystem complex—a theory first suggested by plant ecologist Jim Griffin in a 1972 article appearing in the *California Native Plant Newsletter*. Vegetation development on ancient terraces in Monterey is analogous to that which has developed on terraces at Jug Handle State Reserve on the Mendocino coast. Another workshop held in Carmel in October 1994 focused on the devastating impact of pitch canker, a disease that has been spreading rapidly from its initial outbreak among planted trees in Santa Cruz County in 1986. The pitch canker conference highlighted work by plant pathologists and entomologists investigating this virulent pathogen, which is believed to have been introduced from the southeastern United States or Mexico. Local foresters demonstrated treatments designed to control the spread of what some analysts fear could ravage our native Monterey pine forests.

Public concern for Monterey pine forest habitat has been heightened by a series of controversial issues, including pending development projects, aggressive fire suppression measures, and the specter of genetic contamination from earlier plantings of Monterey pines of unknown origin. A local prohibition of non-native stock has only

Sandmat manzanita (*Arctostaphylos pumila*) (top) is a rare plant, CNPS list 1B, found on Terraces 4 and 5 in the Del Monte Forest and in the maritime chaparral at Fort Ord. Photograph by Nicole Nedeff. Because of its shrinking range, there are numerous rare species in Monterey pine forests such as Yadon's rein orchid (*Piperia yadonii*) (bottom). Photograph by Deborah Hillyard.

Fog drip, enhanced by understory vegetation, provides essential moisture to the Monterey pine forest in Del Monte. Photograph by Mel Pankratz.

recently been recommended after years of planting with pines mostly from New Zealand nurseries developed on timber plantations. Along with the proliferation of non-native Monterey pines in the forest, French broom, pampas grass, and other invasive exotics have spread rapidly into disturbed areas, prompting public and private calls for their eradication.

The tenets of conservation biology suggest that the healthiest and most diverse forests are those with the largest yet most compact acreage, the purest genetic stock, and the lowest ratio of perimeter or edge to size. Therefore, it is important to preserve the largest blocks of forest possible as a buffer against the edge effect, particularly against diseases such as pitch canker. In order to include the full range of Monterey pine forest terrace subtypes, as continuous a gradient as possible should be preserved between the ocean and inland populations. Further study of the genetics and ecology of the Monterey pine is needed to quantify these general conservation recommendations.

Mary Ann Mathews, Box 381, Carmel Valley, CA 93924; Nicole Nedeff, Box 1525, Carmel Valley, CA 93924

THE MONTEREY ECOLOGICAL STAIRCASE AND SUBTYPES OF MONTEREY PINE FOREST

by Paul D. Cylinder

In the spring of 1994 the California Department of Fish and Game and The Nature Conservancy funded a project to assess the condition of the Monterey pine (*Pinus radiata*) forest on the Monterey Peninsula and to gather data for the development of a forest conservation plan. Underlying the study were three assumptions: that good conservation planning should begin with saving all the pieces; that the Monterey pine forest cannot be treated as a single ecological unit since a variety of forest subtypes are recognizable; and that geology and soils are key to understanding the distribution and ecology of these subtypes. As part of this study, Wayne Verrill and I described the correlation between the soils, geology, and vegetation of the peninsula and surrounding areas where Monterey pine forest occurs. Wayne conducted the soils analysis and I described the vegetation.

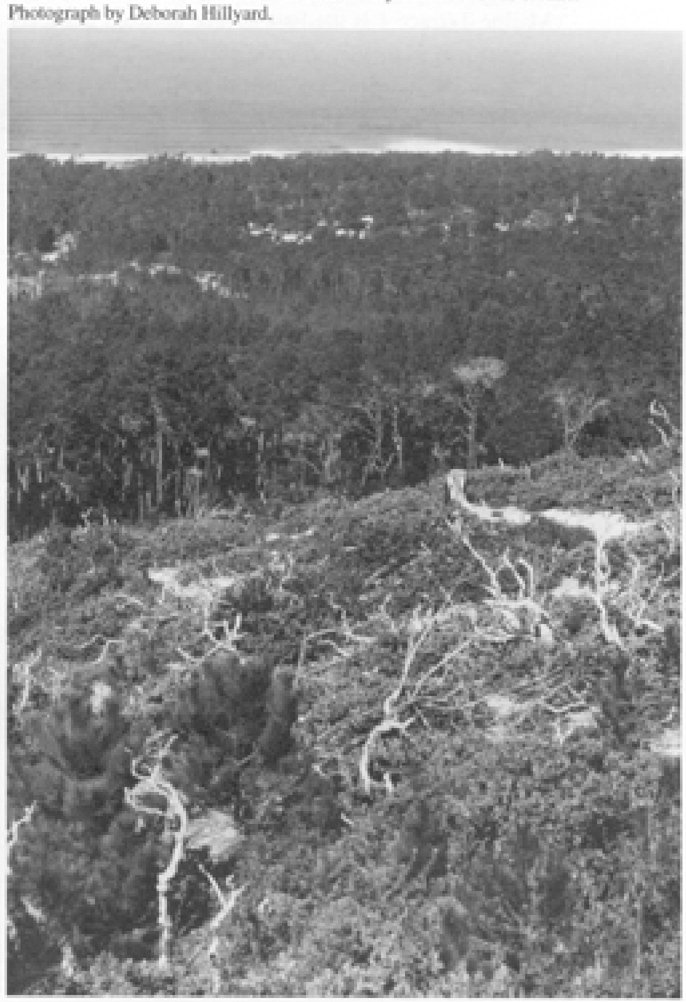
The Monterey peninsula is well studied. The flora has been documented in published floras, and soils have been mapped by the U.S. Soil Conservation Service (SCS). The Monterey pine, Monterey pine forest, and the unusual pygmy forests on Huckleberry Hill and near Gibson Creek all have been studied. More recently, the geology of the peninsula has been described and the geologic relationships elucidated between geomorphic surfaces (areas of similar age, composition, and form).

Combining this previous work and using a recently prepared geologic map to guide us, we have characterized the soils and vegetation to describe an ancient ecological "staircase" consisting of six step-like terraces cut into the peninsula by wave action and uplift, and we have created a classification system for Monterey pine forest subtypes. The ecological staircase is remarkably similar to that described twenty-five years ago by Hans Jenny and others for coastal Mendocino County, but the relationships between soils, vegetation, and geomorphic surfaces had not been previously explained for the Monterey Peninsula.

The study was divided into a discussion of discrete geomorphic surfaces that support Monterey pine forest or that were considered important to an understanding of the limits to the distribution of Monterey pine forest. Vegetation and soils on seventeen geomorphic surfaces were divided into five groups: marine terraces with the lowest, youngest terrace nearest the ocean and increasing in elevation and distance from the coast in a staircase fashion; intervening slopes between marine terraces defined by the terraces that surround them; dune systems of various ages; inland geologic formations, areas underlain by or supporting exposed shale or granite bedrock referred to as shale bedrock and granite bedrock formations; and drainages that cut through all the other geomorphic formations.

Three major dune systems occur on the Monterey Peninsula. These are the recent dunes of the Holocene epoch, the youngest dunes; dunes deposited in the late Pleistocene epoch, middle-aged dunes; and dunes of the middle to late Pleistocene epoch, the oldest dunes. The youngest dunes were formed about 6,000 to 10,000 years ago, and middle-aged and oldest dunes were formed about 100,000 years ago; some of the oldest dunes are half a million to a million years old.

A 1994 photograph looking over lower (younger) staircases across part of the S.B. Morse Reserve, which was extensively burned in a 1987 fire. Photograph by Deborah Hillyard.



Marine Terraces

Six marine terraces are found on the Monterey Peninsula and Point Lobos. These are numbered from 1 through 6, starting with the youngest terrace at the lowest elevation near the coast and rising to the oldest terrace at the highest elevation on top of Huckleberry Hill.

The soils on the six terraces represent a chronosequence, or time sequence, of development from youngest to oldest terraces. Because the terraces are generally level, soils have formed in place over long periods. The chronosequence displays a clear development sequence of soil types.

Leaching of minerals and clay from upper horizons to lower horizons is the most noticeable aspect of soil development with age. As clay is carried down through the soil by water, it accumulates in lower horizons to form a claypan that restricts plant roots and collects water. Once the claypan is formed, newly leached clay collects on top and the surface soil horizon becomes thinner over time. The oldest soils, which occur on the oldest terraces, have surface horizons leached of plant nutrients and dense, thick claypans at shallow depths. These old soils are the least hospitable to plant growth.

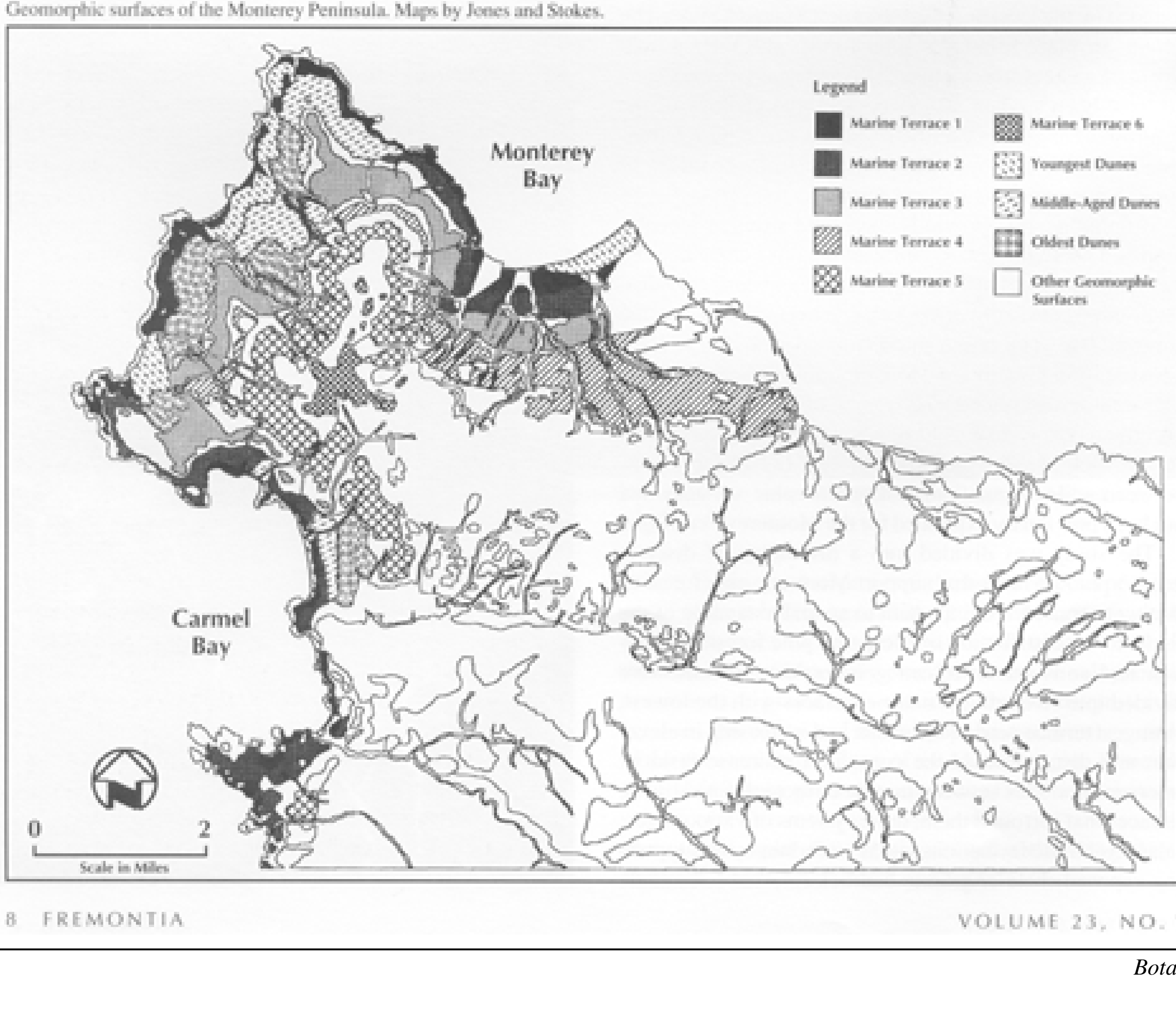
Marine Terrace 1 is the first terrace up from sea level and the youngest of the Pleistocene marine terraces at Monterey. In places along the Monterey Peninsula, Terrace 1 is covered by the youngest sand dunes; where beaches exist, they are lower in elevation and are between Terrace 1 and the ocean. Very little of this terrace remains in a natural condition. Most has been developed or landscaped. Several soil types may be present on Terrace 1, some of which may show minimal soil development.

