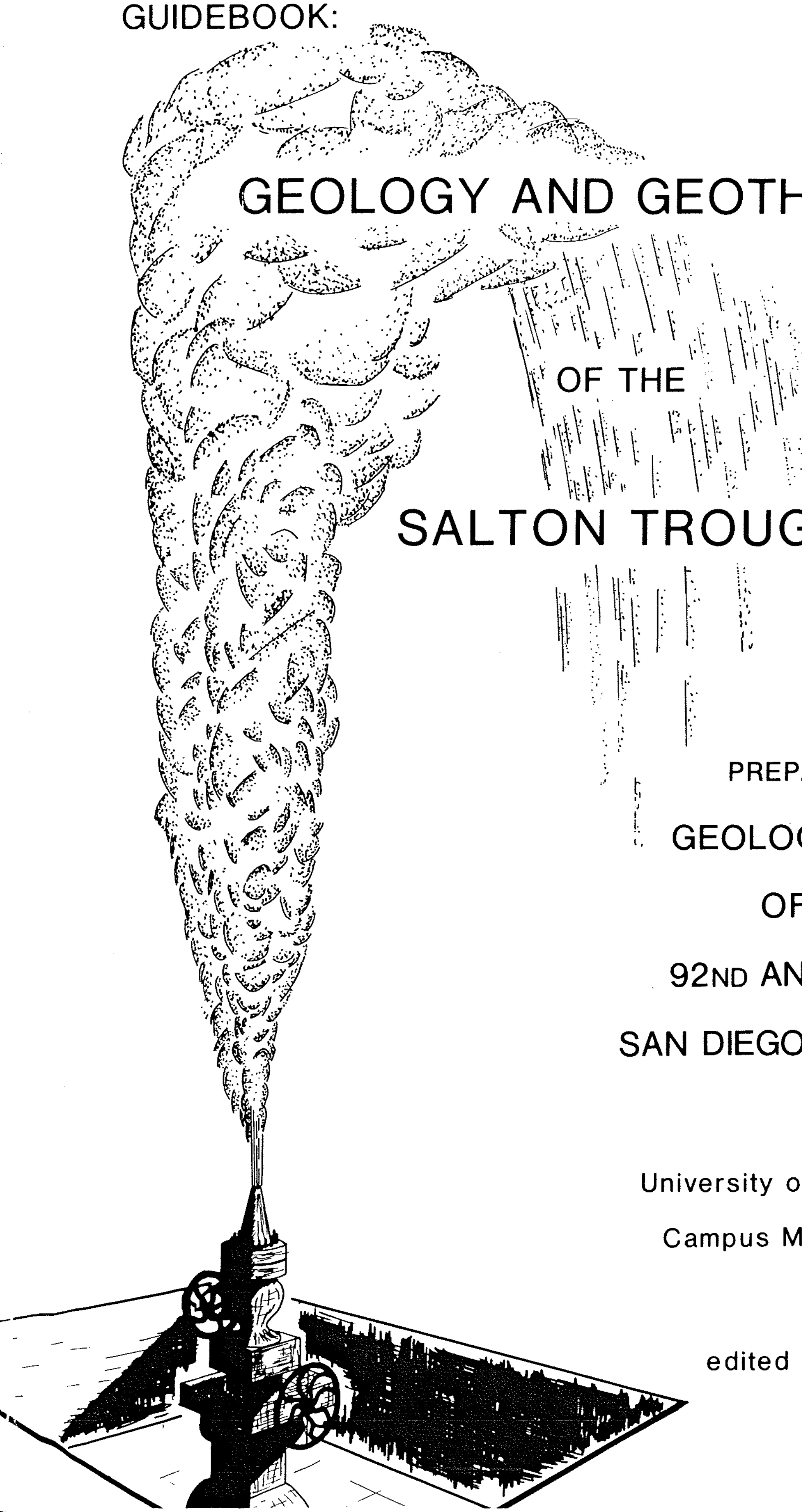
GUIDEBOOK: FIELD TRIP No. 7



GEOLOGY AND GEOTHERMICS OF THE SALTON TROUGH

PREPARED FOR THE

GEOLOGICAL SOCIETY OF AMERICA

92ND ANNUAL MEETING

SAN DIEGO, NOVEMBER, 1979

University of California, Riverside

Campus Museum Contributions

Number 5

edited by: W. A. Elders

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EDITED BY: W. A. ELDERS

FIELD TRIP LEADERS:

S. BIEHLER
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HISTORICAL PREFACE:

MAN AND THE NATURE ON THE COLORADO DELTA

"CALLIFORNIA, a large country of the Weft Indies, lying between 116° and 138° W. long. and between 23° and 46° N. lat. It is uncertain whether it be a peninfula or an ifland."

So runs the entire entry on *"Callifornia"* (sic) in the first edition of the Encyclopaedia Britannica published by a *"Society of Gentlemen"* in Edinburgh, Scotland, in 1771.

Comparisons between this and descriptions of California in modern encyclopedias exemplify the incredibly rapid growth of human settlement and of knowledge about California in the intervening two hundred years. Yet uncertainties remain. Nowhere else in North America are these uncertainties more apparent than in Alta and Baja California. The uncertainties are greatest where the struggles between man and nature are greatest. Nowhere else in North America is this struggle more intense than in the arid west, where the burgeoning population of the Californias is making ever-increasing demands upon the limited resources of the fragile desert environment.

The epitome of this struggle is to be seen in the low desert of the Colorado Delta. Here the mean annual precipitation averages between 5 and 10 cm and the average temperature for July exceeds 33°C, with maximum high temperatures of up to 51°C. Sheltered in the lee of the coastal mountains, which trap the rains of storms sweeping down the Pacific Coast, its low rainfall, high temperatures, abundant sunshine and strong drying winds make it one of the hottest and driest climates in the world.

Until the initiation of colossal irrigation schemes in the 1920's, it was also one of the most desolate regions of North America. Now irrigation has transformed the landscape. Seen from the air, the checkerboard greens of the irrigated areas end, as if slashed by a giant knife, against the browns, greys and yellows of the salt bush, creosote scrub, salinas, sand dunes, and tidal flats of the delta region. Differences in the availability of water and in irrigation practices make the international border between Alta and Baja California visible to the naked eye even at the altitude of an orbiting astronaut.

The extremes of the climate are matched by the extremes of the terrain. The delta occupies a roughly triangular depression, about 300 km long and 160 km wide, known as the Salton Trough. It is separated from the Pacific Ocean to the southwest by the Peninsular Ranges, from the Mojave Desert to the northeast by the Chuckwalla and Chocolate Mountains, and bounded to the south by the Gulf of California. The Colorado river, a river 2,250 km long which drains an area of 625,000 km^2, enters the trough at Yuma, about midway along the eastern boundary, and flows south to the Gulf. The depression is partly filled by the deposits of the delta which is divided by a purely political boundary into the Mexicali Valley to the south and the Imperial Valley to the north. Much of the Imperial Valley is occupied by a closed basin below sea level called the Salton Sink, the bottom of which lies at an elevation of 83 meters below mean sea level.

In 1539, only 47 years after Columbus' discovery of America, three Spanish ships under Francisco de Ulloa had reached the head of the Gulf of California. In the following year Melchoir Diâz followed the Gulf northward and penetrated overland into the delta region until turned back by "fields of boiling mud" (Pourade, 1971). He died accidently on the return trip. The overland route to California became known as "El Camino del Diablo - The Devil's Road."

Juan de Oñate's expedition, *en route* from New Mexico, descended part of the Colorado River to its mouth in 1605. However, in 1615 Juan de Irturbe reported that California was in fact an island, as he had sailed as far as 34° N. lat. in the isthmus which separated it from the mainland. The mapmakers fell into line, showing the "Strait of California" also opening into the Pacific to the north.(Caughey, 1970).

Undeterred by geographic uncertainties, Father Eusebio Francisco Kino, between 1698 and 1702, travelled overland between Sonora, Arizona and lower California. He saw that the peninsula and the mainland came together as a single land mass. Similarly, ignoring the doubts of the gentlemen in distant Edinburgh, the expeditions of Juan Bautista de Anza succeeded in twice crossing the Salton Trough from Sonora to Mission San Gabriel in California in 1774 and 1775 (Pourade, 1971).

Like the Israelites on their exodus from Egypt to the Promised Land, these travelers crossed the hostile desert, but no parting of the sea was necessary as Irturbe's isthmus was not found. In 1775 de Anza, at the head of a caravan of 240 people, missionaries, soldiers, muleteers, wives and children, cowboys, servants, and interpreters, with 695 horses and mules, and 302 cattle, forded the Colorado near Yuma, accompanied by crowds of Indians. Ahead of them lay a range of sand hills 85 km long, 15 km wide, the Algodones Dunes. They skirted this barrier to the south at Laguna Santa Olaya, burnt by the desert sun, and dried out by the desert wind. They crossed the Salton Trough in bitter cold, in a snowstorm which lasted several days.

De Anza called his route "El Camino de los Muertos" - "The Road of the Dead." His colonists mostly came from the semi-tropical climate of Sinaloa and Jalisco. In the bewildering climate of the Colorado Desert they had lost half their cattle and many of their pack animals, but only one member of their party.

Yet this hostile environment of the delta supported an indigenous population adapted to its conditions. In 1605, Oñate had estimated there were 22,000 Indians living along the Colorado River between its confluence with the Gila River and the Gulf (Aschmann, 1966). The Colorado River was then, and still is, the lifeblood of the region: the Nile of America. It was the key to their struggle for survival, for each year these Indians planted crops of fast-growing maize, beans and squash in the area inundated by the summer floods, as the snow melt brought silt from the mountains of the interior.

In the Imperial Valley, the part of the Salton Sink below sea level occupies a belt 140 km long and up to 48 km wide. Encircling this depression is the well-developed shoreline of a vanished body of water, first described by the early railroad surveyors (Blake, 1857). This shoreline was then thought to mark a former arm of the Gulf. However it was later shown that its elevation is approximately 12 meters above present mean sea level and that its presence records the existence of a former freshwater lake, now known as *"Lake Cahuilla"* (Buwalda and Stanton, 1930). The lake owed its existence to a period when the river flowed north, filling the Salton Sink, before spilling over a threshold in the apex of the delta and reaching the Gulf. This freshwater lake existed from about A.D. 900 to 1400 (Steere, 1952). It dried up when the river returned to its southerly course. Scattered middens, and other artifacts, along the 325 km length of the shoreline, are mute testimony to the considerable population of Indians who derived a livelihood from Lake Cahuilla (Aschmann, 1966). In the absence of a Gibbon to chronicle the *"Rise and Fall of the Cahuilla Empire"*, we can only surmise that many thousand of these Indians were forced to seek other habitable territory as the lake disappeared.

Changes in the availability of water have caused other dramatic social and economic consequences since the European settlement of the region, and will continue to do so in the future. On several occasions in the nineteenth century, flood waters of the Colorado River spilled northwards into the Salton Sink, creating temporary pastureland in the arid desert. For almost 30 years, beginning in 1859, Oliver M. Wozencraft campaigned for his idea of constructing a gravity-fed canal to bring irrigation waters from the Colorado into the basin permanently. The plan met with much skepticism. In 1857 the United States War Department had assigned the exploration of the lower Colorado to Lieutenant J. C. Ives, who succeeded in ascending the river as far as Black Canyon. His report had been discouraging for future development. He wrote in part, *"The Colorado River, last explored, is of course altogether valueless. It can be approached only from the south, and after entering it, there is nothing to do but leave. Ours was the first, and will doubtless be the last, party of whites to visit this profitless locality. It seems destined by nature that the Colorado River, along the greatest portion of its lone majestic way, shall be forever unvisited and unmolested."* (quoted in Steere, 1952). What would Juan de Oñate have thought of these assertions? The river did not remain unmolested for long. In 1898 the California Development Co., under C. R. Rockwood, was formed to irrigate the Imperial Valley. The company invited the famous irrigator George Chaffey, fresh from his labors on the Murray River in South Australia, to engineer the project. After a reconnaissance of only six weeks the route of the main canal was chosen, following the dry bed of the Alamo River, a former distributory of the Colorado (Lee, 1963).

A year later water flowed to the basin. At this time, possibly because of Chaffey's connections with the British Empire, the name *"Imperial Valley"* was chosen as being more likely to attract investment than the older name of *"Salton Sink."* Between 1900 and 1904 some 950 km of canals were constructed and 48,500 hectares came under irrigation. Settlers arrived by the thousands and Imperial County was carved out of the eastern end of San Diego county. The intake was at Hanlon Heading, just north of the international border, but the canal curved 80 km into México to skirt the Algodones Dunes, which had also caused a diversion in de Anza's *"Camino de los Muertos."* After Chaffey had left the project, in the summer of 1904, a combination of low water level in the river and silting in the canal persuaded the Company to make a new penstock 6.5 km south of the border. By that time the population of the Valley had risen to 10,000.

This skirmish in the struggle between man and nature rapidly escalated into a full scale war. Unprecedented floods in the spring of 1905 washed away the intake and control of the river was lost. By June the flood had scoured a gap in the levee 760 meters wide and 10 meters deep. Soon the full flow of the Colorado was being diverted north. The flow created the Alamo and New Rivers which rapidly incised, cutting back their channels several hundred meters a day. More than 110 km of the tracks of the Southern Pacific Railroad were destroyed and the cities of Brawley, El Centro and Mexicali were seriously threatened. The cataracts formed in the distributaries of the flood crumbled and receded upstream towards the border towns, widening and steepening as they went. The waterfall was 10-15 m high on the New River as it approached Calexico and Mexicali. Numerous buildings were undermined and collapsed into the swirling torrent, and the irrigation network so painstakingly developed was destroyed. A new Lake Cahuilla was in the making (Lee, 1963). By 1907 this new lake, *the Salton Sea*, was 65 km long by 20 km wide, with a maximum depth of 24 meters. It was rising at 16 cm a day. The California Development Co. declared bankruptcy.

Appeals to the federal government for help proved fruitless. The answer came that the source of the flood, although the product of American engineering, was in Mexico. However, President Theodore Roosevelt requested the Southern Pacific Railroad to help, and E. H. Harriman pitted the full resources of the Railroad against the river. This involved building a spur line 15 km long to the break in the levee, dumping 6,000 carloads of rock and driving 1200 piles. Over a year of effort by 2,000 laborers and a cost of $3 million were needed to close the gap and redivert the flow. Within five years evaporation caused the level of the lake to fall 7.5 meters; it sank to a level of -76 meters by 1921. It was not until 1936, after extensive litigation, that the Railroad received $1,012,655 in partial reimbursement from the government.

In 1911 the Imperial Irrigation District was formed and in 1916 it acquired the assets of the former California Development Co. from the Southern Pacific Company. The Colorado was further regulated when the U.S. Bureau of Reclamation constructed the Hoover Dam and created Lake Mead in 1934-35, at a cost of $165,000.000 By 1938 construction of three smaller flood control works the Parker, Davis and Imperial Dams downstream had completed the taming of the river. In 1942 the All-American Canal was also essentially completed. This takes water from the Imperial Dam, 30 km upstream from Yuma, and distributes it by gravity to the Imperial and Coachella Valleys, serving an irrigated area of 192,500 hectares. Similar canals have been constructed in the Mexicali Valley. Today the Salton Sea is maintained by the runoff of this irrigation.

These irrigated areas together constitute the largest single desert irrigation development in the western hemisphere. The Imperial Valley has become the fifth largest agricultural area in the U.S.A., with an annual production worth approximately $600 million. Similarly, agriculture in Mexicali Valley supports a population of close to half a million people. The desert blossoms with alfalfa and cotton and the odor of cattle feedlots pervades the air.

However, the struggle between man and nature continues with the search for Geothermal Resources. The existence of hot springs and fumaroles in the Salton Trough must certainly have been known in Pre-Columbian times. Paleoindians <u>may</u> even have witnessed eruptions of the Salton Butte volcanoes or perhaps the volcano Cerro Prieto. Our dating of these volcanoes is not yet refined enough to be sure. Perhaps the "fields of boiling mud" which turned back Melchoir Diaz in 1540 are the same we can see today at Laguna Volcano, near the Cerro Prieto geothermal field.

As long ago as 1927, the existence of boiling springs led to wells being drilled in an attempt to harness power in the Salton Sea geothermal field (Siegfried, 1925). Dry ice plants operated there from 1933 until 1954 using CO_2 from shallow wells. The encroaching waters of the lake and changing needs for refrigeration caused their abandonment. Between 1957 and 1965 twelve deep wells were drilled in this area in search of steam. However, severe corrosion and scaling problems defeated these early attempts at power production and chemical recovery (Lande, 1979).

At about this time, detailed investigations began at Cerro Prieto, which culminated in the construction of a power plant of 75MW in 1973. This was increased in size to 150MW in April 1979. Up until that date the plant had produced 3.5 billion KWH of electricity. This amount would have required the consumption of 5.5 million barrels of oil in a conventional power plant. Current plans call for increasing the installed capacity to 400MWe by 1985. Already 65 deep wells have been completed there.

Meanwhile, several cryptic geothermal fields, i.e., geothermal anomalies which lack any surface expression, had been discovered in both the Imperial and Mexicali Valleys. These new discoveries stimulated renewed activities in the Imperial Valley, where currently a total of 63 production wells have been drilled, a 10 MW plant has been completed and several others are planned. At the same time, investigations of use of geothermal brines for chemical recovery, space heating and cooling, and for process heat are underway. According to a recent estimate by the United States Geological Survey, the six identified geothermal fields in the Imperial Valley, which have reservoir temperatures greater than 150°C, could produce an aggregate of 6,800 MWe for 30 years (Brook, <u>et al</u>., 1978, p 48).

The existence of this available energy resource so close to the densely populated coastal regions of Southern California, together with rapidly escalating costs for alternative sources of energy, have intensified the struggle between man and nature. Many difficult engineering, economic and environmental problems still remain to be faced, not the least of which is the availability of cooling water for the plants. However, geothermal resource investigations in the Salton Trough are experiencing a phase of explosive growth, even with these uncertainties.

Nowhere else in the *"Peninfula of California"* is the struggle between man and nature made more manifest than on the Colorado Delta. In spite of the uncertainties, nowhere else are the rewards more clear.

W. A. Elders
U.C. Riverside
October 1979

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THE GEOLOGICAL BACKGROUND OF THE GEOTHERMAL FIELDS OF THE SALTON TROUGH

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INTRODUCTION

The physiographic province known as the Salton Trough is a fascinating but frustrating laboratory for geological inquiry. There are three main reasons why I feel a mixture of incentive and inhibition about working there. Firstly, it is one of the most accessible places where a major plate boundary can be observed on land. Here a mid-ocean ridge system changes into a "leaky" transform system and runs into a continent. It is therefore one of the most active tectonic regions of the earth. Secondly, it is on land only because of the action of a vigorous, major, exotic river, in an otherwise arid region, which deposited an enormous delta (Figure 1). The basin is the repository of the detritus eroded from the Colorado Plateau. As such it lacks the awe-inspiring drama and the exposures of the Grand Canyon of Arizona. A combination of poor exposures and hostile summer climate make it appear to be an unlikely choice of site for university professors and students to work. Any geologist working there rapidly becomes a convert to the efficacy of the ultimate geophysical tool - the drilling rig, a technique whose cost is far beyond university budgets. The third reason is that the Trough contains more than 10% of the identified hot-water hydrothermal convecting systems in Western North America. This has stimulated a large amount of geophysical exploration and drilling. However, much of this new information, at least in the Imperial Valley, is proprietary and is therefore, for good reason, unavailable to university researchers.

In spite of such problems, the newly emergent discipline of geothermics provides ample opportunities for useful and eclectic applications of geology, geophysics and geochemistry. For example, as a student I studied in the metamorphic terrain of the Precambrian of southern Norway. However, metamorphism remained for me a somewhat mysterious and remote process. In the Salton Trough it is possible to stand where greenschist metamorphism is going on only 1500 m beneath our feet. Metasomatism becomes less of a mystery when, at the turn of a valve, steam and hot water can be seen and heard flowing at forty to fifty thousand kilograms an hour.

The fifteen or so papers which follow in this guidebook, although they represent a broad spectrum of information and ideas on the geology and geothermics of the Salton Trough, also represent a biased review. They represent the results of my choice of whom to invite to contribute and the choices of those invited to participate. Consequently, due to these vagaries and to problems with releasing proprietary information, there are important omissions in this guide. For example, certain aspects of the geophysics and certain geothermal fields receive short shrift. This paper will attempt to address some of these sins of commission and omission, drawing on published sources.

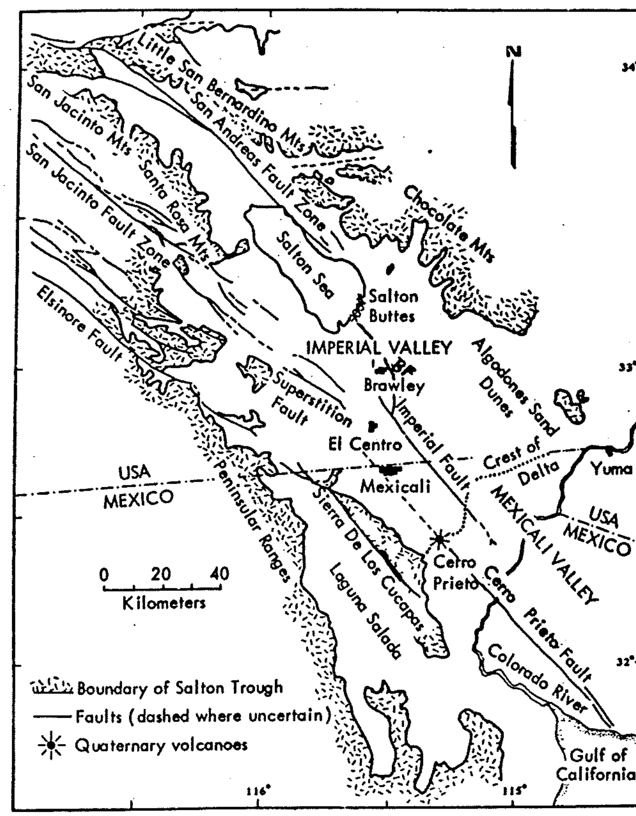

Fig.1. Index map of the Salton Trough the major faults are shown. B.F. - Brawley Fault.The dotted line shows the crest of the delta.

THE SALTON TROUGH AS A DELTA

The present apex of the Colorado River delta forms a low divide (11 m above sea level at its lowest point) between the Imperial Valley to the north and the Mexicali Valley to the south (Frontispiece). Most of the Imperial Valley lies below sea level. At its northern end is the Salton Sea, which covers about 930 km^2 and has a surface elevation of about 70 m below sea level. Water entering this basin can only escape by evaporation. The Colorado River enters the Salton Trough from the east at Yuma 43 m above sea level. The delta slopes northward (at 0.8 m/km) into the Salton Basin and southward (at ∿0.35 m/km) to the Gulf of California (Thompson, 1968). During 1905 to 1907, the Colorado flooded over the delta crest into the Salton Basin, forming the Salton Sea (Sykes, 1937; also Preface, this volume). Although the remaining natural discharge of the River is now into the Gulf of California, inflow of Colorado River water via irrigation canals permits the Salton Sea to persist.

These observations are the key to understanding the history of sedimentation in the basin. The Salton Trough is an actively growing rift valley, in which sedimentation has almost kept pace with tectonism. Formation of the delta perpendicular to the length of the Gulf of California rift has isolated the Salton Basin from the Gulf, forming a closed sedimentary basin 200 km long and up to 90 km wide. When the river flowed to the Gulf, it graded its bed to sea level. There was, therefore, a greater gradient to the north to the closed basin. In times of flood, when the river topped its levees, any distributaries which flowed north could capture the flow. Thus the basin filled until it spilled over the low point of the crest of the delta. The river then graded its bed to the elevation of the lake it had created, 11 m above sea level. At this point the gradient to south to the sea would be steeper than that to the north. Consequently in times of flood, when the river topped its levees, any distributaries which flowed south could capture the flow. Thus the delta oscillated between two metastable conditions.

Since its formation, the Salton Basin has therefore undergone cycles of filling with freshwater lakes and desiccation as the Colorado River changed course, alternately flowing north or south. Sediments from the walls of the Basin form marginal alluvial fans, but the Colorado River has dominated the sedimentary history.

The deltaic deposits consist of interbedded, poorly fossiliferous, sand, silts, clays, and pebble conglomerates (Van De Kamp, 1973). These rocks are interpersed with lake sediments and reworked eolian deposits. The percentage of sand bodies in the delta sediments decreases away from the delta apex towards the northwest (Randall, 1974). However, rather little is known of the nature and age of the sedimentary rocks in the central part of the Basin. The deepest wells yet drilled in the Mexicali and Imperial Valleys penetrate 3-4 km of apparently Pleistocene fluvatile and lacustrine sediments (Merriam and Bandy, 1965; Muffler and Doe, 1968; De la Peña and Puente, 1979, this volume).

The stratigraphy of the Neogene rocks cropping out in structurally complex zones on both sides of the Imperial Valley has been summarized by Dibblee (1954), and by Sharp (1972). Included in these formations are a few marine units, the oldest of which may be as old as Miocene. Maximum marine submergence occurred during the Pliocene, and intermittent shallow marine environments persisted in the western part of the Imperial Valley until middle Pleistocene (Woodard, 1974). Such marine rocks have not been reported from any of the numerous drill holes in the main part of the valley.

In this deltaic environment correlation of stratigraphic units in the subsurface becomes particularly difficult. Even at the outcrop, correlations are not easy because of abrupt lateral facies changes (Wagoner, 1977). The stratigraphic sections shown in Figure 2 record the changing conditions in the basin. The oldest Tertiary sedimentary units rest on the crystalline rocks, high above the basin on its western side. These are the Jacumba Gravels which are older than 19 my. According to Minch (1972), at their time of deposition stream courses apparently trended southwestward across what is now the Peninsular Ranges. The sediment source was in Sonora. Thus at that time there was neither a Gulf of California nor a Salton Trough (Gastil *et al*. 1979).

The Miocene sedimentary rocks of the Anza Formation, in the southwestern Imperial Valley, are fan deposits and conglomerates which record early nonmarine deposition in a closed basin. The Middle to Late Miocene Split Mountain and Mecca Formations, and the Pliocene Imperial Formation are arenites and mudstones which together record a major marine incursion into the basin in late Miocene to early Pliocene time. The upper part of these formations record a gradual change to continental conditions. This marine embayment apparently stretched into the area of Yuma and along the valleys of the Colorado and Gila Rivers, as the marine Bouse Formation of Arizona is apparently partly correlative with the Imperial Formation and is approximately 5 million years old (Olmsted and others, 1973). The marine embayment also stretched as far north as Whitewater in the Coachella Valley. Thus the Salton Trough was already well defined at that time.

Lucchitta (1972), in discussing the early history of the Colorado River in the Basin and Range Province, suggests that a large river, an ancestral Colorado, entered the Bouse marine embayment from the north, progressively filling it and reaching the Salton Trough. Late Cretaceous foraminifers, apparently derived from the Mancos Shale of the Colorado Plateau, have been reported from the Imperial and younger formations (Lucchitta, 1972) indicating that the ancestral river was bringing sediment into the Salton basin, occupied by sea water at that time. However, this river did not exist before 10.6 m.y. ago. As the delta continued to

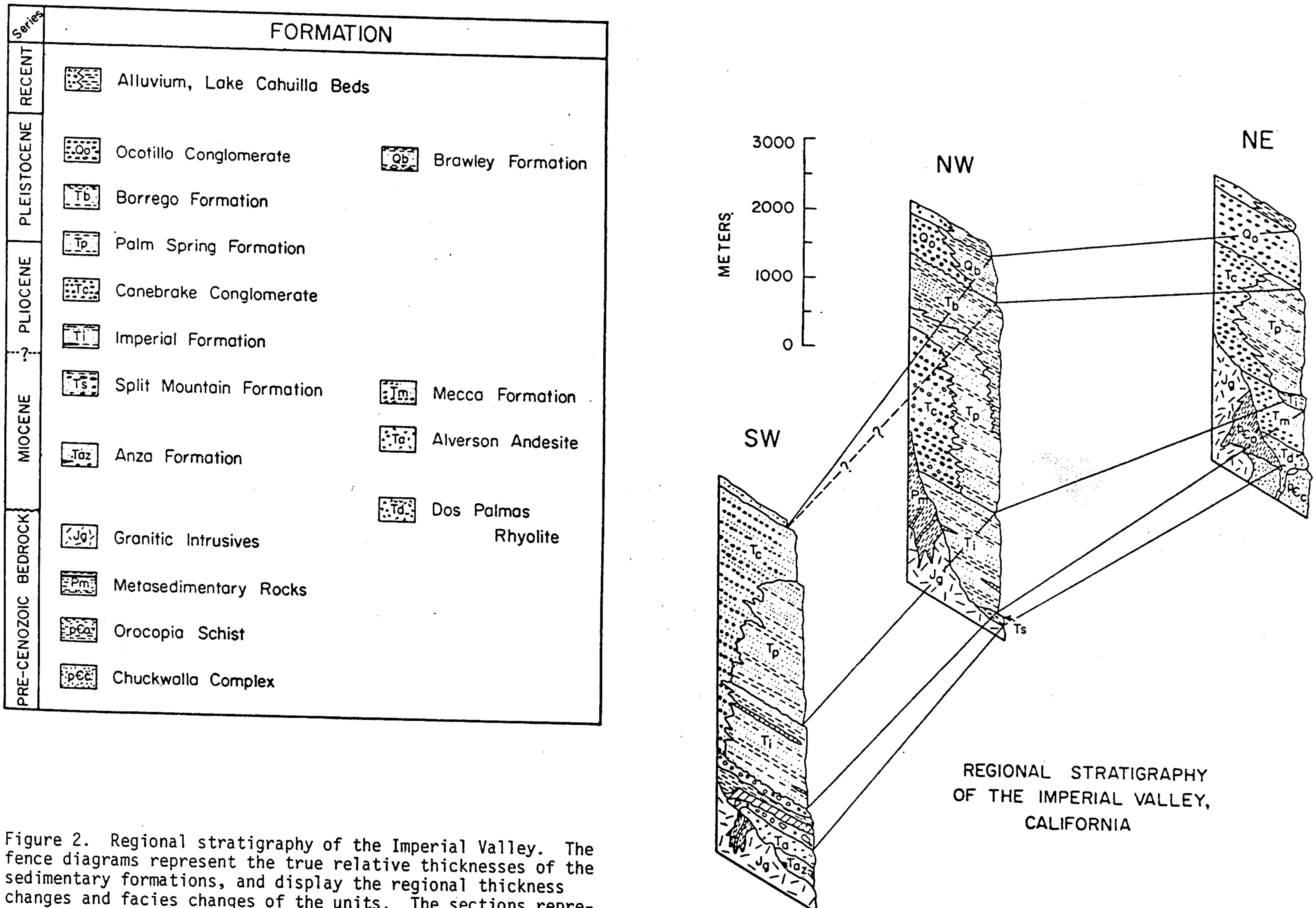

Figure 2. Regional stratigraphy of the Imperial Valley. The fence diagrams represent the true relative thicknesses of the sedimentary formations, and display the regional thickness changes and facies changes of the units. The sections represent three basic regions in the Salton basin: southwestern, northwestern, and northeastern Imperial Valley. The horizontal scale is schematic. Adapted from Dibblee (1954) and Woodward (1974), by Wagoner (1977).

fill the trough, conditions gradually changed from marine, to deltaic, to subaerial. A well developed Colorado River existed by 3.3 m.y. b.p. (Lucchitta, 1972). Since that time deposition has apparently kept pace with subsidence of the basin.

The Canebrake Conglomerate represents a coarse basin-margin facies of the Imperial and Palm Springs Formations (Figure 2) occurring mainly along the west side of the basin. The Palm Springs Formation is a fluvial and deltaic deposit formed throughout the basin, whereas the Brawley and Borrego Formations represent the lacustrine sedimentation, which was dominant in the basin during the Pleistocene, with intermittent marine incursions. The Ocotillo Conglomerate is the western terrestial basin-margin facies of these Pleistocene Formations. Finally, the Lake Cahuilla beds represent the most recent in a series of Holocene fresh to brackish water lakes which have occupied the closed Salton Basin as the river flowed north.

STRUCTURE OF THE SALTON TROUGH

The geothermal fields of the Imperial and Mexicali Valleys lie within the Colorado Delta at the head of the Gulf. The basin containing the delta, the Salton Trough, is the landward extension of the Gulf. In location, gross structure, and size it is clear that it belongs to the Gulf of California tectonic regime. In both the Gulf and the Trough, rapid tectonic deformation and patterns of high heat flow, seismicity, sedimentation, and Quaternary volcanism reflect the transition from a divergent to a transform plate boundary. They are both dominated, at present, by "leaky" transform faulting, with tensional zones developed at the ends of right-stepping en echelon strike slip faults (Elders and Biehler, 1975).

The Mexicali-Imperial Valley is a roughly triangular basin some 350 km long and 120 km wide at its southern end. It is a broad, structural trough partly filled with a vast accumulation of mainly continental sedimentary rocks of late Tertiary to Recent age, deposited by the Colorado River (Sharp, 1972). It is a complex rift valley bordered by mountains consisting of Mesozoic, and older, granitic and metamorphic rocks, with some Tertiary volcanic rocks. It has steep, step-faulted margins and a broad, relatively flat basement floor beneath a cover of sedimentary rocks 6 to 7 km thick in the center of the Imperial Valley (Biehler et al. 1964; Elders et al. 1972). These rocks are transected by three major fault systems, which trend northwest-southeast: the San Andreas, San Jacinto, and Elsinore fault zones (Figure 1). Numerous subsidiary blocks and basins are aligned along these major strike-slip faults (See Vonder Haar, 1979, Figure 1, this volume).

Seismic activity along these faults makes the Salton Trough one of the most earthquake-prone areas in North America. There have been more than 12 earthquakes of magnitude greater than 6.0 (Richter scale) in the area this century. The seismicity is characterized by both main-shock aftershock sequences and by earthquake swarms (Hileman et al. 1973; Thatcher and Brune, 1971). The earthquake of October 15th 1979 ($M = 6.4$) seems to have been of the classic mainshock - aftershock type, whereas in 1972,1975 and 1976 earthquake swarms occurred south of Brawley (Fig. 1). These swarms produced more than 1,000 small earthquakes in only a few days (Some with magnitudes of 3 or more) (Johnson and Hadley,1976).

There seems to be a pattern of major earthquakes on the major faults with swarms occurring at their ends where they step across to the next fault in the series.

All of the hypocenters observed in the Salton Trough and the Northern Gulf of California are shallower than 15 km and most originate at less than 6 km. Therefore, nearly all strain release is in the upper 10 km. Work on surface seismic-wave dispersion suggests that the crust beneath the Imperial Valley thins to about 20 km and that the crust under the northern half of the Gulf may be only 10 km thick (Thatcher et al. 1971; and in Elders and Biehler, 1975). Certainly, a large part of the regional gravity anomaly can be explained in this way.

A complete Bouguer anomaly map of the Salton trough indicates that the earth's crust is isostatically compensated south of the Salton Sea, where the valley, although underlain by 6 km of low-density sediments, is characterized by a broad gravity maximum (Biehler, 1964). Immediately north of the Salton Sea, where the thickness of sediments in the Coachella Valley is less than 3 km, the residual gravity anomaly is markedly negative, reaching a minimum of -44 milligals. A regional Bouguer anomaly map of southern California based on 28,000 gravity measurements was compiled by averaging Bouguer anomalies within 20-km squares and producing a smoothly contoured map (Figure 3).

Because features like the Imperial Valley have widths considerably in excess of 20 km, this does not remove the effect of the low-density sediments in the southern portion of the Salton trough. On the basis of basement seismic refraction, borehole, and geological data, a density model of the sediments of the Imperial Valley was constructed and used for the gravity calculation (dashed lines in Figure 3) If the effect of the low-density sediments in the Imperial Valley is removed by gravity stripping, crust-mantle models can be computed (Elders et al. 1972; see also Meidav and Howard, 1979, Figure 1, this volume).

These models indicate that the crust beneath the axis of the trough is either (i) about 8 km thinner (thickness 20 to 22 km) or (ii) of higher density (density excess 0.10 gram per cubic centimeter) than the normal continental thickness and density for the surrounding area. Combinations of these two models will also fit the gravity anomaly. These rapid lateral changes are attributed to processes that cause the crust to undergo ductile thinning and basification, becoming more oceanic in character to the south.

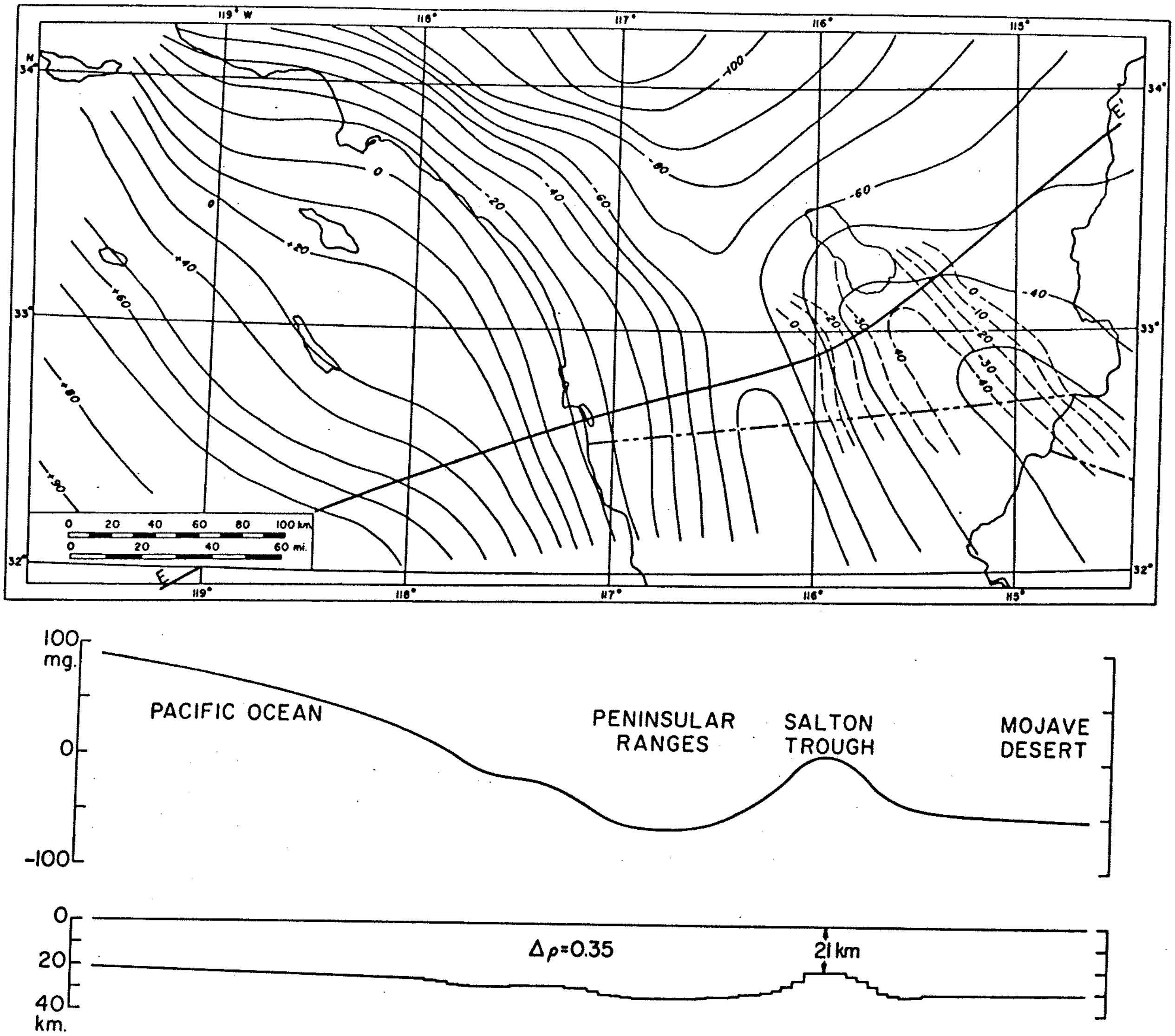

Figure 3. (A) Regional Bouguer gravity anomalies of southern California from the continental borderland to the Colorado River. The solid lines are isogal contours. The dashed lines, south of the Salton Sea, represent the gravitational effect of low-density sediments in the Imperial Valley. (B) A crust-mantle model, computed along the line *EE'* in (A), showing the thinner crust beneath the Salton trough. (After Elders et al., 1972).