Terrace 1 supports northern coastal scrub and coastal prairie vegetation. Coastal scrub supports a dense shrub cover with a good mix of species. Dominant species are coyote brush (*Baccharis pilularis*, erect and prostrate forms), blue blossom (*Ceanothus thyrsiflorus*), California blackberry (*Rubus ursinus*), poison-oak (*Toxicodendron diversiloba*), and bush monkeyflower (*Mimulus aurantiacus*). Coastal prairie supports native perennial bunchgrasses, non-native annual grasses, and native and non-native herbs. At Point Lobos State Park there is a good example of coastal prairie with mima mound microrelief.

Monterey cypress (*Cupressus macrocarpa*) and Monterey pine are unable to colonize Terrace 1, possibly because of the saline-sodic soils or salt spray from the ocean.

A minimal rise in elevation and a short intervening slope distinguishes Terrace 2 from Terrace 1. Terrace 2 is

Geomorphic surfaces of the Monterey Peninsula. Maps by Jones and Stokes.



covered by the oldest sand dunes along the west side of the peninsula. A large segment of Terrace 2 remains in natural condition on Point Lobos. Two distinctly different soil types are characteristic of Terrace 2, and the two vegetation communities of Monterey pine and Monterey cypress forest associate with these different soil types. The Monterey pine forest occurs on a variant of the Santa Ynez soil series. The Santa Ynez soil, derived from marine sand and clay sediment, is a fine sandy loam with a clay layer at varying depths. The pine vegetation causes these soils to be acidic. The Sheridan soil series on which Monterey cypress grows is markedly different from the Santa Ynez series. Farther inland, away from the near shore microclimate, Monterey pine forest occurs on the Sheridan soil series. Sheridan soils are formed from decomposed granite bedrock, are not strongly acidic, and do not have a clay layer.

Monterey pine forest on Terrace 2 may support nearly pure stands of Monterey pine or a mix of pine and coast live oak (*Quercus agrifolia*). The understory is a carpet of low shrubs that opens up at some sites to a cover of duff and grass. The dominant understory shrubs are poison oak and bush monkeyflower.

Monterey cypress forest typically supports pure stands of Monterey cypress. Very old Monterey pines are mixed with a multi-aged stand of cypresses at Crocker Grove on Cypress Point. The Monterey cypress forest understory supports sparse shrub and grass cover where the canopy is more open and very low vegetative cover, mostly duff, where the canopy is dense.

Marine Terrace 3 generally ranges in elevation from 140 to 220 feet. A large section of Terrace 3 above Spanish Bay is covered by older sand dunes. Almost all of Terrace 3 has been developed and landscaped. The primary soil type characteristic of Terrace 3 is the Narlon series. It is similar to the Santa Ynez series, but has a more strongly leached upper horizon, stronger acidity and lower fertility, and a thin, dark-colored surface horizon. A claypan is present, but depths to the claypan are widely variable, ranging from sixteen to fifty-six inches.

Terrace 3 supports a forest of Monterey pine and coast live oak. Probably none of the sites we surveyed on Terrace 3 support typical vegetation, but hints of the natural cover are provided by small patches of less disturbed vegetation. On Terrace 3 the Monterey pine forest canopy is relatively open, and some stands may be woodland with a grass understory rather than a closed forest. Coast live oak is a common associate. In woodlands the understory is mostly bunchgrasses and has the look of coastal prairie. European annual grasses, especially ripgut brome (*Bromus diandrus*), dominate other sites. Shrubs are sparse, occurring as dense patches of poison oak and bush monkeyflower.

Marine Terrace 4 generally ranges in elevation from 240 to 300 feet. Almost all of Terrace 4 on the Peninsula has been developed, with few natural areas remaining. A large piece of Terrace 4 with natural vegetation occurs inland along State Route 68. The primary soil type of Terrace 4 is the Narlon series also found on Terrace 3. Soil characteristics are generally in the same range, with typically depths of three to three and a half feet to the claypan. At least two other soil types are found on Terrace 4. One is an undescribed series that Wayne has provisionally termed the Sunridge series. It has a weakly to strongly iron-cemented hardpan at a shallow depth of one to two feet. On Terrace 4 segments along State Route 68, the source of alluvium is shale and the soil is the Chamise series.

On the peninsula, Terrace 4 Monterey pine forest can have an open or closed canopy. Coast live oak is an occasional to common associate. At some sites Bishop pine (*Pinus muricata*) grows mixed with Monterey pine in open canopy stands. Monterey pines on Terrace 4 appear to be stunted in height, becoming flat-topped at about fifty to seventy feet tall. The understory may be grassland with scattered patches of dense, shaggy-barked manzanita or more uniform shrub cover with a mix of shaggy-barked manzanita, huckleberry, California coffeeberry, bush monkeyflower, and blue blossom. The vegetation on Chamise soils on Terrace 4 includes open woodlands of Monterey pine with a strong component of coast live oak, oak woodland and savanna, and grassland.

Marine Terrace 5 generally ranges in elevation from 370 to 540 feet. It is the best preserved of the six terraces, with large undeveloped areas remaining. In addition, it is the only terrace that contains pygmy forest. The Narlon series and Sunridge series occur on Terrace 5. A third undescribed soil series, similar to the Narlon series and provisionally termed the Huckleberry series, also occurs. Huckleberry soils have an iron-enriched claypan that, where exposed on road cuts, hardens into a cemented pan called ironstone.

Variations in Narlon series soil characteristics on Terrace 5 can be correlated with vegetation changes from Monterey pine forest to Monterey pine-Bishop pine forest to pygmy forest. The soil characteristics that vary are depth of litter layer, thickness of A horizon, depth to claypan, and soil pH. Depth to claypan is greatest for Monterey pine forest, intermediate for Monterey pine-Bishop pine forest, and shallowest for pygmy forest. In pygmy forest soils, depth to claypan is typically less than twenty inches and as shallow as four inches and acidity is the greatest.

Vegetation on Terrace 5 was divided into three phases: Monterey pine forest, Monterey pine-Bishop pine forest, and pygmy forest. Monterey pine forest on Terrace 5 supports an open canopy of Monterey pine with coast live oak. The pines are stunted, becoming flat-topped at about fifty to sixty feet tall. The understory is a mix of open grass and duff with patches of dense shrubs. Shrub cover is a fairly even mix of shaggy-barked manzanita, Hooker's manzanita (*Arctostaphylos hookeri* var. *hookeri*), sandmat manzanita (*A. pumila*), California coffeeberry, bush monkeyflower, poison oak, and coyote brush.

Monterey pine-Bishop pine forest supports a mix of Monterey pine and Bishop pine in open stands. The Monterey pine are stunted in height, but form the canopy above a subcanopy of Bishop pine and smaller Monterey pine. The understory is an even mix of shrubs. The dominant shrubs are shaggy-barked manzanita, Hooker's manzanita, coyote brush, and bush monkeyflower.

The dominant trees in pygmy forest are Bishop pine and Gowen cypress (*Cupressus goveniana* subsp. *goveniana*). These trees are typically ten to twenty-five feet tall. Monterey pines are sometimes scattered through the pygmy forest. The Monterey pines grow taller (about twenty to thirty feet tall) than Bishop pine or Gowen cypress, but are severely stunted from their normal height. The understory in mature pygmy forest is dominated by shaggy-barked manzanita and huckleberry, with occasional California coffeeberry. Recently burned pygmy forest has much higher shrub and herb diversity than mature pygmy forest.

Marine Terrace 6 generally ranges in elevation from 600 to 800 feet. It forms the summit cap in several segments on Huckleberry Hill. Most of Terrace 6 has been developed, but remnant natural areas remain. The primary soil series of Terrace 6 is the Huckleberry series; small areas of the Narlon series may also occur. Soil characteristics are within the range for pygmy forest, but no pygmy forest areas have been observed, an interesting situation deserving of more study.

Terrace 6 supports Monterey pine forest in an open overstory. The pines are flat-topped and stunted at about forty feet. Scattered Bishop pines are present. The understory supports dense cover of huckleberry and shaggy-bark manzanita. Where the canopy is more open the understory supports Hooker's manzanita. Very few coast live oaks are found in these forests; however, scattered individuals of madrone (*Arbutus menziesii*) and Scouler's willow (*Salix scouleriana*) can be found here.

The Monterey pine grows on six step-like ancient terraces, uplifted over geologic time, with different forest subtypes that have developed in relationship to localized geology and aging soils. Photograph by Deborah Hillyard.

Slopes Between Marine Terraces

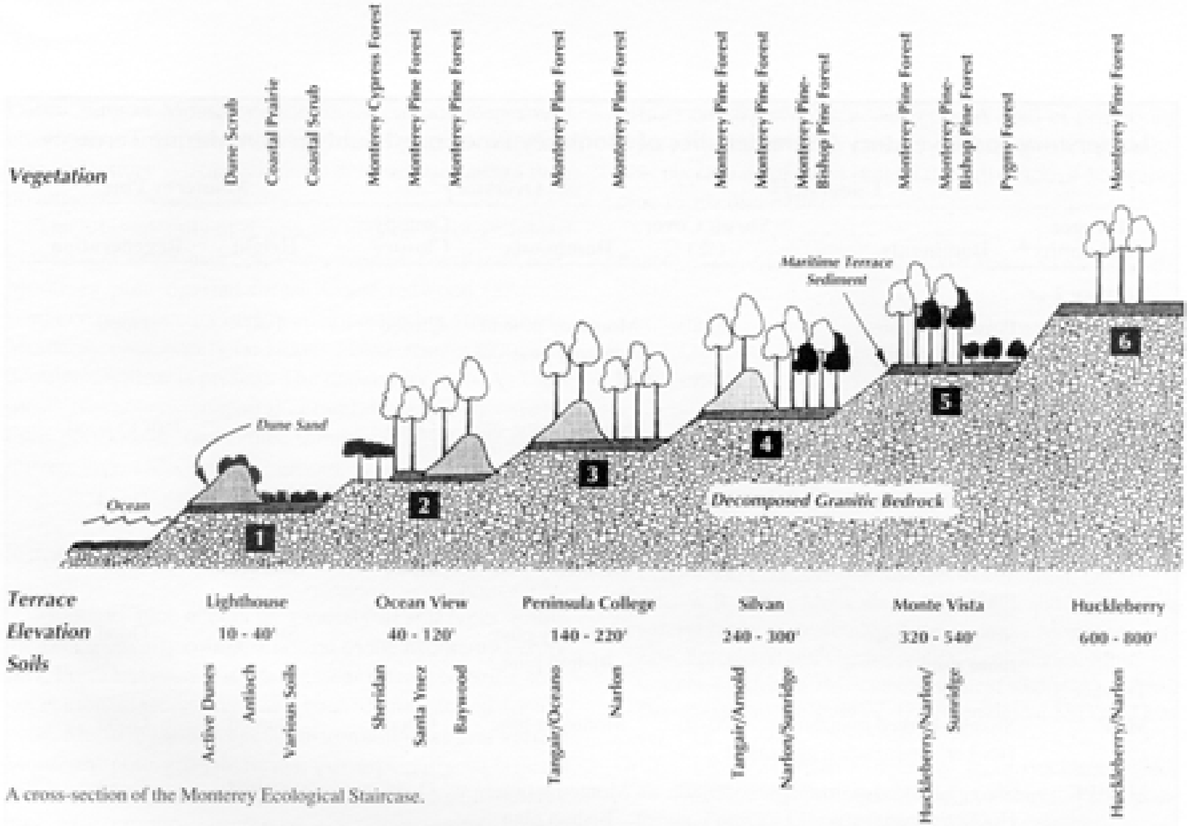
Because of better soil drainage and the lack of a restricting claypan or hardpan, Monterey pines grow to full height on the intervening slopes between marine terraces. Monterey pine occurs in pure stands on slopes between Terraces 1 and 2, with coastal scrub or coastal prairie species in the understory. The soils on slopes between Terraces 2 and 3 and between Terraces 3 and 4 are most likely the Sheridan series, with inclusions of other soil types on decomposed granitic bedrock. Vegetation on slopes between Terraces 2 and 3 is Monterey pine forest, with scattered coast live oak. The understory is a carpet of poison-oak and bush monkeyflower. A good grass cover is present, including bunchgrasses. The slopes between Terraces 3 and 4 support Monterey pine forest with an understory of shaggy-barked manzanita and huckleberry. Coast live oak are common.

Soils on slopes between Terraces 4 and 5 include the Narlon and Huckleberry series; other soil types may occur. Soils on slopes between Terraces 5 and 6 include the Sunridge series, as well as the Sheridan and related series formed on decomposed granite. Slopes between Terraces 4 and 5 and between Terraces 5 and 6 support Monterey pine forest. Coast live oak is common, and the understory is dense shaggy-barked manzanita and huckleberry. Some of the slopes between Terraces 5 and 6 support Bishop pine forest. These forests are composed of dense, nearly pure stands of full-sized Bishop pine on slopes above the Bishop pine pygmy forest. Understory vegetation is sparse.

Sand Dunes

Three major dune systems occur on the Monterey Peninsula. These are the recent dunes of the Holocene epoch, the youngest dunes; dunes deposited in the late Pleistocene epoch, middle-aged dunes; and dunes of the middle to late Pleistocene, the oldest dunes. Sand dunes of different ages have accumulated on portions of Terraces 1 through 4. Formations of dunes in four age groups, one from the Holocene and three from the Pleistocene, have been recognized in the Monterey pine area. The oldest group, known as Aromas sand, is of limited extent on the Monterey Peninsula (found only in Carmel) and we grouped it with the oldest dunes.

The youngest dunes are the active dunes in the process



A cross-section of the Monterey Ecological Staircase.

of stabilizing and vegetating. The soil type is loose sand with no pedogenic development. Primary soil characteristics are very high permeability, very low water-holding capacity, and low fertility.

The youngest dunes support dune scrub habitat. The dune scrub is dominated by beach sagewort (*Artemisia pycnocephala*), mock heather (*Ericameria ericoides*), sea-cliff buckwheat (*Eriogonum parvifolium*), bush lupine (*Lupinus arboreus*), bush monkeyflower, and prostrate and erect forms of coyote brush.

The middle-aged sand dunes occur inland of the youngest dunes and Terrace 1 and, in Carmel, inland of Terrace 2 as well. The characteristic soil type is the Baywood series, which has some accumulation of organic matter to a depth of twenty to forty-eight inches. This results in increased water-holding capacity and increased fertility, allowing the establishment of Monterey pine.

Middle-aged dunes support Monterey pine forest with a closed canopy at maturity. The Monterey pines achieve full height in multi-storied stands. Coast live oak is common and forms a subcanopy. The understory is rather open with much duff and grass along with low shrubs. The dominant understory species are poison-oak, bracken fern, California blackberry, and snowberry.

The oldest dunes generally occur further inland than the middle-aged dunes. Only very small, isolated areas remain in a semi-natural condition. Four dune soil types, Oceano, Elkhorn, Tangair, and Arnold, occur on the oldest dunes. Soil characteristics include organic matter accumulation and a subsoil accumulation of clay. The Elkhorn series is further developed than the Oceano series with respect to both surface organic matter accumulation and subsoil clay accumulation. The Tangair series is a more developed soil than the Elkhorn. The Arnold series is undoubtedly a paleosol, a relict soil formed in a paleoclimate.

Natural vegetation on oldest dunes was determined based on observations of remnant patches and the experience of local experts. The oldest dunes support Monterey pine forest. Coast live oak is present. The understory is open and grassy along with areas of sparse shrub cover including poison-oak, bracken fern, snowberry, and California blackberry.

Shale and Granitic Bedrock

Monterey pine forests extend a considerable distance inland from the coast and well inland of the marine terrace and dune sequence. The two principal geologic bedrock types are granite and shale. Shale bedrock begins around the summit of Huckleberry Hill and extends eastward to Jacks Peak and beyond. The granitic bedrock underlies the Monterey Peninsula west of Huckleberry Hill and extends eastward of Point Lobos.

The principal soil supporting Monterey pine on shale bedrock is the Santa Lucia series. Santa Lucia soils are fine textured with good structure and moderate fertility and water-holding capacity. These soils are more hospitable to plant growth than are soils of the marine terraces

Understory and Overstory Characteristics of Monterey Pine Forest Subtypes on Marine Terraces

	Understory		Overstory		Monterey Pine	
Terrace Community*	Dominants	Shrub Cover (%)	Dominants	Canopy Closure	Height	Regeneration
Terrace 2						
MPF	Poison-oak; bush monkey flower	50-80	Monterey pine or Monterey pine-oak	Closed	Full	Good
Terrace 3						
MPF	Grass; poison oak	10-40	Monterey pine-oak	Open	Full	Fair to good
Terrace 4						
MPF	Shaggy-barked manzanita; huckleberry	40-60	Monterey pine	Closed	Stunted	Good
MPF	Grass; Shaggy-barked manzanita	20-30	Monterey pine	Open	Stunted	Poor
MPBPF	Shaggy-barked manzanita	50-80	Monterey pine; Bishop pine	Open	Stunted	Good
Terrace 5						
MPF	Shaggy-barked manzanita; Hooker's manzanita; grass/duff	20-30	Monterey pine	Open	Stunted	Good
MPBPF	Shaggy-barked manzanita; Hooker's manzanita	50-80	Monterey pine; Bishop pine	Open	Stunted	Good
PYF	Shaggy-barked manzanita; huckleberry	50-80	Bishop pine; Gowan cypress	Open to closed	Severely stunted	Poor
Terrace 6						
MPF	Huckleberry; Shaggy-barked manzanita	50-80	Monterey pine	Closed	Stunted	Good

* Community classifications:

MPF = Monterey pine forest MPBPF = Monterey pine-Bishop pine forest PyF = pygmy forest

and dune systems. Another soil on shale bedrock is the Reliz series. Reliz soils are shale clay loams of steep slopes; they support chaparral vegetation rather than Monterey pine forest.

Vegetation communities on related shale soils are Monterey pine forest, chaparral, coastal scrub, coast live oak woodland, and grassland. The Monterey pine forest supports full-sized Monterey pines about eighty to 100 feet tall. Coast live oaks, about thirty to fifty feet tall, form a subcanopy. The understory is an open grass cover with some sites dominated by low shrubs such as poison-oak, bush monkey flower, California blackberry, coyote brush, and California coffeeberry.

The principal soil supporting Monterey pine forest on granitic bedrock is the Sheridan series. Sheridan soils are coarse sandy loams with soil characteristics similar to the Santa Lucia series. Another soil found on granitic bedrock is the Cieneba series. Cieneba soils are gravelly soils of steep mountain slopes; they support chaparral vegetation rather than Monterey pine forest.

The vegetation of inland granitic soils includes Monterey pine forest and maritime chaparral. The Monterey pine forest is well developed and multi-storied. Pines are full sized. The understory includes sites with a rather even mix of huckleberry, coyote brush, California coffeeberry, shaggy-barked manzanita, and poison-oak and sites dominated by one or a few of these species.

The maritime chaparral occurs on inland granitics on hilltops where soils are shallow. This chaparral has a high species diversity. Dominant species are shaggy-barked manzanita, Hooker's manzanita, and chinquapin. Scattered Monterey pines are present in the chaparral in stunted form.

Drainages

Sandy alluvial soils occur in drainages and canyon riparian areas separating the marine terraces and dune segments. Drainages on the Monterey Peninsula and Point

Lobos support Monterey pine forest on side slopes and channel bottoms. Here Monterey pines grow to full size. The understory is usually a more diverse assemblage than on adjacent terraces.

The alluvial soils of drainages that cut through inland granite and shale bedrock often support coast redwood-Monterey pine riparian forest. Coast redwood (*Sequoia sempervirens*) occurs on lower slopes and in streambeds. Monterey pine occurs on slopes above stream channels. Scouler's willow is present. The understory includes California blackberry, chaparral currant, huckleberry, swordfern, poison oak, ceanothus, thimbleberry (*Rubus parviflorus*) and, unfortunately, broom.

Summary and Importance for Conservation

Monterey pine occurs on a variety of soil types within the pedogenically complex region of the Monterey Peninsula, Point Lobos, and adjacent areas inland. Specific soil-vegetation associations have been demonstrated for diverse Monterey pine vegetation communities and variant Monterey pine growth forms. An especially significant soil-vegetation association is the occurrence of Monterey pine as a primary species on a six step marine terrace ecological staircase and soil chronosequence.

Monterey pine also occurs on sand dune soils, dominating the vegetation on stabilized Pleistocene dunes (middle aged and oldest dunes), where sufficient accumulation of organic matter has occurred in sand dune soil development.

Inland areas within the summer fog zone support Monterey pine communities on upland soil types formed from decomposed shale and granite.

The classification of subtypes of Monterey pine forest and recognition of the relationships between forest subtypes and geomorphic surfaces are key components in the development of a meaningful conservation plan for Monterey pine forest. This information will allow conservation planning efforts to take into account the protection of the full range of variation in this rare natural community. Estimates of the historical extent of forest subtypes can be made based on geologic maps and can be used to assess historical loss of forest subtypes.

The results of this study indicate that Monterey pine forest cannot be treated as a single entity. Subtle but strong differences can be found between Monterey pine forests growing on different geomorphic surfaces and soils. Historical losses of Monterey pine forest have not been evenly distributed across these forest subtypes. Little natural forest remains on Terrace 3, Terrace 4 on granite substrate, Terrace 6, and the oldest dunes. Many forests on intervening slopes between terraces have been preserved because the topography makes them unsuitable for development. Most of the historical forests on inland shale and granite bedrock remain. Continued development pressures threaten forests on all geomorphic surfaces. A goal of preserving representative stands of functional forest on each geomorphic surface would best protect the full range of Monterey pine forest diversity.

Paul Cylinder, Jones and Stokes, 2600 V Street, Sacramento CA 95818.

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Lace lichen has colonized these pines growing close to the sea on Terrace 2 which is well preserved at Pt. Lobos State Park. Photograph by Linda L. Smith.

PITCH CANKER AND ITS POTENTIAL IMPACTS ON MONTEREY PINE FORESTS IN CALIFORNIA

Thomas R. Gordon, Karen R. Wikler, Andrew J. Storer, and David L. Wood

Over the past century, North American forests have sustained considerable damage due to the introduction of exotic plant pathogens. Most notable are the catastrophic consequences that have followed the establishment of the fungal pathogens responsible for chestnut blight, Dutch elm disease, and white pine blister rust. To this list may now be added *Fusarium subglutinans* forma specialis *pini*, the fungus responsible for the disease called pitch canker. The forma specialis designation is appended to the species name to identify those strains which are pathogenic to pine; hereafter the pathogen is referred to as *F. s. pini*. This fungus was first described as a pathogen of pines in the southeastern U.S. and thus may be regarded as indigenous to North America. In California, where the pathogen was identified as a cause of tree mortality in Santa Cruz and Alameda counties in 1986, it is clearly an exotic pest.

Indigenous organisms have a history of interacting with co-occurring species and selection tends to dampen the extreme changes that may result, for example, from the susceptibility of a particular plant species to a pathogenic fungus. Thus highly susceptible species tend to decline in abundance and highly aggressive pathogens are disadvantaged by the loss of their preferred host. Over time such processes lead to the stability that allows the establishment of forested ecosystems to persist over hundreds or even thousands of years.

In contrast, exotic pathogens encounter an array of species with which they have no history of previous interactions. In most cases, an introduced pathogen would not encounter a suitable host and therefore would not survive. Successful establishment is more likely where a pathogen is "preadapted" to a particular host. Such was the case for *F. s. pini*, an aggressive pathogen of pines in the southeastern U.S. Although Monterey pine (*Pinus radiata*) was known to be susceptible to pitch canker, it was not among the species grown in areas where the disease previously occurred. Natural infections of Monterey pine were not observed until the pathogen was introduced into California. Because the California populations of Monterey pine had not previously been exposed to *F. s. pini*, there was no prior selection for resistance to pitch canker.

The epidemic of pitch canker that has developed in California can be attributed, in large measure, to the extreme susceptibility of Monterey pine and its popularity as an ornamental tree. Because of its rapid growth and attractive form, Monterey pine has been widely used in landscape settings such as parks and golf courses and to provide visual relief and noise barriers along state and local rights of way. The pathogen was presented with a spatially interconnected supply of host trees that allowed for incremental spread through large areas of coastal California.

Rapid dispersal of the pitch canker pathogen in California appears to have been greatly facilitated by the develop-

The fading tree in the foreground was infected near the soil line by the pitch canker pathogen, causing the death of the tree. Surrounding trees are healthy. This photograph was taken at a Christmas tree farm in Southern California. Photograph by Tom Gordon.

ment of new associations with insects that feed and reproduce on Monterey pine. This includes the Monterey pine cone beetle (*Conophthorus radiatae*) and several species of both twig beetles (*Pityophthorus* spp.) and engraver beetles (*Ips* spp.), all of which are native to California. All these insects are known to carry *F. s. pini* and, collectively, they are thought to be responsible for initiating most of the infections that occur under natural conditions in California.