HYDROTHERMAL SYSTEMS IN THE SALTON TROUGH

The Gulf of California and the Salton Trough are characterized by a high regional heat flow. In addition, the deep basins within the Gulf geothermal anomalies can have very high heat flow values, as high as 10×10^{-6} cal cm^{-2} S^{-1} (Lawver, Williams and Von Herzen, 1975). On land more than a dozen geothermal anomalies have been recognized. These include the Salton Sea, Westmoreland, Brawley, Heber, East Mesa, Dunes, Glamis, and Border geothermal fields in the Imperial Valley (See Smith, 1979, Figure 1, this volume) and the Cerro Prieto, Tulecheck, Panga de Abajo, Mesa de Andrade, Mesa de San Luis, and Desierto de Altar geothermal fields of the Mexicali Valley. Of these only the Salton Sea and Cerro Prieto fields have any surface manifestations such as hot springs and fumaroles. These two fields are also associated with Quaternary volcanoes. The remainder have been discovered by geophysical surveys, using gravity, thermal gradient and electrical resistivity measurements. The high thermal gradients are thought to be related to circulation of convecting hot groundwater in the thick sedimentary fill (Dutcher et al. 1972). These thermal anomalies coincide with low-amplitude, positive, residual-gravity anomalies with closures of 2 to 20 mgals (Elders et al. 1972).

The higher gravity near the thermal anomalies probably reflects one or both of the following: (i) increased density of the sediments due to cementation, recrystallization, and thermal metamorphism by circulating hot brines; (ii) the emplacement of higher density igneous rocks. Both have been encountered in boreholes. For example, dikes of altered rhyolite and basalt have been encountered in several boreholes in the Salton Sea Geothermal field (Robinson, Elders and Muffler, 1975). One of the wells in the Heber geothermal field also encountered a hydrothermally altered diabase dike 15 m thick (Browne, 1977).

However, a much more pervasive source of excess mass is the hydrothermal alteration of the sediments. For example, intense metamorphism of the sedimentary fill occurs in the Salton Sea geothermal field. Active formation of greenschist facies rocks is occurring at depths of 1 to 2.5 km below the surface, where the temperature ranges up to 365°C (Muffler and White, 1969; McDowell and Elders, 1979, this volume). Brines recovered from these depths contain up to 25 wt% of total dissolved solids (Helgeson, 1968). These brines contain up to 155,000 ppm of Cl, 50,500 ppm of Na, 28,000 ppm of Ca, 17,500 ppm of K, 2,200 ppm of Fe and 200 ppm of Li, 550 ppm of Zn, 100 ppm of Pb, 10 ppm of Ca and 1 ppm of Ag. Active ore formation is going on in the reservoir involving formation of, in order of decreasing abundance: pyrite, hematite, sphalerite, chalcopyrite, pyrrhotite, marcasite and galena (McKibben, 1979).

Similar geothermal gradients are encountered in the Cerro Prieto geothermal field, however the brine is much less saline. Typically it contains only 13-15,000 ppm of Cl, 7-8,000 ppm of Na, 5-600 ppm of Ca, and 1500-2,000 ppm of K. The hydrothermal minerals encountered are similar to those seen in the Salton Sea field, however the degree of recrystallization is less intense (Elders, Hoagland, McDowell and Cobo, 1979, this volume). However, in both of these geothermal fields hydrothermal alteration has a marked effect on the physical properties of the sediments, reducing porosity and increasing density. There is therefore a transition in the nature of the permeability in these reservoirs from a matrix porosity in the upper part of the reservoir to a fracture-dominated permeability at depth (Elders, 1977; Elders, Hoagland and Olson, 1978).

In terms of temperature and salinity the Brawley geothermal field appears to be intermediate between the Salton Sea field and the other identified geothermal fields of the Salton Trough. Although a dozen or so deep wells penetrate the reservoir at Brawley, little public information is available at this time. However it appears that temperatures in excess of 290°C and salinities of 100,000 ppm T.D.S. have been encountered there.

Such high temperatures and highly saline brines have not been found in the other thermal anomalies drilled to date. Temperatures from 150 to 250°C and brines containing from 3,000 to 20,000 ppm of total dissolved solids are much more characteristic. Examples from East Mesa and Heber are discussed later in this volume (Smith, 1979; Salveson, 1979). Similarly, the degree of metamorphism observed is characteristically less than that seen in rocks from the Salton Sea and Cerro Prieto fields (Hoagland and Elders, 1977).

Surface expression of these thermal anomalies is retarded by impermeable caprocks. For example, the Salton Sea geothermal field has an impermeable caprock of lacustrine clays up to 450 m thick (Helgeson, 1968; Randall, 1974). The Dunes hydrothermal system, on the other hand, has an impermeable caprock developed by self-sealing. In the upper 300 m of a 612-m deep borehole in this field, there are seven intervals of intense sandstone-to-quartzite cementation, with densities as high as 2.55 g/cm^3 and porosities as low as 3% (Elders and Bird, 1974; Bird, 1975).

VOLCANISM IN THE SALTON TROUGH

Young volcanoes at the Cerro Prieto and Salton Sea fields are apparently part of the suite of volcanic activity associated with the East Pacific Rise and the Gulf of California. The Barcena volcano in the Revillagigedo Islands on the East Pacific Rise (R in Figure 5) erupted in 1952. Basalt dredged from the deep basins and occurring on the islands in the Gulf is olivine tholeiite similar to that found on the East Pacific Rise and other ocean spreading centers (Hawkins, in Elders and Biehler, 1975; Batiza, 1977). Cores of similar basalt, together with hydrothermally altered sediments of greenschist facies, were also recently obtained by the I.P.O.D. project in the Guyamas Basin (Curray, Moore et al. 1979).

The Cerro Prieto volcano is a lithoidal, calc-alkaline rhyodacite cone, containing a few percent of andesine and pyroxene, which appears to be the product of a single eruptive cycle (Table 1). The marked lack of erosion of the cone attests to the relatively youthful age of this eruption, although it has not been precisely dated, as yet, it is known to have been magnetized in the Recent normal polarity interval and is therefore younger than 700,000 years. Such calc-alkaline rhyodacite volcanism appears to be characteristic of the Pleistocene Gulf of California (Gastil et al. 1979).

At the south end of the Salton Sea are five small extrusive rhyolite domes arranged along a northeast trend. These domes, collectively known as the Salton Buttes, were extruded onto Quaternary alluvium. A single K-Ar age determination on the westernmost dome, Obsidian Butte, gave an age of approximately 16,000 years (Muffler and White, 1969). Two of the domes, those at Red Hill, are linked by subaqueous pyroclastic deposits; the others are single extrusions with or without marginal lava flows. All of the domes consist of low-calcium, alkali rhyolite with only 1 or 2% crystals (Table 1). Similar rocks recovered from geothermal wells had been altered extensively by water-rock reactions. The fresh rhyolites are identical in composition to soda rhyolites erupted on the islands of the East Pacific Rise and have similar primitive Sr^{87}/Sr^{86} ratios (Robinson, Elders and Muffler, 1975). Basaltic rocks occur as xenoliths in the domes and as subsurface dikes, sills, or flows. Except where hydrothermally altered by brines, these rocks are also identical to low-potassium tholeiitic basalts erupted on the East Pacific Rise and on islands in the Gulf of California (Robinson, Elders and Muffler, 1975). These observations support the hypothesis that the conditions that control magma genesis under the Salton Trough and the Gulf of California are similar to those operating beneath oceanic spreading centers.

Numerous partly melted granitic xenoliths in these rhyolite domes show various degrees of either cotectic melting along quartz-feldspar boundaries or disequilibrium incongruent melting of hydrous-ferromagnesian minerals. These granite inclusions contain notably higher SiO_2, CaO, and Na_2O and lower total iron than the enclosing rhyolite. The compositions and textures of these rocks suggest that they are fragments of the basement rather than being cogenetic with the rhyolites. This bimodal basalt-rhyolite assemblage in the Salton Sea geothermal field is believed to have formed in two stages by partial fusion of mantle periodotite, forming successive rhyolitic and basaltic melts. After formation, the rhyolite magma was only slightly contaminated by continental crustal material.

A compound, positive, magnetic anomaly, only in part due to the exposed rhyolites, is associated with the Salton Sea geothermal field. A long magnetic high, 5 to 8 km wide, is centered on the southern half of the lake and extends 28 km in a northwesterly direction. Griscom and Muffler (1971) interpret this high as being due to intrusive rocks at depths greater than 2 to 2.5 km. These rocks may take the form of a stock-sized pluton or more likely a concentrated dike swarm. Also, associated with the magnetic and heat-flow anomaly is a residual-gravity anomaly of approximately +22 mgals. The amplitude of the gravity anomaly suggests a center of gravity for the excess mass at about 6 km depth (Biehler, personal communication, 1974). Therefore, there are several lines of evidence indicating that the heat source for this anomaly is an igneous intrusion.

In contrast, none of the geophysical anomalies at Cerro Prieto seem to be directly related to igneous intrusion above the basement, nor have such rocks been encountered during drilling.

TABLE 1

Chemical Analysis of Volcanic Rocks in the Salton Trough

	Cerro Prieto (Average of 2)	Obsidian Butte (Salton Sea) (Average of 5)	Basalt Xenoliths (Salton Sea) (Average of 4)
SiO_2	68.62	73.6	52.19
TiO_2	0.54	0.04	1.79
Al_2O_3	15.58	13.5	14.73
Fe_2O_3 *	5.59	2.8	9.63
MnO	0.10	0.05	0.17
MgO	0.87	0.21	6.79
CaO	4.68	0.9	10.36
Na_2O	2.73	4.5	3.57
K_2O	1.29	4.1	0.42

Source: Elders et al. (1978); Robinson, Elders and Muffler (1975).

*Total Fe

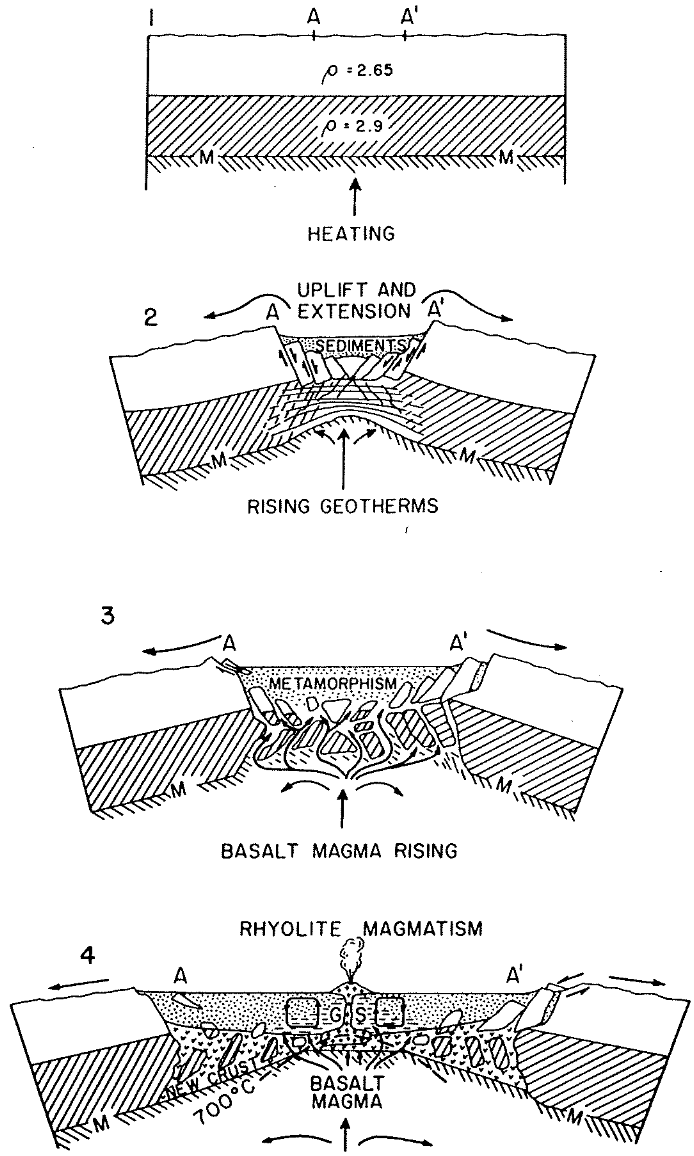

Figure 4. Model of rifting and magma generation. The sections are drawn parallel to strike-slip faults. (Stage 1) Two layers of crust overlie a hot zone in the mantle. *M*, Moho discontinuity; *A* and *A'*, reference points for later movements. (Stage 2) Upward and lateral expansion; a trough is initiated and partly filled in by sediments. (Stage 3) The widening trough is invaded by basaltic magma; metamorphism of the sediments and gravitational sliding of the tilted walls occur. (Stage 4) Melting of the basement and extrusion of rhyolitic magma. Ascending hot brines cause greenschist metamorphism *(GS)* at shallow depth.

STRUCTURAL EVOLUTION OF THE SALTON TROUGH

The Salton Trough is an example of a complex rift valley. Figure 4 is a simple two-dimensional cartoon relating rifting to the crustal thinning required by the gravity and seismic data. In the first stage, two layers of continental crust are shown before spreading was initiated. As spreading begins, hot zones in the upper mantle cause thermal expansion and metamorphism, which accompany upward extension and lateral rifting of the crust. Ductile thinning of the lower crust and brittle, tensional failure in the upper crust results in a widening trough, which receives low-density sediments. The rifting and sedimentation are contemporaneous so that older sediments are deformed and faulted and younger sediments grow progressively thicker toward the axis of the valley.

In the third stage, the rising temperatures in the upper mantle produce basaltic magma, which invades and metamorphoses the lower crust. This efficient process of heat transfer causes greater thermal metamorphism of the sedimentary pile and even more thinning of the crust away from what is now an active spreading center. Tilting of the valley walls causes gravitational sliding of the uplifted basement toward the rift valley. The basement beneath the trough is now new crust, of more oceanic type, created by intrusion of basaltic magma into the older continental crust and younger sediments.

Plumes of hot brine are largely responsible for the development of greenschist metamorphism in the sediments. When the 700°C isotherm rises high enough into the crust, granitic basement rocks begin to melt. Finally rhyolitc magma from the mantle brings up fragments of basalt, metamorphosed sediments, and granitic basement.

Whether derived from the mantle (as at Salton Sea) or from remelting of the basement (as at Cerro Prieto), magmas in the Salton Trough are generated in an environment of crustal dilation. The areal extent of the gravitational and thermal anomalies suggests that intrusions are occurring in the basement at the southern end of the Salton Sea.

These two-dimensional models deliberately ignore the important translational motions on the major transcurrent faults in the region. The cross sections are oriented parallel to and between major strike-slip faults and, therefore, oblique to the valley. If we attempt to relate the sequence to space as well as time, it might correspond to a rift valley developing progressively from south to north. In order to relate this cartoon to these faults it is necessary to consider these deformations on both large and small scales.

THE SALTON TROUGH AS A PLATE BOUNDARY

More than 50 years ago Wegener, as part of his comprehensive scheme of continental drift, proposed that the 1500 km long morphotectonic depression of the Gulf of California formed by separation of the peninsula of Baja California from mainland Mexico (Wegener, 1924). This idea remained dormant until the advent of plate tectonics when it was eagerly revived (Hamilton, 1961; Wilson, 1965; Larson et al., 1968; Moore and Buffington, 1968; Atwater, 1970; Larson, 1972; Elders et al., 1972; and Moore, 1973).

These authors regard the Gulf of California as containing a plate boundary transitional between the purely divergent East Pacific Rise to the south and the transform boundary of the San Andreas Fault System to the north (Figure 5).

Paleontological evidence suggests that the Gulf of California has existed for the last 15 million years. Marine foraminifera of late Miocene to early Pliocene age attest to the existence of deep water in the Gulf from 11 to 6 million years ago (Ingle, 1973; and in Elders and Biehler, 1975). At this time the Gulf may have been about two-thirds its present size, having formed as a volcano-tectonic rift zone similar to the rifts commonly formed behind island arc-trench systems (Karig and Jensky, 1972).

The mechanism responsible for the formation of this proto-Gulf is not clear. We can also ask in what way is the modern Gulf related to strike-slip faulting? This problem was discussed by Carey (1958) who, before the theory of plate tectonics was formulated, coined the term "rhombochasm" to describe the tensional gap formed between en echelon pairs of strike-slip faults (Figure 6A). The "spreading centers" postulated in the Gulf of California (see Figure 6) fit this model remarkably well as they coincide with submarine depressions. The idea is particularly appealing in the case of the southern part of the gulf, where marine geophysical surveys have revealed numerous young topographic depressions in the Gulf floor (Figure 5) bounded by seismically active faults. These closed basins have heat flows several times the crustal average, have positive gravity anomalies of up to +80 mgal, and appear to have been produced by active movement along en echelon fault segments (Moore, 1973). At the mouth of the Gulf, south of the Tamayo fracture zone, spreading on the East Pacific Rise has proceeded at 5.5 cm a year for the last 4.5 million years (Larson, 1972; Atwater and Molnar, 1973).

Because the Gulf does not lie on the small circle about the pole of rotation for the current relative motions between the North American and Pacific Plates (according to Minster et al., 1974 at 50·9°N and 66·3°W), new crust is being generated in the Gulf along a "leaky" transform system. The development of this transform fault system and the rhombochasms (or pull-apart basins in the terminology of Crowell, 1974) appears to date from the time when the Riviera triple junction, between the East Pacific Rise, Rivera Fracture Zone and Middle America Trench, achieved its present configuration 5 million years (Atwater, 1970; Garfunkle, 1973; Crowell, 1979).

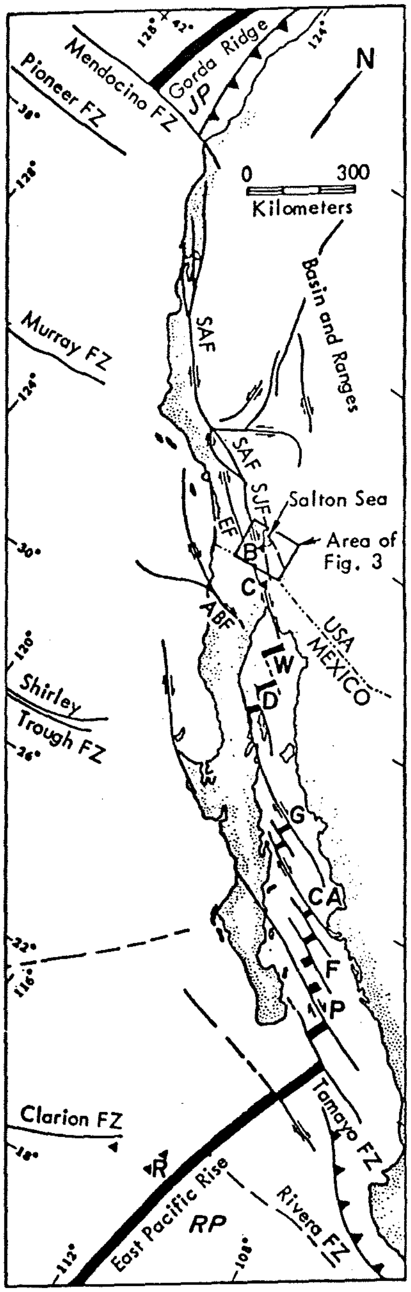

Figure 5. Gross tectonic environment of the Salton Trough. The Pacific Coast of North America is dominated by transform fault systems, which connect the Mendocino triple junction to the Rivera triple junction. Also shown are pull-apart basins between <u>en echelon</u> fault segments in the Gulf of California. Oceanic fracture zones (FZ) and continental faults (F) are solid black lines, dashed where uncertain. Other abbreviations: SAF = San Andreas Fault; EF = Elsinore Fault; SJF = San Jacinto Fault; ABF = Agua Blanca Fault; JP = Juan de Fucca Plate; RP = Rivera Plate; W = Wagner Basin; D = Delfin Basin; G = Guaymas Basin; CA = Carmen Basin; F = Farallon Basin; P = Pescadero Basin; ▲ = Holocene volcanoes; B = Salton Buttes; C = Cerro Prieto; and R = Revillagigedo. From Elders, <u>et al</u>., 1972, Lawver and Williams, 1979, and Dickinson and Snyder, 1979.

Lomitz et al. (1970) and Elders et al. (1972) both suggested that this pattern of transform faults and "pull-apart" basins persists further north into the Salton Trough. However, on land the basins were filled as rapidly as they formed by the deltaic sedimentation (Figure 6). Garfunkel (in Rex et al., 1972) suggests that depressed areas on either side of the apex of the Colorado River delta may be subtle expressions of such tectonic subsidence that have not been obliterated by sedimentation. The en echelon arrangement of the western boundary of the Imperial Valley, with its numerous low embayments, also supports this idea. Figure 7B shows a possible arrangement of tension "pull-apart" basins, compression zones, and strike-slip faults. As an explanation of the numerous active faults diverging northwest from the Salton Trough, Lomnitz et al. (1970) suggested that rates of spreading on individual "spreading centers" decrease progressively northward. Elders et al. (1972) pointed out the consequences of such a model (Figure 6A). If spreading centers X, Y, and Z have velocities of spreading V_1, V_2, and V_3, respectively, the velocity of movement on the fault DC is $(V_1 + V_2)$, but on the extension of this fault CC' it is only $(V_1 - V_2)$. As indicated in Figure 6A, this model of faulting and rhombochasms has a complementary system of left-lateral faults to the southeast. To our knowledge, such a system of left-lateral faults has not been reported either in the Gulf of California or in Sonora.

On the other hand, if we argue that the crustal block lying south and east of the faults (block 2 in Figure 6A) is fixed in position and is not deformed by faults AA', DD', FF', and HH', the spreading centers X, Y, and Z must migrate away from it at velocities V_1, V_2, and V_3, respectively. If V_1 is greater than V_2 and V_2 is greater than V_3, as suggested by Lomnitz et al. (1970), then CD and EF become shorter, and when X and Y overtake Z the pattern becomes en echelon in the opposite sense. This would cause compressional zones between the faults instead of rhombochasms. Several zones of intense folding of Tertiary sediments are known in the Imperial Valley and they appear to have some such genetic relationship to strike-slip faulting, i.e., they appear to form where right-lateral strike-slip faults are en echelon to the left rather than to the right (Garfunkel, in Rex et al., 1971).

The simple conceptual model which we proposed in 1972, shown in Figure 6B, is only one of many possible hypotheses for local patterns of spreading, which might be related in a complex way to the overall relative motion of the lithosphere and asthenosphere in this region. In view of the youth of the valley and the rapidity of its growth, unstable and transient movement patterns are also to be expected.

Since this model was proposed, further insight into the tectonics of the region has come from three sources, i.e., geodetic surveying, further studies in the Gulf, and study of earthquake swarms in both the Gulf and in the Salton Trough.

NEOTECTONICS IN THE SALTON TROUGH

The crust of the Salton Trough is being actively deformed even while you read this guidebook. One way of attempting to determine the tectonic evolution of the basin is to begin by understanding these contemporaneous deformations. Since triangulations began in 1931, there appears to have been several meters of differential, right-lateral movement in the southern part of the Imperial Valley. Similarly, there have been downward level changes of tens of centimeters during this period. The most notable deformations of the survey net are associated with the 1940 El Centro earthquake on the Imperial Fault (M_L = 7.1). Clearly, the Imperial Valley as a whole is undergoing right-lateral horizontal motion and the center is subsiding relative to the walls by steady creep, punctuated by earthquake activity (Elders et al., 1972).

Precise geodetic surveys since 1972 (Lofgren, 1979, this volume) have shown that the land surface of the Imperial Valley sinks as much as 3.5 cm per year relative to the walls. This bussidence is causing a deepening of the trough and a regional tilt from the International Border northward towards the Salton Sea. The contours of elevation change parallel the topographic contours, suggesting that these changes are long-term and are related to the tectonism which formed the Trough (Lofgren, 1979, this volume). Now that the damming of the Colorado River is preventing the entry of sediment into the basin, growth of the delta has ceased. If a subsidence rate of 1 cm/year is maintained in the future, the Gulf will re-enter the basin in only 1200 years.

A recent study by Wilson and Wood (1979) extended this work by using the Salton Sea as a tiltmeter. They examined water-level records from three gauges in the lake. Two gauges at opposite ends of the lake 38 km apart have data on level over a 26-year period. For a 15-year period (1952-1967) there was a steady tilt down to the southeast, at a rate of 0.13 microradians/year. The rate then increased until 1972 when the direction of tilt reversed. The events beginning in late 1972 correspond in timing with the onset of the Southern California uplift, or Palmdale Bulge (Castle et al., 1977). Wilson and Wood (1979) point out that these tilts occur over different time scales. The shoreline of a late Pleistocene lake which predated Lake Cahuilla is reported to have been deformed by downtilting to the southeast, resulting in an elevation change of 35 meters over a length of 24 km (Stanley, 1966). Furthermore, the basement/sediment contact dips southeast from the Salton Sea, towards the International Border (Rex et al., 1971). Thus the short-term tilt direction determined by Lofgren appears to be opposite to the long term direction. If this is true, the present location of the Salton Sea is due to the delta prograding to the northwest more rapidly than the tilting to the southeast occurred.

Two studies of horizontal strains in the Salton Trough have recently appeared. Thatcher (1979) has reinterpreted the data derived from repeated triangulation surveys in 1941, 1954 and 1967 of a

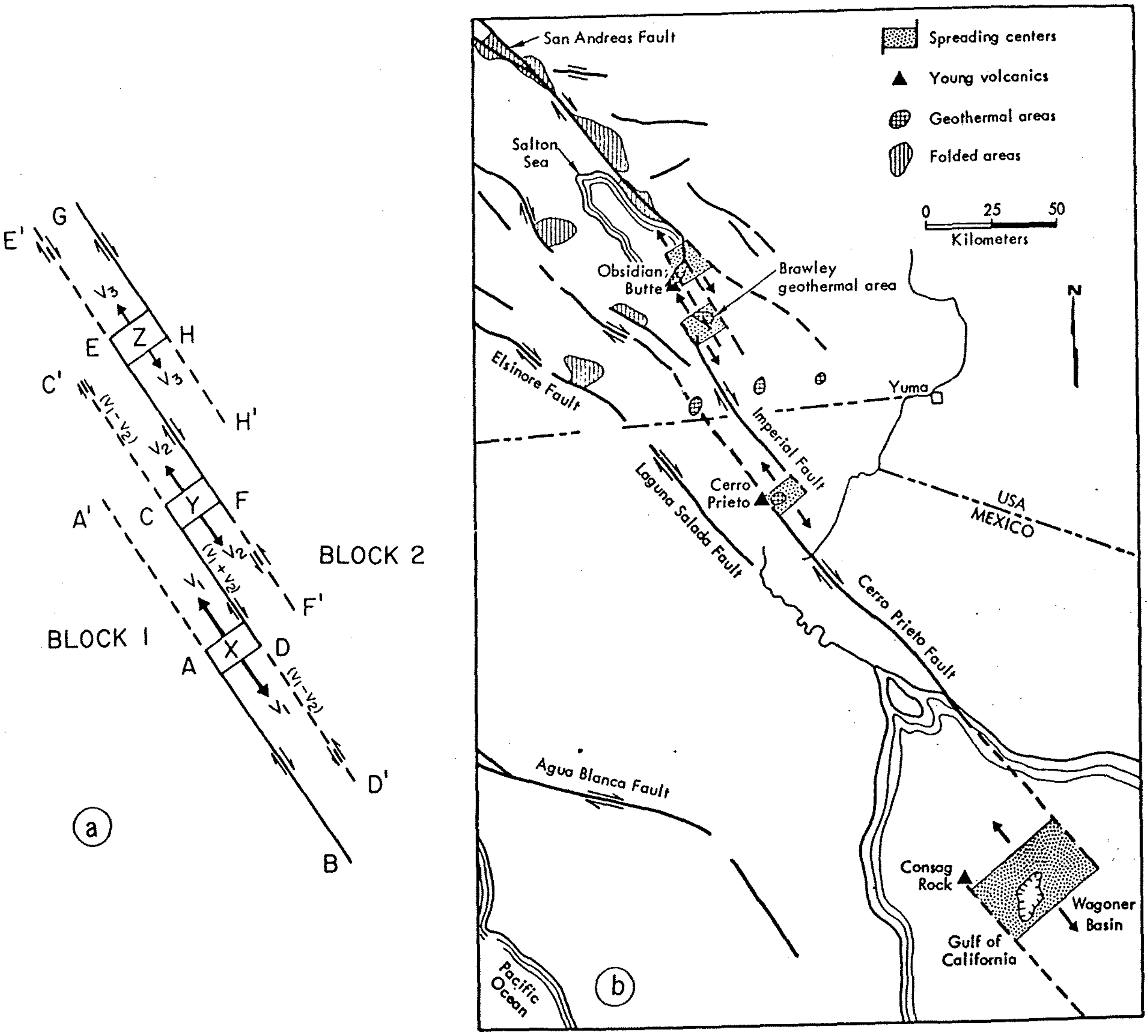

Figure 6. Possible relations between strike-slip (transform) faults and pull-apart basins in the Salton Trough. (a) Tensional zones or rhombochasms between en echelon strike-slip faults. *X, Y,* and *Z* are spreading centers between faults *AB, CD, EF,* and *GH,* with right-lateral motion. If these faults were en echelon in the opposite sense, compression would result between them. V_1, V_2, and V_3 are the spreading velocities on *X, Y,* and *Z,* respectively. If these velocities are unequal, the pattern is unstable. (See text) (b) Possible relationship between pull-apart basins and strike-slip faulting in the Salton Trough. Postulated "spreading centers" or tensional zones, young volcanics, geothermal areas, and zones of intense folding and compression in Tertiary sediments are indicated. (Source: Elders, et al., 1972.)

network established in 1934. The 1934-1941 interval included the El Centro earthquake of 1940 referred to above. The shear strain for this interval can best be explained by 4 m of right-lateral strike-slip motion, to a depth of 10 km, along 55 km of the Imperial Fault. Evidently, the slippage at depth was significantly greater than the observed surface offsets.

In the interval 1941-1954 there was a very regular pattern of right-lateral shear strain parallel to the trend of the local faults amounting to 8.2±1.1 cm/yr of relative displacement across the Imperial Valley. Thus the post-seismic shear strain is quite large and exceeds significantly the coseismic strain. These data can only be adequately explained by assuming that there was a broad zone of episodic post-earthquake strain resulting in several meters of buried slip on the San Andreas, Brawley and Imperial Faults. However, this post-seismic recovery did not persist after 1954 (Thatcher, 1979).

Savage et al. (1979) have extended this study to involve the period 1973-1977 using a new trilateration network across the San Andreas, San Jacinto and Elsinore Faults in the vicinity of the Salton Trough. During this period there were no important earthquakes within the net. The deformation observed appears to be uniform in the time interval observed, as can be illustrated by showing average relative velocities for stations in the network. According to Savage et al. (1979) these velocities are not due to a simple rigid-body rotation, but the increase in relative velocity to the southwest is due to accumulation of shear strain across the northwest trending faults. The velocities tend to be parallel to the axis of the Trough (about N 30° W) rather than parallel to the strike of the fault system (about N 45° W). The total relative motion across the Trough was 5 cm/year. Analysis of the overall strain between 1973-1977 indicates that it was essentially a uniaxial north-south contraction of about 0.3 ppm/yr with no significant strain perpendicular to the axis of the Trough. The strain profile transverse to the Trough shows maximum strains occurring along the trace of the San Jacinto fault, suggesting that it may be more important, at present, than the Elsinore and the Banning-Mission Creek branch of the San Andreas Fault System. Savage et al. (1979) point out that sum of the deep slip vectors on the San Andreas and San Jacinto Faults is about 42 mm/yr and that sum of the deep slip on the Elsinore and Imperial Faults is 53 mm/yr, both of which are close to the relative motion between the North American and Pacific Plates (Atwater and Molnar, 1973).

"SPREADING" IN THE GULF OF CALIFORNIA

Study of the deep basins in the Gulf of California gives a great deal of insight into the recent deformation of the Salton Trough (Henyey and Bischoff, 1973; Bischoff and Henyey, 1974; Lawver and Williams, 1979). In contrast is the typical spreading centers of the mid-ocean ridges, these are depressions rather than rises. Similarly, in contrast to ocean spreading centers, sedimentation is at a high rate and volcanic activity is meager. Similarly paired magnetic anomalies typical of sea floor spreading are lacking (Lawver and Williams, 1979).

The Guaymas Basin appears to be typical of the deep basins in the central and southern part of the Gulf (Figure 7). This basin has a pair of axial rift valleys oriented N 40° E, 3-4 km wide and up to 400 m deep, apparently offset by a transform fault 20 km long (Bischoff and Henyey, 1974; Lonsdale, 1978). Long seismically active transform faults connect the outer ends of these axial troughs with similar troughs in the San Pedro Martir and Carmen Basins, respectively northwest and southeast of the Guaymas Basin (Figure 5). The presence of a fairly thick sediment blanket has an important effect on heat flow. This causes heat flow values measured in a 30 km wide zone to have fairly uniform values of 4 HFU. Such young oceanic crust (4 m.y.) should in theory have a heat flow of 11 HFU, restricted to a much narrower zone. The conclusion is therefore that hydrothermal circulation is an important part of the heat flow (Lawver and Williams, 1979). Hydrothermal deposits were encountered in dives by a deep submersible along the wall of the northern trough (Lonsdale, 1978). Deep-sea drilling by the Glomar Challenger (Curray, Moore et al., 1979) has confirmed this. Drilling at sites 477, 478 and 481 of leg 64 of I.P.O.D. encountered doleritic sills and dikes which had been emplaced into soft, wet, young sediments. Extensive hydrothermal alteration to greenschist facies was encountered in site 477 in response to recent intrusions and a minor amount in site 481. Rates of sediment accumulation were high at all three sites, exceeding 1,200 m per million years, i.e., 1.2 cm/yr (Curray and Moore, 1979).

The detailed topography observed in the troughs of the Guayamas Basin revealed young fault scarps, defining grabens, which expose a 100 m thickness of older pelagic sediments (Lonsdale, 1978). Pillow basalts and other basaltic landforms were not observed in these troughs, in contrast to the situation on the East Pacific Rise. The principal geomorphic effect of the transform faults which terminate the axial troughs appears to be rock slides from the continental margins (Lonsdale, 1978).

EARTHQUAKE SWARMS AND THE SALTON TROUGH

Evidence that the Guaymas basin is actively forming comes from earthquake activity. Reichle (1975) reports an earthquake swarm in the northern basin in 1972 and main-shock after-shock sequence on the Guayamos-Carmen transform in 1974 (Figure 7).

Moving north to the Wagner Basin (W in Figure 5) the northernmost of the closed basins in the Gulf of California, Thatcher and Brune (1971) have described an earthquake swarm that occurred in 1969. Over 70 shocks, with magnitudes of between 4.0 and 5.5 (Richter scale), occurred during a 6-hr period. At the same time, there appeared to be a sympathetic coupling with earthquakes in the next basin to the south, the Delfin Basin (D in Figure 5), suggesting that these two basins are also related by transform faulting.

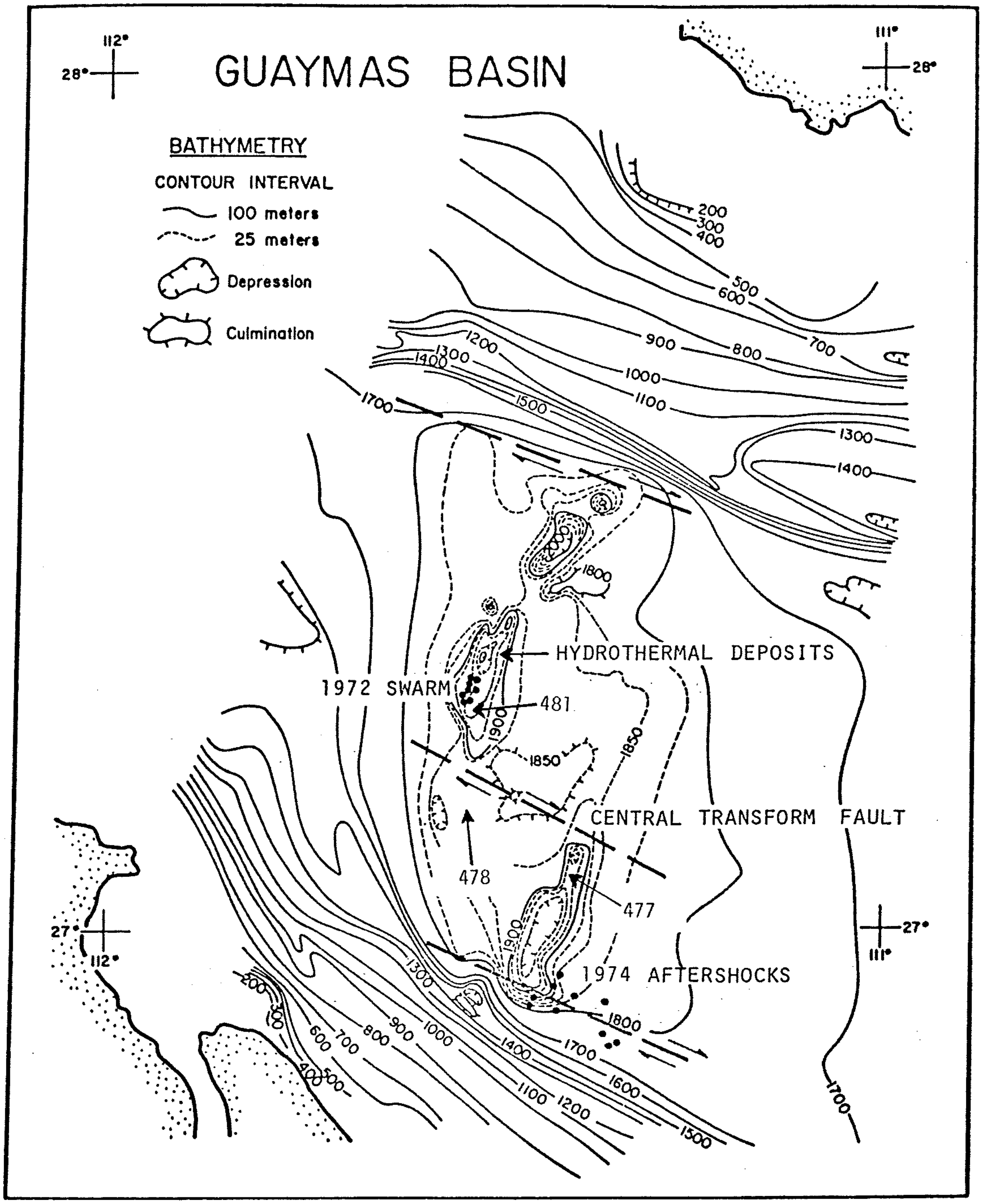

Figure 7. Bathymetry and tectonics of the Guaymas Basin, showing location of hydrothermal and seismic activity and Deep Sea Drilling sites, 477, 478, and 481 (Adapted from Bischoff and Henyey, 1974, Lonsdale, 1978, and Curray, Moore, et al., 1979)

Seismic coupling between the Wagner Basin and the Cerro Prieto "pull apart" zone has not yet been demonstrated. However, the Cerro Prieto fault is one of the most active in the region (see Figure 3 of de la Peña and Puente. C., 1979, this volume).

Furthermore, this zone between the ends of the Cerro Prieto and Imperial Faults is one of high seismic activity (see Figure of Vonder Haar and Puente C., 1979, this volume). The geothermal field of Cerro Prieto is clearly associated with this tensional zone as postulated by Lomnitz et al. (1970) and Elders et al. (1972). I find it an attractive idea to think of it being in a dynamic situation similar to the southern trough of the Guayanas Basin. However continued sedimentation has prevented a topographic depression from forming yet. There is however, ample evidence for the formation of fault blocks along NE-SW normal faults (de la Peña and Puente, 1979, and Vonder Haar and Puente, 1979, this volume).

Both the Brawley and Salton Sea geothermal fields occur between en echelon faults and both have associated earthquake swarms.

Intense earthquake swarms occurred at the ends of the Imperial and Brawley faults in a series of four earthquake swarms between 20 June and 17 July 1973 (Hill et al., 1975), another in January-February 1975 (Johnson and Hadley, 1976; Sharp, 1976), and another in November 1976 (Fuis and Schnapp, 1977). Hill (1977) and Weaver and Hill (1978) have discussed the implications of these swarms for crustal extension (Figure 8). These studies have shown that the earthquakes tend to fall on sets of conjugate planes oriented either parallel or perpendicular to the Brawley and Imperial Faults. Most of the focal mechanisms were strike-slip but others were dilational. Sharp (1976) showed that the area between the offset faults is a slight topographic depression bounded by normal fault scarps striking N-S (Figure 8). In the 1975 swarm displacements of tens of centimeters occurred on the easternmost of these.

Hill (1977) proposed a model for these swarms in which local extension occurs in the regional direction of least principal stress. This may occur if dikes are intruded with their long dimension parallel to the regional greatest principal stress. The earthquake swarms occur as a sequence of shear failures along oblique planes conjugate to the principal stress directions. Johnson (1977) has found a similar result.

Finally, earthquake activity in the Salton Sea Geothermal Field in 1975 was also of the swarm type. Based on microseismic activity Gilpin and Lee (1978) suggested that the Brawley fault, at its northern end, is offset into two segments connected by a leaky transform fault. Once more the crustal spreading is also reflected by normal faulting and crustal shearing by strike-slip faulting.