The infections which result from feeding by twig and cone beetles lead to the girdling of young branches. The death of these infected branches weakens the tree and provides substrate suitable for breeding by twig beetles. Beetles emerging from infected branches commonly carry the pathogen and may proceed to establish new infections. Engraver beetles can introduce the pathogen into larger branches and ultimately the bole or main trunk of the tree. Bole cankers further weaken the tree and render it more prone to engraver beetle attacks. Death of the affected tree often follows, which in turn enhances the reproductive opportunities for both *Ips* and *Pityophthorus* species.

Although it is most conspicuous as a disease of mature trees, pitch canker can also affect seeds and seedlings. Seeds collected in pitch canker-infested areas commonly carry the pathogen, even where they originate from cones on uninfected branches. Infected seeds may fail to germinate or germinate to produce infected seedlings. Infected seedlings may die shortly after germination or survive without obvious symptoms for several months. Consequently, both seed and seedlings can serve as vehicles for dispersal of the pathogen. In fact, the occurrence of pitch canker in Christmas tree farms and the resulting dissemination of infected trees probably contributed to the establishment of pitch canker in California.

Pitch Canker in Native Populations

When pitch canker was first identified in California in 1986, the largest infestation was in Santa Cruz County, located approximately midway between the native stands of Monterey pine at Año Nuevo to the north and the Monterey Peninsula to the south. The apparent absence of the disease in these populations during the early years of the epidemic nurtured the hope that native trees were resistant to pitch canker. This view was consistent with the behavior of the disease in the southeastern U.S., where pitch canker was problematic in plantations and seed orchards but not in wildland situations.

Unfortunately, based on greenhouse tests of clonally propagated trees originally collected by Dr. William Libby, professor emeritus of forestry at the University of California, Berkeley, it was apparent that the majority of genotypes in all native populations of Monterey pine were susceptible to pitch canker. By 1993 pitch canker was observed in native stands at Año Nuevo and on the Monterey Peninsula, laying to rest the hope that they would be spared the ravages of this disease. Finally, in 1994, pitch canker was confirmed to occur in the only other native population in California, located near Cambria. The extent of the infestation indicated that it had been there for at least several years.

The presence of pitch canker in Monterey pine forests requires that management plans reflect consideration of the factors that influence the rate of disease spread. To this end we have established permanent plots on the Monterey Peninsula to monitor the development of pitch canker. A principal objective of our study is to assess the rate of disease spread in each of four landscape types: wild, characterized by a relative lack of human impacts; golf course, where grounds-keeping and related activities di-

A branch tip showing typical symptoms of pitch canker. The site of infection was just below the dead needles and resulted in a girdling lesion that killed the branch distal to the infection. Photograph by Tom Gordon.

Branch and cone showing pitch canker damage.

Case Study: The Asilomar State Park Pine Forest

CALIFORNIA STATE Park ecologist Tom Moss has observed and documented dramatic changes in the Monterey pine forest at Asilomar State Park since 1993 when he noted the first incidence of pine pitch canker there. By 1994 200 trees were infected. By late 1996 nearly 2,000 trees, or more than forty-four percent of the pine forest at Asilomar was affected by the disease. Moss noted during the Monterey Pine Forest Symposium in October 1996 that twenty percent of the young trees, forty-three percent of the "teenage" trees, and fifty-nine percent of the mature pines at Asilomar were currently infected with pine pitch canker disease.

Treatment for the blight at Asilomar includes trimming and the removal of infected trees, most of which are in fragmented portions of the forest. Moss believes Monterey pines have a very low threshold of tolerance for change, particularly change that impacts roots and forest microclimate, such as what typically occurs as a result of development and forest fragmentation. According to Moss, "Changes create stress in trees. Stressed trees attract bark beetles, and may then become infected with pitch canker." Although Moss agreed with other presenters during the panel discussion that preventing the spread of pitch canker was a top priority, he stated that "People and our activities in the forest are the primary factors influencing the spread of pitch canker. Human related activities that increase stress on the trees and forest accelerate the spread of pitch canker." He echoed the concern of many forest watchers on the Monterey Peninsula that development and fragmentation of the remaining large tracts of pine forest will be the catalyst for a significant spread of pitch canker disease. Moss called for management of the pine forest to optimize natural regeneration. He added that in situ conservation of the Monterey pine forest will defend the genetic resources of the trees against the contemporary pitch canker epidemic, and afflictions that may affect the forest in years to come.

rectly impact the trees and associated vegetation; light urban, which includes areas affected either by proximity to roads or vegetation management for fire suppression and/or aesthetics; and urban, which are landscaped properties other than golf courses.

A total of 47 permanent plots have been established on the Monterey Peninsula, ten plots in each of the four landscape types, six additional plots in undisturbed areas owned by the Del Monte Forest Foundation, and one plot that is heavily affected by pitch canker while also showing significant potential for regeneration. The plots, which include a total of 829 mature trees and 1,060 younger trees (seedlings, saplings, and juvenile pines), will be surveyed for the incidence and distribution of pitch canker three times a year for three to five years.

An *Ips* beetle, one of several native insect associates of Monterey pine capable of vectoring pitch canker. Photograph by Andrew Storer.

Within each plot, the growth rate and needle quality of all the mature trees will be monitored. We will also record the incidence of attacks by red turpentine beetle and pitch moth, and the incidence of western gall rust and dwarf mistletoe, in order to evaluate the influence of these factors on the development of pitch canker. Data on seedling survival and tree mortality will be collected, allowing for an analysis of age structure and the potential for regeneration. The species composition of the understory has been characterized in order to assess the influence of groundcover on regeneration.

Prospects for Monterey Pine

Even in the absence of pitch canker, the replacement of dying trees poses a challenge to the persistence of Monterey pine forests. In some of our plots, as in many areas throughout the Monterey Peninsula, stands are composed of a narrow age distribution of trees. Often these trees are near the end of their natural life span and will soon die to yield

But the single most important factor in the abundance of fuel was a wet, sticky snowfall on January 3, 1974 which crushed the crowns of the evergreen trees and shrubs. In many areas the branches broken by this storm in one night added more fuel than had accumulated in more than thirty years of fire control. On tens of thousands of acres at least ten tons per acre of dead fuel were lying on the ground or hanging in the trees. In the worst spots fifty tons per acre of broken branches were present. Then this dead wood was dried during two seasons of drought. Thus, the stage was set for the fury that erupted when lightning set four fires in the Ventana Wilderness on August 1, 1977. One strike was on Marble Peak; another was on South Ventana Cone. After these two lightning-caused fires merged the resulting conflagration was named the "Marble-Cone" fire.

Fire Frequency in the Past

After blaming fire control for causing an "unnatural" fuel level, what can we say about "natural" fire frequency in the Santa Lucias? In the Marble-Cone area almost nothing is known about either lightning- or Indian-caused fires prior to the arrival of the Spanish in 1769. During the Spanish and Mexican eras there were many reports of fires being set by Costanoan and Salinan Indians, particularly in valley or coastal grasslands. But none of these reports specifically is related to the Marble-Cone area. The Esselen Indians, who inhabited most of the Marble-Cone area, were gone before any observations were made of their use of fire. Undoubtedly the Esselens engaged in intentional burning and also caused some accidental fires, but we don't know any details.

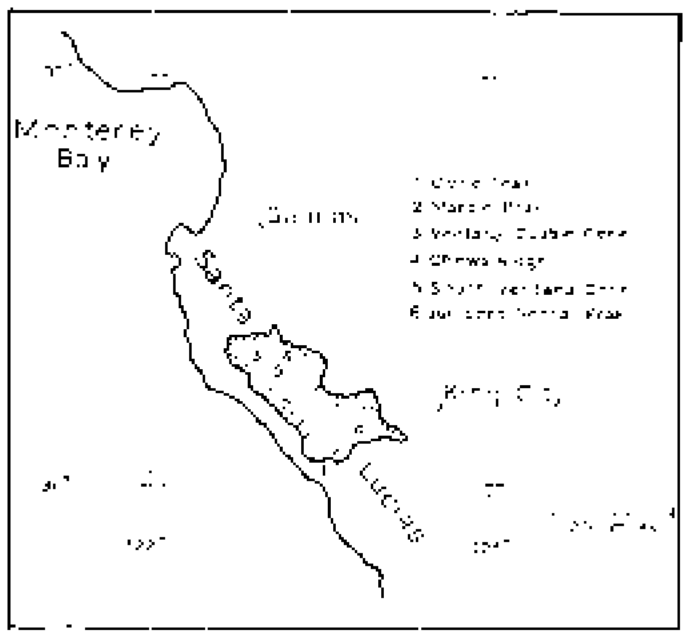
There is no question, however, about the indiscriminate burning of the forests by American prospectors, hunters, and ranchers. By the late 1800s tales of huge fires in the Santa Lucias were common in newspapers and government reports. Federal surveyors seeking lands to become "Forest Reserves" were appalled by the extent of burning and the serious damage to timber and watersheds. One report mentioned that a large region of the central Santa Lucias embracing the upper watersheds of all major streams burned for weeks in 1894. Another report told of a fire which started from an untended campfire near Chews Ridge in July 1903. During the following months the fire burned a strip over six miles wide all the way to the coast. In October 1906 newspapers reported a fire of some 150,000 acres in the Santa Lucias. All these fires burned large portions of the Marble-Cone area. After 1907, when the U.S. Forest Service started to manage the land, the frequency and extent of the fires declined.

Chaparral

Chaparral was a major vegetation type in the area of the burn. South-facing slopes and ridges, densely clothed with tall evergreen shrubs or scrubby live oaks, burned more intensely and more uniformly than other plant communities. One early and striking post-fire response in the chaparral was the unseasonal blooming of Spanish bayonet (*Yucca whipplei*). Apparently scattered plants which had not bloomed in the spring of 1977 were induced to flower by the heat. Within weeks huge panicles of ivory flowers rose above the scorched rosettes. Since the special moths required for pollination would not have been present at this odd season, I assume these flowers produced no seeds.

The scrubby interior live oaks (*Quercus wislizenii*) and canyon live oaks (*Q. chrysolepis*) were seldom completely consumed by the chaparral crown fires; they usually remained as charred trunks, perhaps five to ten feet tall, standing above the ashes. Within a month these oaks and other scrubs, such as coffee berry (*Rhamnus californica*), sprouted vigorously from the base. By the time freezing weather arrived in November many of these burnt shrubs had shoots several feet tall.

The burl-forming shrubs — chamise (*Adenostoma fasciculatum*) and Eastwood manzanita (*Arctostaphylos glandulosa* and its varieties) — often



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The stark, rugged beauty of the Santa Lucia Mountains unfolds in a wilderness landscape dominated by chaparral, exposed bedrock, and occasional oaks and conifers. Photograph by Dan Howe.

THE SANTA LUCIA MOUNTAINS: DIVERSITY, ENDEMISM, AND AUSTERE BEAUTY

by David Rogers

Along the central California coast, between Monterey and San Luis Obispo, a geologically young and still uplifting range of mountains rises abruptly from the Pacific Ocean, forming a backdrop to the dramatic Big Sur coast: the Santa Lucia Mountains. Unlike so much of the landscape of California, which has been greatly altered by human activities, the extremely rugged and inaccessible terrain of much of the Santa Lucia Mountains has sheltered this region from exploitation. With the possible exception of parts of the King Range south of Cape Mendocino, the Santa Lucia Mountains are probably the most pristine of all the Outer Coast Ranges. The flora has thus remained overwhelmingly native, and, due to a number of geoclimatic factors which combine in these mountains, a rich and highly diversified assortment of plants can be found in relatively close proximity within the borders of the range.

At least fifty-seven plant taxa are found only in the Santa Lucia Mountains. The tail end of the great maritime coniferous forests which stretch northward to the southern coast of Alaska lies in the Santa Lucias, and over 220 species are at the southern end of their natural distribution in this range, including many species in the coast redwood (*Sequoia sempervirens*) community. Along the cool, windswept coast are a large number of plants which are restricted to this specialized habitat, and on the higher peaks and ridges, elevations are sufficient to harbor small islands of montane plants, many of which are separated from the nearest populations of their kind by hundreds of linear miles. The hot, dry interior regions of the mountains support a variety of plants which are typical of the more arid Inner Coast Ranges or the mountains of Southern California.

Extreme Topography

The primary features of the Santa Lucia Mountains which have produced such a rich flora are their immediate proximity to the coast and their extreme topography, which ranges from sea level to nearly 6,000 feet. These two physical factors greatly influence the local climatic conditions. On the west, the Santa Lucia Mountains rise steeply from the Pacific Ocean; at Cone Peak, the abrupt ascent from sea level to summit is 5,155 feet. The Santa Lucias terminate on the north as the Monterey Peninsula, which in itself is a well-studied and deservedly famous locale for rare and endemic plants. On the east, the mountains descend into the Salinas River Valley; to the south, they retreat from the coast and diminish in size in San Luis Obispo County.

Rock and soil types also play a role in the diversity of plant life. The northern part of the Santa Lucia Mountains are a complex of Mesozoic granites and variable pre-Cenozoic metasedimentary and metavolcanic bedrock. To the south are Franciscan metasedimentary rocks, broken by bands of ultramafic rocks which include serpentine.

The most geologically impressive region of the Santa Lucia Mountains is the least accessible to the casual visitor, and is largely included in the Ventana Wilderness Area of the Los Padres National Forest in the northern-central part of the range. This region contains nearly all the peaks and ridges over 4,000 feet, including Junipero Serra Peak, which, at 5,868 feet, is the highest point in the Coast Ranges between Snow Mountain (7,056 feet), 230 linear miles to the north in Lake County, and San Rafael Mountain (6,593 feet), 130 linear miles to the south in central Santa Barbara County. The Ventana Wilderness is a dramatic expanse of steep-sided, sharply crested, and typically rocky ridges, cut by deep, V-shaped canyons. Massive rock outcrops and cliffs are common, and so are waterfalls. The perennial streams which race over the bed-rock of the canyon bottoms are often surrounded by almost vertical cliffs on either side. Deep pools that fill the canyon bottom from wall to wall are relatively common, and practically irresistible to a hot, tired hiker.

Most of this remote region was consumed by the massive, 180,000-acre Marble-Cone Fire of 1977, which darkened the skies with smoke as far away as Salt Lake City. Although most of the vegetation which was affected was fire-adapted and is recovering from the burn, numerous dead trees remain on the ridges and slopes as testimony to that event.

Buildings at Tassajara Hot Springs give a human scale to the rugged topography of the surrounding mountains. Photograph by Dan Howe.

Contrasting Climates

The immediate coast and ridges and the rugged mountainous interior of the Ventana Wilderness region receive abundant rainfall in most years. This rainfall is caused by the sudden uplifting of winter stormfronts as they collide with the high ridges, causing the clouds to drop much more of their moisture than they would over a more horizontal landscape. Rainfall is particularly heavy from storm fronts that approach from the southwest, for not only are they warmer and frequently more moisture-laden, but they hit the northwest to southeast axis of the ridges broadside, and are thrust upward with the greatest possible uplift.

Average annual rainfall at Big Sur is nearly sixty inches; at Tassajara Hot Springs, which is about nine miles east, in the rugged interior of the range, average annual rainfall was almost fifty inches during a six-year period in which I monitored precipitation, with a low of twenty-eight inches one year and a maximum of eighty-one inches another year. Annual rainfall totals can exceed 100 inches on the higher peaks and ridges, and, to the best of my knowledge, the highest official annual rainfall record in California is still at Cold Spring Camp, above the Big Sur River on the Coast Ridge, where 161 inches of rain fell during the rainy season of 1940-41. Snow is relatively common on the higher peaks and ridges during the winter, and major storms can drop many feet of snow in short periods of time. In contrast to the well-watered western slopes, the eastern slopes of the Santa Lucia Mountains that approach or directly face the Salinas Valley receive much less rainfall, and most of the Salinas Valley floor has an annual average rainfall of less than fourteen inches.

The summer weather pattern along the coast and in the coastal canyons of the Santa Lucia Mountains is typical of the coastal regions of Northern and Central California. Low clouds tend to hang along the immediate coast, penetrate into the seaward-facing canyons in the late afternoon and evening, and persist until the warmth of the next day's sunlight evaporates them. This maritime influence has an almost constant cooling effect, and the coastal summers are quite mild. The high ridges of the mountains, however, prevent these cooling coastal fogs from spreading far inland, and summers in the central and interior canyons are hot and dry, with afternoon temperatures often exceeding 100 degrees.

The ridges along the immediate coastline are so effective in blocking the maritime air that coastal fog rarely reaches the interior canyons. When fog does move in to cool the heated peaks and valleys, it approaches from the east, opposite the seacoast, when an exceptionally heavy summer fog has crept deep into the Salinas Valley.

The oceanic influence along the coast not only cools the coastal slopes and canyons in the summer, but also helps keep them relatively warm in winter, for the temperature of the ocean changes little between the seasons. The winters in the central and interior canyons, however, are much colder, with morning temperatures often falling below freezing.

Unusual Neighbors

The combination of these geoclimatic conditions produces numerous specialized habitats in which a wide variety of diverse plants exist in more or less close geographic proximity in the Santa Lucia Mountains. Common in the upper regions of the Big Sur River watershed are lush canyon bottoms dominated by coast redwoods and other typical species, overhung by dry, rocky, slopes covered with chaparral species such as Spanish bayonet (or Our Lord's candle, *Yucca whipplei* ssp. *percursa*), along with other species which are more typical of the chaparral of Southern California.

One of the most interesting meetings of two species is that of the coast redwood and California sycamore (*Platanus racemosa*). The sycamores exhibit a peculiar form of growth when having to deal with the "sunlight-stealing" redwoods. In more or less open places in which there is sufficient underground moisture, the sycamores tend to be low and spreading, with many tortuous branches. In areas in which they must coexist with other riparian tree species, they have a more erect posture, although their branches are often sinuous enough to take advantage of any easily exploitable source of sunlight. When growing in association with redwoods, however, the sycamores take on a remarkable posture, for then they grow extremely tall, but also extremely erect, with vertical trunks often free of branches for more than half of the height of the tree. One of the pleasures of exploring the Santa Lucias lies in encountering these strange meetings of unlikely associates.

Santa Lucia Endemics

The Santa Lucia Mountains have long been noted for their endemism, and Jepson referred to this region as the Lucian Endemic Zone. By my calculation, there are over fifty-seven species in the Santa Lucia Mountains which

Belying its name, the upper reaches of the Arroyo Seco contain deep pools that hold water even during a drought year. Photograph by David Rogers.

are found nowhere else. An overwhelming majority of these endemic species are included on the CNPS inventory of rare and endangered vascular plants. While the majority of these endemic species are probably recently evolved, some, such as the Santa Lucia fir (*Abies bracteata*) and Monterey cypress (*Cupressus macrocarpa*), are relics from a much more ancient time.

Within the Unique Endemic Zone there are a number of smaller pockets of endemism. This mosaic of diversity makes the mountains a miniature version of the highly endemic California Floristic Province. The Monterey Peninsula region is perhaps the best known of these regions, home to numerous endemics that include Monterey cypress, Gowen cypress (*C. goveniana*), Tidestrom's lupine (*Lupinus tidestromii* var. *tidestromii*), and the Point Lobos brodiaea (*Brodiaea versicolor*). The rugged peaks of the northern-central Santa Lucia Mountains shelter another region of unique plants such as the aptly named Santa Lucia fir, Santa Lucia lupine (*Lupinus cervinus*), and Santa Lucia bedstraw (*Galium clementis*), and Butterworth's buckwheat (*Eriogonum butterworthianum*). On the eastern flanks of the Santa Lucia Range is the Indian, San Antonio, and Nacimiento River area, where one can find the San Antonio Hills monardella (*Monardella antonina*), Jolon clarkia (*Clarkia jolonensis*), and purple soaproot (*Chlorogalum purpureum*). Just south of the Monterey County line is what Robert Hoover refers to as the "Cruzian pocket of endemism," a region centered around the Arroyo de la Cruz in northwestern San Luis Obispo County. From this southern locale come dwarf goldenstar (*Bloomeria humilis*), Hearst's manzanita (*Arctostaphylos hookeri* ssp. *hearstiorum*), and maritime ceanothus (*Ceanothus maritimus*).

Also noteworthy are a number of plants which are very near to being endemic to the Santa Lucia Mountains, and

Some Plants Which are Endemic to the Santa Lucia Mountains

APIACEAE (Parsley Family)
- *Lomatium parvifolium* var. *pallidum*

ASTERACEAE (Sunflower Family)
- *Cirsium fontinale* var. *obispoense*
- *Haplopappus eastwoodiae*
- *Hemizonia paniculata* ssp. *increscens*
- *Layia carnosa*
- *Malacothrix saxatilis* var. *arachnoidea*
- *M. saxatilis* var. *commutata*

CRASSULACEAE (Stonecrop Family)
- *Dudleya bettinae*
- *Dudleya abramsii* ssp. *murina*

CYPERACEAE (Sedge Family)
- *Carex obispoensis*

CUPRESSACEAE (Cypress Family)
- *Cupressus goveniana* (Gowen cypress)
- *Cupressus macrocarpa* (Monterey cypress)

ERICACEAE (Heath Family)
- *Arctostaphylos edmundsii* var. *parvifolia*
- *A. glandulosa* var. [illegible]
- *A. hearstiorum*
- *A. hookeri*
- *A. hooveri*
- *A. luciana*
- *A. montereyensis*
- *A. obispoensis*
- *A. pechoensis*
- *A. pilosula*

FABACEAE (Leguminosae) (Pea Family)
- *Lupinus* [illegible] (Santa Lucia lupine)
- *L. cervinus*
- *L. tidestromii* var. *tidestromii*
- *Trifolium trichocalyx*
- *T. polyodon*

GROSSULARIACEAE (Gooseberry Family)
- *Ribes menziesii* var. *hystrix*
- *R. sericeum* (Santa Lucia gooseberry)

LAMIACEAE (Labiatae) (Mint Family)
- *Monardella antonina*
- *M. palmeri*
- *M. subglabra*
- *Pogogyne clareana*

LILIACEAE (Lily Family)
- *Allium hickmanii*
- *Bloomeria humilis*
- *Brodiaea terrestris* var. [illegible]
- *B. versicolor* (Pt. Lobos brodiaea)
- *Chlorogalum purpureum*

MALVACEAE (Mallow Family)
- *Malacothamnus jonesii*
- *M. palmeri*
- *M. palmeri* var. *involucratus*
- *M. palmeri* var. *lucianus*
- *Sidalcea hickmanii*
- *S. hickmanii* ssp. *anomala*

ONAGRACEAE (Evening Primrose Family)
- *Clarkia jolonensis*

PINACEAE (Pine Family)
- *Abies bracteata* (Santa Lucia fir)

POLYGONACEAE
- *Chorizanthe breweri*
- *Centrostegia vortriedei*
- *Eriogonum butterworthianum*

RANUNCULACEAE (Buttercup Family)
- *Delphinium hutchinsoniae*
- *D. umbraculorum*

RHAMNACEAE (Buckthorn Family)
- *Ceanothus maritimus*
- *C. rigidus*

RUBIACEAE (Madder Family)
- *Galium californicum* ssp. *luciense*
- *G. clementis* (Santa Lucia bedstraw)
- *G. hardhamiae*

SCROPHULARIACEAE (Figwort Family)
- *Collinsia antonina*
- *Mimulus guttatus* ssp. *arenicola*
- *Orthocarpus densiflorus* var. *obispoensis*

Chaparral and exposed rock (above) cover the steep terrain in the central part of the Ventana Wilderness, with oaks confined to the north-facing slopes. This view is from the Indians Road, looking northwest into the mountainous interior. Photograph by David Rogers. The tall, pointed trees in the foreground (below) are Santa Lucia firs (*Abies bracteata*), surrounded by ponderosa pines (*Pinus ponderosa*) and mixed oak and madrone woodland. Nestled among the massive sandstone boulders of the Vaqueros Formation at Church Creek Divide, these firs survived the Marble-Cone fire of 1977. Photograph taken in June, 1958, by Vern Yadon.

many of these plants were formerly listed as endemic until their discovery outside the range, typically in the Gabilan Mountains to the east, or the La Panza Range on the southeast. These plants, some of which are a conspicuous and characteristic part of the regional landscape, include the Santa Lucia sticky monkey-flower (*Mimulus bifidus* ssp. *fasciculatus*), woolly yerba santa (*Eriodictyon tomentosum*), small-leaved lomatium (*Lomatium parvifolium*), Jolon brodiaea (*Brodiaea jolonensis*), Lewis' clarkia (*Clarkia lewisii*), Douglas' spineflower (*Chorizanthe douglasii*), and Hardham's evening-primrose (*Camissonia hardhamiae*).

Disjunct Populations

In contrast to the endemic plants, which are found nowhere else beyond the boundaries of the Santa Lucia Mountains, is a group of disjunct species which put in a brief appearance in these mountains, but are most commonly found elsewhere. Many of these plants are restricted to the higher peaks and ridges of the Santa Lucia Mountains, but there are species which occur in more mesic spots, and some species appear even at the lower elevations.