CONCLUSIONS

Any model of the Salton Trough - Gulf of California rift system might attempt to explain the following aspects of the geology and geophysics: (i) the youth of the trough, (ii) active right-lateral, strike-slip faulting, (iii) many large areas of anomalous high-temperature gradients, (iv) volcanic episodes suggestive of two different mechanisms of magma generation, (v) rapid lateral change in the geophysical properties of the crust from north to south, (vi) gravity models suggestive of thinning of the crust from 30 km in the north to a maximum of 22 km in the south with apparent up-welling of the mantle, (vii) geodetic measurements, and (viii) seismic studies.

The model proposed in Figure 6, with appropriate modifications as suggested by Figure 8, in which "pull apart" basins occur at the ends of right-stepping, dextral transcurrent faults, still seems applicable. These pull apart structures may occur in widely different scales. Two examples with roughly similar scale are the Brawley gap (Figure 8), which appears to have opened about 10-15 km, and the Guayamas gap which has troughs each about 5 km wide, but a total width of 20 km if we count the central transform fault (Figure 7). One difference between these two gaps is that the width of the Brawley gap represents slightly more than half the crustal thickness, whereas the Guayamas gaps may represent spreading which is up to twice the crustal thickness at that point. Perhaps this accounts for some of the difference between these two structures.

Other differences could be due to the difference in sedimentation rates and in their relative ages. If we accept the simple kinematic model of Figure 6A the spreading rate of the Brawley gap would be the sum of the deep slip vectors on the Imperial and Brawley faults. Savage et al. (1979) gave a value of 46±21 mm/yr on the Imperial Fault and Thatcher (1979) reports a geodetic value of 5 mm/year for creep on the Brawley fault. This implies a half spreading rate of about 2.5±1 cm/yr (V in Figure 7A). This would require between 1 million and 450,000 years to form the gap. If we assume that the slip on the pair of faults forming the Guayamas Basin is equal to the relative motion of the North American and the Pacific Plates (i.e., 5.5 cm/year) then the half spreading rate is about 11 cm/year. This implies the Guayamas Basin had only about 200,000 years to form. Presumably the gap at the Salton Sea field is bigger and older and is partly occupied by new crust, the source of the gravity and magnetic anomalies. However these pull apart gaps are clearly younger than the age of the onset of spreading at the mouth of the Gulf.

It is noticeable, however, that the hottest geothermal fields (Salton Sea - 365°, Cerro Prieto - 350°C, and Brawley - 295°C), are all situated in young pull apart zones. The other geothermal fields

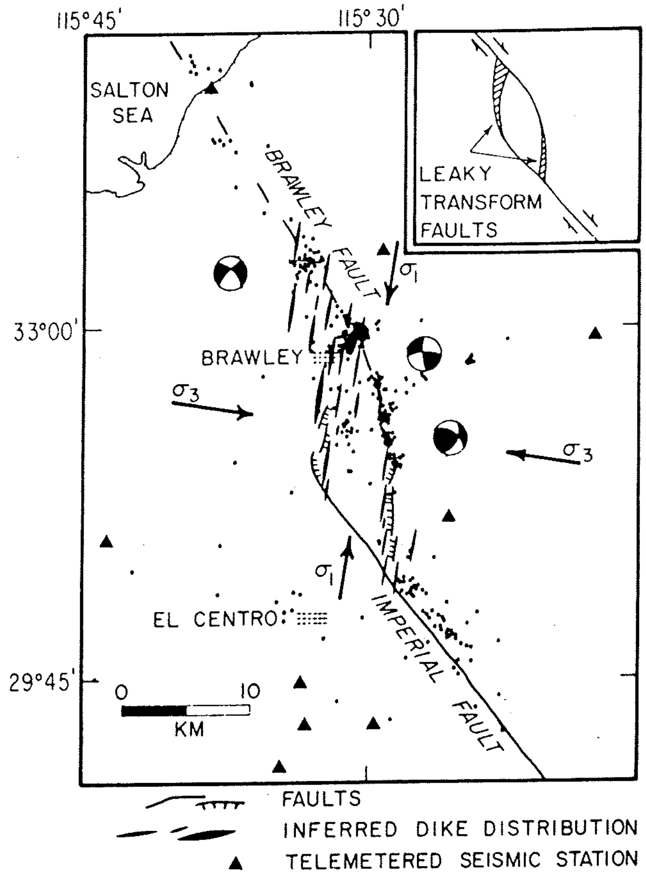

Figure 8. Map of the central part of the Imperial Valley, showing epicenters for the earthquake swarms in June 1973 (Hill et al., 1975) and January 1975 (Johnson and Hadley, 1976). Hachures indicate down-dropped side of normal faults (Sharp, 1976). Focal spheres illustrate typical fault plane solutions, with darkened quadrants representing compressions, white quadrants dilations. Insert suggests an overall pattern where inferred dikes are intruded into the leaky transform system. (Figure is from Hill, 1977).

On October 15, 1979, at 4:16 pm, a damaging earthquake (M_L = 6.4) was centered approximately 16 km east of Calexico on the Imperial Fault. This was followed by an aftershock swarm with magnitudes up to 5.0. The M = 7.1 earthquake of 1940 produced 2 meters of offset. If seismic slip has proceeded at 4 m/year since that time, we might expect 1.5m of offset produced by this new earthquake. At the time of writing (October 16, 1979) few details are available.

such as Heber and East Mesa are associated with the less active extensions of the transform faults ("half faults", e.g. C'-C and D-D' in Figure 6A). Perhaps this type of thermal feature owes its existence merely to deep circulation of water into open faults rather than to intrusion of dikes into the sediments.

It is obvious that the gaps seen at Salton Sea, Brawley and Cerro Prieto are in themselves insufficient to explain the crustal dilation of the Trough in the last 4.5 million years. A spreading rate of 5.5 cm/year should have produced 250 km of offset in that time. Many more such tensional zones may have existed or be in the process of formation, arranged in tandem and in parallel, as a series of pull apart structures and blocks, i.e., rhombgrabens and rhombhorsts. For example, Laguna Salada is a good candidate for such a rhombgraben, or pull apart structure. Several other basins with internal drainage along the west side of the Trough appear to have similar configurations. Perhaps the loci of extension are relatively short-lived and spreading jumps from place to place as the fault pattern changes. We also need to explain the change of strike of the faults from the N 45° W of the San Jacinto to the N 30° W of the Imperial Fault. There remain many other unanswered questions which the rapid pace of geological, geochemical and geophysical studies in the area are now addressing.

ACKNOWLEDGEMENTS

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THE GEOTHERMAL FIELD OF CERRO PRIETO*
(EL CAMPO GEOTERMICO DE CERRO PRIETO)

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ABSTRACT

The geothermal zone of Cerro Prieto is situated in the State of Baja California, Mexico, and is, at present, the principal field utilizing natural steam for the generation of electrical energy in Latin America. The installed capacity in 1979 is 150MWe and by 1986 is is estimated that the production will be 400 MWe.

The area of production is located 28.6 km south of the city of Mexicali. The region is topographically flat and semi-desert, and has been principally formed by the sediments deposited by the flow of the Colorado River, which empties into the Gulf of California.

To the northwest of the geothermal field is found the only topographic prominence within the valley, called the volcano of Cerro Prieto, from which the geothermal field gets its name. This volcano has a rhyodacitic composition and is of Pleistocene age. West of the volcano the main topographic elevations occur, the closest being the Sierra de los Cucapás, of predominantly granitic composition, with minor amounts of metasedimentary and metamorphic rocks.

Geologically the Mexicali Valley is a delta formed mainly by sediments deposited by the flow of the Colorado River. These sediments of Cenozoic age were only partly penetrated during the drilling of the well Prian 1, which attained a depth of 3,500 m, without reaching the basement. Their maximum thickness has been proved indirectly, by seismic reflection, to be more than 4,750 m at a point 2 km to the northeast of the present production field, between the settlements of Patzcuaro and Oaxaca.

In the geothermal zone of Cerro Prieto and its surroundings, various different methods of investigation have been applied: gravity, magnetics, geoelectricity (dipole-dipole and Schlumberger), spontaneous potential, magnetotellurics, passive seismics, remote sensing, ground noise, seismic refraction and reflection, and mercury prospecting.

To date, the indirect methods which have provided the best information on the buried structures have been, in order of importance, seismic reflection and refraction, gravity and magnetics. However, none of these methods has yet been successful in locating the deep zones, where the aquifers of hot water are likely to be found. The four geophysical methods referred to above have provided data on the buried sedimentary and igneous structures. These data, when correlated with the information obtained from the wells already completed, such as lithology, temperature gradients, electric logs, geochemistry, etc., have helped us to determine the locations of explorations wells such as M-93, T-366 and NL-1 with very satisfactory results. As a consequence the known extent of the geothermal field of Cerro Prieto has been expanded by an area of approximately 7km^2 to the southeast and east of the present operating geothermal electric plant.

Tectonically, the field is located in one of the southeast branches of the fault system called the San Andreas. The principal faults which dominate in this zone, the Cerro Prieto and Imperial faults, with a NW-SE strike, form a tectonic complex of transform type and, as a consequence, a spreading center which has given rise to eruption of the volcano Cerro Prieto, the formation of the geothermal field, deep topographic depressions and constant evidence of earth movements (earthquake swarms).

ABSTRACTO

La zona geotérmica de Cerro Prieto, se localiza en el estado de Baja California, México y es en la actualidad el principal campo de explotación de vapor endógeno para la generación de energía eléctrica en Latinoamérica, 150MW en 1979, y para 1986 se estima que la producción sea de 400MW.

El área de explotación se localiza a 28.6 Km al Sur de la ciudad de Mexicali. La región es topográficamente plana y semidesertica, ha sido conformada principalmente por los sedimentos depositados por las corrientes del Rio Colorado, las que desembocan en el Golfo de California.

Al NW del campo geotérmico se localiza la única prominencia topográfica dentro del valle, denominada volcán de Cerro Prieto del que se ha originado el nombre para el campo geotérmico;

*Translated from the original Spanish by the editor.

dicho volcán, es de composición riodacítica y de edad Pleistocénica. Hacia el W del volcán se presentan las principales elevaciones topográficas, siendo lo más cercana, la Sierra de los Cucapás de composición predominantemente granítica y en menor proporción rocas metasedimentarias y metamórficas.

Geológicamente el valle de Mexicali, es un delta formado principalmente por sedimentos depositados por las corrientes del Rio Colorado, dichos sedimentos de Edad Cenozoica, han sido cortados en parte, mediante la perforación del pozo Prian 1, comprobándose espesores hasta de 3500m sin haber llegado al basamento e indirectamente mediante la sísmica de reflexión un espesor de más de 4,750m. detectandose este a 3 Km al NE del campo actual de explotación, entre los ejidos Patzcuaro y Oaxaca.

En la zona geotérmica de Cerro Prieto y sus alrededores se han aplicado diferentes métodos de investigación: gravimetría, magnetometría, geoelectricdad (dipolo-dipolo y Schlumberger), potencial espontáneo, magnetotelúrico, sísmica pasiva, percepción remota, ground noise, sísmica de refracción, de reflexión y prospección mercurial.

A la fecha los métodos indirectos que han proporcionada mejor información de las estructuras sepultadas, han sido en orden de importancia, sísmica de reflexión, de refracción, gravimetría y magnetotemetría. Con ninguno de ellos ha sido posible localizar al presente las probables zonas profundas, donde se encuentran los acuíferos de agua caliente. Los 4 métodos geofísicos antes mencionados, han proporcionado datos de las estructuras sedimentarias e ígneas sepultados, los que correlacionados con la información obtenida mediante los pozos ya construídos como: lithología, registros de temperatura, registros eléctricos, geoquímica, etc., nos han ayudada para determinar los sitios de los pozos exploratorios, como el M-93, T-366 y NL-1 conresultados muy satisfactorios y debido a ello el campo geotérmico de Cerro Prieto se ha expandido en un área aproximada de 7 Km^2 hacia el SE y E de la actual planta geotermoeléctrica en operación.

Tectónicamente, el campo se localiza en uno de los ramales del sistema sureste de fallas denominado San Andrés, siendo las fallas principales que gobiernan en esta zona, las de Cerro Prieto e Imperial, de rumbo predominante NW-SE, las que forman el complejo tectónico del tipo transforme y como consecuencia un centro de dispersión que ha dado origen a la emisión del volcán de Cerro Prieto, la formación del campo geotérmico, depresiones topográficas produndas y la constante evidencia de movimientos telúricos (enjambres de temblores).

INTRODUCTION

The Republic of Mexico is a country which is formed geologically by rocks from Precambrian to the most Recent. The sedimentary rocks containing our principal deposits of petroleum and coal are in the east and southeast of the country. In the central part of Mexico a conspicuous volcanic belt occurs, which runs NW-SE from the Pacific Ocean to the Gulf of Mexico, called the Neovolcanic Axis. This volcanic belt contains the majority of the hydrothermal surface manifestations of the Republic of Mexico, which comprises a total of approximately 130 geothermal zones (Figure 1). Of these, only two geothermal fields are being developed at present; these are, in order of importance with respect to generation of electrical energy, Cerro Prieto, B.D., 150,000KWe in 1979 and 400,000KWe by 1985; and Los Azufres in the State of Michoacán with 30,000KWe by 1983. Another field in which electrical energy was generated was Pathé in the State of Hidalgo, with 3500KWe in 1961 (Figure 1).

LOCATION

The geothermal field of Cerro Prieto is located 28.6 km SE of the City of Mexicali, B.D., between the meridians of 114°40 and 115°33' longitude west of Greenwich and between the parallels 31°55' and 32°44' north latitude, on the deltaic plain of the Colorado River. The volcano Cerro Prieto forms a point of reference adjacent to the production field.

GENERAL SURFACE GEOLOGY

The zone is found restricted to areas formed by the valley fill, and to the vicinity of igneous intrusive and volcanic bodies, metasedimentary rocks, and metamorphics. Only a brief, very generalized description, beginning with the oldest rocks to the most recent, will be given (Figure 2).

Prebatholithic Rocks. They are represented by metasedimentary rocks: mudstones, limestones, sandstones and conglomerates (Hirsch, 1926; Bernard, 1968; both *in* Gastil *et al*. 1975) and metamorphics: marble, gneiss and schists (McEldowney, 1970; *in* Gastil *et al*. 1975), which are assigned a Mesozoic age and in some cases are probably Paleozoic (metasedimentary belt). These rocks occur in the Sierra de los Cucapás, Sierra del Mayor and the Sierra Pinta, to the west and south, respectively, of the geothermal field of Cerro Prieto.

Batholithic Rocks. The best examples of these intrusive rocks are near the geothermal field of Cerro Prieto, and form the greater part of the Sierra de los Cucapás and Sierra del Mayor; they are principally granitic and tonalitic rock types. A Cretaceous age of between 102 to 119 million years has been measured for these plutonic rocks (Silver and Banks, 1969; *in* Gastil *et al*. 1975).

Post-Batholithic Volcanic and Sedimentary Rocks. The volcanic rocks consist mainly of andesites, rhyolites and dacites of Miocene-Pliocene age (Krummenacher and others, 1969; McEldowney, 1970; both *in* Gastil *et al*. 1975), which occur only in the Sierra Pinta, 75 km south of the geothermal zone of Cerro Prieto. The rhyodacite volcano of Cerro Prieto is of Pleistocene-Holocene age

(Bernard, 1968; Robinson and Elders, 1971; both in Gastil et al. 1975).

The deltaic sediments of continental origin which formed the Mexicali Valley occur in the eastern part of the Cerro del Centinela, Sierra de los Cucapás and Sierra del Mayor. To the east they extend as far as the Mesa de Sonora (Desierto de Altar), to the north and northeast they form the Imperial Valley and East Mesa in the United States of America, and to the south they are interrupted by the waters which form the Gulf of California. To the west of the geothermal zone of Cerro Prieto, deposits of sands and gravels occur, which form the alluvial fans of the Sierra de los Cucapás.

TECTONICS

This portion of the American continent has been of interest to various researchers specializing in plate tectonics, principally due to the behavior and activity of the San Andreas Fault (Figure 3).

Various workers (Lomnitz et al. 1970; Elders et al. 1972) have postulated a tectonic model for this region to explain the behavior of the major fault blocks, their movements and the consequences derived from time; for this they applied the mechanics which governs transform faults and their secondary effects (Figure 4). At present, and in accord with the earlier postulates and with the latest results obtained from seismic reflection studies (H. Fonseca, personal communication, 1979), we believe that the tectonics affecting the rock masses in this region of the Mexicali Valley is effectively a type of transform faulting with right-lateral movements. These movements have also caused secondary faults trending oblique to the principal faults. The major faults we have termed the NW-SE Cerro Prieto system, and the oblique secondary faults we have termed the NE-SW Volcano system (Puente and de la Peña, 1978). The Cerro Prieto system generally occurs with strike-slip displacement and the Volcano fault system tends to occur en echelon with downthrow to the southeast.

RESULTS OF EXPLORATION AND SUBSURFACE STUDIES

The production field is situated over a sequence of Cenozoic, continental deltaic sediments (Figure 5). These have been penetrated to date by 65 wells drilled for the location and exploitation of aquifers of hot water.

Attempts made by study of lithology, paleontology, petrography and electric logs to correlate index horizons, have proved impossible because of the interdigitation of the sediments and their lenticular nature, and because of tectonic and metamorphic effects. Only by means of electric logs have the production zones been correlated (Abril and Noble, 1978) (Figure 6).

Because of the impossibility of making correlatings of layers or similar strata, we decided to divide the deltaic sequence into unconsolidated sediments, termed "Unit A" (UA), formed of clays, muds, sands and gravels in non-uniform sequence, and consolidated sediments which we termed "Unit B" (UB), consisting of shales and sandstones, also in an irregular sequence; these last overlie unconformably the granitic basement, "Unit C" (UC). This determination was made on the basis of analysis of samples of cores and drill cuttings obtained since 1977 (Puente and de la Peña, 1977). The cross sections produced using the criteria mentioned were compared with the results obtained from seismic refraction (Calderón, 1964) (Figure 7). A reasonable concordance is observed between the depth of the contact between UA/UB and UC, with the seismic velocities of each lithological unit. The sediments of unit UA have seismic velocities between 1,750 and 2,750 m/sec., the consolidated sediments have seismic velocities between 3,100 and 4,300 m/sec., and unit UC (basement) has velocities between 5,000 and 5,700 m/sec.

The information obtained on the basis of correlations between UA and UB was used in siting the exploration wells NL-1, M93 and T-366; the results have been very satisfactory. Due to the success obtained in these wells (temperatures greater than 340°C at depths between 2,500 and 3,350 m), the area of the geothermal field has increased approximately 7 km^2, principally towards the southeast and east of the geothermal electric plant currently in operation.

On the basis of this distinction of petrological separation, we have developed several geologic sections, of which we are showing only four here (Figures 8, 9, 10, 11 and 12). These sections cut the most important structural features yet known in the geothermal field of Cerro Prieto.

It has been estimated that the thickness of the deltaic sediments (UA and UB) in the old production zone (M-9 to M-10, section CC', Figure 9) is between 2,500 m and 3,000 m and towards the east and southeast of the operating geothermal electric plant it is between 3,500 and 4,500 m.

The depth of the production zones varies according to the position of the contact between units A and B (Puente and de la Peña, 1978) because some of the aquifers of hot water with potential for industrial exploitation are found as shallow as 1,000 to 1,300 m, intermediate ones are between 1,300 and 1,700 m, and the deepest are between 1,700 and 3,350 m.

The configuration of the contact between the lithological units A and B substantially conforms to that of the basement (Fonseca, 1979, Figures 13 and 14). This indicates that the tectonic effects which have displaced the basement are reflected, although in minor scale, in the consolidated deposits of Unit B, which have various differences of level. There is a 100 m difference in level of Unit B in wells M-20 and M-8, 220 m difference between wells M-46 and M-48, 510 m difference between M-10 and M-123, and up to 900 m between the levels in M-51 and M-92. In contrast, in Unit C are found much greater differences of level, in much shorter distances, for example, at the power plant the basement is located at a depth of 2,750 m, but it falls to a depth of more than 4,750 m near Hildago (Figure 13). This drop represents a pronounced inclination. These depressions of the basement detected by seismic reflection (Figure 13) up to 5,000 m in depth and those parts of the basal rock closest to the surface, which are between 1,500 and 2,500 m depth, represent significant secondary effects of the mechanism which generally governs the process of transform faulting.

Another important characteristic which can be appreciated in the configuration of the basement is that the deep zones coincide with negative gravity anomalies. Furthermore it is very noticeable how the uplifted blocks are aligned preferentially with a NW-SE direction, localizing them in the area west of the railway, in contrast the subterranean deep basins occur to the east and southeast.

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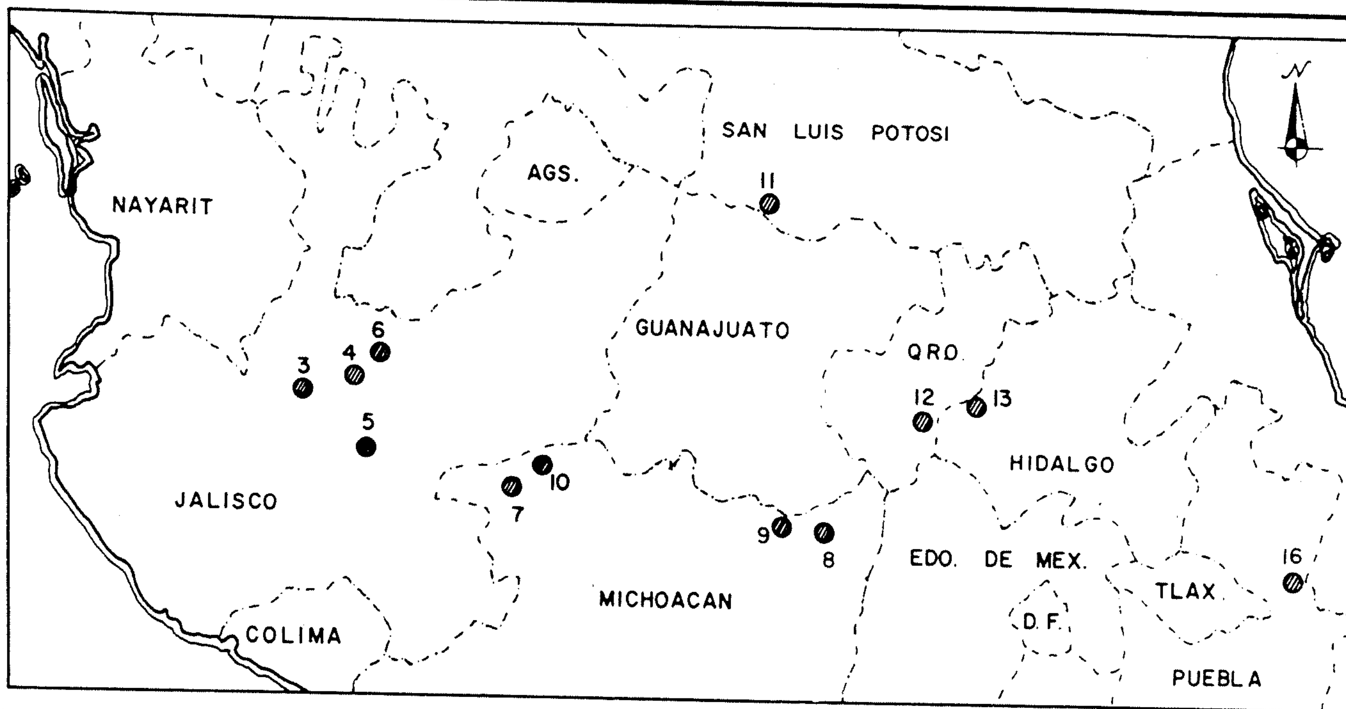
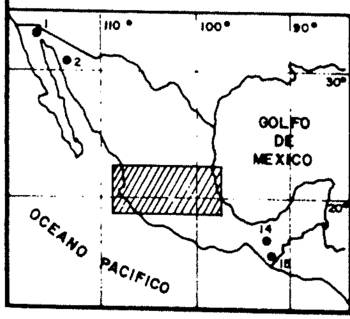




1- CERRO PRIETO, B C N
2- DESIERTO DE ALTAR, SON
3- HERVORES DE LA VEGA, JAL
4- LA PRIMAVERA, JAL
5- SAN MARCOS, JAL
6- LA SOLEDAD, JAL
7- LOS NEGRITOS, MICH
8- LOS AZUFRES, MICH.
9- LAGO DE CUITZEO Y ARARO, MICH
10- IXTLAN DE LOS HERVORES, MICH
11- EL GOGORRON, S L P
12- SAN BARTOLO, QRO
13- PATHE, HGO
14- EL CHICHONAL, CHIS
15- TOLIMAN, CHIS
16- LOS HUMEROS, PUE

Figure 1:
Location of the most important Geothermal Fields of the Republic of Mexico.

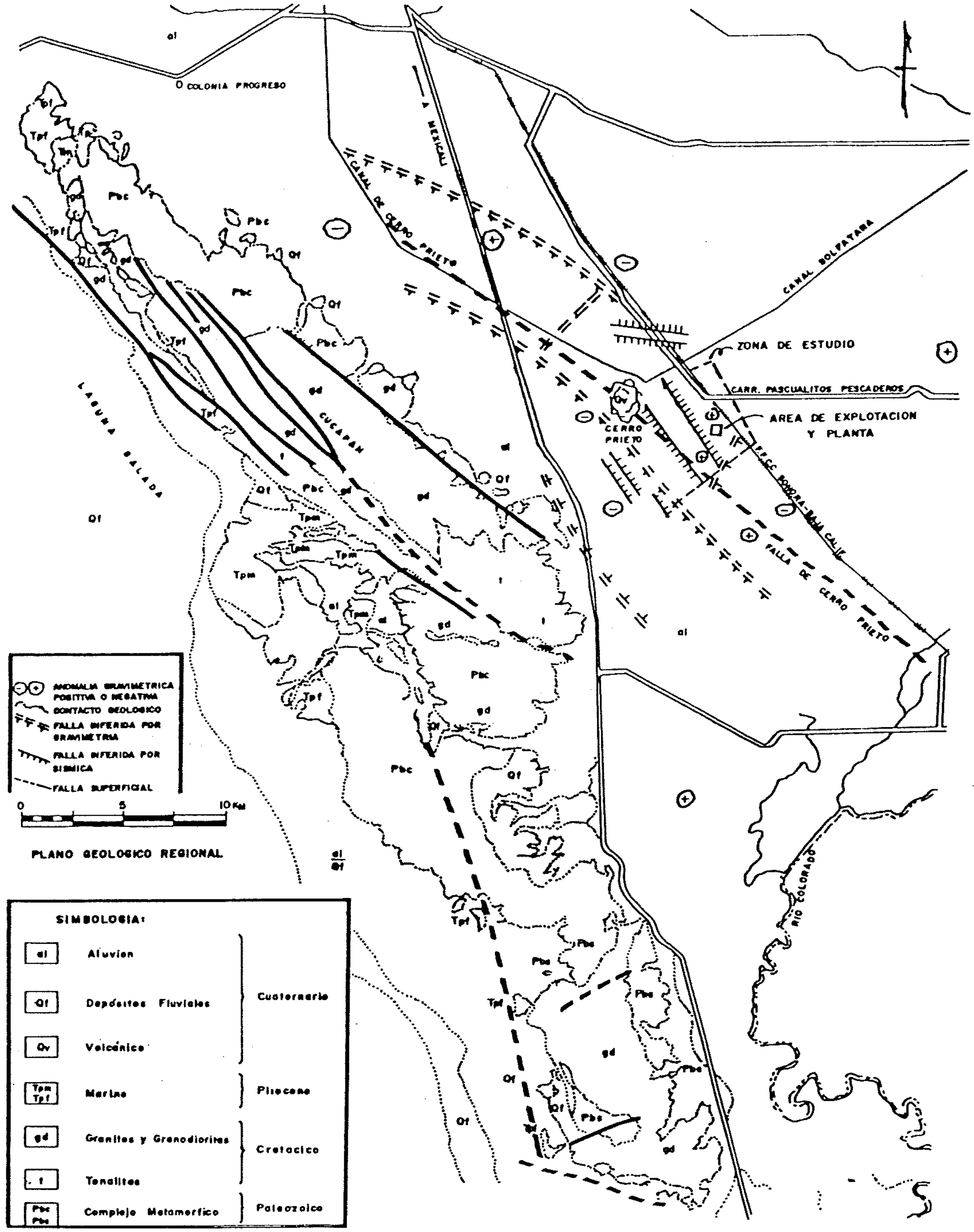


Figure 2: Regional Geologic Map

Legend

al - alluvium
Qf - Quaternary River Deposits
Qv - Quaternary Volcanics
Tpm Tpf - Pliocene Marine
ge t - Cretaceous Granites and Tonalites
Pbc Pbs - Paleozoic Metamorphic Complex

"Anomalia gravimetrica"-Gravity anomaly
"Contacto geologico"-Geologic contact
"Falla inferida por gravimetrica"-Fault inferred by gravity
"Falla inferida por sismica"-Fault inferred by seismics
"Falla superficial"-Surface fault

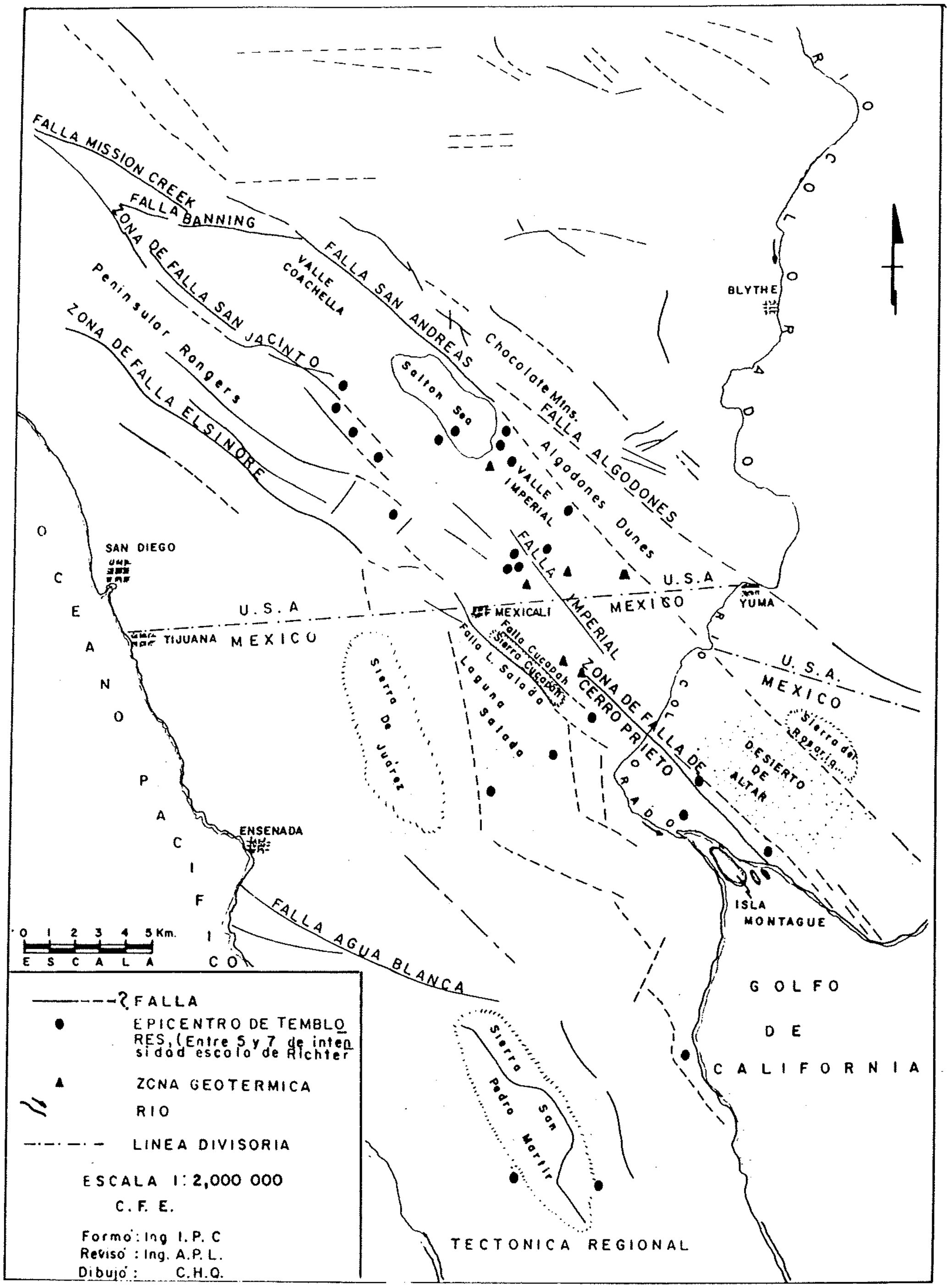
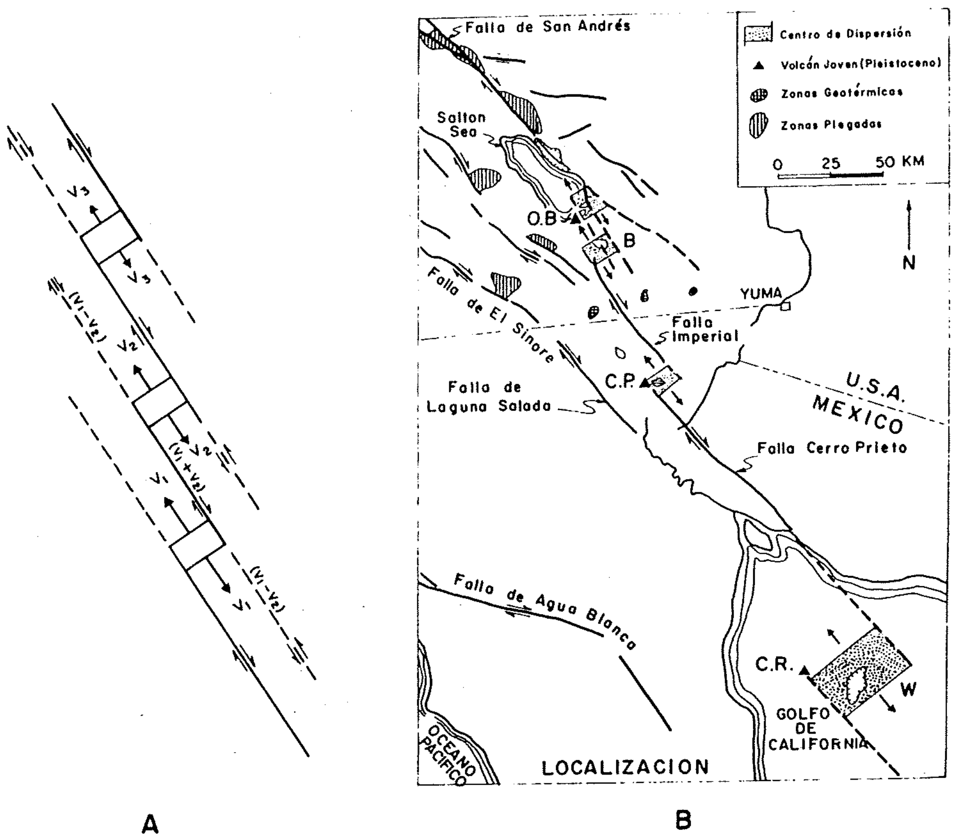


Figure 3: Regional Tectonics

"Falla" - Fault
"Epicentro de Temblores (Entre 5 y 7 de intensidad escala de Richter)" - Earthquake epicenters (Magnitudes 5-7 on the Richter scale)
"Zona Geotermica" - Geothermal Zone
"Rio" - River
"Linea divisoria" - Dividing line



A.– Modelo de Fallas transformes y Centros de Dispersión propuesto por Lomnitz, W. Elders y otros (1972)

B.– Localización de ellos en los Valles Imperial y Mexicali.

Formó: Ing. I.P.C.
Revisó: Ing. A.P.L.
Dibujó: C.H.Q.

C.F.E

Figure 4:

A. Model of transform faults and spreading centers proposed by W. Elders, et al, (1972).
B. Location of them in the Imperial and Mexicali Valleys.

"Centro de Dispersion" - Centers of spreading
"Volcan Jovan (Pleistocene)" - Young Pleistocene Volcanoes
"Zonas Geotermicas" - Geothermal Zones
"Zonas Plegadas" - Compressional Zones

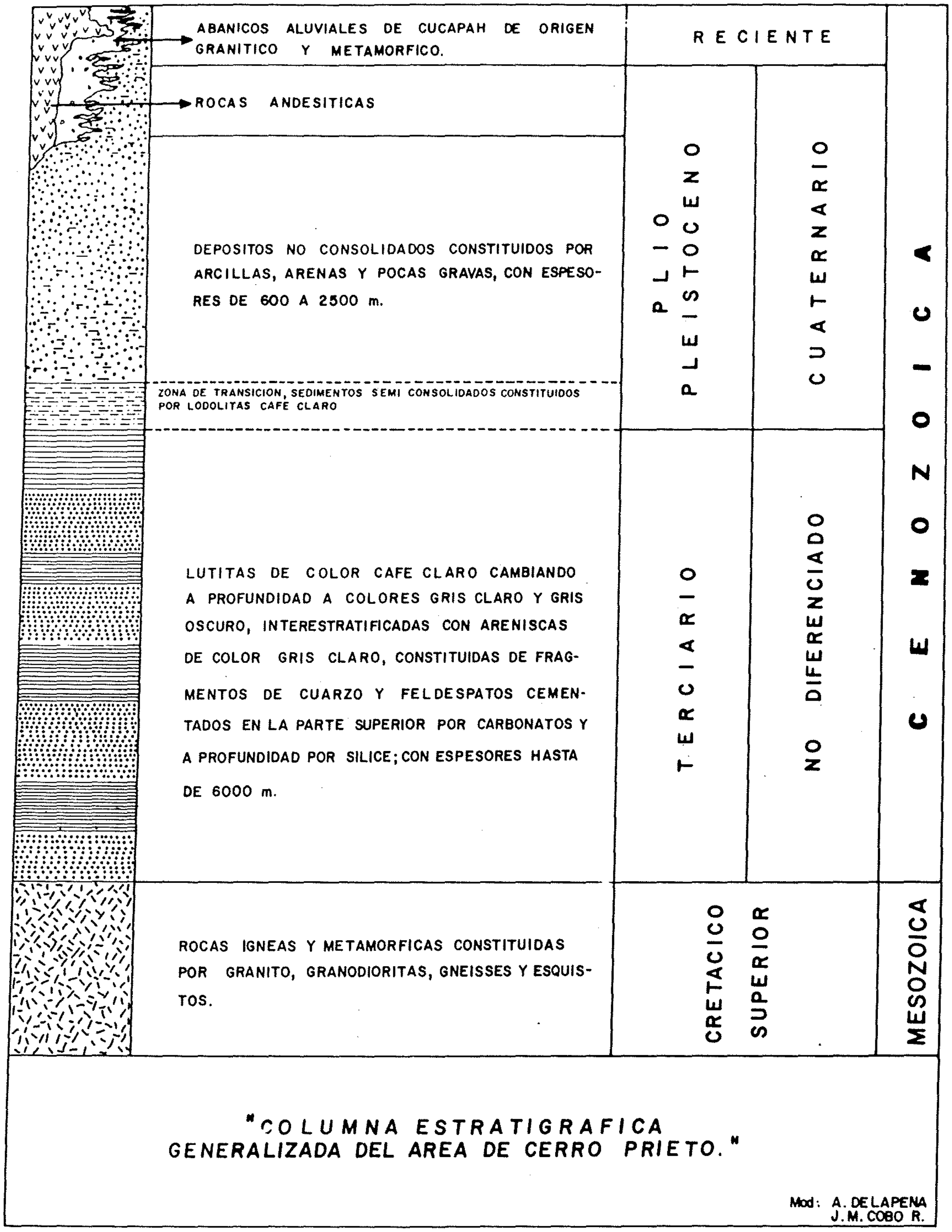


Figure 5: Generalized stratigraphic column of the area of Cerro Prieto (Explanation from youngest to oldest)

Alluvial fans of Cucapah, of granitic and metamorphic origin

Andesitic rocks

Unconsolidated Deposits consisting of silts, sands and a few gravels, with thickness of 600 to 2500 m.

Zone of transition, semi-consolidated sediments consisting of light brown mudstone.

Light brown shales changing at depth to light grey and dark grey color, interstratified with sandstones with light grey color, consisting of fragments of quartz, and feldspar, cemented in the upper part by carbonates and at depth by silica; with thickness up to 6000 m.

Igneous and metamorphic rocks, consisting of granite, granodiorites, gneisses and schists.