Plants which are restricted to the higher elevations are typically montane species, and the nearest populations of their kind appear in the higher mountains of the Northern Coast Ranges; the Sierra Nevada; or the Sierra Madre, San Gabriel, San Bernardino, San Jacinto, or Peninsular ranges of Southern California. Such plants include sugar pine (*Pinus lambertiana*), incense-cedar (*Libocedrus decurrens*), Indian's dream or cliff-brake (*Aspidotis densa*), *Sanicula graveolens*, red-eyed hulsea (*Hulsea heterochroma*), rose and yellow lupine (*Lupinus stiversii*), Sierra gooseberry (*Ribes roezlii*), Sierra onion (*Allium campanulatum*), small-leafed cream-bush (*Holodiscus microphyllus*), and western pipsissewa (*Chimaphila menziesii*).

Purple amole (*Chlorogalum purpureum* var. *purpureum*) (top) is endemic to a small area near Jolon, in the east-central portion of the Santa Lucia Range. This species is on the CNPS List 1B and is a Category 1 candidate for federal listing. Morro manzanita (*Arctostaphylos morroensis*) (above) grows only in the vicinity of Morro Bay, at the southern end of the Santa Lucia Mountains. As is the case with many of the Santa Lucia endemic plants, this species is on the CNPS List 1B, and is a Category 1 candidate for inclusion on the federal endangered species list. Photographs by William Follette.

Representatives from the North

At least 225 species of plants are at their most southern Coast Range distribution in the Santa Lucia Mountains, although some of these plants may actually extend their ranges to a more southern latitude in the Sierra Nevada or in the higher mountains of Southern California. Within this association of plants from the north, four groups stand out: maritime or coastal plants; plants associated with the redwood forests; the plants which are more or less montane by nature, and are mostly restricted to higher elevations; and plants which are more generally distributed in the Santa Lucia Mountains.

The first group, plants which are more or less confined to the dunes, bluffs, or scrublands of the immediate coast, includes footsteps to spring (*Sanicula arctopoides*), pearly everlasting (*Anaphalis margaritacea*), the prostrate form of coyote brush which grows only along the coast (*Baccharis pilularis* ssp. *pilularis*), coast rock-cress (*Arabis blepharophylla*), bearberry (*Arctostaphylos uva-ursi*), multicolored lupine (*Lupinus variicolor*), stinging phacelia (*Phacelia malvaefolia*), beach strawberry (*Fragaria chiloensis*), coast iris (*Iris longipetala*), coast onion (*Allium dichlamydeum*), Johnny-tuck (*Orthocarpus castillejoides*), coast buckwheat (*Eriogonum latifolium*), coastal rein orchid (*Habenaria elegans* var. *maritima*), and many more species.

The second group of plants from the north are those that are associated with the redwood forests of the coastal canyons. These forests are best developed in the Santa Lucia Mountains in the Big Sur River watershed, the Little Sur River watershed, and the numerous watersheds of smaller streams which feed directly to the ocean. In these moist canyons grow the coast redwood, red alder (*Alnus rubra*), licorice fern (*Polypodium glycyrrhiza*), lady fern

Some Plants in the Santa Lucia Mountains Which are Substantially Disjunct from the Nearest Populations of their Species

ADIANTACEAE (Maiden-Hair Fern Family):
- *Aspidotis densa* (Indian's dream, cliff-brake)
- *Cheilanthes gracillima* (lace fern)

APIACEAE (Parsley Family):
- *Sanicula graveolens*

APOCYNACEAE (Dogbane Family):
- *Apocynum pumilum*
- *Cycladenia humilis* var. *venusta*

ASTERACEAE (Sunflower Family):
- *Chrysothamnus nauseosus* ssp. *albicaulis* (rabbitbrush)
- *C. nauseosus* ssp. *mohavensis*
- *Calycadenia truncata*
- *C. truncata* ssp. *microcephala*
- *Hieracium argutum* var. *parishii*
- *Hulsea heterochroma* (red-rayed hulsea)
- *Madia elegans* ssp. *wheeleri*

BRASSICACEAE (Mustard Family):
- *Erysimum capitatum* (coast wallflower)
- *Streptanthus tortuosus* (mountain streptanthus)

CUPRESSACEAE (Cypress Family):
- *Calocedrus decurrens* (incense cedar)

CYPERACEAE (Sedge Family):
- *Carex multicaulis*
- *Eleocharis pauciflora*

EUPHORBIACEAE (Spurge Family):
- *Euphorbia serpyllifolia* var. *hirtula*

FABACEAE (Pea Family):
- *Lupinus sericeus*
- *Lotus argophyllus* var. *fremontii*

GROSSULARIACEAE (Gooseberry Family):
- *Ribes roezlii* (Sierra gooseberry)

JUNCACEAE (Rush Family):
- *Juncus bryoides*

LILIACEAE (Lily Family):
- *Allium burlewii*
- *Allium campanulatum* (Sierra onion)

ONAGRACEAE (Evening-Primrose Family):
- *Gayophytum heterozygum*

ORCHIDACEAE (Orchid Family):
- *Corallorhiza maculata* (coral root)

PINACEAE (Pine Family):
- *Pinus ponderosa* (ponderosa pine)
- *Pinus lambertiana* (sugar pine)

POLYGONACEAE (Buckwheat Family):
- *Eriogonum spergulinum*
- *Eriogonum nudum* var. *pauciflorum*

PYROLACEAE (Wintergreen Family):
- *Chimaphila menziesii* (western pipsissewa)

RANUNCULACEAE (Buttercup Family):
- *Thalictrum fendleri* (meadow rue)

ROSACEAE (Rose Family):
- *Holodiscus microphyllus*

SALICACEAE (Willow Family):
- *Salix melanopsis* var. *bolanderiana*

SCROPHULARIACEAE (Figwort Family):
- *Penstemon grinnellii* ssp. *scrophularioides*

SELAGINELLACEAE (Little Club-moss Family):
- *Selaginella hansenii*

VIOLACEAE (Violet Family):
- *Viola purpurea*
- *Viola lobata*

(*Athyrium filix-femina* var. *sitchense*), sword fern (*Polystichum munitum*), California shield fern (*P. californicum*), inside-out flower (*Vancouveria planipetala*), wake robin (*Trillium ovatum*), red clintonia (*Clintonia andrewsiana*), California rhododendron or rose-bay (*Rhododendron macrophyllum*), redwood sorrel (*Oxalis oregana*), redwood violet (*Viola sempervirens*), ladies' tresses (*Spiranthes porrifolia*), bleeding hearts (*Dicentra formosa*), gnome plant (*Hemitomes congestum*), and others. Except for a small grove that grows in northwestern Santa Barbara County, Douglas fir (*Pseudotsuga menziesii*) could also be included.

The third group of plants which are at their most southern distribution in this region are those which are more or less confined to the higher peaks and ridges. These are the montane species: lace fern (*Cheilanthes gracillima*), woodland madia (*Madia madioides*), mountain streptanthus (*Streptanthus tortuosus*), big-leafed sandwort (*Arenaria macrophylla*), and leafless shinleaf (*Pyrola picta forma aphylla*).

The fourth group of the northern element plants are those which are not restricted to the specialized habitats of the three preceding groups, but are more widespread, their distribution apparently determined by the "rainy belt" of the Santa Lucia Mountains. Such plants include broad-leafed aster (*Aster radulinus*), western coltsfoot (*Petasites palmatus*), rock daisy (*Erigeron petrophilus*), grand hound's tongue (*Cynoglossum grande*), Brewer's rock-cress (*Arabis breweri*), common snowberry (*Symphoricarpos rivularis*), live-forever (*Dudleya cymosa*), cow-parsnip (*Heracleum lanatum*), the gooseberries *Ribes menziesii* and *R. californicum*, white brodiaea (*Brodiaea hyacinthina*), red fescue (*Festuca rubra*), red larkspur (*Delphinium nudicaule*), alum root (*Heuchera micrantha* var. *pacifica*), yerba santa (*Eriodictyon californicum*), redwood penstemon (*Keckiella corymbosa*), and many more.

The Flavor of the South

Another group of plants which are present in the Santa Lucia Mountains are reminiscent of the hillsides of Southern California. Some of these southern element plants, like Spanish bayonet, woolly blue curls (*Trichostema lanatum*), and big-berried manzanita (*Arctostaphylos glauca*), which are widespread and conspicuous in the Santa Lucia Mountains, occur at parallel or more northern latitudes in the more

The Santa Lucia fir (*Abies bracteata*) is the rarest fir in North America, and is endemic to the Santa Lucia Mountains. It grows on two distinctly different but equally fire-resistant habitats: in deep, shady canyons; or on exposed ridgetops, bare cliffs and slopes, and rock outcrops. Its erect growth form and sharp, spire-like crown are easily recognized, even at a distance. Photograph by William Follette.

arid Inner Coast Ranges. Almost ninety species, however, do reach their most northern distribution in the Santa Lucia Mountains.

Many of these southern element plants are found along the immediate coast or coastal strand, such as coast live-forever (*Dudleya caespitosa*), the sunflower *Venegasia carpesioides*, spectacle pod (*Dithyrea maritima*), sea lavender (*Limonium californicum* var. *mexicanum*), and dune buckwheat (*Eriogonum parvifolium*). A larger group of plants that are more widespread includes species typical of many Southern California habitats, including the coastal mountains of Southern California (the Santa Ynez, Santa Monica, and Santa Ana mountains); the mesic elevations of the higher mountain ranges (the San Gabriel, San Bernardino, San Jacinto, and Cuyamacas mountains); and riparian areas.

The more widely distributed southern element plants include California lobelia (*Lobelia dunnii* var. *serrata*), California peony (*Paeonia californica*), prickly poppy (*Argemone munita*), the index "burn species" *Phacelia brachyloba*, the showy scarlet larkspur (*Delphinium cardinale*), chaparral bedstraw (*Galium angustifolium*), flannel bush (*Fremontodendron californicum* ssp. *obispoense*), bajada lupines (*Lupinus concinnus*, *L. agardhianus*), turkish rugging (*Chorizanthe staticoides*), and large-flowered coyote mint (*Monardella macrantha*). Even cacti (*Opuntia phaeacantha* or *O. occidentalis*) are present on the south-facing slopes to the east-southeast of San Luis Obispo.


The showy, saffron-orange flowers of Santa Lucia sticky monkey-flower (*Mimulus bifidus* ssp. *fasciculatus*) are a common sight in the chaparral of the Santa Lucia Mountains. Photograph by William Follette.

Exploring the Santa Lucias

With such a wealth of highly diverse, endemic, and disjunct native plants, the Santa Lucia Mountains offer an enthusiast of native Californian plants a wide selection of habitat types to explore and enjoy. California Coast Highway 1 allows relatively easy exploration of the Big Sur coast, although frequent stops and car-window botanizing may be difficult on this sometimes narrow and well-travelled road. A more leisurely exploration is possible on two dirt roads, Tassajara Road and Indians Road, which offer access to the northern and central areas of the mountains. To the south, the Nacimiento-Fergusson Road from Jolon to Highway 1 transects the range at about mid-point, and offers a car-bound explorer the best vantage of the transitions between the interior and coastal elements of the flora of the Santa Lucia Mountains. From the Nacimiento-Fergusson road, a side trip to the north up the Coast Ridge Road leads to some of the montane elements of the Santa Lucia Mountains, near the summit of Cone Peak. At this point, everywhere one looks one sees species which are either endemic to the Santa Lucia Mountains or greatly disjunct. Far to the south, Highways 46, 41, and 101 pass through the very southern, and diminished, end of the range.

Remoteness and inaccessibility have kept much of this wild mountainous area from disturbance, and access to most of the range requires hiking. For those who want to explore by foot, I suggest the twenty-seven-mile Pine Ridge Trail, from China Camp on Tassajara Road to the Forest Service Station at Big Sur. Don't go in reverse order unless you're up for the steep, 3,500 plus foot climb through chaparral from the Big Sur River to the summit of Pine Ridge!

Because there is no public transportation connecting these points, two cars are needed for this hike: park one in the parking lot at the Big Sur Forest Service Station, and drive other one to China Camp. This trail offers a wide variety of habitats, from open, grassy meadows teeming with wildflowers in the late spring to early summer, to coniferous forests of ponderosa pine, incense-cedar and the endemic Santa Lucia fir; chaparral (and fantastic views) on the steep descent down to the Big Sur River; and redwood forests along the last half of the trail, from Redwood Camp to Highway 1. I suggest giving yourself three days and two nights out. One night might be spent in idyllic Pine Valley, and the other at Sykes Camp on the Big Sur River, where you can bathe in the undeveloped hot springs, a short distance downstream. An excellent guide is a map of the Ventana Wilderness, published by the Forest Service, and I advise a call to the Forest Service Headquarters in King City in advance to find out about road and trail conditions—landslides and fallen trees can periodically block access. Whichever way you choose to travel, the Santa Lucia Mountains offer a rich opportunity to explore a dramatic landscape and discover a wide variety of native Californian plants.