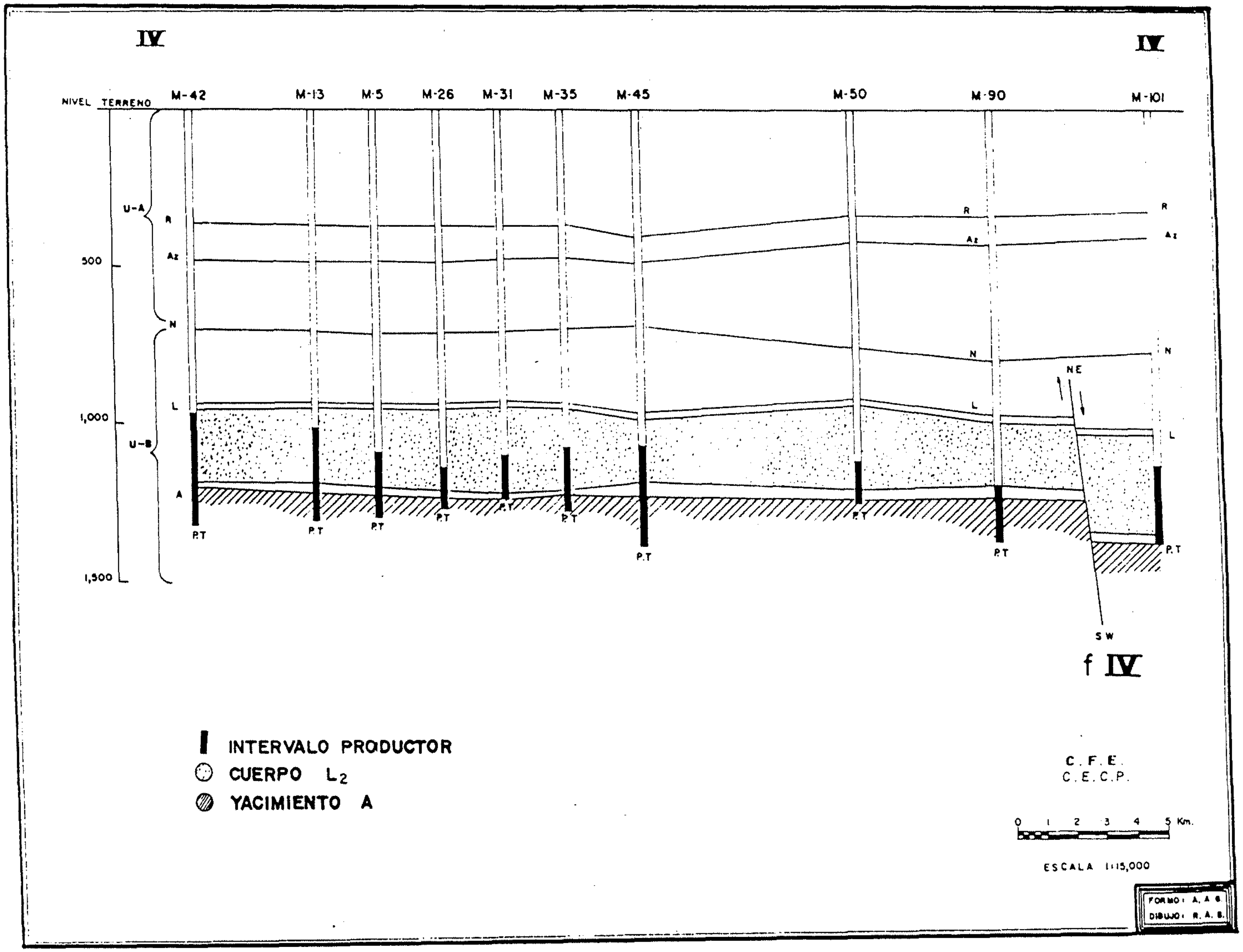


Figure 6: Correlation of production zones by electric logs
"Nivel terreno" - ground level; "Intervalo Productor" - production interval; "Cuerpo L_2" - Body (unit) L_2; "Yacimiento A" - Bed A

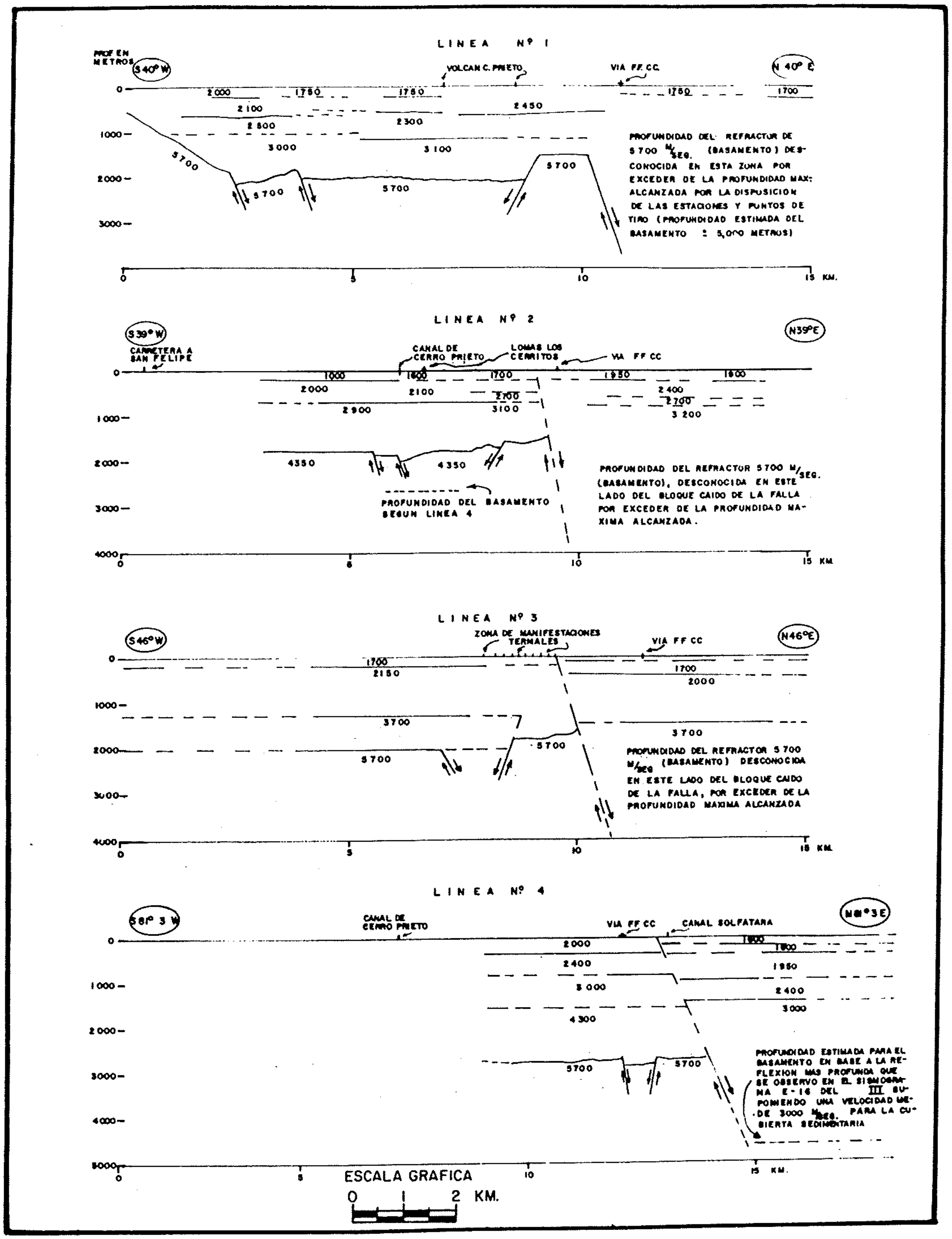
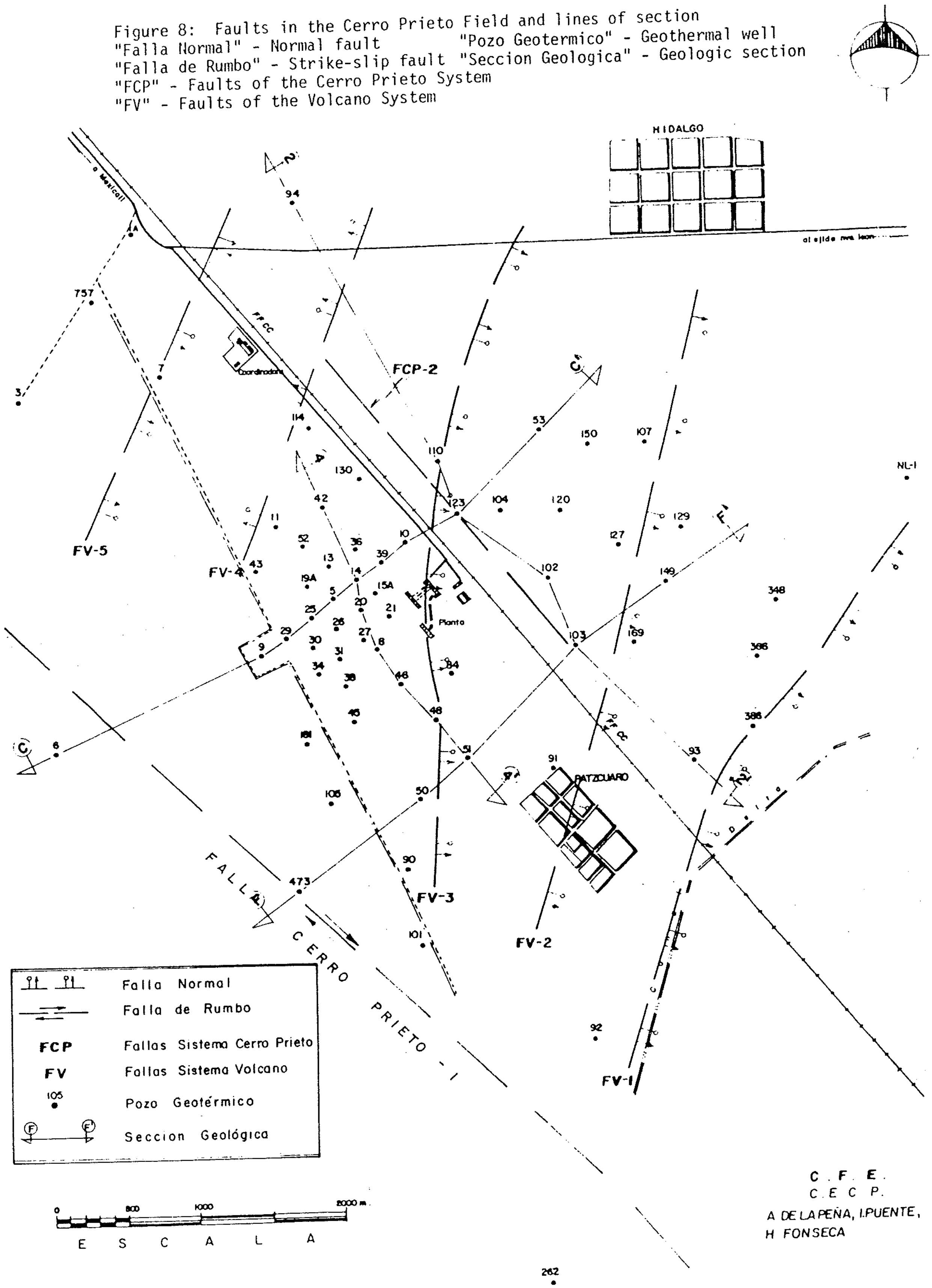


Figure 7: Seismic refraction lines 1,2,3 and 4 across the area. The depth of basement to the east and north-east in the down-thrown block of the fault is unknown as the 5700m/sec refractor was not reached in that area.

Figure 8: Faults in the Cerro Prieto Field and lines of section
"Falla Normal" - Normal fault "Pozo Geotermico" - Geothermal well
"Falla de Rumbo" - Strike-slip fault "Seccion Geologica" - Geologic section
"FCP" - Faults of the Cerro Prieto System
"FV" - Faults of the Volcano System



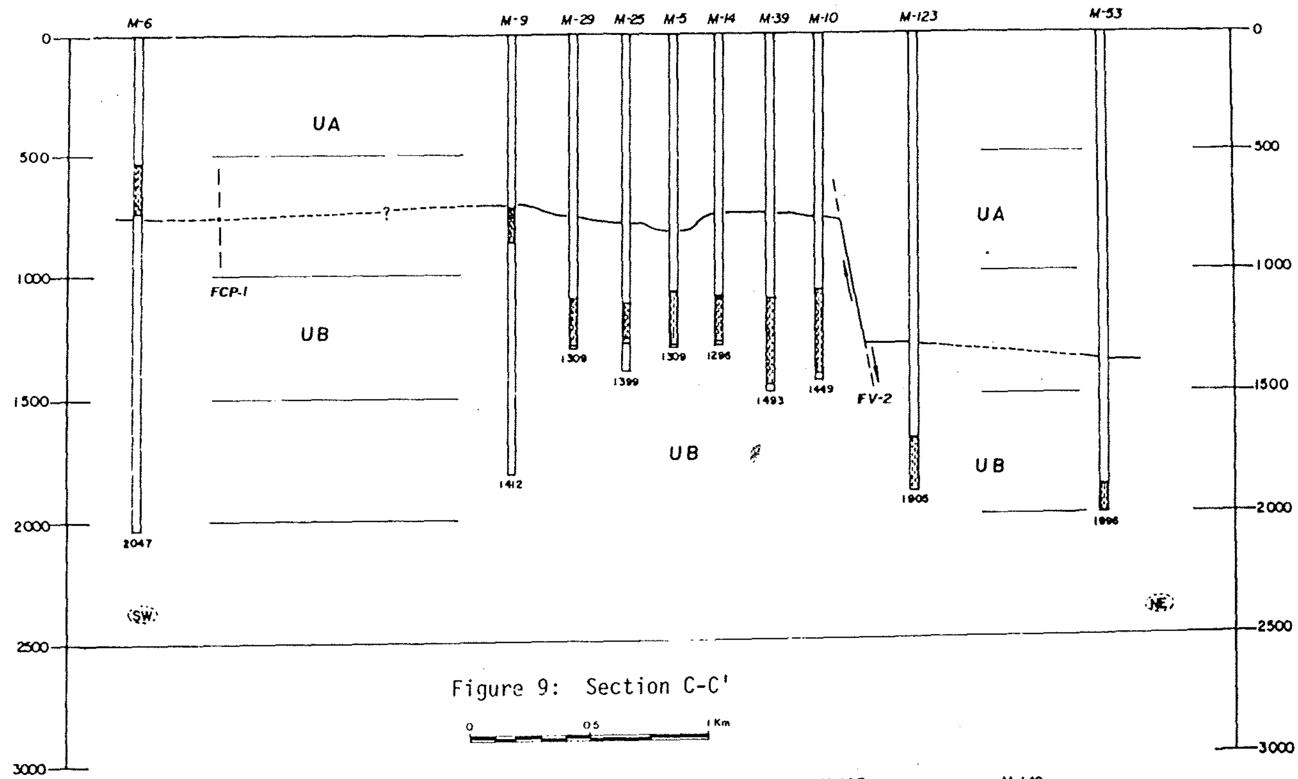


Figure 9: Section C-C'

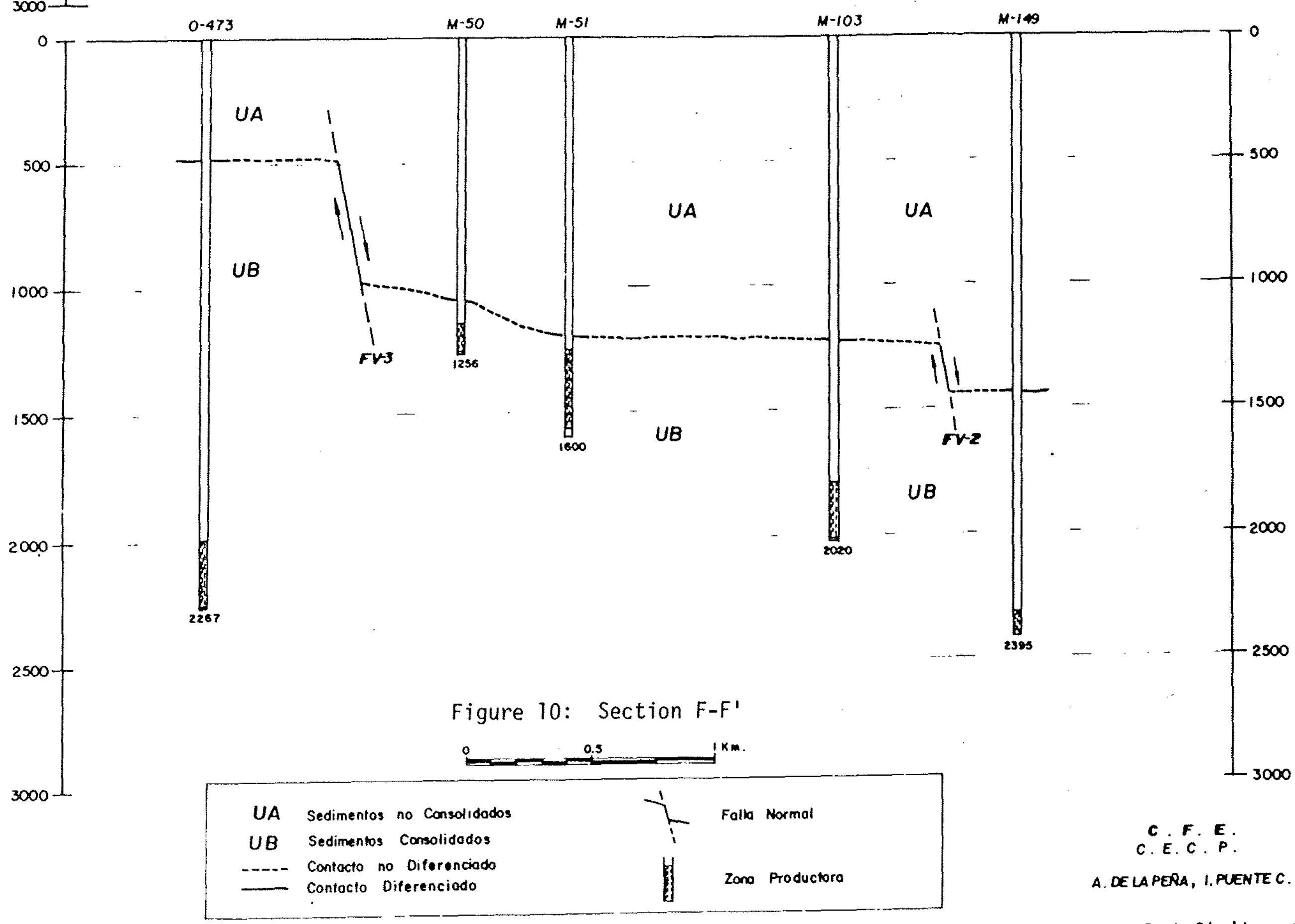


Figure 10: Section F-F'

"UA" - Unconsolidated sediments; "UB" - Consolidated sediments; "Contacto no Diferenciado" - Indefinite contact; "Contacto Diferenciado" - Definite contact; "Falla Normal" - Normal Fault; "Zona Productora" - Zone of production

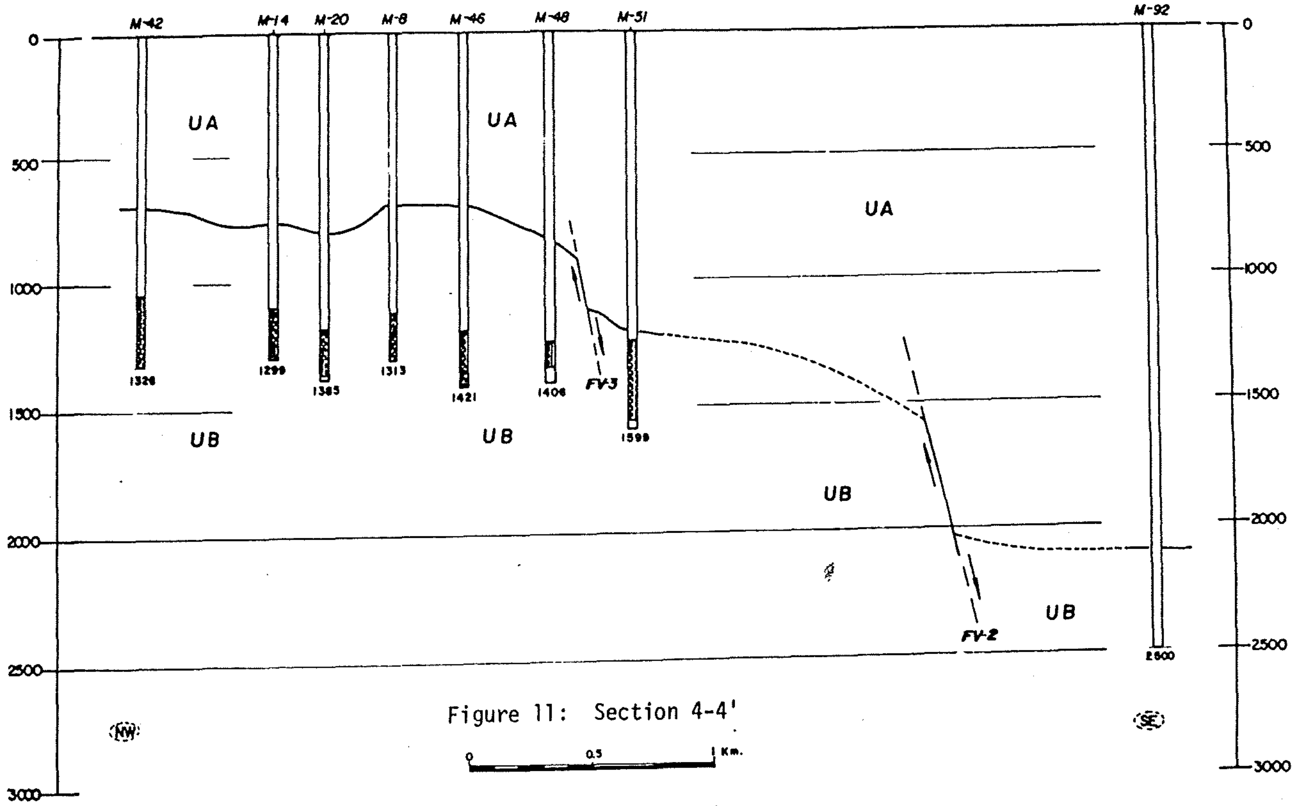


Figure 11: Section 4-4'

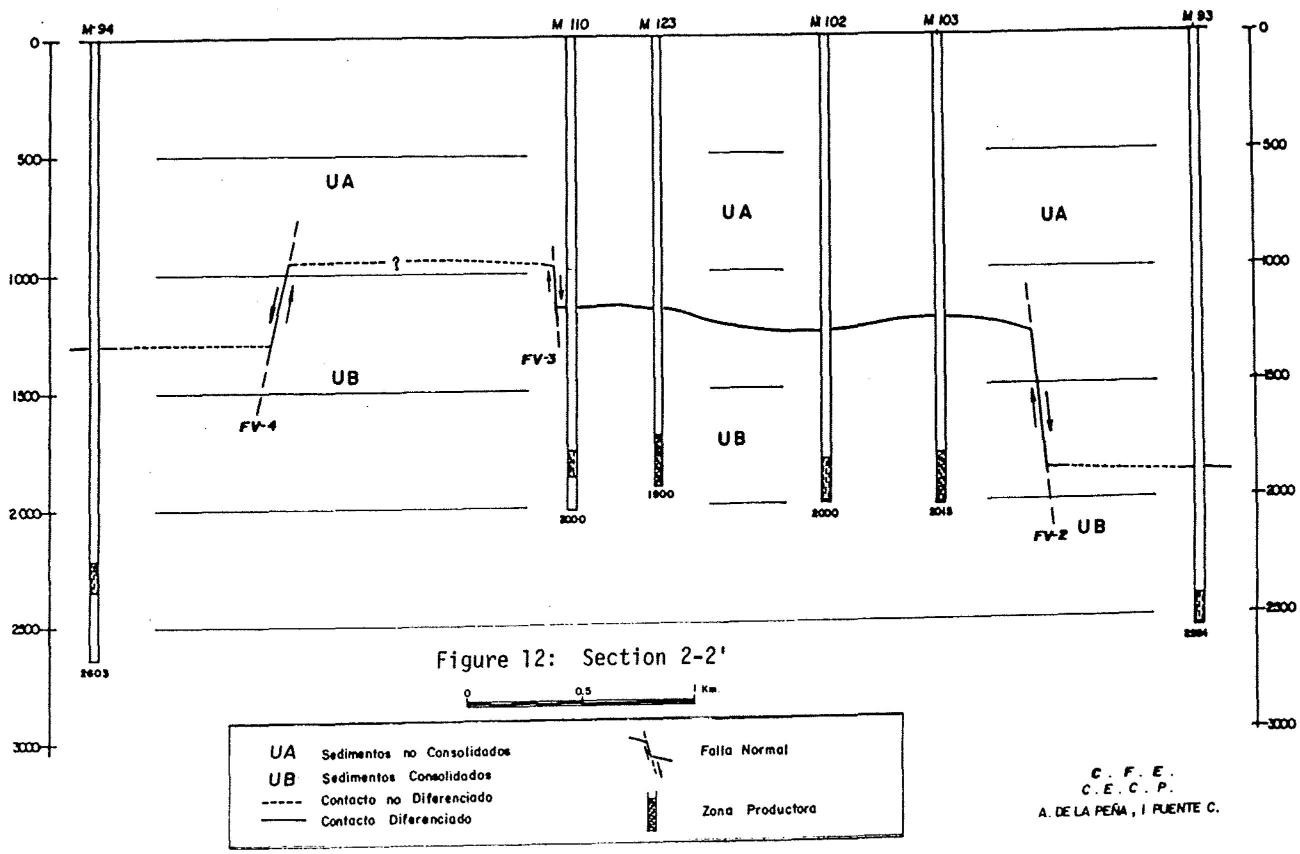
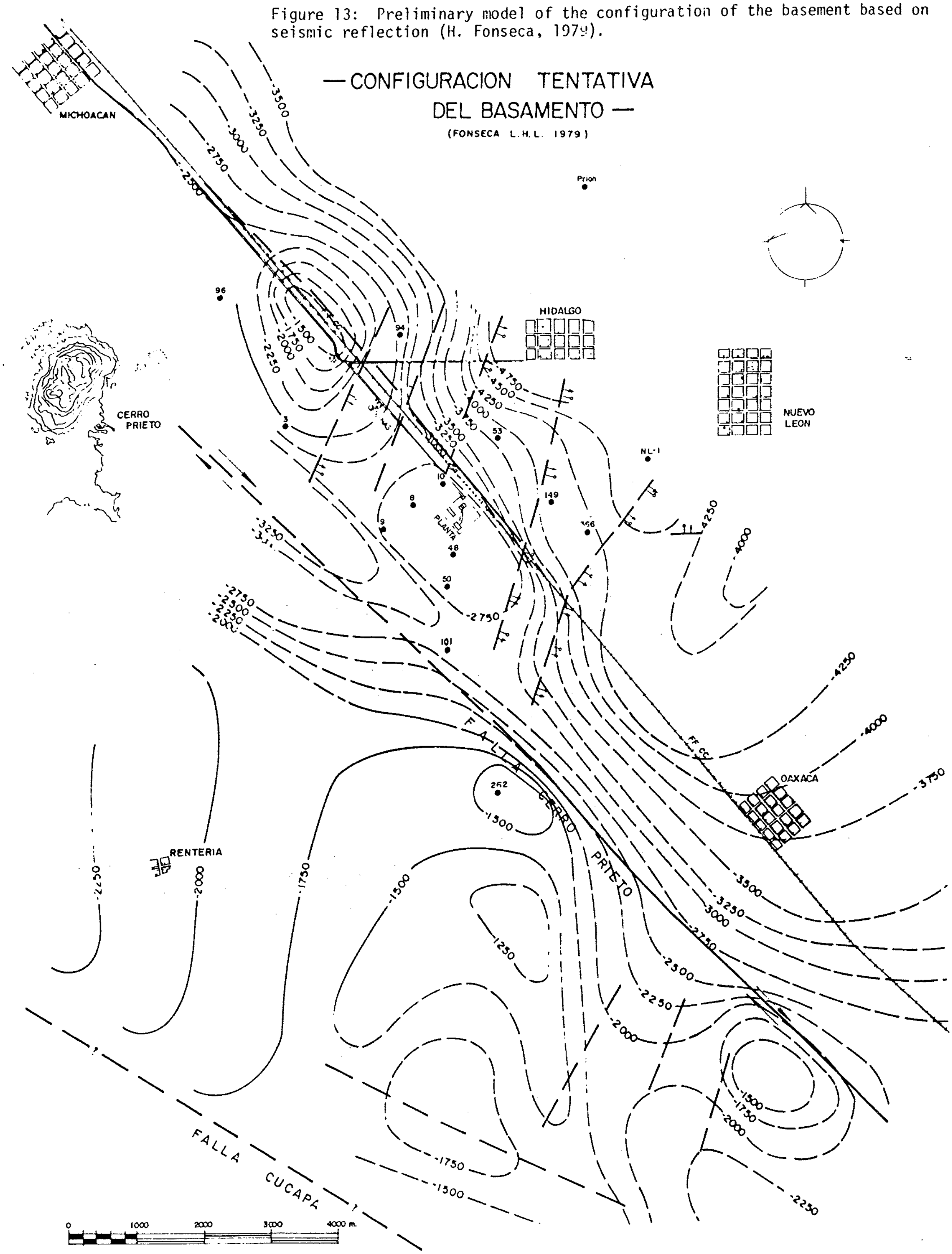


Figure 12: Section 2-2'

"UA" - Unconsolidated sediments; "UB" - Consolidated sediments; "Contacto no Diferenciado" - Indefinite contact; "Contacto Diferenciado" - Definite contact; "Falla Normal" - Normal Fault; "Zona Productora" - Zone of production

Figure 13: Preliminary model of the configuration of the basement based on seismic reflection (H. Fonseca, 1979).



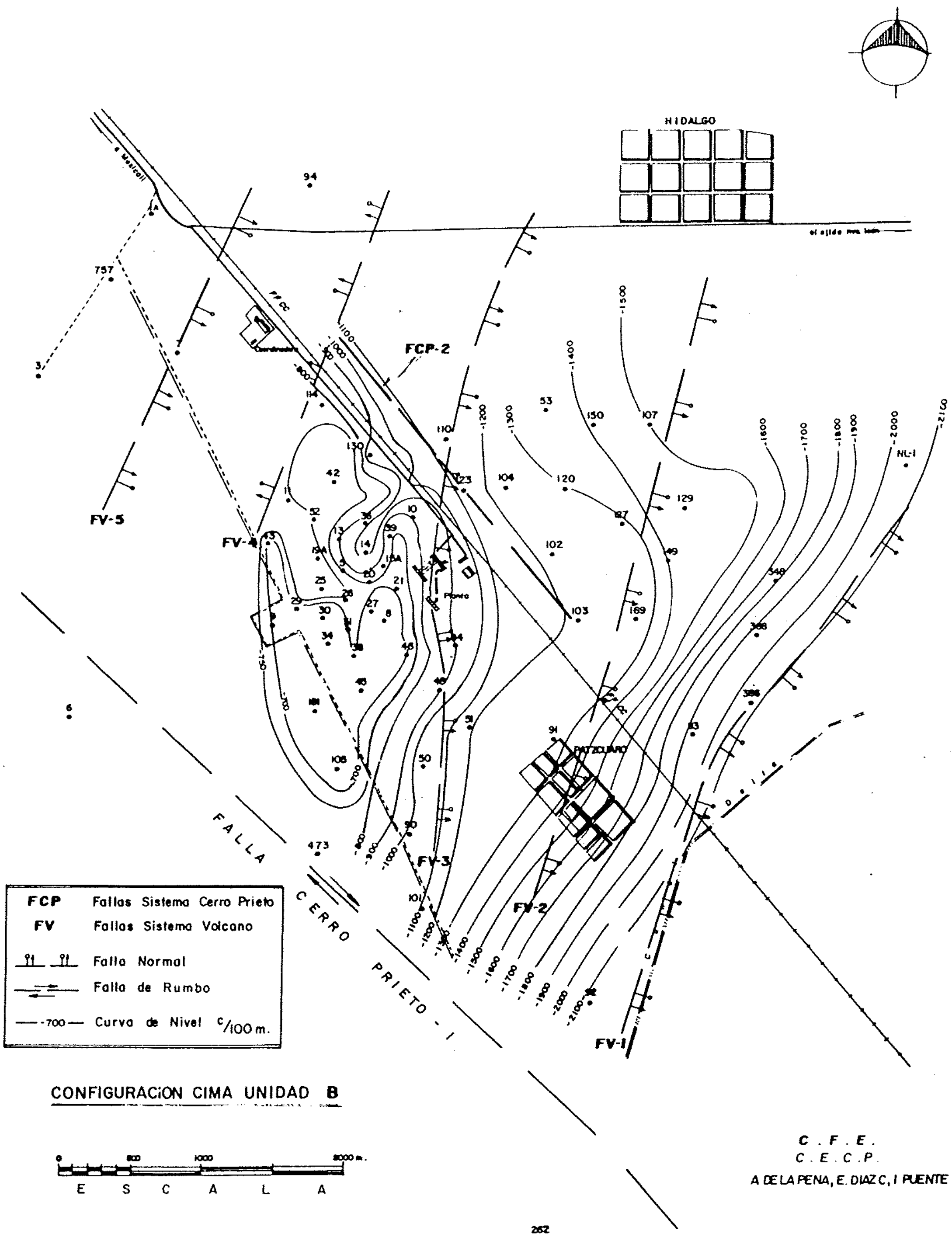


Figure 14: Configuration of the top of unit B
"FCP" - Faults of the Cerro Prieto System
"FV" - Faults of the Volcano System
"Falla Normal" - Normal fault
"Falla de Rumbo" - Strike-slip fault
"Curva de Nivel" - Contours of depth in meters below the surface

HYDROTHERMAL MINERAL ZONES IN THE GEOTHERMAL RESERVOIR OF CERRO PRIETO

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Abstract

Detailed petrologic studies completed to date on ditch cuttings and core from 23 wells in the Cerro Prieto field have led to recognition of regularly distributed prograde metamorphic mineral zones. The progressive changes in mineralogy exhibit a systematic relationship with reservoir temperature.

The Cerro Prieto reservoir consists of a series of sandstones, siltstones, and shales composing part of the Colorado River delta. The western part of the field contains relatively coarser sediments apparently derived from the Sierra de los Cucupahs, immediately to the west of Cerro Prieto. The most abundant detrital minerals in the sediments include quartz, feldspar, kaolinite, montmorillonite, illite, chlorite, mixed-layer clays, calcite, dolomite and iron hydroxides. Some of these minerals were also formed diagenetically.

The following progressive stages of post-depositional alteration in response to increasing temperature have been observed: (1) Diagenetic zone (low temperature), (2) illite--chlorite zone (above ∿ 150°C), (3) calc-aluminum silicate zone (above ∿ 230°C) and the biotite zone (above ∿ 325°C). These zones are transitional to some degree and can be further subdivided based on the appearance or disappearance of various minerals.

One immediate application of these studies is the ability, from a study of cuttings obtained during drilling of a well, to predict the temperatures which will be observed when the well is completed.

Introduction

As part of the collaborative program at Cerro Prieto between Comisión Federal de Electricidad (CFE) of Mexico and the Department of Energy (DOE) of U.S.A., petrological studies have been carried out on subsurface cuttings and cores recovered by drilling. Ing. Juan M. Cobo of CFE has had responsibility for supervising the collection of the downhole samples at the well head and for preparing initial lithological descriptions. Splits of these samples were also supplied to the senior authors at the University of California, Riverside (UCR) for detailed laboratory investigations. By September 1978, petrological studies of twenty-three wells had been completed at UCR (Figure 1).

Petrological studies can be used to characterize subsurface lithology and assist in making correlations between wells for structural intrepretations (Puente, 1978). However, the emphasis of the work at UCR has been on the nature and distribution of hydrothermal minerals. We have demonstrated that in the geothermal reservoir of Cerro Prieto various hydrothermal minerals occur in equilibrium within specific temperature ranges (Elders, et al., 1978). The degree to which equilibrium is attained depends upon the permeability and the rate of temperature change in the aquifers.

Once the relationship between temperature, permeability, and hydrothermal mineral assemblages has been established, immediate practical applications may result. For example, mineral assemblages characteristic of high temperature and good permeability can be distinguished from those of low temperature and poor permeability in cuttings obtained during the drilling of a well. This information is useful in aiding decisions about well completion and the siting of future wells, in advance of the flowing and testing of the borehole being drilled. It may take several weeks to reestablish an "equilibrium" temperature gradient in a well due to the effects of drilling, whereas a preliminary petrologic study of a well can be completed in a few days, if suitable laboratory facilities are available.

In our earlier reports on Cerro Prieto, we have tended to emphasize these predictive applications of petrological studies (Elders, et al., 1977; Elders, Hoagland and Olson, 1978). However, we believe that there are potentially even more valuable applications of petrology, yet to be fully developed. The distribution of hydrothermal mineral assemblages is related to the pattern of fluid flow and heat transfer in a geothermal system, before it is affected by production and reinjection. In principle it should be possible to use diagnostic mineral assemblages to identify and delineate the "heating volume", (i.e. that part of the geothermal reservoir closest to the heat source, where the geothermal fluids are being heated), the "discharge volume" (i.e. zones where hot fluids are ascending and being cooled), and the "recharge volume" (i.e. zones where cold fluids are descending and encountering hotter

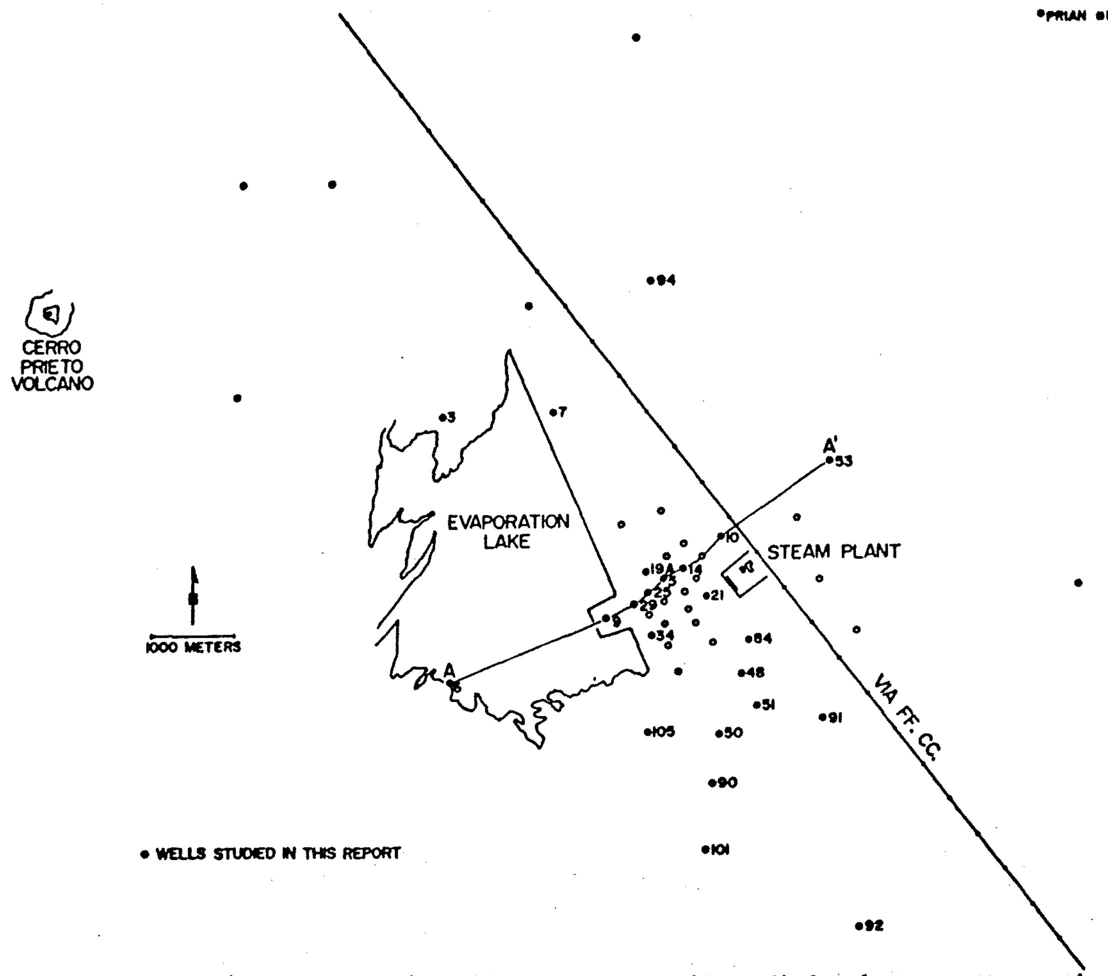

Figure 1. Cerro Prieto geothermal field showing the wells studied and the profile A-A'.

rocks). Each should have characteristic mineral assemblages and rock textures.

Study of these mineral assemblages, together with other methods of geothermometry, such as fluid inclusions and light stable isotope ratios, can also provide information on the history of the geothermal system (Elders, et al., 1978; Olson, 1978). In certain cases we have been able to distinguish rocks which are being heated by recent incursions of hot brine from rocks which have been cooled by interaction with colder water. Further studies, currently underway, are aimed at determining not only the direction of temperature change, but its timing. These studies will involve use of other geothermometers such as vitrinite reflectance of phytoclasts in the sediments and attempts at fission track dating of suitable hydrothermal minerals (C. Barker, personal communication, 1978).

Another important aspect of the petrology of geothermal systems concerns the relationship between porosity, permeability, and hydrothermal reactions (Elders, 1977). Water/rock reaction at Cerro Prieto has greatly affected the physical properties of the reservoir. Precipitation of minerals in pore spaces obviously reduces porosity and permeability. However, in these rocks, solution of minerals may have the same effect because it can occur selectively at grain-to-grain contacts of framework minerals, reducing the pore volume. Fracture permeability plays an increasingly important role in the deeper, hotter, parts of the reservoir, as is indicated by the more common occurrence of mineralized veins. Mineralization acts to seal these fractures and successive episodes of fracturing and sealing are recorded in the vein minerals. There is, therefore, a clear connection between the petrography and the petrophysics of the reservoir.

These investigations of the applications of petrology to the geothermal field of Cerro Prieto are currently underway and more are planned for the future. The emphasis in this report will therefore be on documenting the occurrence of hydrothermal minerals as a function of temperature and their distribution within the reservoir. More extensive interpretations and applications of these data must await future work.

Methods of Study

Only limited amounts of core are available from the wells drilled to date, so that our data are largely based on well cuttings or small rock chips. Easily disintegrated rock types are therefore under-represented in the samples and mixing and contamination with drilling mud is a constant

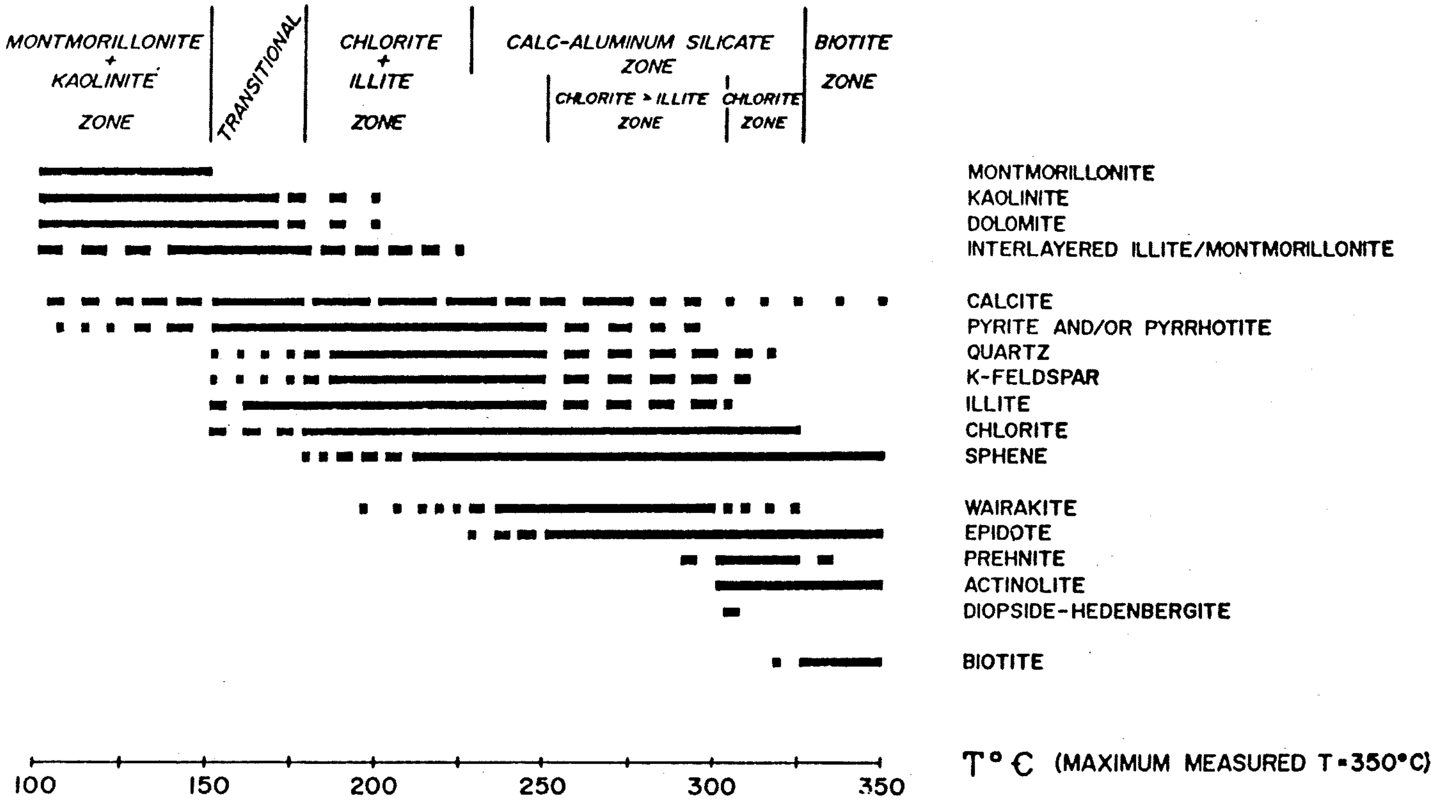

Figure 2. Mineral zones in sandstones at Cerro Prieto as a function of temperature.

problem. The depths reported are measured from the Kelly drive and are not corrected for lag time.

Samples were washed to remove drilling mud and described with the aid of a binocular microscope. Representative material was selected for thin section study and for quantitative X-ray diffraction analysis using an automated X-ray system (Johnson et al., 1977). Other studies included microprobe analysis of minerals, fluid inclusion geothermometry and light stable isotope analysis of carbonates (Elders, et al., 1978).

Post-depositional Alteration

Three groups of diagenetic and hydrothermal minerals are found at Cerro Prieto, (a) "pore-filling cements", (quartz, calcite, dolomite, K-feldspar, pyrite, and pyrrhotite); (b) "calcium-aluminum silicates", produced by decarbonation reactions, (epidote, prehnite, actinolite and wairakite), and (c) "authigenic phyllosilicate minerals", formed by dehydration and reaction of detrital kaolinite, montmorillonite, mixed-layer illite-montmorillonite, illite, chlorite and biotite (hydrothermal illite, chlorite and biotite).

These hydrothermal minerals occur in temperature dependant mineral assemblages illustrated in Figure 2. This diagram summarizes the diagenetic and hydrothermal minerals zones in sandstones as a function of temperature. Low temperature minerals tend to persist to higher temperatures in shales as the lower permeability of shales hinders water/rock reactions.

Montmorillonite-kaolinite zone (Below 150-180°C)

This zone is defined by the presence of detrital or diagenetic kaolinite and/or montmorillite, with or without dolomite and expandable illite/montmorillonite interlayers. This mineral assemblage is best recognized using X-ray diffraction (Figure 3). However, in many wells the high temperature boundary of the zone, where it is transitional into the illite-chlorite zone, exhibits a characteristic color change in shales from shades of brown to gray. This same transition often corresponds to the boundary between consolidated and unconsolidated rocks (Puente, 1978).

Illite-chlorite zone (150-180°C to 230-250°C)

The lower end of this zone is marked by the disappearance of kaolinite and dolomite and the progressive decrease of interlayered illite-montmorillonite. The high temperature boundary is marked by the first appearance of hydrothermal epidote (230-250°C).

Within the illite-chlorite zone pore-filling cements including quartz, calcite, K-feldspar, pyrite and pyrrhotite are abundant and may give the rock a quartzitic or hornfelsic texture.

Calc-aluminum silicate zone (230-250°C to 350°C)

Epidote first occurs as aggregates of minute acicular crystals in pore spaces, but at higher temperatures it occurs as large blocky crystals forming new framework minerals. Wairakite usually accompanies the first occurrence of epidote (Figure 4). This zone can conveniently be subdivided

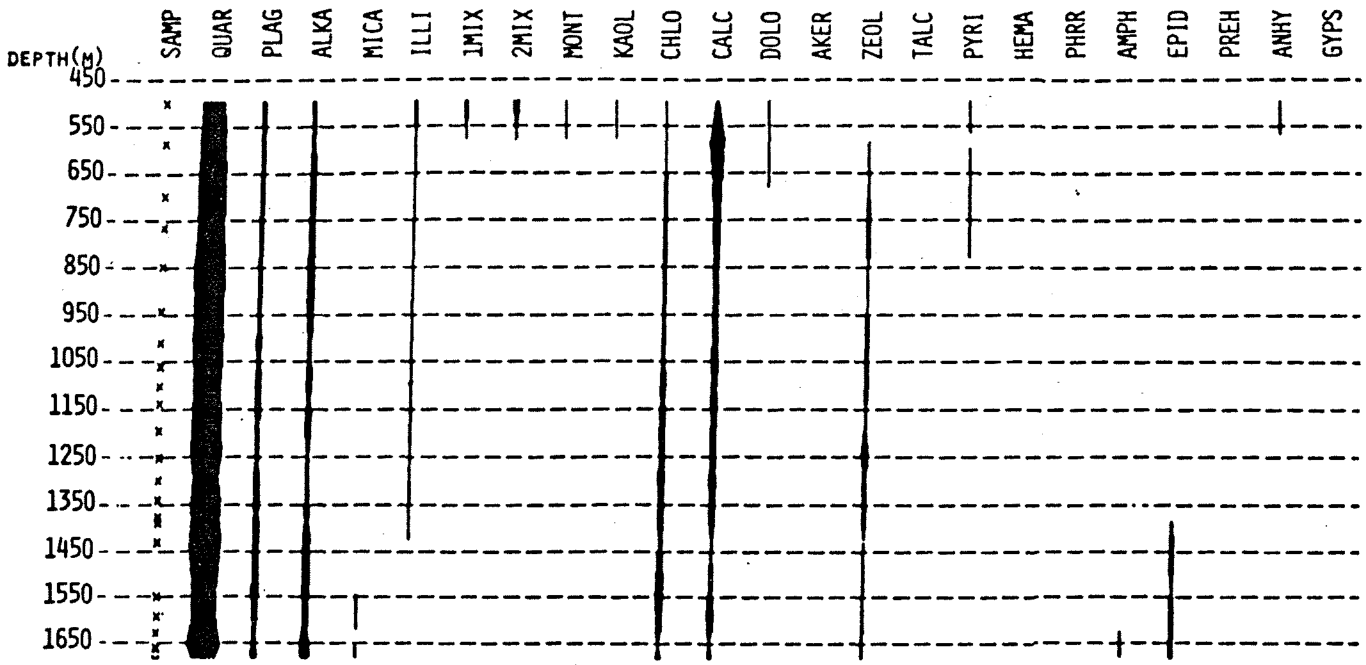

Figure 3. "Spindle diagram" showing relative abundance of minerals as a function of depth in sandstones from Well M105. The width of the black bars is proportional to the relative abundance of the relevant minerals. SAMP - sample spacing; QUAR - quartz; PLAG - plagioclase; ALKA - K-feldspar; MICA - muscovite and biotite; ILLI - illite; 1MIX - illite/montmorillorite, 25% expandable; 2MIX - illite/montmorillorite, 50% expandable; MONT - montmorillonite; KAOL - kaolinite; CHLO - chlorite; DOLO - dolomite; AKER - ankerite; ZEOL - wairakite; TALC - talc, PYRI - pyrite; HEMA - hematite; PHRR - pyrrhotite; AMPH - amphibole; EPID - epidote; PREH - prehnite; ANHY - anhydrite and GYPS - gypsum.

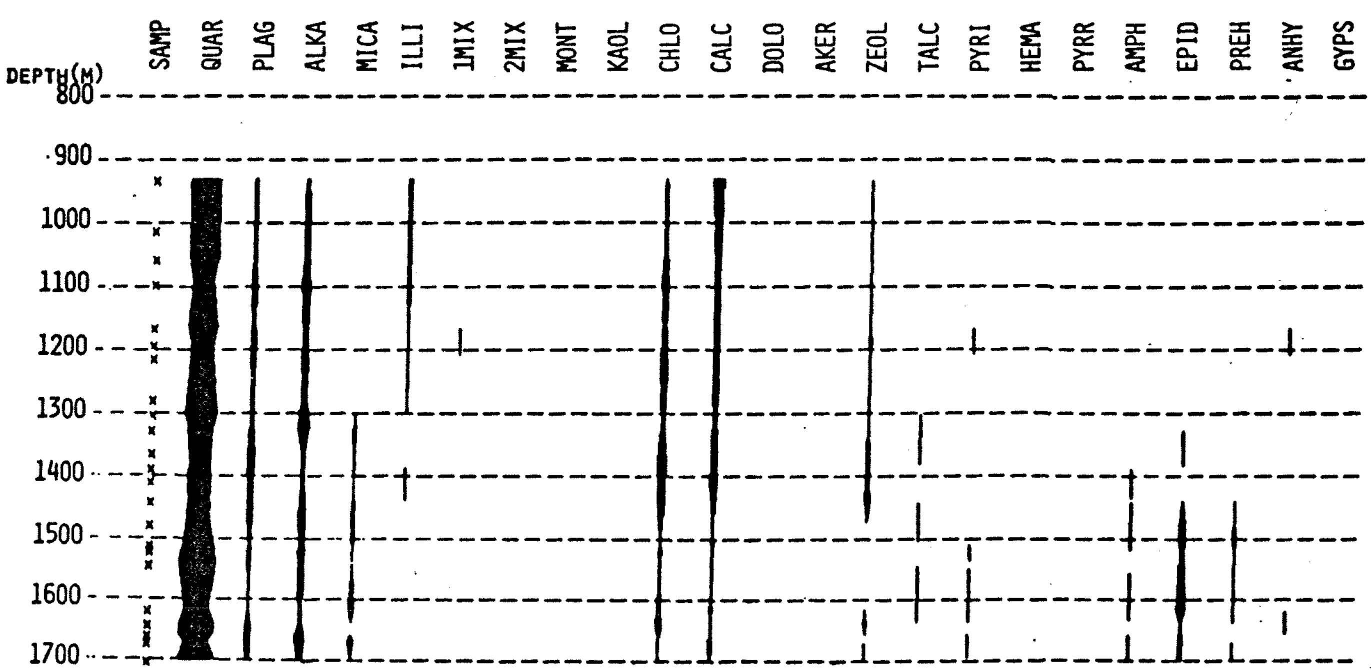

Figure 4. Relative abundance of minerals in sandstones from Well M84. (For an explanation of the abbreviations see the legend of Figure 3). The transition from subzone 2 to subzone 3 within the calc-aluminum silicate zone is shown by the disappearance of zeolite and the appearance of abundant epidote, actinolite and prehnite at about 1450 m.

into three subzones: (1) below 250°C, the "chlorite + illite + epidote" subzone, with roughly equal amounts of chlorite and illite; (2) below 290-300°C, the "chlorite > illite" subzone, where the ratio chlorite/illite is 3/1, and coarse-grained epidote is abundant; (3) above 300°C, the "chlorite" zone with only trace amounts of illite and abundant epidote, prehnite and actinolite but with progressively smaller calcite content. These rocks are often distinctly hornfelsic in texture.

Biotite zone (above 315-325°C)

This zone is the final mineral zone encountered at Cerro Prieto. It is defined by the first occurrence of biotite (315°C). It occurs both as scaly aggregates in former pore spaces and as pseudomorphs of earlier chlorite. Epidote and actinolite persist through this zone, but illite is generally absent and chlorite is present in only trace amounts. No new phases occur between 325°C and the maximum temperature of 347°c encountered in the wells so far investigated.

Distribution of the Hydrothermal Mineral Zones

The occurrence of these mineral zones is sufficiently systematic to permit mapping them across the reservoir. This has been done in two ways. Figures 5 and 6 illustrate the distribution of hydrothermal minerals in sandstones and in shales, respectively, along an approximately E.-W. cross-section along the line A - A' of Figure 1.

Similarly, Figure 7 shows a map giving the contours of the depth to the first occurrence of hydrothermal epidote across the field. Comparable maps have been prepared for the other mineral zones in both sandstones and shales (Elders, et al., 1978). It is immediately apparent that the pattern of mineral zonation is remarkably similar to the pattern of isotherms. Clearly temperature is the principal control over the mineralization. Although the mineralogic transitions in sandstones and shales are similar, a given transition occurs at systematically greater temperature in shales than in sandstones. The higher permeability of sandstones facilitates the reactions between rocks and hydrothermal fluids. Further inferences which can be made from the distribution of mineral zones include the presence of a structural or stratigraphic barrier to fluid circulation trending NE-SW between Wells M84 and M91. Our data also show that the wells which currently supply steam to the generating plant appear to lie in the zone where maximum hydrothermal activity is shallowest.

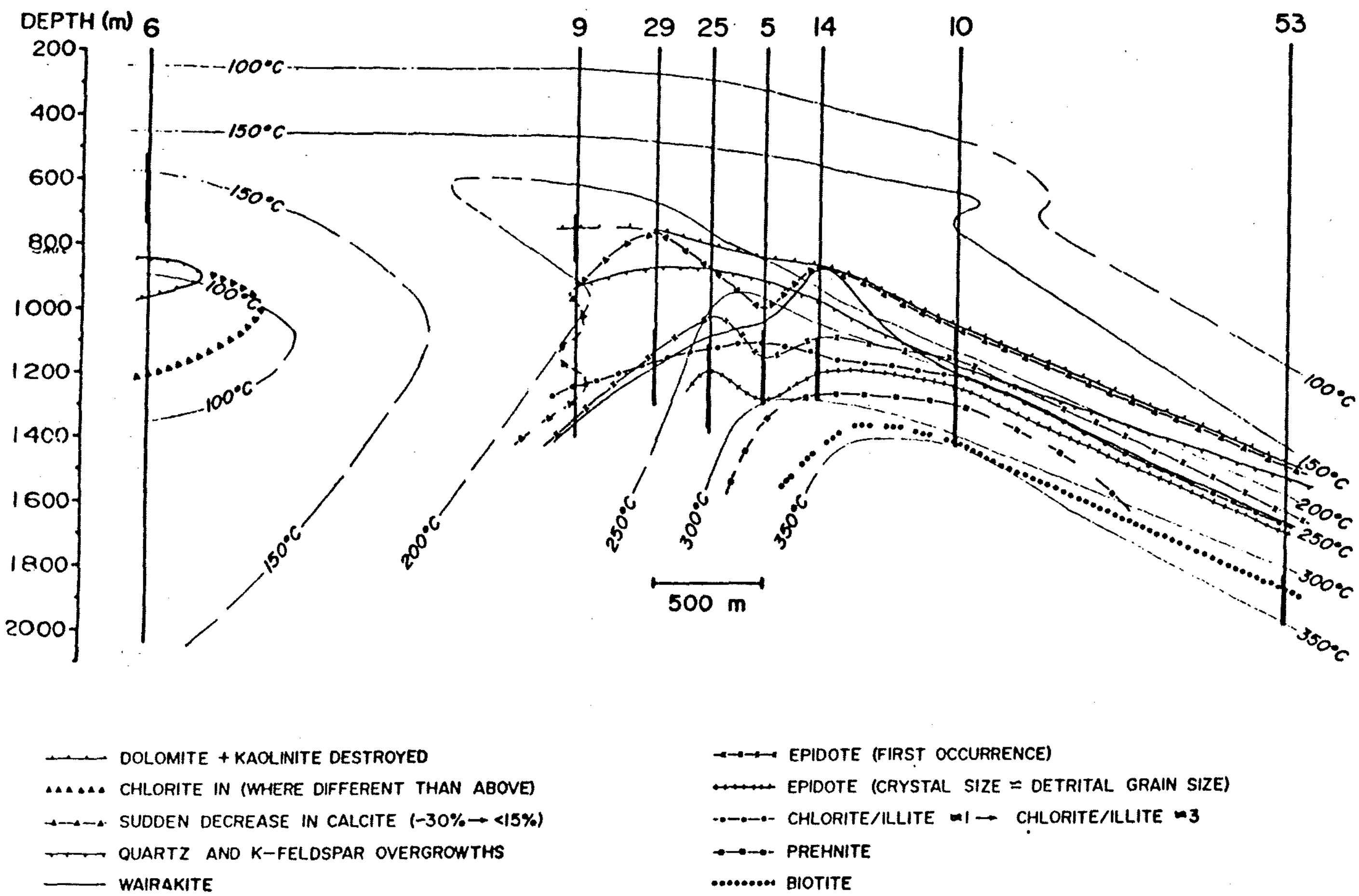

Figure 5. Distribution of mineral zones in sandstones along the profile A-A'. Isotherms modified from Mercado (1976).

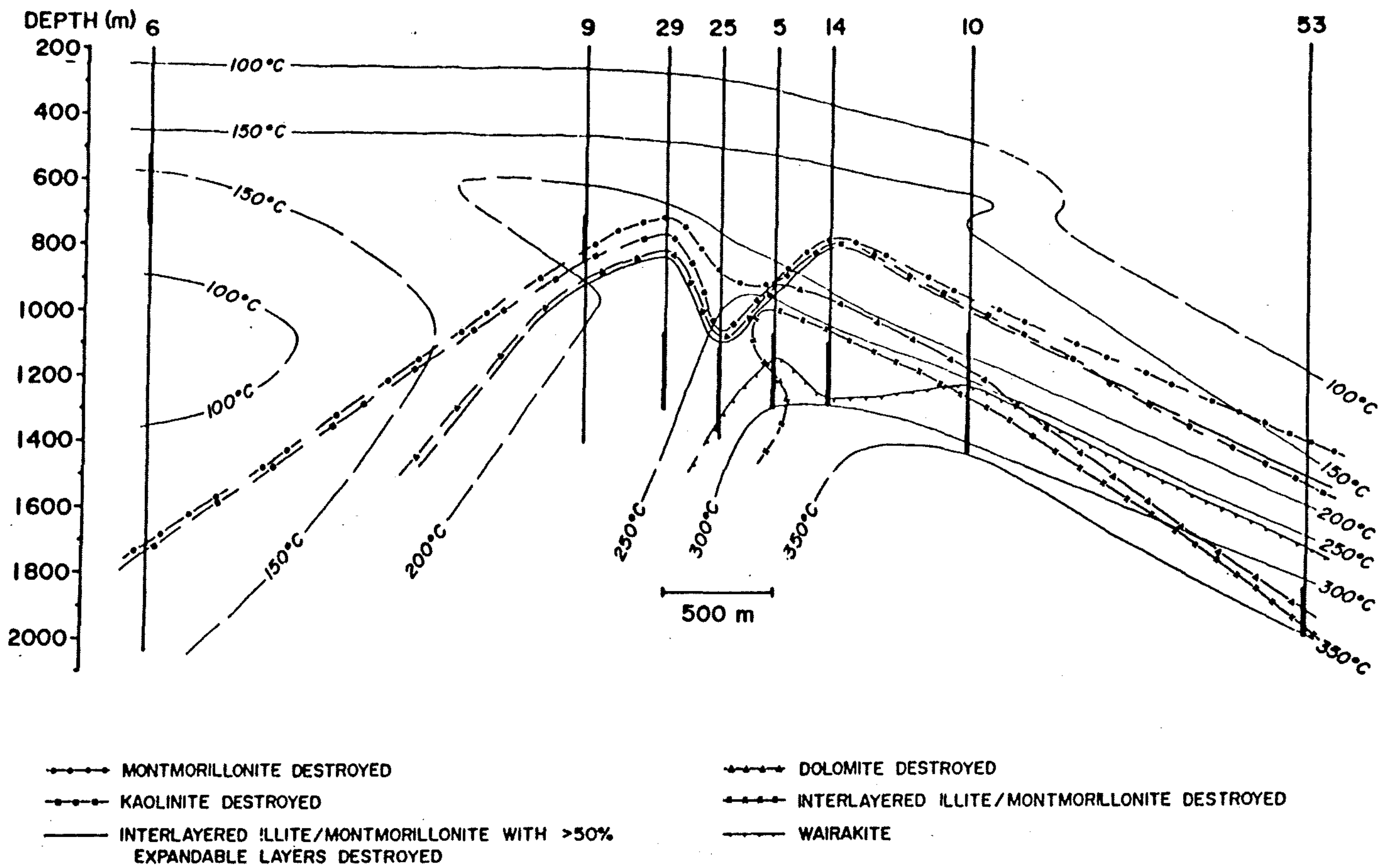

Figure 6. Distribution of mineral zones in shales along the profile A-A'. Isotherms modified from Mercado (1976).

Surprisingly, our data on mineral distribution do not appear to show the effects of the major NW-SE trending fault which has been postulated to run between M10 and M53 (Noble, et al. 1977; Puente, 1978). Of the two wells we have studied which lie to the northeast of the postulated fault only one, M53, shows hydrothermal alteration. The other, Prian No. 1, therefore, appears to lie outside the geothermal field. Study of more wells on that side of the fault should reveal whether the fault does, in fact, affect the fluid flow and the mineral zonation.

Discussion

The most dramatic effect of hydrothermal metamorphism is to indurate the sediments, reducing porosity and increasing density. In the upper part of the reservoir the permeability is dominated by porous sandstones. With increasing temperature and depth and progressive water/rock reaction there is probably a transition to fracture-dominated permeability.

The transition from unconsolidated to consolidated rocks may occur in different ways in different parts of the reservoir. Induration may be due to the interplay of (a) compaction due to burial in a subsiding basin; (b) cementation by pore-filling calcite, quartz, adularia and pyrite; and (c) metamorphic reactions involving dehydration and decarbonation reactions in which new framework minerals form. Figure 8 shows three of many possible situations in which the transition between unconsolidated and consolidated rocks may or may not be affected by faulting. Because of possible diversity in their origin, we suggest that the transitions between unconsolidated and consolidated rocks are post-depositional horizons which cannot easily be used for stratigraphical correlation. Similarly, these transitions must be used with caution in making structural syntheses, as hydrothermal alteration may predate or postdate faulting.

Although some of the aims outlined in the introduction have been addressed in this report, further work is necessary to achieve the goal of elucidating the pattern of fluid flow. Simple solubility considerations suggest that calcite cementation is more likely where cold water is encountering hotter rocks, whereas quartz and K-feldspar are more likely to be precipitated where hot water encounters colder rock (Hoagland and Elders, 1978). However, we are not able as yet to delineate the discharge and recharge volumes of the reservoir.

The interpretations we have offered must be regarded as preliminary. Their chief limitation is that we have so far restricted our considerations only to the petrologic data we have reported here. A more comprehensive geologic model will have to await integration of an enormous and diverse body of data which is now being generated and published as the result of the international cooperation underway. These data include fluid chemistry, surface geophysics and geology, downhole well logging, reservoir engineering, petrophysics, and further drilling. Thus we anticipate that our interpretations will be modified and improved by this friendly collaboration.

Acknowledgements

The authors are grateful to Ing. Hector Alonso Espinosa of CFE and his staff at Cerro Prieto for supplying us with information and for much fruitful discussion. Laboratory facilities used at UCR have been made possible by geothermal grants from NSF-RANN and USDI-USGS during the past several years. The quantitative X-ray diffraction data were the work of P. Collier and P. D. Johnson. Funding for the work at UCR came from the U.S. Department of Energy Geothermal Reservoir Management Program.

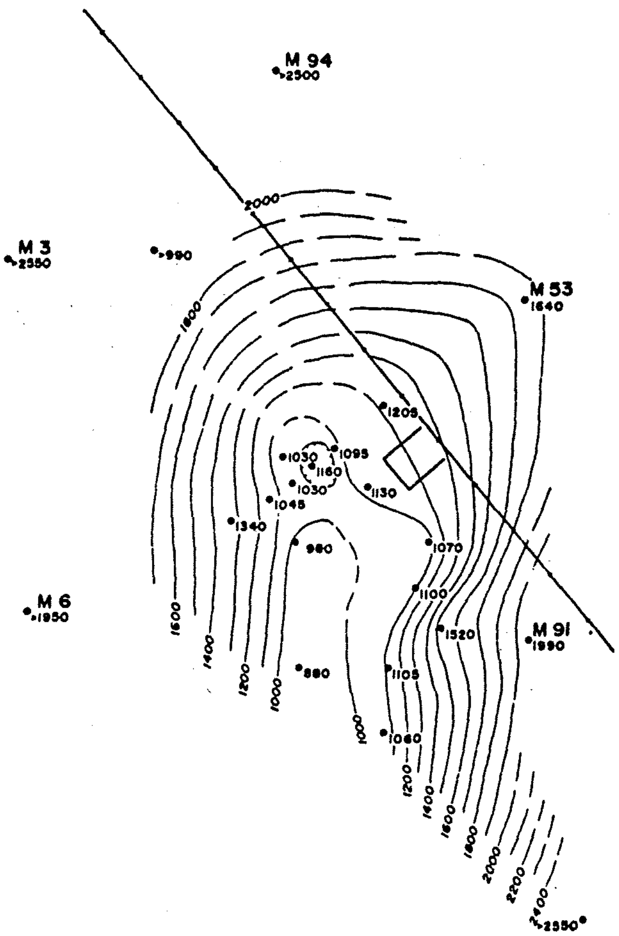

Figure 7. Depth to first occurrence of epidote in sandstone (230-250°C). Contour interval = 100m.

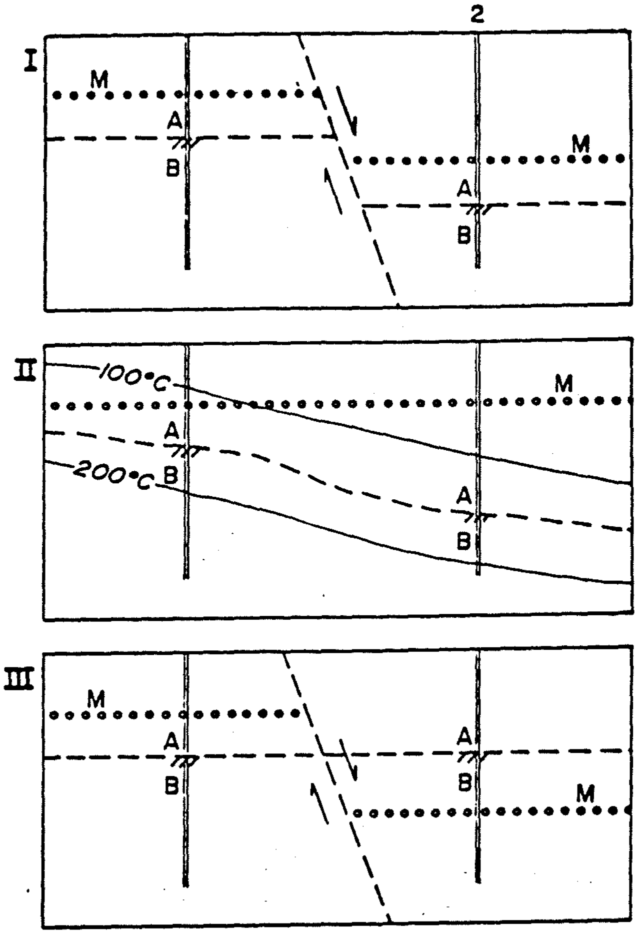

Figure 8. Three hypothetical relationships between unconsolidated rocks (A) and consolidated rocks (B) in two adjacent boreholes, 1 and 2. M indicates a stratigraphic marker. In case I both the marker M and the A/B transition are offset by a fault. In case II there is no offset of M but the A/B transition occurs at different depths due to mineral reactions controlled by temperature. In Case III M is offset by a fault but the induration responsible for the A/B transiton post-dated the fault.

This is report No. UCR-IGPP 79/2 of the University of California, Riverside, Institute of Geophysics and Planetary Physics.

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This paper is reprinted from the Proceedings of the First Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico, held September 20-22, 1978, in San Diego, California.

TOUR OF MAGMA ELECTRIC CO. EAST MESA GEOTHERMAL R&D FACILITY

HOSTED BY THOMAS C. HINRICHS

MAGMA ELECTRIC CO.
P.O. Box 2082
Escondido, California 92025

The purpose of the facility is to demonstrate on a small scale the practicality of electrical power generation from low temperature hydrothermal resources and uses pumped well sand a binary fluid as the power fluid in the system - specifically the "Magmamax Power Process" (Patented by Magma Energy, Inc.) The Facility has four process streams - 1.) Geothermal brine for energy input, 2.) Isobutane for power recovery from the brine, 3.) Propane for power recovery from the exhaust heat in the isobutane and a minor amount from the brine, and 4.) Cooling water for heat rejection. The geothermal brine system, consisting of piping, pumps, valves and controls utilizes brine from five wells and transfers the heat in to power fluids in the heat exchangers. The cooled brine is injected back in to the reservoir. The isobutane system has a turbo-generator of 10.5 Mw capacity and the propane system, 2.2 Mw. capacity. All of the heat input to the isobutane system comes from the geothermal brine and 20% of the input into the propane system. The majority (80%) of the heat in the propane comes from the exhaust heat in the isobutane turbines. The cooling system has adequate storage for hot and cold water to allow the evaporative cooling, done by spraying the hot water in the air, to be carried out over a 16 hour period to take advantage of the lower wet bulb temperatures during the off peak period. Make up water to replace evaporation and drift and to maintain the solid level in storage below ground water level comes from the East Highland canal (Approx. 400,000 gpd). Evaporation and blowdown are the only normal emissions and there are no byproducts.

A HISTORY OF GEOTHERMAL DRILLING IN THE IMPERIAL VALLEY

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California Division of Oil and Gas
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Surface manifestations of geothermal activity in the Imperial Valley have been noted by local inhabitants for many years. Live steam fumaroles, mud volcanoes, and boiling mud pots had been observed near the extinct volcano now known as Mullet Island.

During construction of irrigation works aimed at diverting Colorado River water into the Imperial and Coachella Valleys, control of the river was lost in 1905: for a little over a year the river changed its course and emptied into the Salton basin, forming the Salton Sea. Most of the mud pots and fumaroles near Mullet Island were covered by the rising waters. They were exposed again for a time when the water level dropped due to evaporation, but in recent years the level of the sea has been steadily rising and most of the mud pots are once again under water. The present level of the Sea is maintained by irrigation runoff from the Coachella and Imperial Valleys. A small remnant area of the mud pots is still visible in the NW¼ of Sec. 24, T. 11S., R. 13E., about two and one-half miles southeast of Mullet Island.

The first attempt to exploit the geothermal resources of the area was a result of a report to the Southern Sierras Power Company (Siegfried, 1925). Three wells were drilled in 1927 and 1928 by the Pioneer Development Company on Mullet Island (Wynn, 1975). The deepest of these went to 1,473 feet and all three produced steam, hot water, and non-condensible gases. Steam pressures and volumes were not considered sufficient for commercial operation and the wells were abandoned.

During drilling and production of these first wells, it was noted that they produced large amounts of carbon dioxide gas. This observation led to the formation of the Salton Sea Products Corporation, which began exploring for carbon dioxide gas. The second well drilled in this venture, in 1932, about a mile northeast of Mullet Island, was the discovery well for the Imperial Carbon Dioxide field, which produced commercially from 1933 to 1954 (Rook and Williams, 1942). The carbon dioxide was recovered from shallow sands 200 to 700 feet deep. Two processing plants were built in the field to convert the carbon dioxide to dry ice. This field was abandoned in 1954 because of depletion of the producing sands, the rising waters of the Salton Sea, which inundated many of the wells, and the development of modern refrigerated transport.

What is generally considered to be the discovery well for the Salton Sea Geothermal field, the first well in the Imperial Valley to produce substantial amounts of steam, was Kent Imperial Corporation "Sinclair" 1, Sec. 10, T. 12S., R. 13E. This well was a promotional oil prospect and was drilled in 1957 and 1958 to 4,725 feet. The well was tested, produced hot water and steam, and in 1959 a small pilot plant including separators, condensers, and generators was installed at the wellhead. This test facility was operated intermittently for several months until it became scaled up at the surface. Due to legal as well as mechanical complications, the well has not been produced since.

The confirmation well, the first one to be drilled expressly for steam, was Joseph I. O'Neill, Jr. "Sportsman" 1, Sec. 23, T. 11S., R. 13W. It was drilled in 1961 to 4,729 feet about four miles northeast of "Sinclair" 1, and was completed as a good steam producer. During the period following the drilling of "Sportsman" 1, from 1961 through 1964, ten more geothermal wells were drilled in the immediate vicinity, resulting in the completion of eight of these as steam producers. All of these wells produced from hot water reservoirs; and because of flashing of steam in the well bores due to reducing pressures, they produced a mixture of steam and water at the wellhead. Analyses of the produced water indicated a surprisingly large amount of minerals in the brine, with some wells indicating concentrations over 300,000 ppm total dissolved solids. The brine was also slightly caustic, and severe corrosion and scaling problems accompanied the production. Recognizing the potential for mineral recovery from the brines, the Morton Salt Company (Imperial Thermal Products, Inc.) and the Union Oil Company erected small pilot plants in an effort to develop the minerals present in the brine. After a few years of experimentation with brine production and electricity generation, these ventures were terminated as uneconomical and the plants were closed down.

During the period 1965-1971, no deep geothermal test wells were drilled in the Imperial Valley. Standard Oil Company of California had drilled a deep oil exploration well in 1963 to 13,443 feet, near the center of the valley, in which abnormal temperatures were encountered. They subsequently drilled 17 shallow (500 feet) temperature test holes in the southern portion of the valley. In 1965, the University of California at Riverside began intensive geothermal investigations of the Imperial Valley that lasted through 1970. This program, later supported by the U.S. Bureau of Reclamation, the National Science Foundation, Standard Oil Company of California, the Chevron Oil Field Research Company, and the Imperial Irrigation District, incorporated Standard's previous work and included heat flow, resistivity, gravity, seismic surveys, and more than one hundred shallow temperature hole tests. The results of this study pointed up several significant geothermal anomalies, most of which had been previously unknown. The University has continued their investigations of the area through to the present time.

Twelve wells were drilled in the valley in 1972, the year that marks the beginning of the current drilling phase. Five, including one observation well, were located in the Salton Sea Geothermal field; three on the Heber anomaly; one on the East Mesa anomaly; and one on the Dunes anomaly. All of these wells were completed as potential steam or hot water producers. Two wildcat wells drilled off the mapped anomalies were abandoned as "dry" holes. To date, the Salton Sea Geothermal field, including the Westmorland area, has had thirty wells drilled in it. Six of these are injection wells and one is an observation well. Seven of the wells formerly capable of production have already been abandoned.

Heber was the second proven geothermal anomaly. This area was known to be abnormally hot as a result of the drilling of the Amerada Petroleum Corporation "Timken" 1, Sec. 28, T. 16S., R. 14E. in 1945. In 1963 Standard Oil Company of California confirmed the existence of the anomaly with a series of shallow temperature holes, which they followed later, in 1971, with geophysical work. The discovery well, Magma Energy, Inc. "Holtz" 1, Sec. 32, T. 16S., R. 14E., was drilled in 1972 to 5,147 feet. To date eight potentially productive wells and seven deep observation wells have been drilled in the area. All the wells have been shut in since drilling except for short, intermittent testing periods. Chevron Resources Company has signed agreements to furnish the geothermal resources necessary to supply a 50 megawatt plant to be constructed by Southern California Edison. Scheduled completion date is 1982.

The third proven geothermal anomaly was the East Mesa. This area is entirely controlled by the federal government, which supported the early work done by the University of California. The anomaly was first delineated by this work. The discovery well was the U.S. Bureau of Reclamation "Mesa" 6-1, Sec. 6, T. 16S., R. 17E., drilled in 1972 to 8,030 feet. To date, twenty-two wells have been drilled in this field. Magma Power Company has completed a 10 megawatt plant in the southern portion of the field, and Republic Geothermal, Inc. has announced plans to construct a 50 megawatt plant in the northern portion of the field. The Bureau of Reclamation has constructed a test facility on the site of the discovery well where geothermal research and development testing can be performed under actual field conditions, using producing geothermal wells. The facility has been made available to outside interested researchers.

The next geothermal anomaly to be proven was Brawley. In 1975, Union Oil Company of California drilled "Veysey" 1, Sec. 15, T. 13S., R. 14E., to 8,385 feet. To date, eleven wells have been drilled in this field. Union has announced plans to construct a 10 megawatt plant in the area. Completion is scheduled for 1980.

In 1978-79, McCulloch Geothermal Corporation drilled "Mercer" 1-28, Sec. 28, T. 14S., R. 14E., to 12,910 feet as the discovery well for an as yet unnamed field (between the Brawley and the Heber fields). To date one disposal well has been drilled, but no confirmation wells have been started.

Since 1972, a total of eight "wildcat" geothermal wells have been drilled off of the known resource areas that have been, or should be, abandoned as "dry" (cold) holes. In all, sixty-three production wells have been drilled in the producing areas along with nine wells specifically drilled for injection purposes.

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MONITORING CRUSTAL DEFORMATION IN THE IMPERIAL VALLEY - MEXICALI VALLEY STRUCTURAL TROUGH*

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Experience in many areas of the world indicates that significant ground movement frequently accompanies the extraction of large quantities of fluids from subsurface reservoirs. This may result from compression of the fluid-bearing reservoir rocks due to induced fluid stresses (Lofgren, 1968 and 1969; Poland, 1972) or from deep-seated tectonic adjustments triggered by the withdrawals (Lofgren, 1973). Both vertical (Poland, 1972, Table 1) and horizontal (Mayuga and Allen, 1969; Hunt, 1970; Castle and Yerkes, 1976) components of deformation are frequently observed. Even subtle changes in fluid stress at depth may cause widespread surface ground movements, suggesting the magnitude and types of problems that can be expected in Imperial Valley and Mexicali Valley as the exploitation of geothermal resources intensifies.