David Rogers, 440 Lily Street, San Francisco, CA 94102.

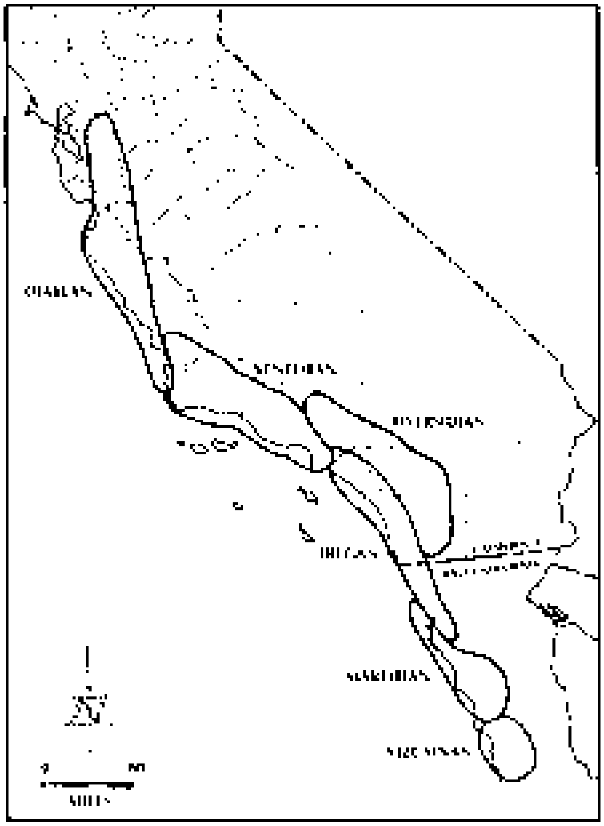
A trail on McGinty Mountain in San Diego County leading through a coastal sage scrub community. Photographs by Tom Oberbauer.

CALIFORNIA'S COASTAL SAGE SCRUB

by Sandra DeSimone

THE MILD MEDITERRANEAN-type climate that draws many people to California is characterized by warm, dry summers and cool, moist winters. Worldwide this type of climate is limited to five disjunct geographic regions: parts of California, the Mediterranean basin of Europe, central Chile, the southwestern region of South Africa, and parts of western and southern Australia. All five regions support various types of shrubland vegetation, some of which, though dissimilar in species composition, share many structural and functional similarities as a result of convergent evolution under similar selection pressures.

In California two major shrubland types are distributed within the Mediterranean-climate zone: chaparral and coastal sage scrub. Because coastal sage scrub is occasionally overlooked as a vegetation type distinct from the better known chaparral, the overview that follows includes comparative features of the two communities. Chaparral, a hard-leaved (sclerophyllous) shrubland, has analogs in all four other Mediterranean-climate regions and is one of the most extensive vegetation types in California, occupying about five percent of the total area of the state. It occurs in the Coast Ranges and foothills of the Sierra Nevada from southwestern Oregon and Northern California to the mountains of Southern California and northern Baja California, with disjunct extensions in the summer-rainfall areas of Arizona and northern Mexico. Coastal sage scrub, a soft-leaved (malacophyllous) shrubland, is similar in form and structure but not species composition to the *phrygana* in Greece, *batha* in Israel, *tomillares* in Spain, and *jaral* or *matorral* in Chile. In California coastal sage scrub is much more limited in distribution than chap-



Location of coastal Mediterranean climate shrub associations based on Westman's 1983 analysis.

arral and occurs scattered mostly along the coast from the San Francisco Bay region southward to El Rosario in Baja California, predominantly at elevations below 3,000 feet. Within the range of distributional overlap of the two shrublands, coastal sage scrub may temporarily occupy disturbed locations and generally occurs on sites with less seasonal moisture from either lower rainfall or such habitat characteristics as fine-textured soils or slope aspect. Many structural and functional features of coastal sage scrub are related to its relatively dry (xeric) habitat.

Coastal sage scrub differs dramatically from chaparral in form and structure. Chaparral vegetation averages six to nine feet in height and is usually dense and nearly impenetrable, whereas coastal sage stands are less than six feet in height and have more open canopies. Understory herbs are reduced to minimal cover in chaparral by five years after recurring fires that are typical of most Mediterranean climate regions. However, in part because of its more open canopy, there is a persistent herbaceous understory in coastal sage scrub that remains an important part of total cover (greater than twenty percent) for twenty years or more following fire.

Although coastal sage species occur in gaps in chaparral and tall, sclerophyllous leaved shrubs appear occasionally in coastal sage scrub stands, composition of the two shrublands is distinct. The predominant chaparral shrub in California is chamise (*Adenostoma fasciculatum*). On north-facing slopes, California scrub oak (*Quercus berberidifolia*) or species of manzanita (*Arctostaphylos*) and California lilac (*Ceanothus*) replace chamise. Other important widespread chaparral shrub species include toyon (*Heteromeles arbutifolia*), mountain mahogany (*Cercocarpus betuloides*), holly-leaved cherry (*Prunus ilicifolia*), and redberry (*Rhamnus crocea*). California sagebrush (*Artemisia californica*) is the most common and widespread shrub species of coastal sage scrub. Other characteristic coastal sage species are California buckwheat (*Eriogonum fasciculatum*), several sage species (white sage, *Salvia apiana*; black sage, *S. mellifera*; purple sage, *S. leucophylla*), California encelia (*Encelia californica*), brittlebush (*E. farinosa*), and San Diego sunflower (*Viguiera laciniata*). Evergreen, sclerophyllous shrubs distributed singly in coastal sage stands include laurel sumac (*Malosma laurina*) and lemonadeberry (*Rhus integrifolia*).

Physiology and phenology of chaparral and coastal sage scrub dominants are also generally quite distinct, but recent research has shown that surprising similarities exist among some species. Physiologists had once believed that coastal sage species were "drought evaders" and chaparral species were "drought tolerators." Leaves of most dominant coastal sage shrubs are partially or totally shed as the summer drought season progresses (drought evasion) in contrast to sclerophyllous, heavily cutinized leaves of chaparral shrub species that are retained year-round (drought tolerance). However, it has now been demonstrated that many coastal sage shrub dominants are seasonally dimorphic and tolerate summer drought. Such shrubs produce small summer leaves in the axils of larger main-shoot leaves that are retained through the dry season after the larger leaves have been shed and that tolerate severe water stress. Seasonal dimorphism is the most common strategy for dry season reduction of transpiring surface in the *phrygana* of Greece and has also been observed in Chilean *matorral*.

The timing of vegetative growth in both shrubland types is strongly tied to rooting depth and availability of soil moisture. Coastal sage and chaparral species (or individuals) with shallow roots respond soon after the commencement of fall rains, but deep-rooted chaparral shrubs initiate new stem growth principally in spring. Evergreen chaparral leaves photosynthesize throughout the year but at lower rates than at least the main-shoot leaves of coastal sage shrub species.

Leaves of shrub species from both chaparral and coastal sage scrub have qualities that may act to reduce herbivory. Undigestible fibers in leathery chaparral leaves as well as high concentrations of chemical compounds (tannins) that form undigestible complexes with proteins may reduce palatability to herbivores. The aromatic leaves of many coastal sage species contain a different class of chemical compounds, terpenes, which are also thought to reduce herbivory. However, researchers have found significant herbivore effects on some chaparral species, despite high tannin concentrations. Studies of the "bare zones" that are devoid of common annual species and are occasionally found at boundaries between coastal sage scrub and non-native grasslands indicate that secondary chemicals (terpenes) from the shrub leaf litter might protect shrub seedlings from herbivores.

Recurring fire is a disturbance common to Mediterranean-climate zones; both Californian shrubland types show resilience, depending on fire parameters and species life histories. A general distinction in post-fire response has been identified for chaparral shrubs between species that resprout and those that recruit seedlings after fire. In coastal sage scrub the distinction is less clear. Like the facultative resprouter *Adenostoma fasciculatum* in chaparral, many dominants in coastal sage scrub return after fire with both resprouts and seedlings depending on such factors as fire intensity and frequency, geographic location, and plant size and physiological condition.

Recent studies have shown that both chaparral and coastal sage scrub may maintain vigorous stands over extended fire-free periods. With the exception of chaparral obligate seeders, which are dependent on post-fire seedling recruitment for population maintenance or expansion, shrub species of both vegetation types continually produce new shoots from basal buds. However, seedlings of resprouting chaparral shrubs are observed only in the long absence of fire (greater than fifty years), while seedlings of coastal sage shrub species are reported in the literature to occur in stands from two to twenty-five years post-fire. Indeed, some researchers believe that continual recruitment under the relatively open shrub canopy maintains vigorous coastal sage scrub stands over long fire-free periods.

Because coastal sage scrub is generally distributed at lower elevations than chaparral, it has been subject to extensive degradation and clearing as urbanization spreads in California. As a result, there has been substantial habitat

Coastal sage scrub in bloom with the San Diego sunflower (*Viguiera laciniata*) in the foreground.

loss for a variety of animal species as well as an increased number of rare and endangered plant species. Slender-horned spineflower (*Dodecahema leptoceras*) is an endangered plant species on both state and federal lists that occurs almost exclusively in coastal sage scrub (alluvial fan subtype). Other rare species, such as many-stemmed dudleya (*Dudleya multicaulis*), also occur in several other plant communities. Biologists are currently concerned about a growing number of non-listed plant species associated with coastal sage scrub that are sensitive and declining.

Variation in Coastal Sage Scrub Vegetation

Generally, dominant life forms shift from northern to southern regions within the entire coastal sage scrub range. Evergreen, winter deciduous, and drought-deciduous species are mixed in the north. Drought deciduous species increase in importance farther south; then, near the Mexican border, there is an increase in stem succulents (in the families Cactaceae, Crassulaceae, and Euphorbiaceae).

The highly diverse nature of mature coastal sage scrub over environmental gradients at several spatial scales is reflected in various classification systems. Researchers have shown that coastal sage scrub varies floristically, not only with change in latitude and climate at the largest scale of the full coastal sage distributional range, but also with topographic features at the relatively small scale of several thousand acres. In the brief review of coastal sage scrub classification that follows, the reader will note an unfortunate absence of standardized terminology for vegetation units.

In the early 1980s the late Walter Westman sampled ninety-nine stands of mature (more than seven years post-fire) coastal sage scrub over its entire range and, after application of multivariate analytical techniques, identified two major "formations" defined by form and structure: coastal sage scrub of Alta California, dominated by drought deciduous and seasonally dimorphic species, and coastal succulent scrub of Baja California, dominated by succulents and completely deciduous species. Within these formations Westman recognized several floristically defined "associations." Associations of the coastal sage scrub formation are divided into northern coastal scrub (Diablan association) and southern coastal sage scrub (Venturan, Riversidian, and Diegan associations). Within coastal succulent scrub, there are two floristic associations: Martirian and Vizcainan. Associations reflect a geographic/climatic gradient of increasing evapotranspirative stress from northern to southern and coastal to inland sites. Westman's classification is comparable to an earlier qualitative system devised by Axelrod in 1950. Thorne's 1976 classification also includes a northern and southern division, but identifies additional island and ocean bluff associations in southern coastal sage scrub. See bluff succulent and Maritime sage scrub.

Axelrod noted in 1978 that the major geographical associations of coastal sage scrub are not designated by distinguishing species because each one includes several distinct communities whose composition depends on such factors as slope exposure, soil depth, and local climate. Several researchers have observed coastal sage variation within study areas that encompass portions of the full range. Kirkpatrick and Hutchinson (in 1977 and 1980) sampled 120 coastal sage sites between Santa Barbara and Banning in what appear to be the Venturan and Riversidian associations. They describe eleven different sub-groups (their "associations") whose distribution patterns are influenced by a gradient in mean annual range in temperature from cooler coastal locations to generally warmer inland areas, as well as by changes in elevation, aspect, and substrate. Paysen and colleagues of the U.S. Forest Service devised a vegetation classification system for the Southern California region in 1980 that recognized eight different soft chaparral (coastal sage scrub) "series" that are differentiated by dominant overstory species. Working in the Santa Ana Mountains of Southern California, Pequegnat, in 1951, noticed that "climax sagebrush is not everywhere uniform" and identified two "ecologic associations" in which overstory species shift in dominance.