Because the Imperial Valley-Mexicali Valley structural trough is tectonically highly active, the differentiation of induced crustal changes from regional tectonism will be difficult. Only by precisely monitoring the local and regional and crustal changes as they occur, and correlating these with regional seismic events and local gravity and reservoir-production changes, can the effects caused by geothermal developments be recognized. The threat of induced widespread land subsidence areas of geothermal fluid extraction is of particular concern. Not only are the thick unconsolidated and semiconsolidated alluvial deposits of these valleys compressible, but the increases in effective stresses induced by the geothermal production will be transmitted considerable distances both vertically and horizontally.

Networks of precise vertical and horizontal geodetic control have been established in both Imperial and Mexicali Valleys. Periodic resurveys of these networks will measure crustal deformation as it occurs. The following two open-file reports by the U.S. Geological Survey give background information on the geodetic monitoring networks in these valleys, and for Imperial Valley give preliminary interpretation of significant crustal changes measured between 1972 and 1977, prior to geothermal developments. These reports, "Measured crustal deformation in Imperial Valley, California", open-file report 78-910 by Ben E. Lofgren and "Monitoring crustal strain, Cerro Prieto geothermal field, Baja California, Mexico", open-file report 79-204 by Ben E. Lofgren and Bruce L. Massey, are reprinted here in their entirety except for the deletion of the survey station descriptions, pages 10 through 27 of report 79-204.

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*This paper is an introduction to the two papers which follow.

MEASURED CRUSTAL DEFORMATION IN IMPERIAL VALLEY, CALIFORNIA*

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Sacramento, California

ABSTRACT

Precise geodetic surveys since 1972 indicate that significant vertical deformation of the land surface continues in Imperial Valley, California. Measured vertical changes as great as 3.5 cm per year indicate that two types of tectonic movement are occurring: (1) a downward regional tilt of the valley surface from the Mexican border northward toward Salton Sea, and (2) a deepening of the structural trough presently occupied by Salton Sea. A comparison of 1972-77 change contours with 1927 topographic contours shows gross parallelism, suggesting that the recent deformation is a continuation of the tectonism that formed the Salton trough. Ground movement since 1972 has tended to steepen slightly the gradients of streams, canals, and drains on the valley floor and to increase the capacity of Salton Sea. A usable record of eight years of background measurements of tectonic change are available prior to the impact of geothermal production in Imperial Valley

INTRODUCTION

Imperial Valley is part of a deep, sediment-filled structural trough on the border between the continental block of western United States and the oceanic block of the eastern Pacific. Major and minor faults, largely masked by young alluvium (Dutcher, Hardt, and Moyle, 1972), traverse the relatively flat valley surface. Currently, this is one of the most tectonically active areas of the country. Within the valley, at least four known geothermal resource areas (Fig. 1) are being considered for electric-power generation. Present contracts schedule geothermal production in three scattered areas within two years.

One of the potential hazards of geothermal production in Imperial Valley is the threat of induced land subsidence and crustal deformation (Lofgren, 1973). Survey networks of precise vertical and horizontal control have been monitored since 1972 to detect possible crustal deformation prior to geothermal production, and thereby establish background rates of tectonic movement prior to the impact of induced changes (Lofgren, 1974).

*This is a reprint of USGS open-file report 78-910.

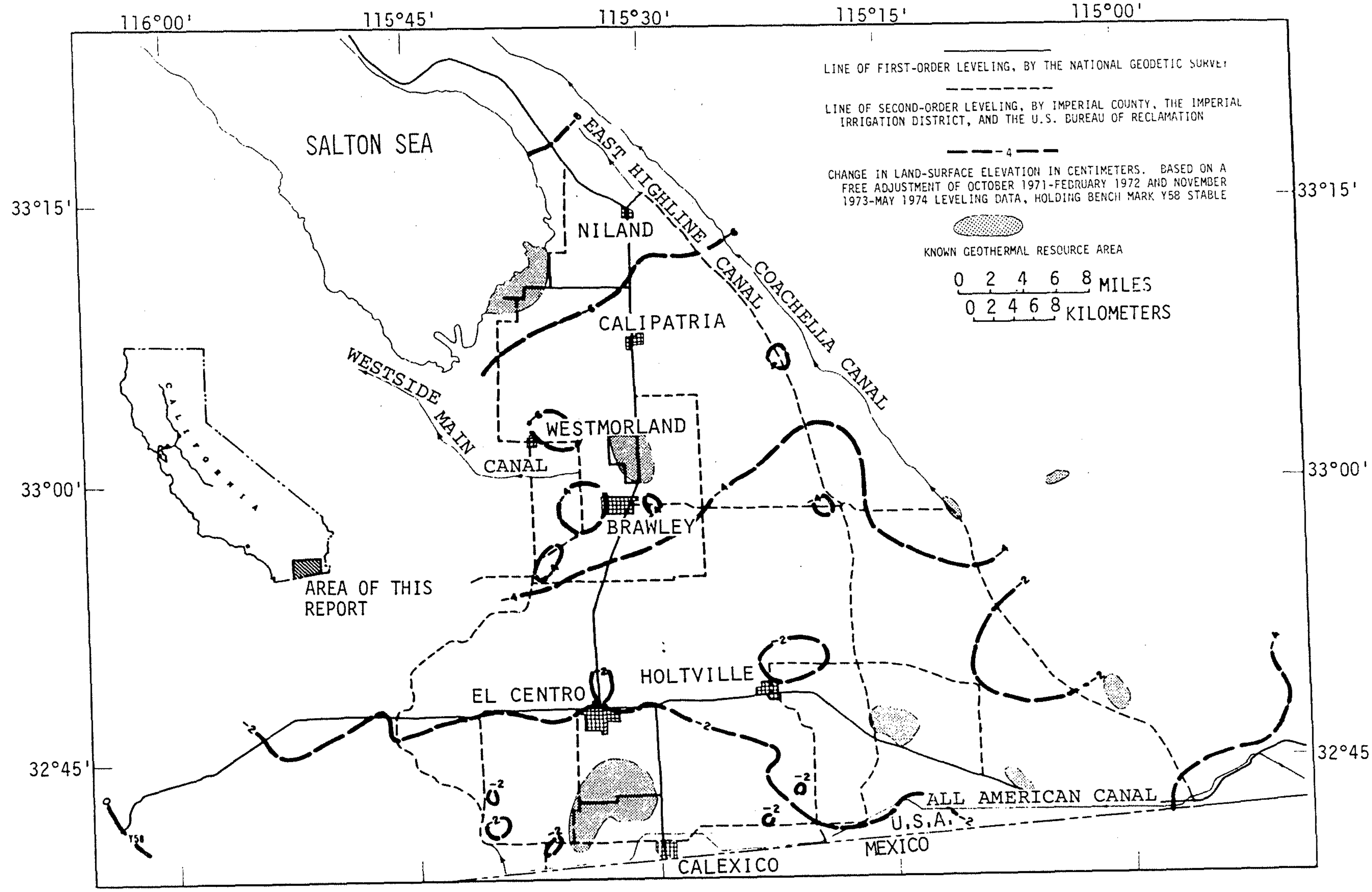
This report consists essentially of three maps of measured vertical changes in the land surface based on 5 years of leveling control as part of the Imperial Valley geothermal subsidence detection program coordinated by Imperial County. All leveling in this interpretive study was by the National Geodetic Survey, Imperial County, the Imperial Irrigation District, and the U.S. Bureau of Reclamation. Funds for the leveling were provided by numerous private and government organizations.

Three epochs of leveling control are the basis for the maps in this report, (1) October 1971-February 1972, (2) November 1973-Map 1974, and (3) November 1976-April 1977. All changes are based on a free adjustment of field survey data by the National Geodetic Survey. This entails the holding of only one bench mark in the network as an assumed-stable reference. In this study, bench mark Y58, 50 km southwest of El Centro, shows zero change; all other marks show their relative movement with respect to bench mark Y58. Free-adjustment elevations for all bench marks in the network for each of the three epochs of leveling were computed by the National Geodetic Survey; reference tabulations are in the files of the Geological Survey and the Imperial County surveyor's office.

Only vertical changes are considered in this report. No attempt is made here to report or interpret the small rates of horizontal ground movement being measured as part of this geothermal research investigation.

MEASURED CHANGES

Figure 1 shows the network of first-order and second-order leveling, geothermal areas (anomalies), and principal canals in Imperial Valley, and also the contours of relative change in land-surface elevation for the 2-year period 1972-74. Changes are with respect to bench mark Y58 and considerably outside of the structural trough southwest of El Centro. Although change contours are quite irregular, and numerous isolated closed-contoured areas appear, the general trend of change was a quite uniform down-to-the-north tilt of the land surface toward Salton Sea. The rate of change in elevation was about 3 cm per year in the 70 km between the Mexican border and the Sea.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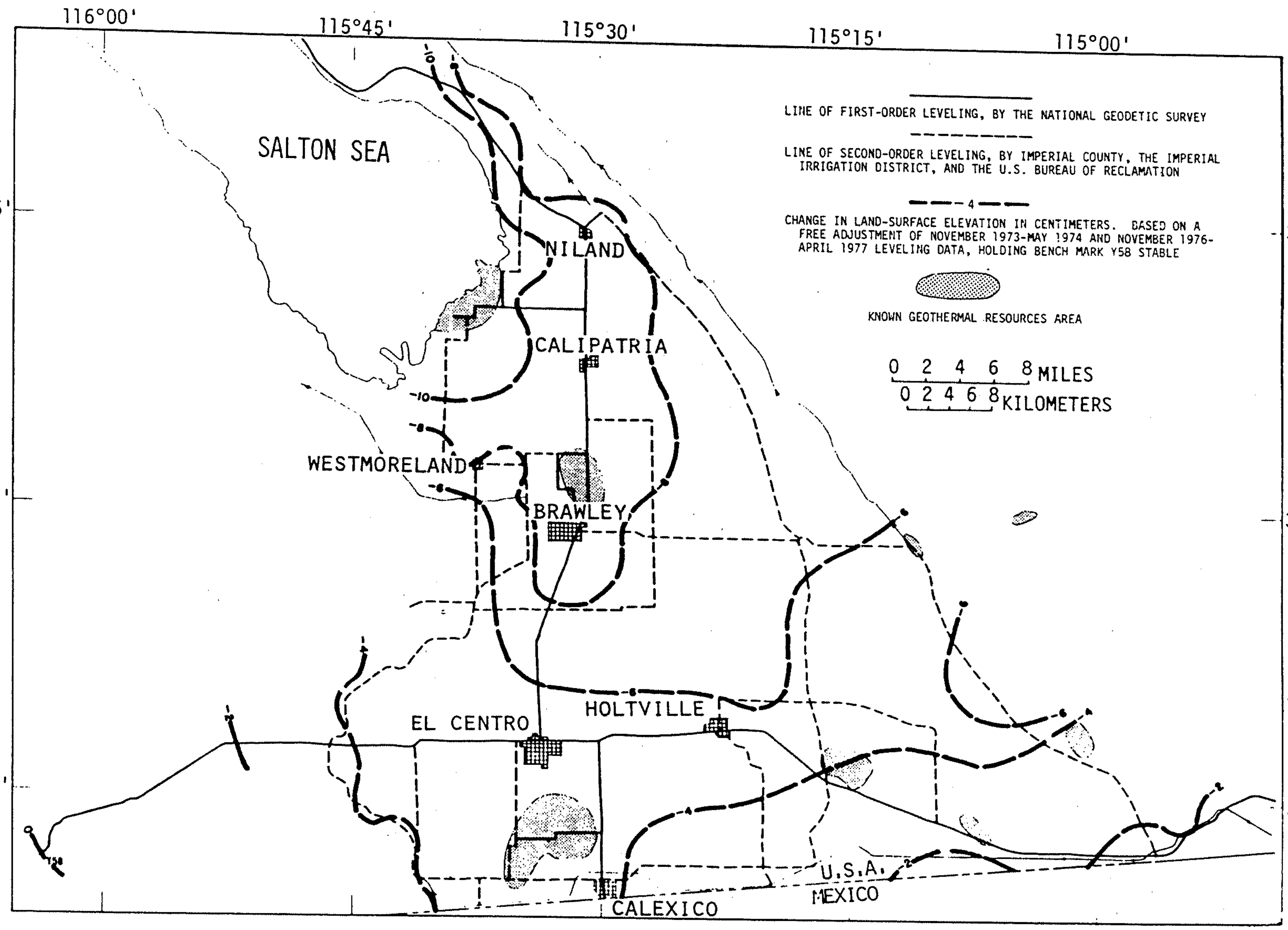
LINE OF FIRST-ORDER LEVELING, BY THE NATIONAL GEODETIC SURVEY
LINE OF SECOND-ORDER LEVELING, BY IMPERIAL COUNTY, THE IMPERIAL IRRIGATION DISTRICT, AND THE U.S. BUREAU OF RECLAMATION
4
CHANGE IN LAND-SURFACE ELEVATION IN CENTIMETERS. BASED ON A FREE ADJUSTMENT OF OCTOBER 1971-FEBRUARY 1972 AND NOVEMBER 1973-MAY 1974 LEVELING DATA, HOLDING BENCH MARK Y58 STABLE
KNOWN GEOTHERMAL RESOURCE AREA
0 2 4 6 8 MILES
0 2 4 6 8 KILOMETERS
SALTON SEA
EAST HIGHLINE CANAL
COACHELLA CANAL
NILAND
CALIPATRIA
WESTSIDE MAIN CANAL
WESTMORLAND
BRAWLEY
CALIFORNIA
AREA OF THIS REPORT
EL CENTRO
HOLTVILLE
ALL AMERICAN CANAL
U.S.A.
MEXICO
CALEXICO
Y58

FIGURE 1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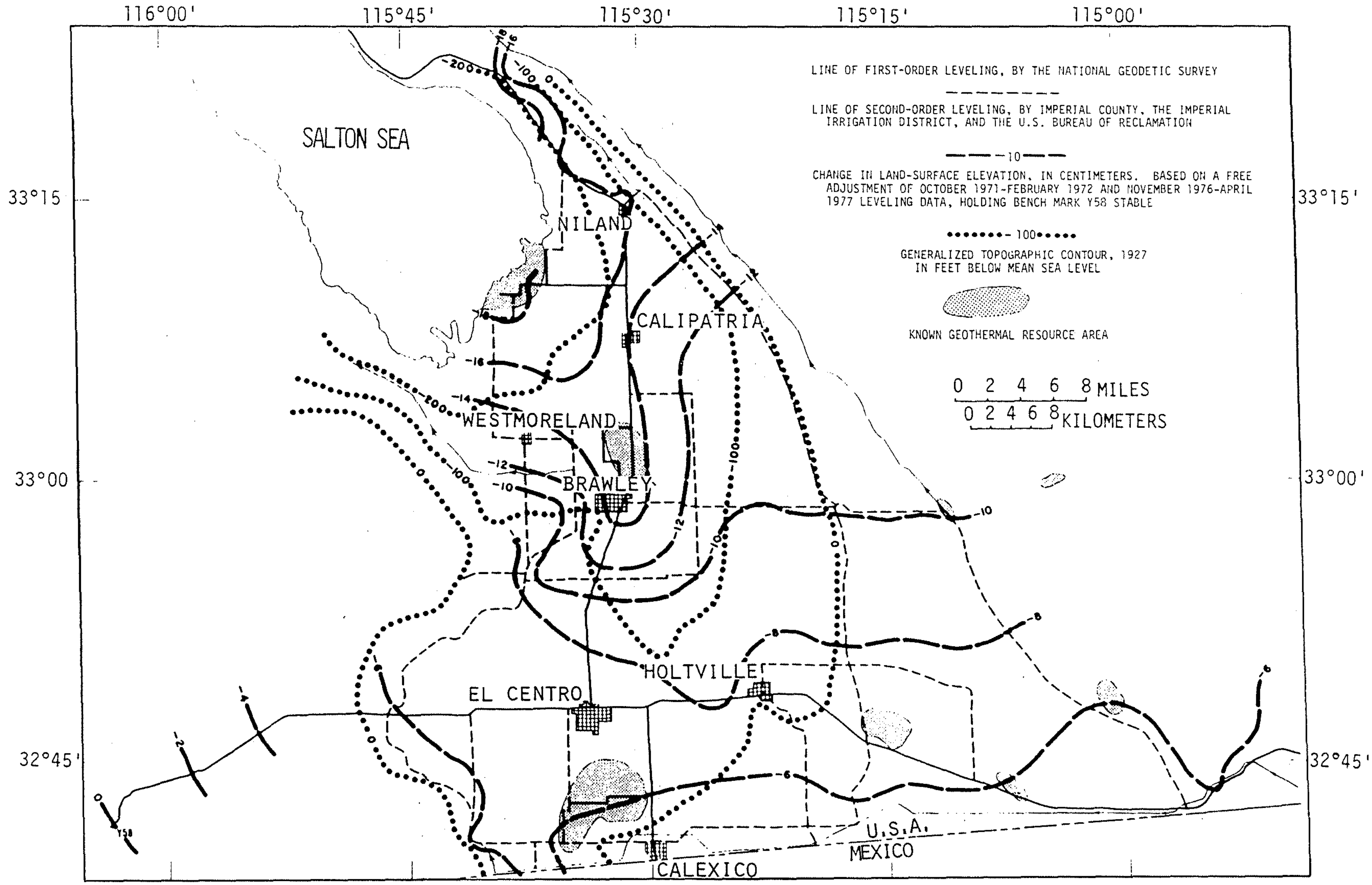
BRAWLEY
EL CENTRO
HOLTVILLE
CALEXICO
U.S.A.
MEXICO
LINE OF FIRST-ORDER LEVELING, BY THE NATIONAL GEODETIC SURVEY
LINE OF SECOND-ORDER LEVELING, BY IMPERIAL COUNTY, THE IMPERIAL IRRIGATION DISTRICT, AND THE U.S. BUREAU OF RECLAMATION
CHANGE IN LAND-SURFACE ELEVATION IN CENTIMETERS. BASED ON A FREE ADJUSTMENT OF NOVEMBER 1973-MAY 1974 AND NOVEMBER 1976-APRIL 1977 LEVELING DATA, HOLDING BENCH MARK Y58 STABLE
KNOWN GEOTHERMAL RESOURCES AREA
0 2 4 6 8 MILES
0 2 4 6 8 KILOMETERS

FIGURE 2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BRAWLEY
HOLTVILLE
EL CENTRO
CALEXICO
U.S.A.
MEXICO
LINE OF FIRST-ORDER LEVELING, BY THE NATIONAL GEODETIC SURVEY
LINE OF SECOND-ORDER LEVELING, BY IMPERIAL COUNTY, THE IMPERIAL IRRIGATION DISTRICT, AND THE U.S. BUREAU OF RECLAMATION
CHANGE IN LAND-SURFACE ELEVATION, IN CENTIMETERS. BASED ON A FREE ADJUSTMENT OF OCTOBER 1971-FEBRUARY 1972 AND NOVEMBER 1976-APRIL 1977 LEVELING DATA, HOLDING BENCH MARK Y58 STABLE
GENERALIZED TOPOGRAPHIC CONTOUR, 1927 IN FEET BELOW MEAN SEA LEVEL
KNOWN GEOTHERMAL RESOURCE AREA
0 2 4 6 8 MILES
0 2 4 6 8 KILOMETERS

FIGURE 3

Measured changes in land-surface elevation for the 3-year period 1974-77 are shown in Figure 2. Change contours during this period reflect two distinct types of deformation, (1) a downward tilt toward the north of about 3 cm per year, and (2) an apparent deepening of the structural trough. Significantly, the shapes of the -2-cm and -4-cm change contours define a deforming trough extending considerably south of the Mexican border. It is also noteworthy that the control mark in bedrock terrain in the southeast corner of the mapped area showed only 2 cm of change during this 3-year period.

Figure 3 shows the combined changes of Figures 1 and 2 spanning the years from 1972 to 1977, and also the generalized 1927 topographic contours of the valley floor. This longer base of reference gives a more reliable picture of the complex and rapid tectonic deformation occurring at depth beneath the camouflaging, relatively flat, valley floor. Change contours for this 5-year period clearly reflect the same patterns of vertical tectonic deformation, (1) the down-to-the-north tilt of about 3 cm per year from the Mexican border to Salton Sea, and (2) the marked deepening of the structural trough presently occupied by Salton Sea. Of particular interest is the close parallelism between the 1972-77 change contours, the 1927 topographic contours of the valley trough, and the present shoreline of the Sea (Figure 3). One gets the strong impression that changes of the past 5 years are a continuation of the same tectonic processes that formed the Salton trough during the past millennia. Even the northeast-trending transverse fault system south of Brawley that was so active during the January 1975 earthquake swarm (Johnson and Hadley, 1976) is reflected in the change contours of 1972-77.

CONCLUSIONS

(1) Significant tectonic deformation continues on the floor of the Imperial Valley structural trough. The configuration and rates of vertical changes are in apparent harmony with tectonic trends that have persisted through past millennia. Most of the deformation is apparently aseismic.

(2) Measured ground movement from 1972 to 1977 indicates a relative deepening of the structural trough, with the cropland at the southern shoreline of the Sea sinking about 3.5 cm per year with respect to bench mark Y58 outside of the trough. This crustal deformation has tended, in general, to steepen the gradient of streams, canals, and drains, and to increase the storage of the Salton Sea. Not all of the inundation of croplands at the south end of the Sea is due to rising water in the Sea; some is due to the sinking of the land surface--at rates as great as 4 cm per year.

(3) Because geothermal production and ground-water developments to date are minimal in Imperial Valley, all measured 1972-77 changes are attributed to tectonism.

(4) The possible loading effect of water and sediment in the Salton trough since the turn of the century on observed sinking of the trough should be investigated. Reservoir loading frequently causes a downwarping of crust, due to the stresses imposed on the underlying basement. It is entirely possible that part of the tectonic change measured by the 1972-77 leveling is related to the loading of imported irrigation water and the filling of the Sea. There is no evidence of any other type of man-induced subsidence in the valley.

(5) In order to differentiate natural tectonism from induced changes caused by geothermal developments, it is essential that the collection of geodetic data be continued as geothermal developments progress

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MONITORING CRUSTAL STRAIN, CERRO PRIETO GEOTHERMAL FIELD, BAJA CALIFORNIA, MEXICO*

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ABSTRACT

Significant ground deformation may be occurring in the Cerro Prieto geothermal area, Mexicali Valley, Mexico, as a direct result of extensive withdrawals of geothermal fluid and of continuing tectonism. In order to measure the magnitude and rate of this deformation, three networks of precise geodetic control were established in 1977-78, as part of an international agreement between Mexico and the United States. This report gives the background data for one of these survey nets--a local network of precise horizontal control designed to monitor the horizontal component of ground movement in the area of geothermal production. It represents the first year's effort of a 3-year investigation by the U.S. Geological Survey. It is anticipated that the network of horizontal control will become part of the monitoring program of the Mexican Comision Federal de Electricidad (C.F.E.) for periodic surveys.

Fifty-nine lines of precise horizontal control comprising the Cerro Prieto horizontal-control net were established and measured for the first time during January-March 1978. The net encompasses the area of geothermal interest, and spans many of the active local and regional faults. By repeated measurement of the lines in the network, magnitudes and rates of relative ground movement can be calculated. Surveyed control lines of the net tie stations in the geothermal area to bedrock reference stations on Cerro Prieto volcano and four peaks of the Cucupas Mountains. Thus, measured ground movement in the geothermal area can eventually be correlated with regional changes in western Mexicali Valley. To measure accurately the deformation caused by geothermal production and to differentiate this deformation from changes due to other causes are among the challenges of this research program.

INTRODUCTION

The Cerro Prieto geothermal power plant, about 30 km southeast of Mexicali, Baja California (see Page 4, Fig. 1), has generated 75 MW of electrical power since April 1973. It is the first such commercial facility in a liquid-dominated geothermal field in the Americas. Thirteen production wells, clustered in a 1.5-km^2 area and ranging in depth from 800 to 1,400 m (Garcia, 1975), presently discharge the equivalent of about 3,000 m^3 of water per hour, or roughly a depth of 5.5 m of water over the area of the well field each year. Most of this water leaves the area completely, either as evaporation or by canal export; little is reinjected. Construction and continuing geothermal exploration are progressing to double the production at Cerro Prieto in about one year**; ultimate production is projected at more than ten times the present rate. Undoubtedly, this escalating production is affecting subsurface fluid pressures; those changes, in turn, must affect the effective stresses and the recharge characteristics of the geothermal reservoir system.

Crustal deformation commonly occurs in areas where large volumes of fluids are withdrawn from subsurface reservoirs (Lofgren, 1973, 1974; Poland, 1969). Deformation rates are particularly significant where: (1) the sequence of reservoir rocks is thick and compressible; (2) the withdrawal rates greatly exceed the natural and injection recharge so that steep fluid gradients develop, and (3) natural and induced regional tectonism continues to affect the area. Each of these conditions seems to be accentuated at the Cerro Prieto geothermal field. Field evidence suggests that the reservoir system should be undergoing compression due to hydraulic stressed induced in the system--vertical compaction resulting in subsidence of the land surface and horizontal compression reflected to the surface as radial inward ground movement toward the center of field discharge. As in other areas studied, the hydraulically induced changes will be superimposed on the intricate regional pattern of continuing tectonic deformation. Geodetic measurements of induced ground movement at Cerro Prieto are not only of considerable local importance, but they will indicate the types of crustal changes that might occur in liquid-dominated geothermal production areas of the Imperial Valley of southern California and elsewhere.

*This is an abridged version of USGS open-file report 79-204.

**Doubled to 150MW in 1979 (footnote by editor).

In a single-phase fluid system, the volume of reservoir compression is roughly equal to the amount of fluid discharged and not directly replaced by injected fluids or by recharge from the surrounding area. Thus, if the discharge from the reservoir and the reinjection into the reservoir are known, and if the rates of vertical and horizontal shrinkage of the reservoir system are measured, then the regional recharge characteristics of the system can be approximated. With modification to account for the multiphase character of the fluids involved, this same concept can be applied to geothermal reservoir systems. In general, the volume of reservoir compression at Cerro Prieto should approximate the volume of fluid depletion (discharge minus recharge), and the regional bowl of subsidence should extent laterally as far as recharge gradients are significant. Also, the only practical way of reducing or preventing subsidence is to reduce or prevent the depletion of reservoir fluid pressures in that area.

In order to measure the rates of natural and induced crustal deformation in and around the Cerro Prieto geothermal area, three networks of precise geodetic control were established in 1977-78 as part of an agreement between the Comision Federal de Electricidad of the United States of Mexico and the U.S.A. Energy Research and Development Administration (now the Department of Energy). The objectives and assignment of these geodetic surveys are outlined in Task 6 of this agreement, and call for: 6a) a loop of first-order leveling by DETENAL (Direccion de Estudios del Territerio Nacional, Mexico) to measure vertical changes south from the international border through the geothermal field; 6b) a trilateration network of regional horizontal control by the Topographic Division of the U.S. Geological Survey, extending the Survey's crustal-strain net southward beyond Cerro Prieto; and 6) a local network of horizontal control by the Water Resources Division of the Geological Survey in the vicinity of the Cerro Prieto production area to monitor tectonic and induced ground movement in the geothermal production area. Although it is expected that surface changes due to induced hydraulic stresses will be too small to be of environmental concern, it is expected that these movements will indicate hydrodynamic changes occurring in the reservoir system that are of significant import in understanding the resource potential of the region.

This report concentrates on one aspect of the international agreement, subtask 6c--the establishment of a network of precise horizontal-control survey lines to monitor crustal changes as they occur. It includes the basic data of the initial survey--station descriptions, measured distances, and illustrations describing the network layout. No interpretation of strain rates can be made from these initial data. After the second, third, and subsequent surveys of this same net, scheduled for 1978-79, 1979-80, and thereafter, measured changes can be studied for causal relationships. It is planned that this net will be expanded and intensified periodically as needed to keep pace with new needs and developments in the geothermal area.

We acknowledge and extend our appreciation to our Mexican colleagues for their full cooperation and invaluable technical assistance in formulating and completing this research assignment. The close cooperation among all parties involved in the three separate aspects of task 6 has been most gratifying. It is intended that all data for subtask 6c be fully available to all interested researchers. Also, it is hoped that after the scheduled 3-year research of the international agreement is completed, this network survey will become part of the Mexican responsibilities of C.F.E., DETENAL, or some other agency.

NETWORK LAYOUT

Figure 1 shows the network of horizontal survey lines precisely surveyed in February-March 1978 to monitor natural and induced ground movement in the vicinity of the Cerro Prieto geothermal field. Also, the present area of geothermal production (schematically shown as a circle) and the location of inferred faults that subdivide the geothermal field into blocks are shown approximately. Repeated remeasurement of these lines will give changes in length which represent components of ground movement during the intervening time intervals.

Three types of control stations are shown in Figure 1, (a) EDM (electronic distance measurement) sites (solid triangles) from which intermediate-range (described below) laser instruments accurately measure distances, (b) reflector sites (solid circles) at which specially designed retroreflectors are positioned to receive a laser beam from the EDM instrument and reflect it to the EDM instrument without interruption, and (c) a second EDM site (open triangle) located on Cerro Prieto volcano, a station on the regional trilateration network (Fig. 2), from which a second set of distance measurements has been made to reflector sites on the valley floor.

Figure 2 shows the bedrock stations of the regional trilateration network (subtask 6.b., by the Topographic Division of the Geological Survey) extending southward from an existing Geological Survey crustal-strain network north of the international border, and survey ties from these bedrock stations to selected stations of the local net. The location of the geothermal production area is also shown. Two types of control stations are shown in Figure 2, a) trilateration stations located on selected mountain peaks (except two stations, one on the international border, the other west of El Centro) 240 m to over 1,000 m above the valley floor, from which long-distance laser EDM measurements are made, and b) reflector sites (solid triangles) of the local net on the valley floor. The trilateration station on Cerro Prieto volcano has excellent visibility in all directions; however, it is difficult to reach with heavy survey equipment except by helicopter. To facilitate resurveys of the local network spanning the geothermal area, a readily accessible second point was established on the volcano for most of the valley shots.

A typical EDM instrument setup such as that at station M-3, at geothermal well M-3, consists of a centerpunched brass cap set in a concrete monument, slightly above the surface of a constructed pad. A typical reflector setup would be on one of the many concrete canal structures conveniently available for the local stations. Not only are these structures permanent and rigid, but most are elevated enough to allow line-of-sight shots above the vegetation. The actual survey station at these sites is a marked bolt set flush in the concrete bridge deck.

SURVEY EQUIPMENT USED

All surveying in connection with this project was by the U.S. Geological Survey, using highly precise line-of-sight electronic distance measuring (EDM) instruments. To complete a measurement, the EDM instrument was accurately positioned over one station and a specially designed retroreflector assembly was positioned over the station at the other end of the line. Accurate readings of temperature and barometric pressure at and between the stations are an essential part of the measurement.

Two types of EDM instruments were used in these surveys. For the local shots, those shown in Figure 1, an intermediate-range (to about 12 km with ideal visibility) Keuffel and Esser Ranger III* instrument, with an accuracy of about 3 mm per 1 km, was used. For the longer shots of the regional trilateration net a modified Geodolite* with an accuracy of about 2 mm in 10 km was employed. All recorded distance measurements consisted of statistical averages of many readings recorded in a short period of observations along a given line.

MEASURED DISTANCES, HORIZONTAL-CONTROL NET

Listed below in Table 1 are the measured slope distances between stations of the local horizontal-control net (Fig. 1), surveyed during February-March 1978. These distances are actual point-to-point (slope) measurements, using the medium-range EDM instrument, with accuracy of about 3 mm per kilometer of line length.

Table 2 following shows the measured slope distances (point-to-point) for all lines from bedrock control points on mountain peaks to selected stations of the local horizontal net (Fig. 2). Listed distances were surveyed on January 25-27, 1978, using the long-distance EDM instrument, with an accuracy better than 0.3 mm per kilometer of line length. These measurements were repeated 10 days later for verification.

*The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

Table 1.

Measured distances,
local horizontal-control net (See Figure 1)

EDM Station to	Reflector Station	February-March 1978 Point to point distance (meters)
34	33	2522.432
34	35	2812.177
34	29	3123.164
2	14	1265.698
2	15	2042.287
22	6A	1919.015
22	MOJ-6	1864.475
22	MOJ-7	1405.202
22	38	1092.473
22	31	1157.138
22	13	1897.390
M-3	Volcano	3213.145
M-3	6	2747.369
M-3	28	2307.699
M-3	13	1910.641
M-3	M6A	2479.777
M-3	MOJ-6	2487.877
M-3	38	2406.647
M-3	MOJ-7	2346.142
M-3	22	3473.320
M-3	18	3222.779
4	29	1070.698
4	Salado	3862.349
Volcano	10	11892.109
Volcano	30	8410.404
Volcano	3	10449.907
Volcano	32	8754.630
Volcano	21	9518.446
Volcano	37	3991.440
Volcano	8	7841.600
Volcano	29	3893.770
Volcano	24	9551.548
Volcano	34	6945.874
Volcano	4	3072.298
Volcano	BNP 10065	3448.192
Volcano	Salado	1604.604
Volcano	M6A	4650.575
Volcano	MOJ-6	4691.878
Volcano	MOJ-5	4783.261
Volcano	MOJ-4	5023.528
Volcano	7	10971.716

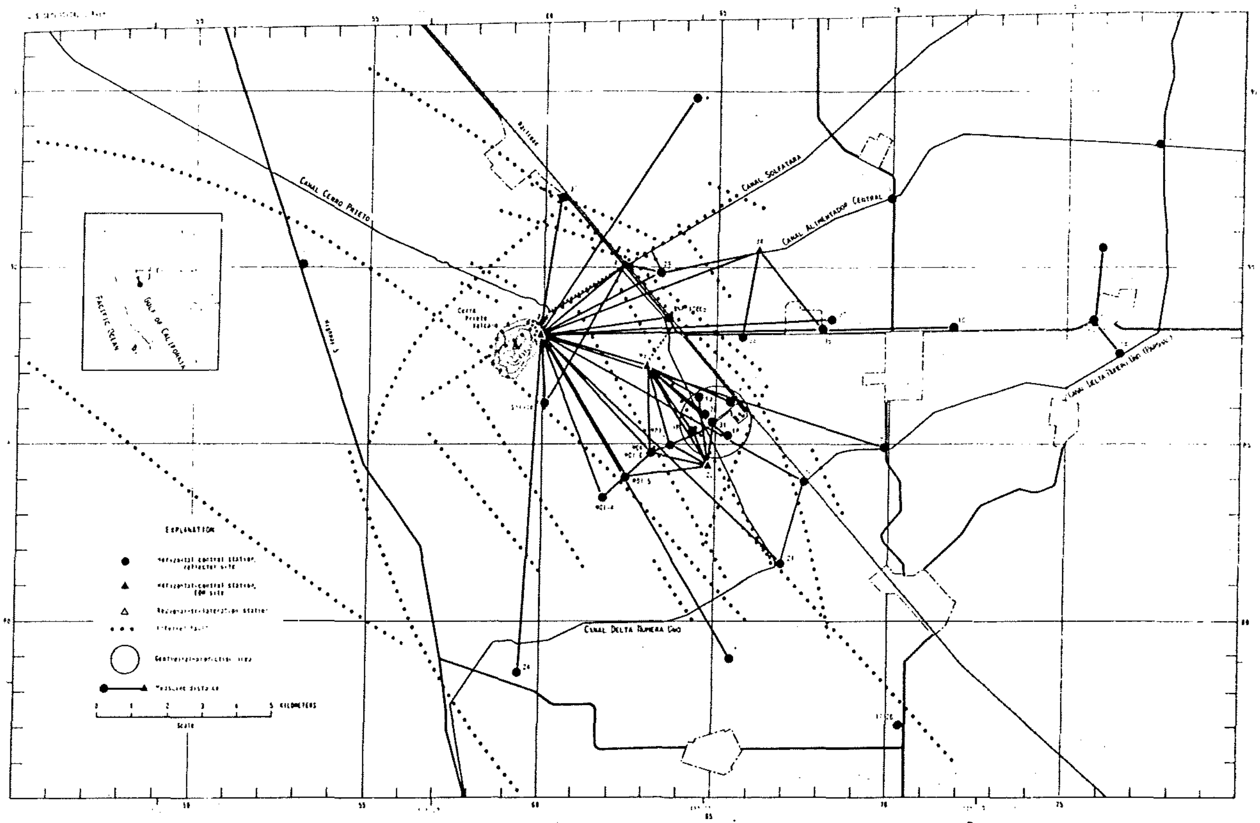

Figure 1 Local network of horizontal-control and inferred faults. Cerro Prieto geothermal area, Mexico.

Table 2.

Measured distances from bedrock control points to selected stations of the local horizontal-control net (See Figure 2)

EDM station to	Reflector station	January 25-27, 1978 Point-to-point distance (meters)
Prieto	1	6,041.4657
Prieto	10	12,561.9504
Prieto	17	15,538.4915
Prieto	24	9,304.0314
Prieto	3	11,013,3099
Prieto	36	19,673.8306
Prieto	4	3,756.4660
Prieto	8	8,421.8342
Prieto	9	11,495.3458
Fierro	4	26,938.3927
Fierro	9	34,569.3571
Fierro	Prieto	24,103.0214
Fierro	Puerta	12,941.1577
Puerta	4	18,376.5329
Puerta	24	14,967.9719
Puerto	Prieto	14,742.7817
Puerta	Mayor	34,703.9614
David	3	28,622.2065
David	17	24,674.6471
David	Puerta	17,440.4652
David	Mayor	18,353.3880
David	Fierro	28,618.3580
Mayor	3	34,819.1186
Mayor	17	27,651.0376
Mayor	Prieto	36,344.0655

SUMMARY

As shown in Figures 1 and 2 and in Tables 1 and 2, the networks of local horizontal control assigned to the U.S. Geological Survey under Subtask 6c of the international agreement have been established and the first year's surveys completed. Expansion and resurveys of these nets are scheduled for 1979 and 1980 by the Geological Survey. It is anticipated that after 1980 the periodic resurveying of these networks will become part of the continuing monitoring program of the Mexican Comision Federal de Electricidad.

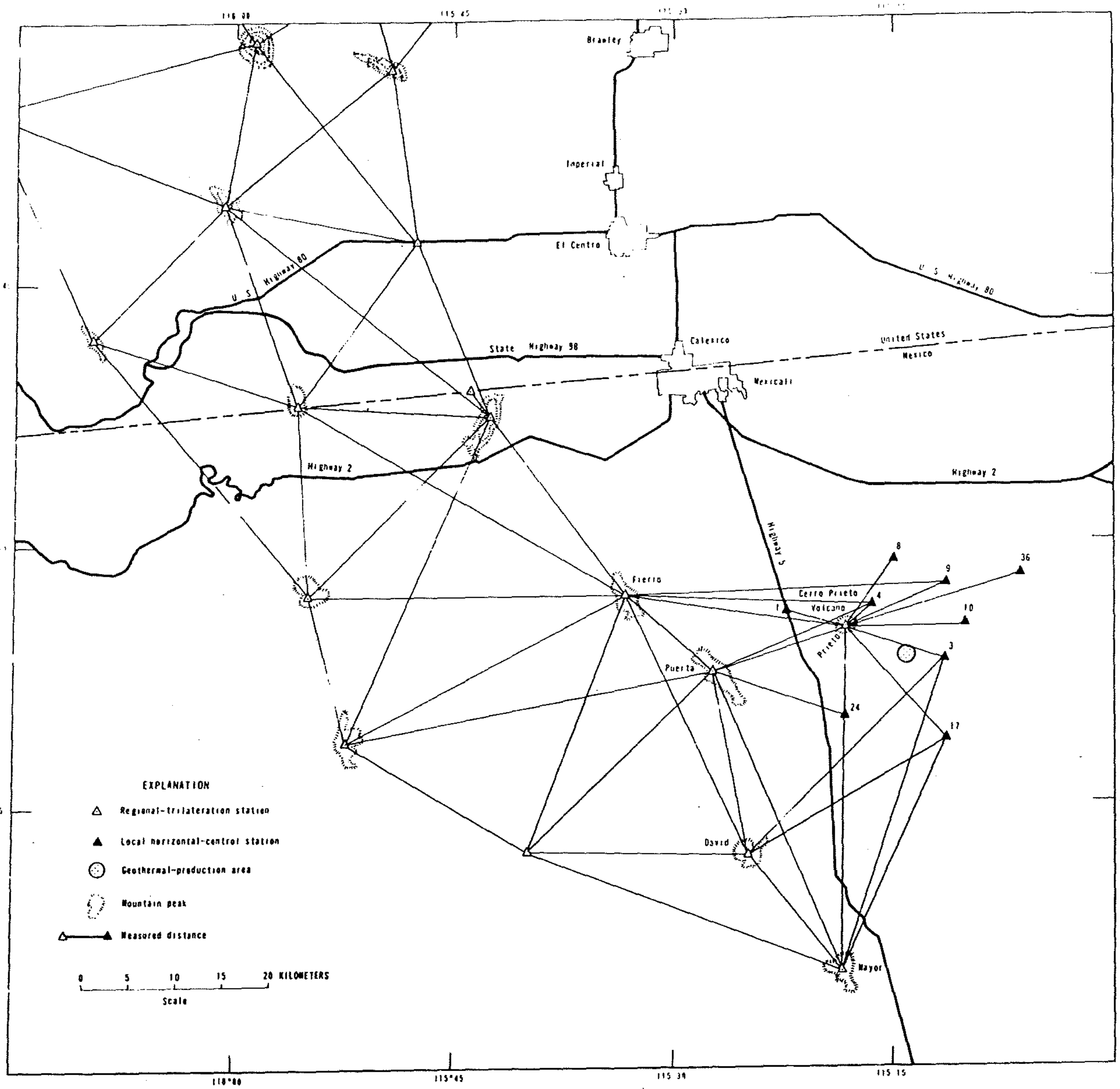

Figure 1 Regional-trilateration network of horizontal-control and bedrock ties. Cerro Prieto geothermal area, Mexico.

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An Update of Tectonics and Geothermal Resource Magnitude of the Salton Sea Geothermal Resource

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Abstract

We have synthesized geological and geophysical data to determine the tectonics of the Salton Sea Geothermal Field region and to re-evaluate its geothermal resource potential. Based upon the existing data, we believe that the Salton Sea high heat flow zone is above a tectonic gap characterized by a depth to the crust-mantle interface of about 14km, by extensive faulting, and by a subsidence rate which is much higher at present than the average geological rate. The tectonic gap is bounded by the Wister and Westmorland faults on the east and west respectively and by the transverse discontinuity and a set of en echelon faults to the north and south. Two epochs of magmatism have taken place in the region within the upper Pleistocene. The stored heat energy within the hydrothermal reservoir at a depth range of 1 to 3 km is about 1.4 x 10^{20} calories which is larger than previous estimates. A large hot dry rock zone must also underly the hydrothermal resource.

Conceptual Model of the SSGF

It is evident that the region of the Salton Sea Geothermal Field ("SSGF") is an active spreading center based upon data from the active volcanism (Muffler and White, 1969), rate of subsidence (Lofgren, 1978), heat flow pattern (Randall, 1974; Palmer, 1975), staircase seismicity pattern (Schnapp and Fuis, 1977; Johnson and Hadley, 1976), preponderance of active growth faults at sea (Meidav, 1968) and south of the Sea (Meidav et al., 1976), the rise of a magmatic pluton (as evidenced from the magnetic data (Griscom and Muffler, 1971), and general geological data (Elders et al., 1972). We present here an update of the evolution and structure of the SSGF, which is a refinement of the models proposed by Elders et al. (1972) and Garfunkel (1972), and a revised resource assessment. No doubt, the current model will require futher refinement as additional data are gathered.

The separation of the Pacific Plate from the American Plate (Atwater, 1970) and its extension through the Gulf of California (Lomnitz et al., 1971) has created extensional stresses in the mantle and crust below the Imperial Valley. Slight differences in crustal rock composition in the SSGF region, characterized by lower melting point, higher plasticity or higher hydrous mineral abundance, has caused that area to flow rheologically in response to the stress. In the first stage, block faulting took place. Older granite masses which were adjacent to the Chocolate Mountains subsided and deltaic deposition occured. This process may have started about four million years ago (Elders et al., 1972) and is continuing at present. With a maximum separation rate of about 8 cm/yr, the average extensional strain rate is about 10^{-7} per year; although, in reality, higher strain rates are calculated for the center of the valley, and lower rates at the margins, based upon Whitten's (1956) and Lofgren's (1974, 1978) data.

Gravity Evidence of Crustal Characteristics

Using Biehler's (1964) Bouguer gravity map, Meidav and Rotstein (1968) calculated a two-dimensional SW-NE model of the Imperial Valley (Figure 1, cross section; see Figure 3 for location of cross section). Evaluating Biehler's density-velocity data, Meidav and Rotstein assigned a mean weighted density of 2.43 gm/cm^3 for the

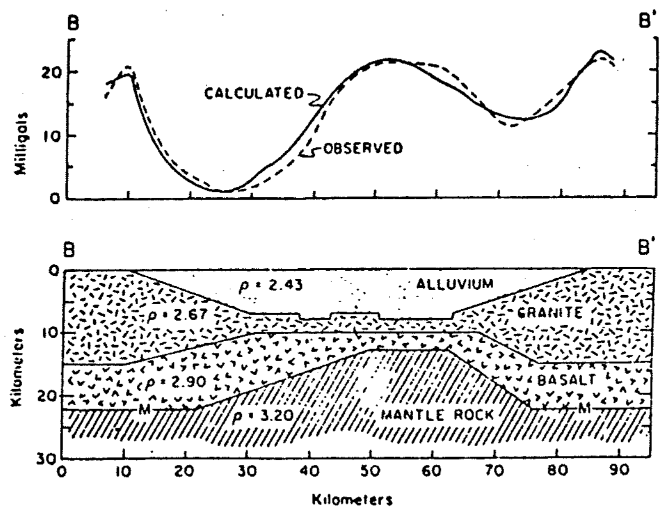

Figure 1: Crustal model of the Imperial Valley based upon gravity data (see Figure 3 for location of section).

Imperial sedimentary section, and an initial depth to basement of 6 km, based upon Biehler's (1964) seismic refraction data. The density for the granite was taken as 2.67, basalt as 2.9, and mantle rock as 3.20. The resultant model (Figure 1) suggests that in order to account for the gravity data, a depth to the Moho of 22 km must be assumed at the margins of the Valley, shallowing to 14 km at the center of the Valley. The density contrast between the alluvium and the granite which it displaces is -.24 (-2.43-2.67). The density contrast between the isostatically rising mantle in the middle of the Valley is about +.3, or about the same order of magnitude (but of opposite sign). Hence, subsidence of the Valley floor must be matched by an approximately equivalent rise in the crust-mantle surface, if isostasy is to be maintained. For periods of time which are large compared with the Newtonian viscosity coefficient of any material, it behaved as though it were a liquid, as far as hydrostatic pressures redistribution goes. Thus, at some depth within the mantle, say 30 km, lithostatic pressures have been everywhere the same, if plastic deformation is equal to or faster than the operating tectonic movement at shallower depths.

In response to the strain associated with separation of the American and Pacific plates, and due to slight heterogeneity in petrology, a gap has been formed in the upper crust. The gap has been filled with low density sediments, reducing the lithostatic pressure within the mantle, causing it to rise and restore isostatic equilibrium. This change caused a rise in the isothermal surfaces within the crust. The rise in turn acted as a feedback causing further reduction in crustal rigidity, and, therefore, accelerating the rheological flow rate of the crust in response to the plate separation forces. This flow, in turn, increased the rate of subsidence of the Valley surface and the Valley floor, eventually leading to volcanism. Review of the subsidence data suggests that the process is faster at present than it has been over the geological past by one order of magnitude. In places it reaches 3.4 cm/yr e.g. at the Salton Sea; Lofgren 1978, as compared with about 3 mm/yr calculated for the average subsidence over about two million years. The accelerated spreading and subsidence in the Salton Sea area has been responsible for at least two epochs of volcanism and suggests that an increased rate of volcanic activity may be anticipated in the future.

The fact that sedimentary in-filling of the Imperial Valley was stopped by man, starting at the turn of the twentieth century, coupled with the ongoing subsidence of about 3.4 cm/yr at the Salton Sea, is creating an upward isostatic stress at the Moho which would require a rise of the Moho of about 22-23 cm/yr, if the stress is instantaneously transmitted. In the long run, this stress may increase the seismicity of the region and decrease the time interval between volcanic episodes beyond the recent rate.

Volcanic Activity

Five small volcanic cones are aligned along the southern end of the Salton Sea. Robinson and Elders (1971) have described the origin of the volcanoes as a response of the basalt to the pull-apart. Muffler and White (1969) have provided a single age dating of the volcanoes at some time between 16,000 and 55,000 years ago.

Both the ground magnetic map of Kelley and Soske (1936) and the aeromagnetic data (Griscom and Muffler, 1971) show that the size of the pluton which underlies the volcanic alignment is much greater than that which would have been caused by five small volcanoes.

Combining the surface geodetic data and the ground magnetometer data, it is possible to show that the large magnetized stock is about four times older than the volcanic eruptions, with the latter having extended out of it a few tens of thousand of years ago. This age determination is calculated from the amount of displacement of the magnetic contours along the Red Hill Fault (Figure 2). There are two offsets of these contours

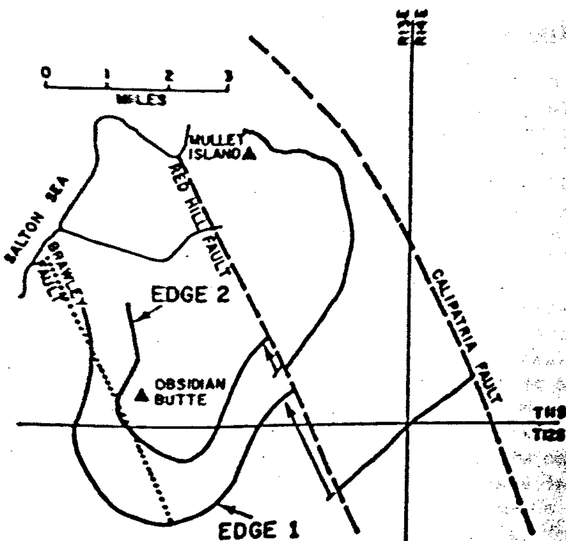

Figure 2: Structural features of the southeastern part of the SSGF, showing the displacement of the edges of two magmatic intusions along the Red Hill Fault. The interpretation is based upon Kelley and Soske's (1936) ground magnetic data.

along the Red Hill Fault; 0.5 km at shallow depths near the young volcanic pile, and about 2 km at greater depth of about 5 km. We assume that the Red Hill fault has been active prior to the older cycle and that it started displacing the deeper stock immediately upon the latter's intrusion into the upper crust. Likewise, immediately after the eruption of the five volcanic cones, perhaps along a northeast-trending dike, their root became subject to the same right lateral movement. Hence, if we assign an age of, say, 50,000 years to the volcanic event, we may deduce that the parent stock is about 200,000 years old assuming a constant rate of displacement.

The data from electrical resistivity, seismology, magnetics, geodetics shows that northwest trending faults and conjugate northeast-trending faults (Figure 3) lace the area. We believe that the Wister Fault forms the northeastern boundary of the developing Salton Sea gap (or rhombochasm), and that the Westmorland Fault forms its southwestern boundary. The northern conjugate boundary

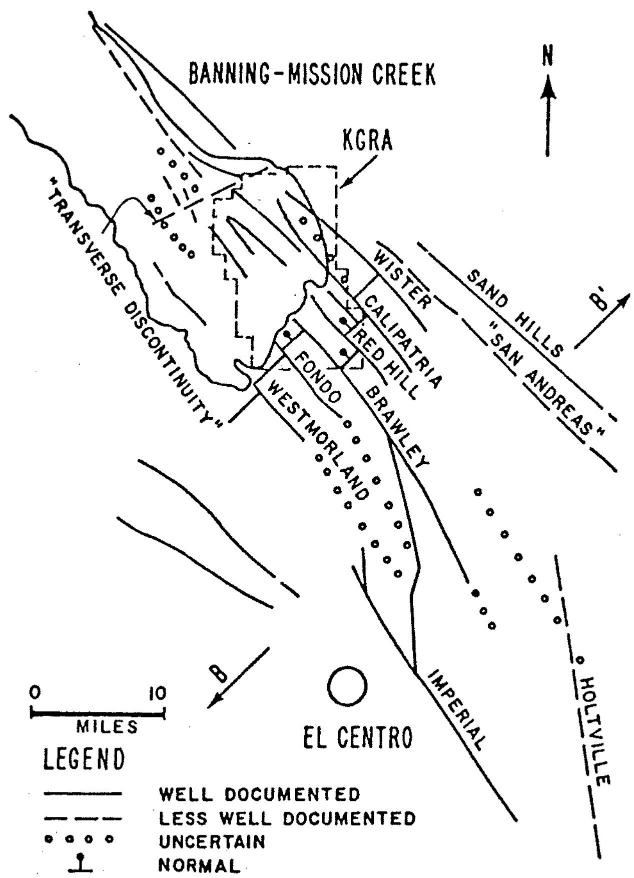

Figure 3: Structural map of the SSGF, based upon combined geophysical data.

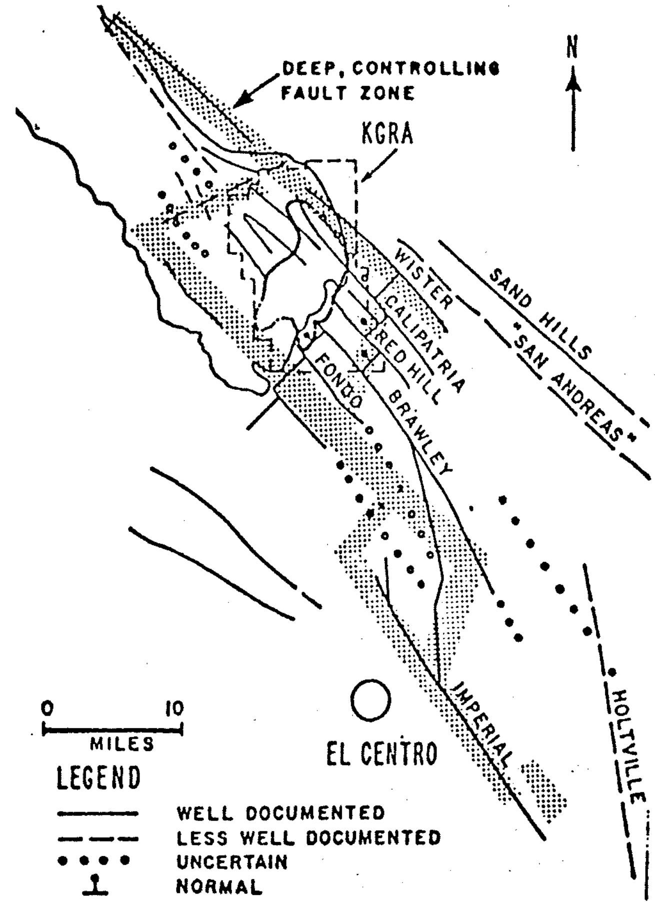

Figure 4: Approximate boundaries of the gap in the region of the SSGF showing the 800 mW/m^2 heat flow contours (area enclosed with dots in southeast part of Salton Sea).

of the gap is the Transverse Discontinuity, which is located approximately where the Sea narrows down, marked by an abrupt change in shallow faulting in the Sea (Meidav, 1968) and by a change in the gravity field from a normal synclinal low to the north, to a gravity high to the south. The southern boundary of the gap is not clearly defined, but may be marked by a set of en echelon conjugate tension faults which occur between the more prominent northwest-trending faults. The approximate southern boundary is shown in Figure 4.

Thermal Regime and Geothermal Resources

Palmer (1975) has constructed an isothermal block diagram of part of the Salton Sea geothermal field, which shows evidence of hydrothermal convection below the cap layer. Palmer's maps show that the isothermal surfaces behave as though the center of heat is located along a northeasterly-trending axis coinciding more-or-less with the axis of the young volcanoes. The isothermal surfaces are oblivious to the vertical or horizontal boundaries, as though the entire system were to consist of a single convective cell. Helgeson (1968) has demonstrated that the salinity-enthalpy-depth relationship in the geothermal system is such that the salinity increase offsets the reduction in density which would normally have taken place with an increase in temperature. This vertical self-equilibration of salinities again suggests that over long time periods (thousands of years), the Salton Sea geothermal system may be considered vertically permeable. We hypothesize that northwest trending faulting, and gap opening (i.e. by transverse faulting) continuously creates new fluid pathways. We deduce from seismological data that brittle fracturing of this type does not extend below basement depth at the Salton Sea geothermal field area namely around 6 km. Hence, the base temperature of the circulating geothermal fluid does not exceed the highest measured temperature (about 340°C) by more than about 160°C assuming a constant gradient from 2 km to 6 km.

Lee and Cohen's (1979) shallow heat flow data indicates that the high heat flow area (more than 200 mw/m^2 or 4.8 HFU) may cover more than 560 km^2. Previously, Lee (1977) demonstrated the validity of shallow heat flow data in the area, by correlating his results with the deeper thermal data at a number of sites. If we take the reservoir thickness as 2 km and the mean reservoir temperature as 265°C, the reservoir energy is about 1.4 x 10^{20} calories, or about 5.86 x 10^{20} Joules. This estimate is about six times greater than that made by Brook et al., in USGS Circular 790 (USGS, 1978).

The USGS team has estimated the electrical energy potential for the Salton Sea Geothermal Field at 3400 MWe for 30 years. The difference between our estimate and that of the USGS results from reevaluation of the resource area due to the new shallow heat flow data. Deeper temperature surveys will be needed to ascertain if our proposed larger resource estimate is justified.

It is impossible at this time to prognosticate the percentage of the accessible resource which will be ultimately harnessed. A host of technological, environmental and institutional barriers is yet to be overcome before the Salton Sea Geothermal resource is fully developed. No consideration of the hot dry rock energy resource was made. However, it is evident that the hot dry rock energy at a depth range of 3-6 km is considerably greater than that of the overlying hydrothermal resource.

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LAWRENCE LIVERMORE LABORATORY TEST FACILITIES AT THE SALTON SEA GEOTHERMAL FIELD, SOUTHERN CALIFORNIA

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The University of California, Lawrence Livermore Laboratory (LLL) has been funded by the DOE (and its precursor organizations) for the last seven years to investigate problems relating to the utilization of high temperature-hypersaline geothermal brine characteristic of the Salton Sea Geothermal Field (SSGS) in Southern California. The SSGS was chosen as the locale for this work because the size of the resource and its proximity to highly populated Southern California cities made the impact of its development on the energy problem potentially great. The technical areas chosen for investigation were selected to best match the scientific resources of the Laboratory, in this case chemistry, materials science and the geosciences. A parallel mechanical engineering effort to design a unique energy convertion machine provided the initial impetus for our work.[1,2]

Typical brines are produced at a wellhead temperature in excess of 200°C with total dissolved solids ranging between 18 to 30 weight percent.[3,4] A major portion of LLL's geothermal activities has been field-oriented. We have studied methods for controlling scale deposition (based on chemical pretreatment of hot brine),[2,5-14] corrosion of well casing and power plant materials[15-26], H_2S abatement[27], and preinjection treatment of spent brine effluents.[28-37] Our reservoir assessment activities have included a program to test production and injection wells that were used to support the jointly operated (DOE-SDG&E-Magma Power Company) Geothermal Loop Experimental Facility (GLEF).[38-52] We have also assessed total geothermal reserves in the Salton Sea known Geothermal Resource Area based on a geophysical model of the resource.[53] To test the model, we designed and then implemented a sub-sea temperature gradient survey, across the southern end of the Salton Sea, via a subcontract to the Institute of Geophysics and Planetary Physics, University of California, Riverside.

FIELD TEST STATION

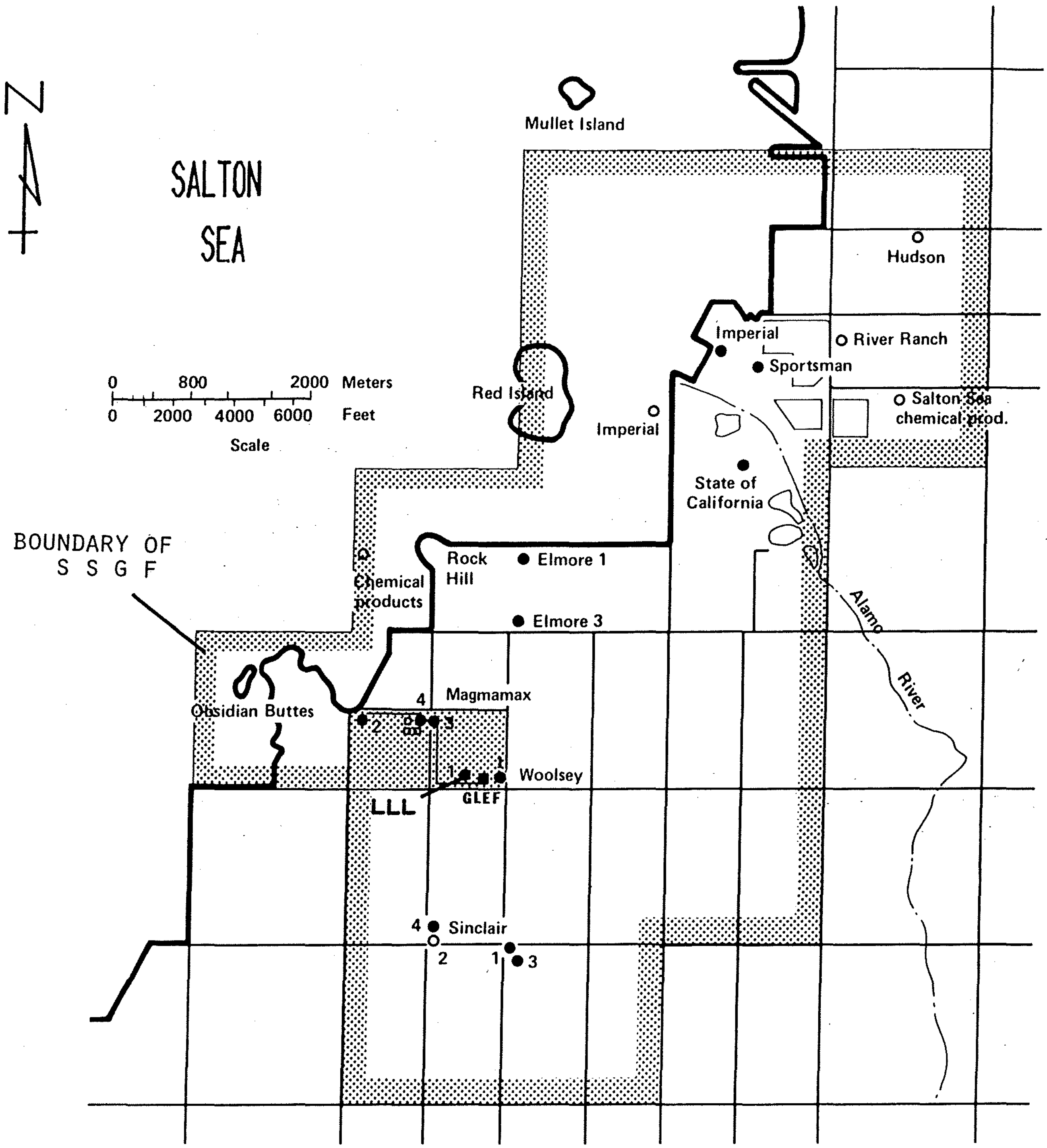
To conduct the field experiments, two self-contained test stations were required. A map of the field area is shown in Figure 1. Through agreement with Magma Power Co. and SDG&E, sites were developed adjacent to the Magmamax No. 1 production well and the Magmamax No. 3 injection well. Continuous injection of untreated brine with a suspended solids concentration of 100 to 300 PPM ultimately resulted in the complete impairment of the Magmamax No. 3 well. Presently, raw effluents are injected into the Magmamax No. 2 well. Effluents produced by the GLEF are preprocessed in a reaction clarifier-filtration system and then injected into a new well located a few hundred feet to the east of the clarifier. Chemical coagulants and flocculants were also extensively evaluated resulting in eventual selection of anionic polymers to significantly enhance performance of a 10 gal/min pilot clarifier. In addition, solids or sludge contact was found to be an extremely effective means for accelerating precipitation of supersaturated species, principally silica, contained in the effluent. The overflow from the clarifier was polished using mixed granular media filters or diatomacous earth pre-coat pressure filters. Filtered effluents contained <1ppm suspended solids and were no longer supersaturated in any potential scale or solids forming species. The tests at this injection site demonstrated the technical and economic feasibility of effluent treatment necessary for sustained subsurface injection in geothermal applications at the SSGS. Our activities at the injection well site were concluded in September 1978 and the test facility was subsequently dismantled and removed.

Our primary test facility is located adjacent to the Magmamax No. 1 production well. This well produces brine at 220°C with total dissolved solids ranging between 18 to 22 weight percent. The actual salinity increases as the production rate increases. A pipeline is also available to permit testing of brine from the Woolsey No. 1 well located about 1500 feet to the east. We are using this facility to evaluate organic compounds which may be useful as scale inhibitors and for an evaluation of the corrosion resistance of various candidate well casing and power plant materials. Following completion of the next series of experiments by Decmeber, 1979, the field facility will be decommissioned and the site will be restored to its initial conditon.

Description - The fenced area shown in Figure 2, occupies slightly over one acre and contains all systems necessary to run experiments without outside support. Hot, two-phase brine enters the site through 3-inch and 4-inch lines, tapped into the main 10-inch production lines close to the

FIGURE 1

SALTON SEA GEOTHERMAL FIELD



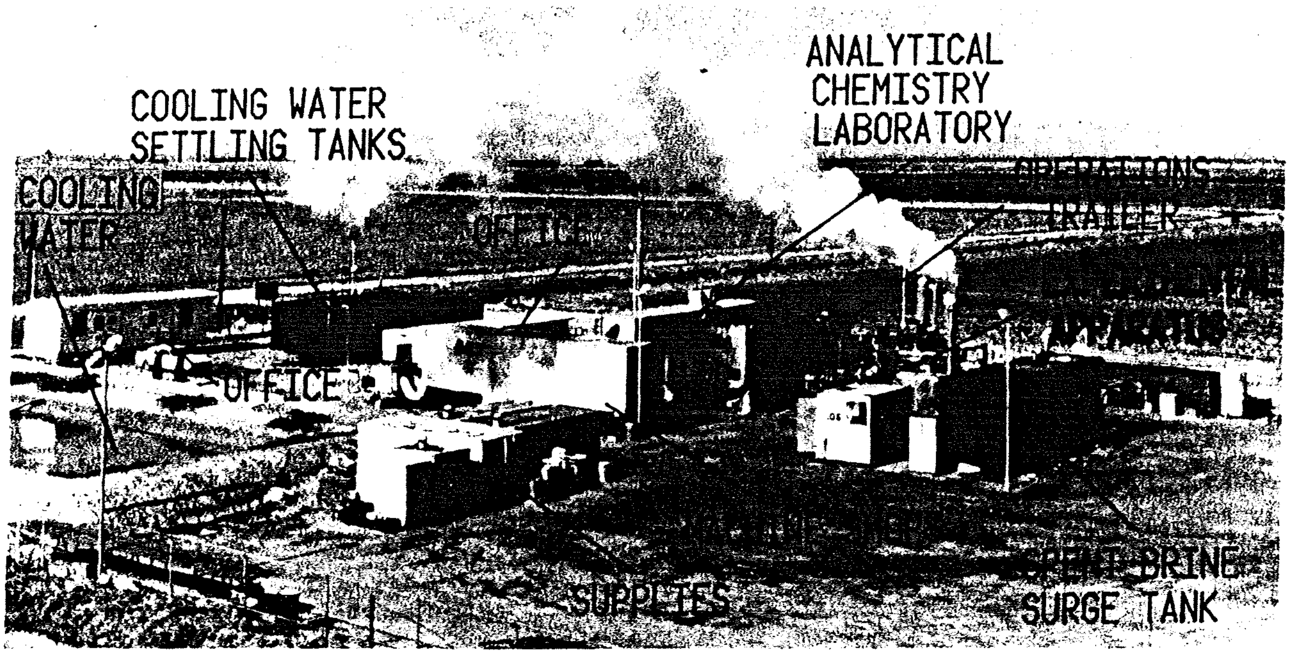


FIGURE 2: LLL GEOTHERMAL TEST FACILITY
Located adjacent to the Magmamax No. 1 wellhead.

Magmamax No. 1 and Woolsey No. 1 wellheads, respectively. Spent brine is pumped from the site through another 3-inch line into the 10-inch reinjection line which carries effluent from the GLEF to a disposal well, Magmamax No. 2 located about 4000 feet to the northwest. The site contains four LLL trailers and two rented trailers. The LLL units consist of a flat bed trailer on which the experimental apparatus is mounted, a control or operations trailer, an analytical chemistry trailer and a shop trailer. The rental trailers provide additional office and work space for such functions as specimen preparation, data reduction, etc. The site also contains a pond and two 20,000 gal. Baker tanks for storing and settling irrigation water used for cooling and other utility purposes.

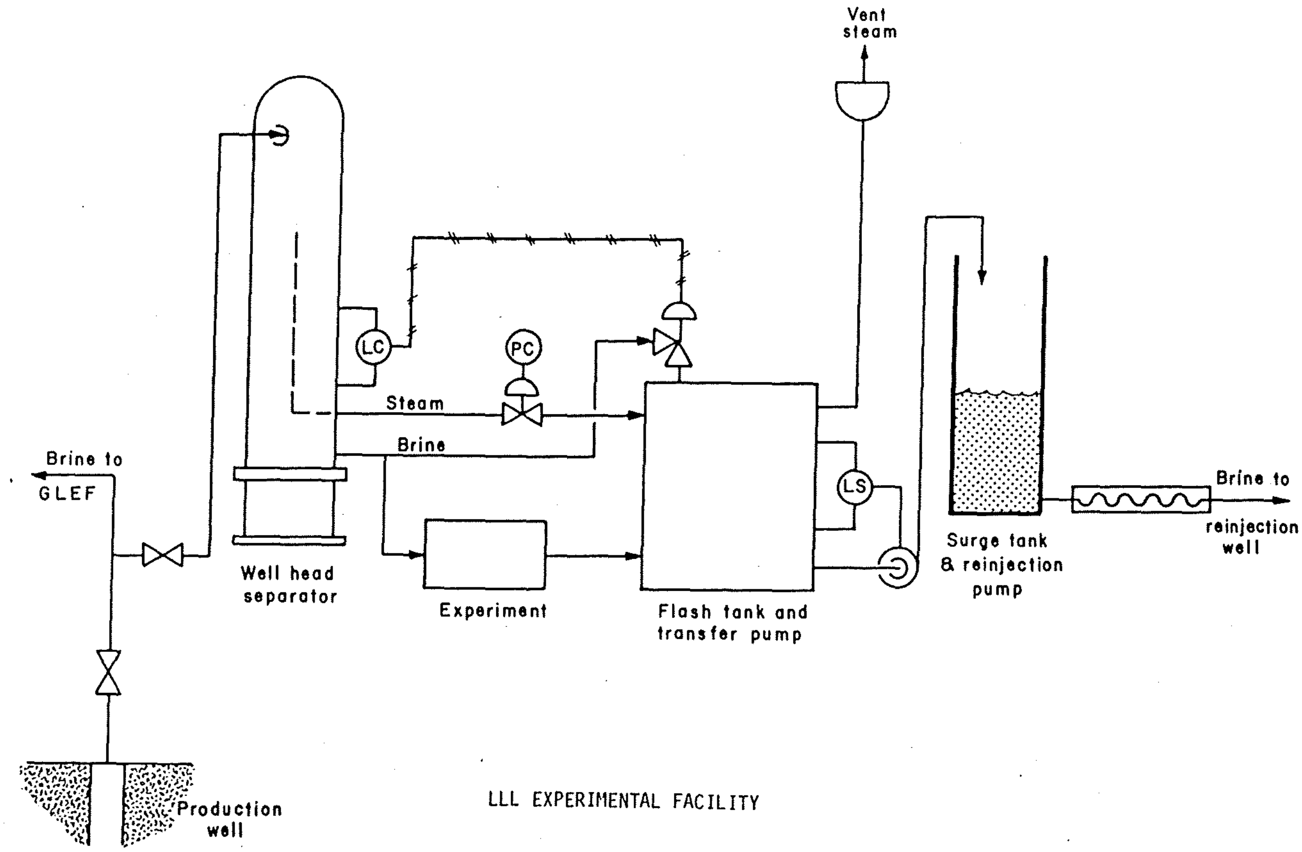
The system used to maintain the flow of brine for test purposes is shown schematically in Figure 3. Two phase fluid flows from the wellhead at a rate of 15,00 to 20,000 pounds per hour into a separator mounted on the end of the flat bed trailer. Steam and brine are separated with minimal pressure drop and the steam fraction is then ejected to the atmosphere through an automated back pressure valve. Part of the liquid phase from the separator provides brine for experiments. The excess fluid flows through a control valve used to maintain the liquid level within the separator. this valve (and a spare) is mounted atop an 8-foot diameter by 5 1/2 foot high flash tank. The tank serves to contain the turbulence of the brine as it flashes from essentially wellhead pressure (250 to 350 psig) to atmospheric pressure. A 3 HP pump periodically empties the tank in response to a level switch into a third 20,00 gal. Baker tank. The brine level in this tank is observed manually and after accumulation of 10,000 gallons is in turn pumped into the reinjection line. The pump used for this last function is a progressive cavity type capable of pumping 60 gpm against a head of 400+ PSI. This high head capability is required in order to match the reinjection pressure that results when the GLEF is in operation. The overall system is controlled from the operations trailer where value controllers, temperature and pressure readouts and flow monitors are assembled in two panels.

The brine stream used for the experiments is passed to the end of the trailer where two parallel flash units are used to drop the brine temperature to 125°C (Figure 4). The dual train system allows us to test the effects of scale inhibitors while simultaneously running untreated brine as a control. Alternatively, two inhibitors can be tested simultaneously. The injection of chemical additives is accomplished with high pressure metering punps. Flow rates are monitored with turbine type flowmeters and their associated electronics which produce digital readouts of flowrate and total flow. An out of range condition is automatically sensed by an alarm system. Brine flow through the experiment is measured with orifice-type meters. Brine temperature in the two second-stage flash drums is automatically maintained by remotely preset and continuously adjustable valves in the steam lines.

SCALE CONTROL EXPERIMENTS

Development of a reliable and cost effective silica scale control method for the Salton Sea Geothermal Field (SSGS) brines would have a major impact on stimulating early commercialization of the SSGS resource. Also, it is likely that methods successful at the SSGS would be applicable to other

FIGURE 3



LLL EXPERIMENTAL FACILITY

silica-scale-dominated hydrothermal resources. Several methods are currently under development.

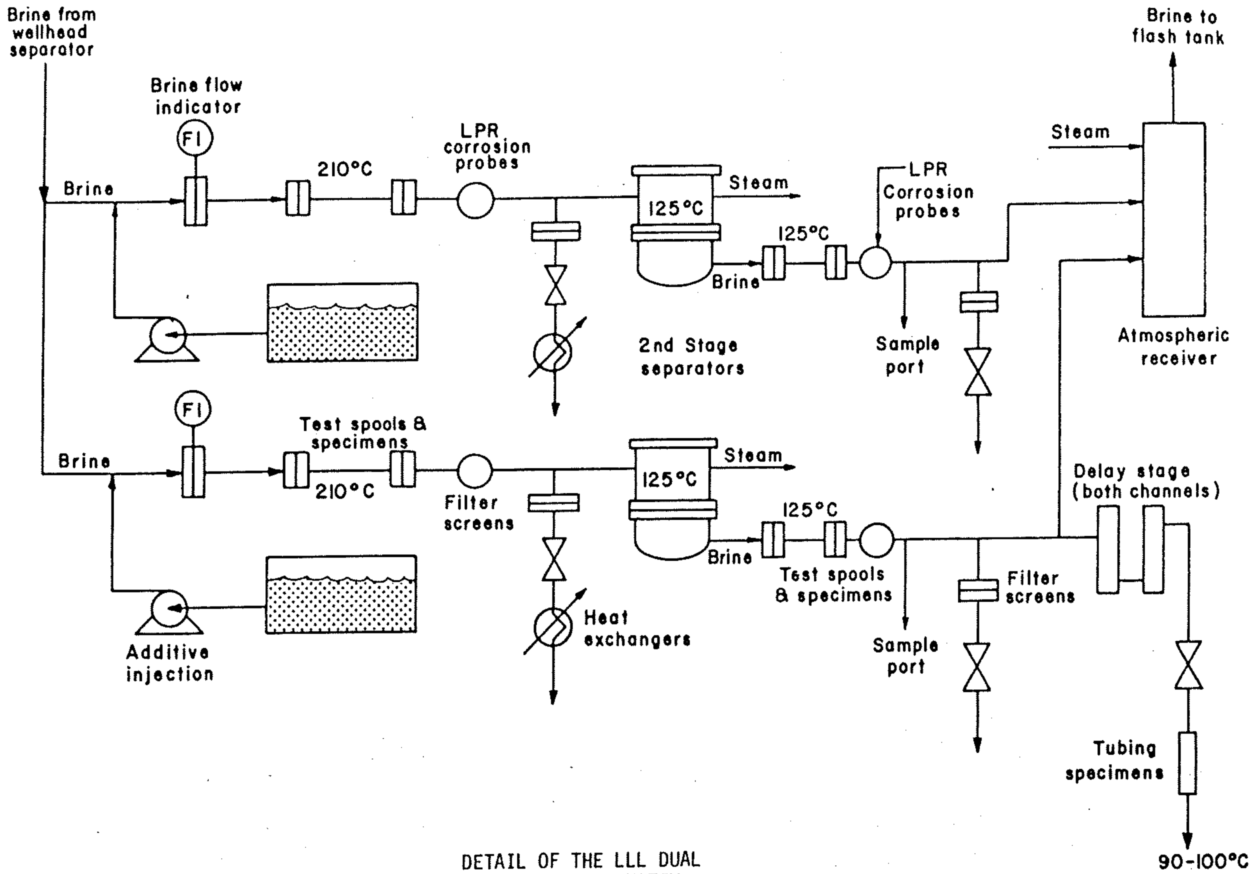
LLL is actively persuing the chemical additive approach which involves filed studies of organic (non-corroding) compounds that can be injected into single or two phase high temperature process streams (200-240°C) for the purpose of inhibiting formation of silica-bearing scales. SDG&E has been evaluating periodic mechanical removal of scale deposits in the GLEF. The last configuration of the GLEF consisted of two parallel double-flash trains - one for each production well. An operating power plant would have three parallel double flash trains, each with a 50% flow capacity to allow one train to be shut down for cleaning without interrupting operations. In general, this approach to scale control is cost-effective. Magma power is evaluating the use of a high temperature-pressure crystallizer in place of the conventional second stage flash unit in a double flash system. The crystallizer provides for the cycling of precipitated sludge to promote auto crystallization of scale-forming species. Initial results have been quite promising.

All of the above mentioned scale control stratagies require operation of a final stage clarifier-filtration system to remove residual suspended solids from spent effluent prior to subsurface brine disposal via injection wells. We are continuing work on the chemical additive scale control strategy because our previous results have been very promising, and the active participation of chemical manufacturers has been helpful in identifying new classes of compounds for testing. We have also recently shown that some of the most active scale inhibitors may actually enhance the performance of the final stage clarification process where the additives begin to function as flocculants. Finally, an effective chemical scale control agent will require a minimum capital equipment expenditure for brine treatment facilities and thereby overall power conversion costs could be reduced.

In the chemical additive approach, we have previously shown that brine acidification to pH 3-4 significantly retards the formation of scale. However, this technique involves increased costs, both for the acid itself and because corrosion-resistant materials must then be used in the critical locations of the plant. Because of our desire to provide options for scale control that do not involve acidification, the bulk of our previous additive work was oriented toward discovery of organic additives that would reduce the scaling rates without a reduction in brine pH.

To date, over 75 additives (including 17 proprietary mixtures) representing a number of different classes of organic compounds, have been field tested for their effect on silica in hypersaline brine. None of the proprietary mixtures

FIGURE 4



DETAIL OF THE LLL DUAL TRAIN FLASH SYSTEM

have had an appreciable effect on the scaling rates; however, several of the generic chemicals have resulted in strong inhibition of the rate of precipitation of silica and have produced up to 80% reductions in the scaling rates in the low temperature (≤100°C) regime. One compound also was found which produced up to a 40% reduction in the scaling rate at 125°C. The most effective organic silica scale inhibitors also significantly alter scale morphology. Preliminary observations, based on tests in the LLL facility, suggest that the efficiency of scale removal techniques under development by SDG&E may be substantially improved by the use of these inhibitors.