During research for my master's thesis I examined coastal sage scrub distribution patterns at an even more contracted spatial scale. I sampled fifty-four sites of uniform age since fire in Venturan-Diegan transitional coastal sage scrub at 4,000-acre Starr Ranch Sanctuary in southeastern Orange County, California. Multivariate analyses, similar to methods used by Westman, revealed five vegetation groupings ("subassociations") characterized by shifts in dominance among five coastal sage shrub species and associated herbs and succulents that were related to change in aspect and soil type. It was not surprising that in topographically diverse southern California I have observed such shifts in coastal sage composition over very short (<150 feet) distances. Subdivisions of coastal sage scrub at Starr Ranch corresponded to species groupings identified by researchers working over larger study areas, which suggested the possibility of identifying dominants and associated species that consistently occur together throughout the southern coastal sage scrub.

Within the last several years biological consultants and county government agencies have also recognized the highly diverse nature of coastal sage scrub in hierarchical classification systems that include subtypes whose composition is strongly associated with localized landscape features such as slope aspect and soil type. The new classification system for California vegetation to be published by CNPS in fall 1995 includes sixteen different coastal sage series. Some series are composed of several subtypes or associations distinguished by differences in understory species. Thus, despite the absence of standardized terminology for hierarchical vegetation units, workers over the last forty years have observed that mature

Coastal sage scrub grows at Bonsall, northern San Diego County, with California sagebrush (*Artemisia californica*) in the foreground and scattered shrubs, laurel sumac (*Malosma laurina*) and lemonadeberry (*Rhus integrifolia*) in the background.

coastal sage scrub is not at all uniform at a regional (northern to southern and coastal to inland California) nor even local (north to south slope stands) scale.

Coastal sage scrub subtypes consistently identified by researchers over the years include several that are distinguished by high cover of a single species such as California sagebrush, black sage, or purple sage. In drier areas further inland in Southern California, coastal sage scrub is commonly characterized by high brittlebush cover. Along the coast, coyote brush (*Baccharus pilularis*) is often the most common shrub species.

Conservation Implications of Variation

The rapid decline of coastal sage scrub under spreading urbanization alarmed scientists as early as 1979, when Klopatek and colleagues estimated that approximately thirty-six percent of the potential area of coastal sage vegetation in California as mapped by Kuchler in 1964, had been lost. Although current quantitative estimates of habitat decline are under dispute, the imperiled nature of coastal sage scrub is reflected in the endangered and threatened status of many associated plant and animal species (about 100 rare, sensitive, threatened, or endangered listings by federal and state agencies) of which the best known is the federally listed threatened California gnatcatcher. Early studies of this tiny bird showed that it appears to be associated with certain floristic and structural coastal sage scrub subtypes in southern California, so that preservation of coastal sage community level diversity may also serve to protect animal as well as plant species associated with particular vegetation and/or physical factors.

Westman observed that the patchy occurrence of coastal sage scrub floristic groupings requires preservation of a larger total area than in more homogeneous vegetation types. He advocated maximum representation of coastal sage community level diversity in preserves by identification of recognized associations and subassociations characteristic typical of particular geographic areas. Such recognition has been facilitated by recent localized classification and mapping efforts, especially in Southern California.

The listing of the California gnatcatcher as a threatened species under the Endangered Species Act and the intense development pressures in Southern California prompted the formation of a panel of prominent scientists to draft conservation guidelines for the Natural Communities Conservation Program (NCCP), which uses coastal sage scrub as a focal community for regional preserve planning in Southern California. The guidelines, published in 1993, explicitly acknowledge that the "composition of coastal sage scrub vegetational subcommunities may vary substantially depending on physical circumstances and the successional status of the habitat." Among the basic tenets of reserve design set out by the guidelines is that reserves should be diverse and represent a range of physical and environmental conditions to protect the range of vegetational variation typical of a geographic area. The NCCP effort is still in progress in five counties in the Southern Californian region. If, in the end, the NCCP reserve design truly reflects a cooperative effort among developers, conservationists, and scientists, we will have preserved in perpetuity one of California's most unique and diverse native plant communities.

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Sandra DeSimone, Box 524, Trabuco Canyon, CA 92678

MAPS

Robert Coleman

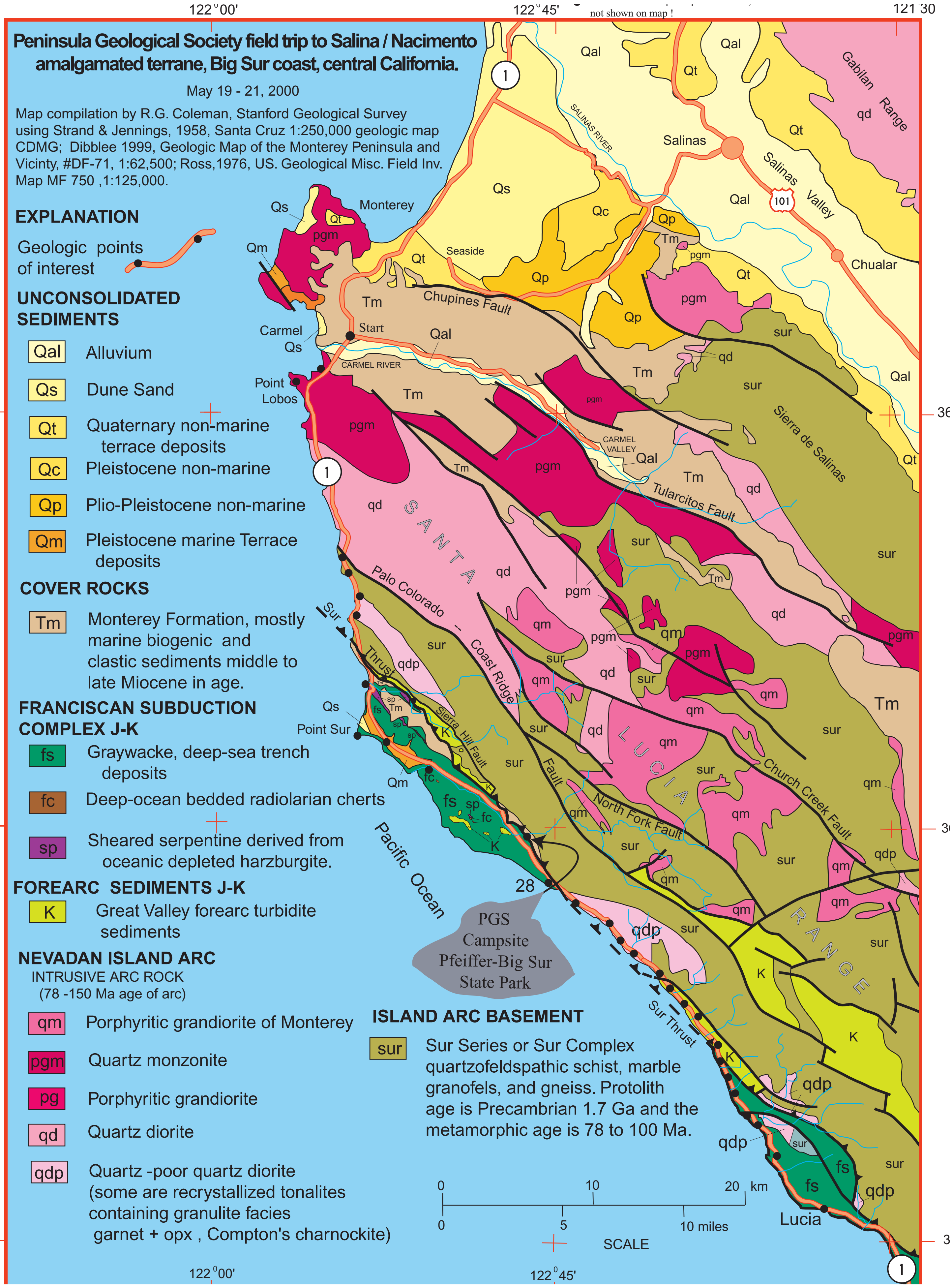
"And some rin up hill and down dale, knapping the chucky stanes to pieces wi' hammers, like sa mony road-makers run daft. they say 'tis to see how the world was made!"

Sir Walter Scott

* Start PGS field trip at Aptos overlook, Watsonville not shown on map !


122 °00'
122 °45'
122 °30'
36 °45'
36 °30'
36 °15'
MONTEREY
SATELLITE IMAGE MAP
MONTEREY, CALIFORNIA
U.S. GEOLOGICAL SURVEY
Colors generally relate to typical features as follows:
Black -- Deep clear water,shadow areas,burn scars
Dark to light blue --Ocean; shallow, turbid water; urban areas; bare soil
Gray -- Dry grassland, rock outcrops or bare soil in upland areas
Dark Red -- Mixed forest and shrub area, kelp
Bright Red -- Growing crops and pasture lands
White -- Dry crops, and stubble fields
0 5 10 km
0 5 10 mi
SCALE

not shown on map !

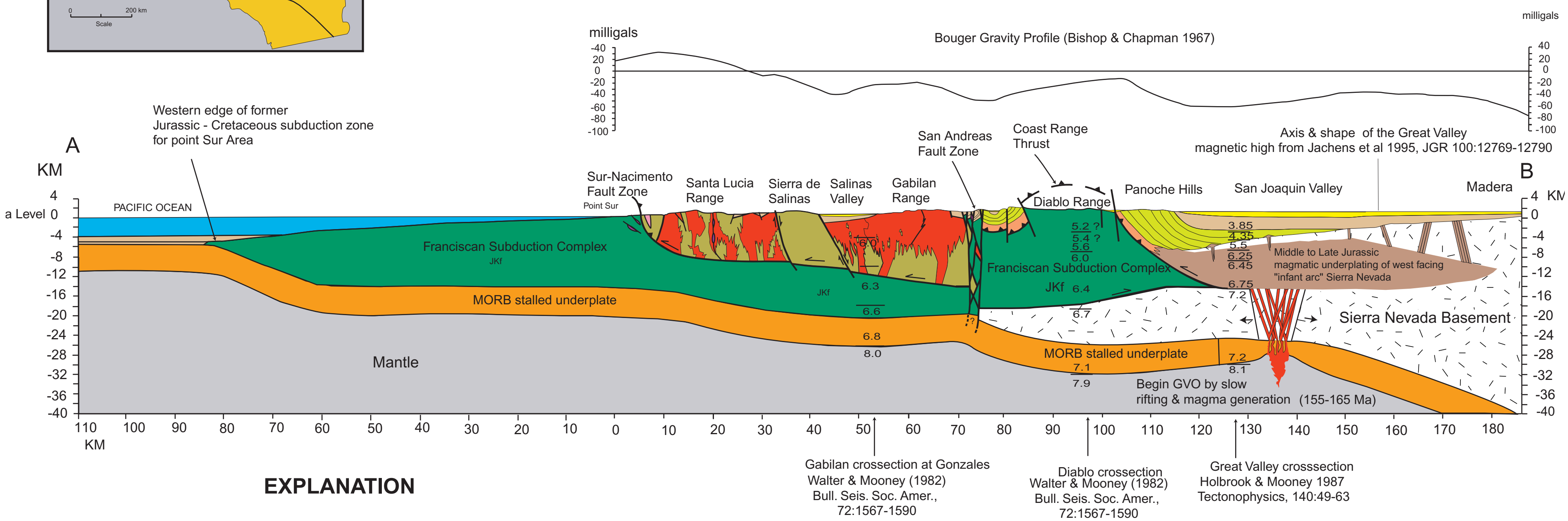


REVISED

CROSS SECTION OF THE SOUTHERN COAST RANGES AND SAN JOAQUIN VALLEY FROM OFFSHORE OF POINT SUR TO MADERA, CALIFORNIA

Donald C. Ross, U.S. Geological Survey (1979)
Geological Society of America, Map & Chart Series v. 28H
Revised by R,G, Coleman Stanford Geological Survey April 2000

Is this a step forward or backward for California Geology ?



EXPLANATION

- Quaternary & Pleistocene
- Tertiary sediments
- Fore Arc Great Valley Cretaceous-Jurassic sediments
- Coast Range ophiolite generated above suprasuduction zone Cretaceous-Jurassic
- Franciscan subduction complex, Cretaceous-Jurassic
- Tonalite — Nevadan Island Arc Intrusive granites 78 - 100 Ma
- Sur Series continental basement 1.7 Ga
- Dikes — Great Valley Ophiolite slow spreading underplating of Sierran Basement
- Mid ocean ridge basalt MORB
- Mantle, depleted harzburgite
- Slow spreading initiates partial melting in the mantle ~ 165 Ma
- Sierra Nevada Basement