The types of chemical compounds and chemical moieties that are effective in inhibiting the silica precipitation and scaling process have now been clearly identified. Cationic nitrogen-containing compounds are the most promising, and among these, three classes - ethoxylated quaternary amines, polyethylene imines, and polyaminoethylenes -- have emerged as the most potent. Several compounds are commercially available within each class, varying in polymeric chain length, ethoxylation, and distribution of functional groups. The compound with the optimum response toward silica within each of these classes remains to be found. Examples of the effect of some organic additives on precipitation of silica from SSGF brine are shown in Figures 5 and 6. To date, the most effective inhibitor identified is PAE·HCl, the hydrochloric acid salt of polyaminoethylene manufactured by Dynapol.[14]

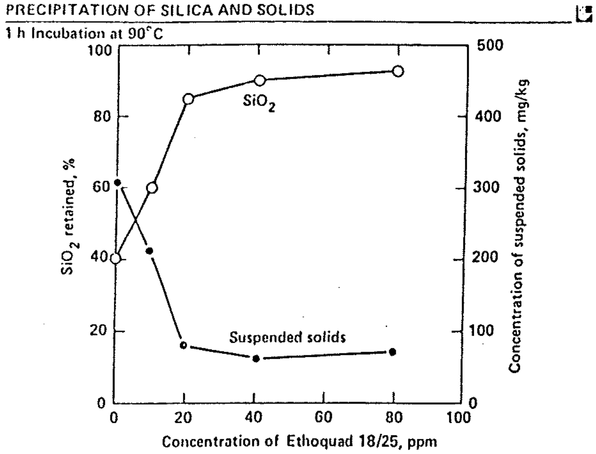
CORROSION EXPERIMENT

We are employing electrochemical monitoring and "large" sample exposure techniques to measure the corrosivity of the geothermal brine and to identify low-cost brine compatable materials. In conjunction with the scaling tests, corrosion probes constructed from various test materials, are inserted into the brine stream. The current generated by general corrosion of the probe is recorded in a device that indicates corrosion rates directly in mils per year.

Potential brine-compatable well casing materials are being evaluated by means of a 1.6-inch O.D., 1800 foot long tubing string inserted in the Magmamax No. 1 well. The string consists of various interconnected 3, 20, and 30 foot lengths of API and ASTM steels and alloys. Some lengths have received special heat treatments to improve their corrosion resistance. We plan to leave the string in the well for a four month exposure period before removing it in January, 1980 for analysis.

FIGURE 5

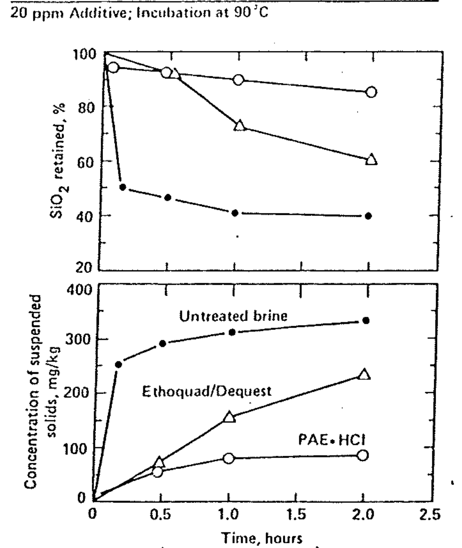
EFFECT OF CONCENTRATION OF ETHOQUAD ON PRECIPITATION OF SILICA AND SOLIDS



(From Ref. 14)

FIGURE 6

INHIBITION OF PRECIPITATION OF SOLIDS AND SILICA FROM GEOTHERMAL BRINE BY ORGANIC ADDITIVES



(From Ref. 14)

The 12-inch diameter by-pass loop located on the 10-inch diameter production-line, about 40 feet south of the Magmamax No. 1 wellhead, consists of five, 5-foot long removable spool pieces. Each spool contains 72 candidate metallic and polymeric power plant material samples. The purpose of this experiment is to establish general corrosion rates and the time dependence of localized corrosion phenomena such as pitting. This experiment will run for five months. Every month one spool piece is removed and the individual corrosion specimens are cleaned and then returned to Livermore for metallographic analysis.

On the basis of our previous tubing sting tests in the Magmamax No. 1 and Woolsey No. 1 wells, we have concluded that conventional low carbon steel well casing (J-55) has an unacceptably high localized corrosion rate. J-55 tubing stings exposed for 2 to 3 months in wells have suffered from perforating-types of corrosion. The general corrosion rate of low carbon steel at temperatures of 200°C is also high (>50 mils per year). Potentially cost-effective alternate materials have been identified. Specially heat treated low carbon steels (N-80 and C-75) and low alloy steels with minor amounts of chromium and molybdenum perform significantly better than the conventional steels. We hope to identify the best alternate materials for service at the SSGF when our current corrosion tests are completed.

The references cited in this report summarize the salient features of the LLL geothermal project to date. In addition, a more complete bibliography of LLL Geothermal Project reports is also available. Copies of these reports can be obtained by writing to:

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GEOTHERMAL METAMORPHISM OF SANDSTONE IN THE SALTON SEA GEOTHERMAL SYSTEM

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INTRODUCTION

Geothermal metamorphism (Muffler & White, 1969) in the Salton Sea (Niland) Geothermal System has produced a series of regular prograde textural and mineralogic changes in the thick, predominantly non-marine sedimentary pile which has filled the Salton Trough since its inception in Late Miocene-Early Pliocene time (Elders & others, 1972). The system is presumably driven by cooling intrusive igneous rocks which have their surface expression in the modern Salton Buttes, one of which has been tentatively dated as 16,000 to 50,000 years old (Muffler & White, 1968). Geothermal boreholes (Fig. 1) have penetrated the geothermal system to a depth of 2469m (River Ranch 1), where sediments of Late Pliocene age were reached (Clayton & others, 1968). The 200°C isotherm of Fig. 1 approximately defines the depth to the top of the main reservoir of the geothermal system.

Investigation of the metamorphic changes within the Salton Sea Geothermal System has been based almost entirely on examination of borehole cuttings. In most of the boreholes, the observed agreement between well logs and cuttings-derived lithologic columns, agreement between measured borehole temperatures and fluid-inclusion temperatures on authigenic minerals from the cuttings, and the very regular prograde changes in mineral textures, assemblages, and compositions with apparent cuttings depth, all imply that the cuttings originated at the depths indicated, and that very little mixing occurred during drilling. The major exception is borehole State of California 1 (Cal State 1), which shows clear-cut evidence of slumping and extensive mixing of cuttings.

This paper is a brief summary of the petrologic results of metamorphism in the Salton Sea Geothermal Field, and is a part of a larger series of investigations on this and other geothermal fields in the Salton Trough carried out under the direction of W.A. Elders at the Institute of Geophysics and Planetary Physics at the University of California at Riverside, California. It is based mainly on a detailed investigation of sandstones from borehole Elmore 1 (McDowell & McCurry, 1977; McDowell, 1978; McDowell & Elders, 1978), on quantitative X-ray diffraction and petrography of sandstones from other boreholes now in progress, and on the results of petrologic and isotopic investigations on the Magmamax boreholes by Kendall (1976). All noted mineral compositions are on a molecular basis and were obtained with the electron microprobe.

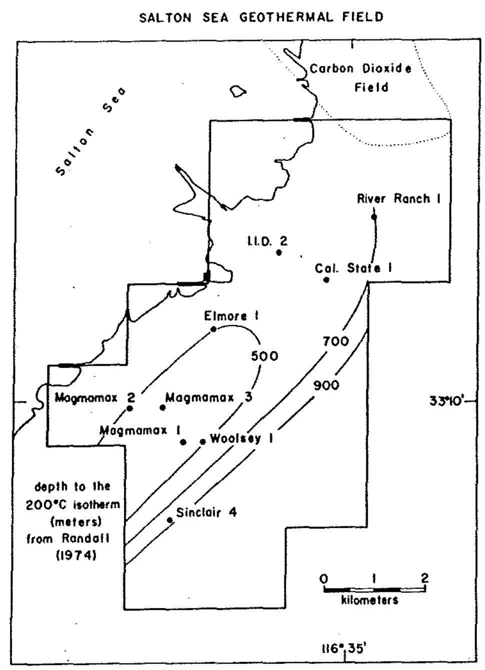

Fig. 1. Depth to 200°C isotherm in meters, and borehole locations, Salton Sea Geothermal Field, California.

The metamorphosed sediments within the geothermal system were originally fine grained to very fine grained terrigenous, deltaic feldspathic sandstone and argillaceous sandstone (average grainsize 0.13±0.05mm, 0.25mm maximum, in Elmore 1), complexly interbedded with lacustrine mudstone and siltstone (Muffler and Doe, 1968; Van de Camp, 1973; Waggoner, 1977). The original clay mineral suite consisted of montmorillonite, illite, and kaolinite, as well as coarser grained detrital biotite, chlorite, and muscovite.

The gross stratigraphy of the geothermal field consists of an upper clay-silt-evaporite lacustrine sequence that thickens northward (Randall, 1974), and a lower interbedded sandstone-siltstone-mudstone deltaic sequence. The lacustrine sequence is almost entirely unconsolidated and predominantly clay, except near the base where loose sand similar in shape, size, and composition to sand grains in the deeper deltaic sandstones becomes abundant. The underlying deltaic sequence consists of an average of 70% mudstone/shale, 5% siltstone, and 25% sandstone (Kendall, 1976), with rare intervals up to 60m thick containing 80% or more of sandstone. Stratigraphic correlations within the deltaic sequence, based on geophysical log interpretation (Randall, 1974; Chan and Tewhey, 1977), lithology, and stable isotope investigations (Kendall, 1976), suggest that the sediments dip gently northward in approximate parallelism with the base of the lacustrine sequence.

Significant amounts of volcanic rock cuttings were noted in borehole Elmore 1. These were predominantly metarhyolite, with occasional olivine basalt (Robinson and others, 1976), and all show extensive evidence of alteration by the geothermal system. The distribution of volcanic material suggests that the borehole intersected thin intrusive dikes or sills, and at the base of the borehole, penetrated a thicker rhyolite body which shows evidence of contact metamorphism of the adjacent sandstones followed by re-equilibration of the contact metamorphic assemblages to normal geothermal assemblages.

TEXTURAL CHANGES

Geothermal metamorphism has produced three texturally defined prograde metamorphic zones, based on petrographic and x-ray examination of sandstone cuttings from various boreholes in the geothermal field. These zones are, in order of increasing depth and temperature, a low porosity carbonate cap, a porous zone, and a low porosity hornfels zone. These zones are well defined in the interior portions of the geothermal field, near the Magmamax and Elmore boreholes (Fig. 1), but are only generally identifiable in boreholes on the margins of the geothermal field.

The carbonate cap consists of sandstone that is completely cemented by calcite which ranges from fine grained aggregates of equant grains to poikiloblastic grains up to 0.3mm in maximum dimension. The quartz, feldspar, and rare chert, shale, and carbonate sand grains are rarely in contact with each other, and visible open pore space is completely lacking in most cases. Calcite typically makes up 30 percent (by weight) of sandstone, while dolomite/ankerite, where it is present, makes up approximately 3 percent. Coarse-grained layer silicates, such as biotite, chlorite, or muscovite, are scattered throughout the carbonate cement, and occasional pockets of porous aggregates of clay-size layer silicates are observed.

The top of the carbonate cap is defined in most cases by the disappearance of both consolidated sandstone and mudstone, and corresponds in general to the contact of the lacustrine and deltaic sequences of Randall (1974). Where most accurately defined, this transition occurs at a temperature of 180°C, although in some boreholes it may occur at temperatures as low as 160°C. The base of the carbonate cap is marked by a decrease in the amount of calcite cement and a corresponding increase in the mutual contacts between sand grains and in the amount of open pore space. This occurs at a temperature of approximately 225°C, although the temperature may range to as low as 190°C.

The porous zone is marked by the appearance of sandstone with open pore space ranging from 15 to 20 volume percent, framework quartz/feldspar grains with less than 20% of mutual contacts, and calcite cement which fills less than half the available intergrain pore spaces and makes up typically from 8 to 18 weight percent of the sandstone. Many pores are partially filled with porous aggregates of chlorite, illite, cherty material, or optically unidentifiable clay size layer silicates, and there is a complete range from layer silicate poor sandstone (arenite) to argillaceous sandstone (wacke) with up to 25% clayey matrix. At the top of the porous zone, the general appearance is that of a relatively unmodified sedimentary rock with little evidence of pressure solution and minimal overgrowth formation, and with grain boundaries that show very little evidence of reaction with the pore fluids.

While the top of the porous zone is abrupt and easily identifiable both petrographically and by x-ray, on increasing depth the porous zone changes gradually and continuously into the deeper hornfels zone. The base of the porous zone has been defined as the depth at which calcite abruptly disappears (1135m, 325°C in Elmore 1), again a transition which is easily identifiable optically and with x-ray. However, in textural terms, the contact between the two zones is continuous.

The main change with increasing depth throughout the porous zone is the progressive diminuation of pore space through the formation and enlargement of overgrowths on quartz and feldspar framework grains. In Elmore 1 the porosity changes from 15-20% at 439m depth (190°C) to 5-10% at 925m depth (308°C), and remains at approximately 5% to the base of the borehole at 2169m (361°C). This is reflected in percentage of mutual contacts among quartz/feldspar framework grains, which changes from less than 20% at 439m to greater than 75% at 925m. In Magmamax 3, an identical change occurs from approximately 650m depth (240°C) to 1100m depth (315°C). A secondary but still important change with increasing depth, in the deeper portions of the porous zone, is the formation of pore-filling radial aggregates of epidote which, on increasing temperature, gradually evolve into large single crystals as the hornfels zone is reached. Typically epidote makes up less than 5% of the sandstone in the porous zone and hence is usually not detected by x-ray. The calcite content remains approximately constant in the range 5-15%.

Other changes through the porous zone include a progressive decrease in the content of pore-filling fine-grained white mica, coupled with an increase in grainsize and eventual recrystallization of the fine-grained white mica into larger single crystals of muscovite. In Elmore 1, all white mica has recyrstallized to muscovite by 800m (290°C), and any fine-grained white mica below that depth is found entirely within feldspar grains as an alteration product.

The result of all these changes is to produce a dense rock with a strongly interlocking granoblastic texture. While quartz and feldspar overgrowths are optically still identifiable at 885m in Elmore 1, recrystallization of the framework quartz and feldspar crystals has proceeded to the point that, at 1135m (325°C), all traces of overgrowths have been annealed away, and most of the original detrital feldspars have been completely made over into homogeneous grains with compositions identical to authigenic feldspar. The resulting hornfels persists with little modification to the base of the deepest and hottest borehole, Elmore 1.

Anhydrite occurs sporadically as a cementing mineral in sandstone. It is usually first detected within 200m of the top of the porous zone, and typically makes up 0 to 6% of the sandstone, although sandstones with up to 35% anhydrite have been observed. It tends to concentrate in certain areas of sandstone, where it completely fills all pores, while the remainder of the rock is anhydrite-free.

MINERALOGIC CHANGES

Within the general textural changes noted above, detailed investigation of sandstone from Elmore 1 has revealed numerous regular variations in mineral assemblages and compositions with depth and temperature. In terms of the key authigenic minerals from sandstone, the porous zone can be equated with chlorite-grade metamorphism, the hornfels zone with biotite-grade metamorphism, and the base of the borehole where andradite garnet appears, with garnet-grade metamorphism. Based on the temperatures in Elmore 1, chlorite-grade extends from approximately 190°C to 325°C, biotite-grade from 325°C to 360°C, and andradite garnet-grade occurs at temperatures of 360°C or more. The x-ray and petrographic investigations now under way indicate that the results of metamorphism in Elmore 1 are similar to those observed in other boreholes in the interior of the geothermal field.

Within the carbonate cap, few changes were noted. Dolomite is no longer detected by x-ray below the midpoint of the carbonate cap, but both dolomite ($Ca_{0.506}Mg_{0.477}Mn_{0.007}Fe_{0.012}CO_3$), in the form of large rounded detrital grains and smaller euhedral rhombs, and ankerite ($Ca_{0.532}Mg_{0.279}Mn_{0.021}Fe_{0.167}CO_3$) in the form of euhedral rhombs, were observed in small quantities in thin section at the base of the carbonate cap. The coarse-grained, often bent and broken, biotite, chlorite, and muscovite plates are unaltered detrital grains whose compositions reflect the source rocks of the sedimentary system. They have not been detectably affected by geothermal metamorphism, probably due to the exceedingly low effective permeability of the carbonate-cemented sandstone. Mixed layer illite/smectite is detected throughout the carbonate cap, and last occurs at depths just deeper than the base of the cap (Table 1). Examination of glycolated specimens from Elmore 1 suggests that these clays contain approximately 20% expandable layers.

The removal of about half the carbonate cement and the resulting increase in porosity at the boundary between the carbonate cap and the underlying porous zone causes a number of significant changes in sandstone mineralogy. The first thin and often discontinuous quartz overgrowths are observed. Minute pyrite cubes first appear, and aggregates of equant red-brown sphene are first observed, both in the matrix of the sandstone. Chlorite becomes significant in x-ray, and bright green patches of authigenic chlorite are first observed in the sandstone matrix. Fine-grained white mica (sericite) first becomes abundant, and the detrital muscovite plates first begin to react at their margins to white mica aggregates. All the detrital biotite is wholly replaced either by fine-grained aggregates of bright green authigenic chlorite, or is pseudomorphed by single crystals of chlorite, resulting in detrital-appearing chlorite grains in the porous zone whose high birefringence (0.021) and extreme pleochroism (to deep red-brown) reflect the high Ti-contents of the detrital biotite grains that were replaced. These latter chlorite grains, throughout the porous zone, are in turn gradually replaced by fine-grained bright green authigenic chlorite. On increasing temperature through the porous zone, authigenic chlorite undergoes a decrease in Al^{VI} and possibly octahedral vacancies, and an increase in total Fe+Mg.

Calcite persists throughout the porous zone as a significant cementing mineral, and appears to be equilibrated with the geothermal system in this temperature range. Thus the porous zone has, in mineralogic terms, been termed the chlorite + calcite zone to emphasize the presence of calcite thoughout this zone.

Coexisting feldspars, in forms ranging from minute euhedral tablets to aggregates of inclusion-filled irregular shaped grains in the sandstone matrix, are present in Elmore 1 at depths of 622m (250°C) or more, and definite feldspar overgrowths on detrital feldspar grains are noted at slightly greater depths. The compositions of the coexisting albite and potassium feldspar appear to define a feldspar solvus, with compositions changing from approximately $Or_{0.3}$ and $Or_{96.0}$, respectively, at approximately 300°C, in the porous zone, to $Or_{0.6}$ and $Or_{93.2}$, respectively, at 360°C, near the base of the borehole.

Epidote is first detected approximately one third of the way into the porous zone, at depths greater than 610m (243°C) in Elmore 1, in the form of aggregates of minute needles scattered throughout the layer-silicate rich matrix of the sandstone. In Magmamax 3, epidote is first detected at depths greater than 780m (280°C) in thin section, while the first epidote in x-ray is not detected until 844m (290°C), the boundary between the porous and hornfels zones. The epidote coarsens on increasing depth and temperature until the radial aggregates have expanded to completely fill many pores. This occurs by depths of 675m (264°C) in Elmore 1, and below this depth, the aggregates of large, blunt epidote blades gradually recrystallize into large, irregular pore-filling single crystals on increasing temperature. Epidote shows very systematic changes with depth and temperature in Elmore 1 (Fig. 2), and an almost identical pattern has been observed by the writer in epidote from borehole M53 on the eastern flanks of the Cerro Prieto Geothermal Field in nearby Mexico (Elders and others, 1978). The abrupt change in epidote composition from Elmore 1 occurs at approximately 1030m (320°C), still within the porous zone where calcite is present. There is significant inter- and intragrain compositional variation of epidote from a given sandstone chip, but the ranges from different sandstone chips from the same depth interval overlap significantly. As indicated by the triangle in Figure 2, epidote becomes significantly more iron rich on the appearance of the andradite garnet near the base of the borehole.

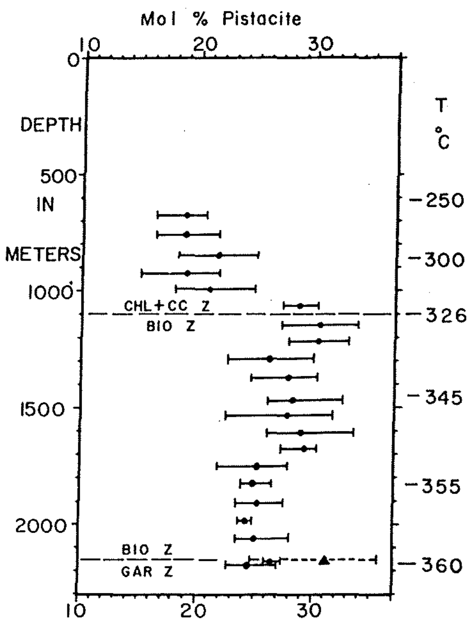

Figure 2. Average (dot) and range (bars) of epidote compositions (mol % pistacite) as a function of depth (m) and temperature (°C) in Elmore 1. Triangle and dashed bars of epidote from garnet-bearing sandstone.

The most significant mineralogic change through the porous zone occurs in the fine grained white mica, which would be termed sericite by most metamorphic petrologists. Both x-ray interpretation after Reynolds and Hower (1970), and Energy Dispersive System microprobe analyses calculated in the manner of Hower and Mowatt (1966), indicate that the white mica changes from a mixed layer illite/smectite with 10-15% expandable layers at depths of 439m (190°C) to an illite with traces of mixed layering (0-5% expandable layers) in the depth range 622 to 675m (250 to 265°C), where epidote first appears. Then, on recrystallization to large single crystals at temperatures above approximately 290°C, the composition changes apparently abruptly to a phengitic white mica. The calculated average mineral formulas (Σcations-Na, K,Ca=6.0) at several depths are:

$K_{0.56}Na_{0.06}Ca_{0.03}Mg_{0.30}Fe_{0.27}Ti_{0.02}Al_{1.40}$ $Al_{0.47}Si_{3.53}O_{10}(OH)_2$ at 439m (190°C, 12% expandable layers)

$K_{0.68}Na_{0.04}Ca_{0.01}Mg_{0.20}Fe_{0.13}Ti_{0.01}Al_{1.65}$ $Al_{0.69}Si_{3.31}O_{10}(OH)_2$ at 675m (265°C, illite)

$K_{0.91}Na_{0.09}Ca_{0.01}Mg_{0.04}Fe_{0.22}Ti_{0.03}Al_{1.70}$ $Al_{0.90}Si_{3.10}O_{10}(OH)_2$ at 990m (315°C, phengitic muscovite)

The compositions of the various white micas have been plotted in the Muscovite-Celadonite-Pyrophyllite system (Fig. 3) after the method of Hower and Mowatt (1966). The trend from a mixed layer illite/smectite with 10-15% expandable layers and a composition of approximately equal parts Mu, Ce, and Py, to a phengitic muscovite, on increasing temperature, is apparent from the figure. In more general terms, most of the analyses plot close to a line between $Ce_{50}Py_{50}$ and $Mu_{90}Ce_{10}$, suggesting that experimental investigations of compositions on the joint $Ce_{50}Py_{50}$ and Mu_{100} might be of critical importance in deciphering the phase relationships of illite and mixed layer clays.

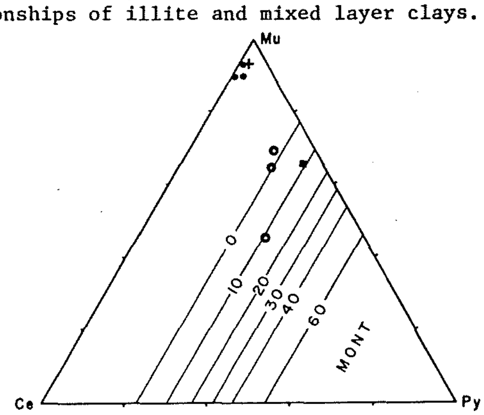

Figure 3. Average composition sericite (open circles), detrital muscovite replaced by sericite (square), coarse grained recrystallized phengitic muscovite (dots), and unequilibrated detrital white mica (cross) at different depths, Elmore 1, in Muscovite-Celadonite-Pyrophyllite system. Contours of percent expandable layers after Hower and Mowatt (1966).

The high Na contents of many individual analyses, which of necessity were made on aggregates of the fine grained white micas, indicates that paragonite is present in trace amounts in at least the upper portions of the porous zone. No analyses of pure paragonitic illite could be obtained, although projections of illite-paragonite mixture analyses suggest the sodic white mica has an Mg/Fe + Mg = 0.10 at 439 m depth, much more iron-rich than the coexisting illite/smectite.

The boundary between the porous and hornfels zones in Elmore 1 is marked by several distinct mineralogical changes, but little overall change in texture of the sandstone. Calcite abruptly disappears, and the pore spaces previously occupied by calcite are at least partially filled by growth of quartz and feldspar without producing visible overgrowths, formation of epidote, and formation of loose aggregates of biotite and, in a few specimens, talc. The net result is very little change in the amount of visible open pore space in the sandstone. This boundary defines the biotite "isograd" in Elmore 1 at 1135m depth and 325°C and a hydrostatic pressure of approximately 110atm using pressure gradient calculated by Helgeson (1968).

Authigenic biotite occurs as blocky, less than 0.02mm, weakly pleochroic very pale green to colorless grains scattered along the contacts of the framework minerals, or as patchy aggregates of minute grains in the pore spaces. At progressively greater depths larger grains develop with a tendency to form sheaf-like or radial fan-shaped arrays, although the maximum grainsize rarely exceeds 0.05mm. The color intensity of pleochroism increases until, at the base of the borehole, colors ranging from very light brown or yellow-brown to light-medium brown or green brown are observed. These changes directly reflect the regular changes in biotite chemistry with depth and temperature that occur in Elmore 1.

On increasing temperature, the biotite changes from a siliceous, K-deficient, phlogopitic biotite (Mg/Mg+Fe = 0.83) at the biotite isograd to a typical low-grade metamorphic biotite (Mg/Mg+Fe = 0.60) at the base of the borehole at 360°C. The chemical changes of biotite through the hornfels or biotite zone are very similar to those observed at lower temperatures in white micas, and include increases in interlayer site occupancy, Al^{IV}, Al^{VI}, and Ti, and decreases in F^-, Si^{IV}, and Mg/Mg+Fe, on increasing temperature. Representative calculated average mineral formulas are:

$K_{0.63}Na_{0.00}Ca_{0.02}Mg_{2.38}Fe_{0.56}Ti_{0.01}Al_{0.03}$
$Al_{0.75}Si_{3.25}O_{10}(OH)_2$ at 1143m (330°C)

$K_{0.80}Na_{0.01}Ca_{0.01}Mg_{1.86}Fe_{1.09}Ti_{0.02}Al_{0.02}$
$Al_{1.07}Si_{2.93}O_{10}(OH)_2$ at 2169m (360°C)

On the appearance of andradite garnet, the composition of the authigenic biotite changes still further to a more iron-rich biotite (Mg/Mg+Fe = 0.52) with slightly more Al^{VI} (0.09) and a higher interlayer occupancy (K=0.83). These trends have been summarized in Figure 4, where the general approach of these biotites on increasing temperature to typical low grade metamorphic biotites is obvious. Using an ideal change of 22.00 and reasonable site-filling restrictions, the very low Al^{VI} content of many of the authigenic biotites requires that the Fe^{+3}/total Fe ratio ranges between 0.14 and 0.22 for these biotites.

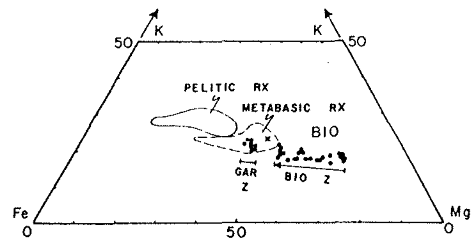

Figure 4. Compositional variation of authigenic biotite in Elmore 1. Arrows indicate compositional change on increasing temperature. Fields outline compositions of typical biotites from pelitic and metabasic metamorphic rocks.

Talc appears at the biotite isograd in some sandstones as aggregates of less than 0.05mm ragged flakes in the pore spaces. Its distribution is very erratic, and it has been positively identified in thin section or by x-ray in only four other sampled intervals in Elmore 1, in the deeper portions of the borehole.

Actinolite, in the form of felted aggregates of minute needles or sheaves of thin bladed crystals, forms very porous aggregates in the pores of some sandstones in Elmore 1, at depths greater than about 1250m (336°C). It was detected in less than 1/3 of sandstones examined, although sandstones with up to 20% actinolite have been observed, and texturally similar actinolite is commonly associated with coarse-grained epidote in veins in shale. The Mg/Mg+Fe ratio of actinolite ranges from 0.5 to 0.8, and no regular compositional trends with temperature have been noted.

The appearance of andradite garnet as irregular shaped coarse-grained single crystals, texturally identical to epidote in the same rocks, marks the appearance of garnet grade metamorphism at a depth of 2155m (360°C) and an estimated pressure of approximately 205atm. hydrostatic pressure in Elmore 1. Garnet makes up approximately 1 to 12% of the sandstone on a modal basis. Sandstone containing garnet has no K-feldspar, abundant albite, and has biotite and epidote of different compositions than garnet-free sandstone from the same depth, implying that these minerals are involved in the garnet-forming reaction. The composition of a typical garnet is:

$Ca_{2.87}Mn_{0.02}Mg_{0.00}Fe^{+2}_{0.10}Fe^{+3}_{1.99}Al_{0.03}Ti_{0.02}$
$Si_{2.97}O_{12}$

Many andradite grains are zoned to titan-andradite at their outer edges, yielding average formula contents of 0.25Ti, 0.26Al, 2.85Si, 1.54Fe^{+3}, and 0.20Fe^{+2}.

The changes in the authigenic mineral assemblages with temperature have been summarized in Table 2. The regular metamorphic zonation in the interior portions of the Salton Sea Geothermal Field begins at temperatures and with clay mineral assemblages similar to those observed in the deepest portions of burial metamorphic sequences such as the Gulf Coast of North America (Hower and others, 1976), and continues through chlorite and biotite-grade metamorphism, just reaching garnet-grade rocks in the hottest parts of the geothermal system. In this temperature interval, the transition from sedimentary textures to low grade hornfelsic textures is very clearly observed in the coarser-grained rocks.

Table 1. Depth in meters/temperature in °C of several important mineralogical changes on increasing temperature and depth in sandstone cuttings. X = defined by quantitative x-ray diffraction analyses. P = defined by petrographic examination. MM3 = Magmamax 3, MM2 = Magmamax 2, E1 = Elmore 1

Borehole	MM3	MM2	E1
Top carbonate cap (P)	360/180	366/160	∿410/∿175
Dolomite/Ankerite out (X)	472/220	450/185	-
Base Carbonate cap (X,P)	579/235	536/215	∿439/∿190
Mixed Layer clay out (X)	597/240	536/215	439/190
Abrupt Decrease in mica content (X)	789/282	655/245	800/290(P)
Epidote in (P)	780/280	594/235	610/243
Epidote in (X)	844/290	728/260	623/250
Abrupt Decrease in calcite (X,P)	844/290	1073/320	1135/325
Total Depth/ Maximum Temp.	1219/324	1313/342	2169/361

Table 2. Summary of Assemblages in Sandstone, Elmore 1.

Zone	Assemblage
	175°C
Carbonate cap	Calcite + Dolomite + mixed layer (20% exp.) +hematite(?)
	190°C
Porous Zone (chlorite grade)	Calcite + chlorite + mixed layer (0-15% exp.) + feldspar(?) + pyrite + sphene ± anhydrite
	243°C
	Calcite + chlorite + illite (<5% exp.) + epidote + albite + K-feldspar + quartz + pyrite + sphere ± anhydrite
	290°C
	Same as above, but illite has recrystallized to white mica or phengitic muscovite
	325°C BIOTITE "ISOGRAD"
Hornfels Zone (biotite grade)	Biotite + quartz + epidote + K-feldspar + albite + pyrite + sphene ± talc ± vermiculite(?) + traces chlorite, muscovite, anhydrite
	340°C
	Same as above, but actinolite appears and muscovite no longer seen
	360°C GARNET "ISOGRAD"
Hornfels Zone (garnet grade)	Biotite + quartz + epidote + garnet + albite + actinolite + pyrite + sphene

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AN OVERVIEW OF SOCIOECONOMIC AND ENVIRONMENTAL STUDIES OF GEOTHERMAL DEVELOPMENT IN THE IMPERIAL VALLEY

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INTRODUCTION

Imperial County has significant exploitable geothermal resources. The size and quality of these are detailed elsewhere in the present volume. As the geologic potential of these resources came to be recognized in the 60s and early 70s, governmental authorities also recognized the necessity for socioeconomic and environmental studies of geothermal development. The Imperial County government had the unusual foresight to seek support from the NSF to study not only the geologic resources, but also the socioeconomic and environmental considerations in developing these resources. As a result a NSF/DOE-sponsored study of County geothermal development was undertaken from 1975 to 1977 by Imperial County, University of California, Riverside, Caltech, and Cal State Fullerton. Many parts of that project are reported on here. Another institution which early recognized the need for such studies was Lawrence Livermore Laboratory. Beginning in the mid-seventies, it sponsored a lengthy series of environmental studies, which will not be reviewed in this paper. One Livermore-sponsored study reported on in this paper is a study of County leadership, as regards geothermal. Other institutions which have studied the environmental/ socioeconomic aspects are the Jet Propulsion Laboratory, VTN Inc., TRW Inc., Westec Services, Geonomics, U. S. International University, Univ. of Oklahoma, and others. Because of their large number, only several of these latter studies can be discussed here. Although the United States contains dozens of KGRAs and one in commercial operation, (The Geysers in Sonoma/Lake Counties, California), most of the socioeconomic/ environmental research on geothermal energy has been concentrated in Imperial County. Some studies (Vollintine and Weres, 1976a; Vollintine and Weres, 1976b, among others) have been done at The Geysers, but studies have lagged rather than preceded the initiation of on-line capacity. In other geothermal areas in the Western U.S., intensive socioeconomic/environmental studies have not heretofore taken place.

The following literature review groups pertinent research in Imperial County into three areas: socioeconomic studies, environmental studies, and policy aspects.

I. SOCIOECONOMIC STUDIES

A. POPULATION ANALYSES

The County's general demography has potential influence on geothermal development (Pick et al., 1976; Pick and Butler, 1979). With an estimated 1975 population of 84,100, there is not a large market for energy consumption in the immediate resource area. Further analysis of the 1975 population reveals a young age structure, a high fertility rate relative to California's, a mortality rate about average for the state, a high proportion of Spanish Americans (henceforth designated as SA)--45 percent in 1970, and a history of net outmigration from the County. Other characteristics of the County are low average income, urban concentration in towns of sizes 4,000 to 20,000, low average educational attainment, and occupational concentration in agriculture. Several of these features appear interrelated. For example, the high proportion SA implies high fertility, because, nationally, SAs are known to have elevated fertility. The history of outmigration, spanning the period 1930-1970, likely stems from lack of educational opportunities, lack of a large local base of non-agricultural jobs, and paucity of amenities in the County.

Another demographic feature of potential importance to geothermal development is proximity to the Mexican border and to the large population of over 1/2 million persons in Mexicali, immediately across the border from the Imperial County town of Calexico. Labor market interactions between Calexico and Mexicali have been less than optimal (Kjos, 1974), but this vast labor supply should not be overlooked in largescale geothermal development.

Study of small County regions, averaging about 800 persons, called enumeration districts by the Census Bureau, was accomplished through the methods of computer mapping and discriminant analysis (Pick and Butler, 1979). Such studies allow comparison of KGRA areas, cities bordering KGRAs, and non-KGRA areas on the basis of their demographic characteristics. Results of these studies are of potential value in geothermal planning. However, it must be recognized that the studies pre-date actual development and that the geothermal resource boundaries do not correspond to

KGRA boundaries, which were established about a decade ago.

B. REGIONAL EMPLOYMENT IMPLICATIONS

Employment implications of geothermal development are important for local residents, local businessmen, the County economy, and advocates of alternative energy sources. A methodological problem for such an employment study is lack of County geothermal capacity at the 1970 Census date, a time which offers the latest complete socioeconomic data. Improved employment studies may be done in the next several decades as significant geothermal power generation comes on line. Given this major limitation, causes of the 1970 regional differences in employment were studied for geothermal and non-geothermal land areas in the County (Pick et al., 1977a; Butler and Pick, 1979a, chapter 3). Nineteen seventy U.S. Census data for EDs were aggregated to match the KGRA boundaries. Regional differences were studied by regression analysis, with employment as the dependent variable and 33 demographic, migration, and economic factors as the independent variables. Employment differences were separately analyzed for the categories, white (including Spanish American but excluding Negro and other races), Spanish American, geothermal, and non-geothermal. The ratio of unemployment to total population was divided into three multiplicative components--age eligibility (i.e., the proportion of total population eligible to work), labor force participation, and unemployment. For the County, results indicate an inverse relationship of age eligibility with household density, specific effects for work force participation, and expected correlations of unemployment with poverty and low income. Applications of these results are strongest for the workforce involved in direct use applications of geothermal energy and for the relatively small population of resident power plant workers, since job locations for these are necessarily close to geothermal areas. Application to electrical consumers is very limited, because widespread extra-local power grid transport invalidates the importance of these proximity relationships.

C. POPULATION AND LABOR FORCE PROJECTIONS

As County geothermal development unfolds over the next twenty to fifty years, the size and distribution of population and features of the labor force will be affected. Again, as no significant power plants have been built, only baseline or projection studies can be performed (Pick and Butler, 1978; Pick et al., 1977a). These studies are based on alternate geothermal growth regimes. The population projections take account of possible non-geothermal effects, such as future nationwide fertility fluctuations.

In the population projections (Pick and Butler, 1978), initial County population was projected by use of age-specific component techniques, based on a series of six regimes of County net migration rates, four of which were energy-related. Projection model (I) assumes zero net outmigration rate. Model (II) is based on the County's historical 1.15% annual net outmigration rate. Models (III) and (IV) are based on an assumed linear increase in County geothermal plant capacity from 1980 to 2005. Models (V) and (VI) are generally similar to (III) and (IV), except plant additions follow the medium estimate of Davis (1976), and population-energy lead and lag times are different.

A different method was used to project displacement of farm laborers by geothermal development (Pick et al., 1977). Farm laborers were assumed to be uniformly distributed in the County's agricultural lands. Ratios of farm laborers to land areas were based on studies by Johnson (1977) and Sheehan (1976). Land displaced and associated laborers displaced by geothermal development were estimated according to three alternative displacement ratios for lands in the well-siting area. Under maximal assumptions, the displacement of farm laborers was projected for year 2020 as only 1.96% of the 1970 farm laborer category.

D. ECONOMIC STUDIES

Effects of productive geothermal resources on the County economy will be felt at the levels of individuals, commercial firms, County governmental revenues and budgets, and the County economy. One economic approach is to study the costs of geothermal development. Results of a study by Larson (1977), projected to 1979, indicate the costs for geothermal field development range from $200 to 400 per kW. Costs of power plant investment for flash steam plants vary from $350 to 550 per kW, while costs for binary plants vary from $400 to 800. per kW. This study also looked at detailed costs, environmental costs, risks and returns on investment, and effects of overall County development on County property taxes.

Specific economic effects of geothermal development within the County (Rose, 1977) include impacts of the construction and operation of power plants on output, income, and employment; impacts on agriculture; implications for manpower training, County income distribution, and economic policy; fiscal impacts; effects on the amenities of life; and environmental control costs. At the level of the entire County economy, an input-output matrix was constructed for the year 1972 and modified to include a geothermal resources sector (Lofting, 1977). The data used to construct the table consisted of derived estimates of County gross domestic output, estimates of final demand for industrial categories, and the 1972 U. S. interindustry transactions table. Not unexpectedly, the input-output study reveals the dominance of agricultural and agricultural-related industries in the County economy. According to model projections, geothermal development will add $700 million (1972 constant dollars) to County personal income by the year 2020.

E. PUBLIC OPINION

A County public opinion survey was performed in the late summer of 1976 to determine citizen viewpoints and knowledge about geothermal resource development. (Butler and Pick, 1977). The survey method was based on a household mail-back questionnaire. Twelve hundred questionnaires were mailed; 269 were returned and utilized in the survey analysis.

Results indicate that most of the population in Imperial County currently are in favor of geothermal development, with almost 90% reporting themselves as being in favor or strongly in favor. This result is in contrast to The Geysers, where 65% of Cobb Valley residents and 75% of Lake County residents supported geothermal development. Other results indicate that only a very small proportion of residents (19%) feel they have a very good understanding of geothermal development and that most residents felt geothermal development should be strictly regulated. Opinions on environmental effects, opinions by different categories of land owners, and other results are discussed in the full report.

The objective of the above study was to assess public opinion for a cross-section of all County residents. Another approach (Ternes, 1978) is to investigate site-specific public opinion towards geothermal resource development --in Ternes' case, the Heber site. Public opinion appears highly different for this one location, Heber, than for the whole County. Given adequate funding, future geothermal public opinion studies may do well to adopt such a site-specific approach.

F. LEADERSHIP

Leadership attitudes towards use of geothermal resources were assessed by a combination of conventional methodologies (Butler and Pick, 1979a, chapter 6, 1979b). As a first step, a list of all influentials in the County was generated. Selected persons on this list were interviewed, and as a result of these interviews, further interviews were done. A total of 105 interviews were conducted. Results indicate a county leadership structure which appears close to monolithic in nature, i.e., with repetitive and predictable patterns of decisions made by an elite group controlling the community. Of those persons identified by the interviews as the six most influential leaders in the County, five were found to be heavily engaged in agriculture or agricultural-related interests and one was a local businessman who also holds an important government position and who is said to represent Mexican-Americans. Comparison of leadership interview results with the public opinion survey revealed substantial agreement between top leaders and the general public.

A study of the broader political and legal environment affecting the County (Buck et al., 1977) revealed the County government's need to establish clearer lines of regulatory authority over geothermal development. To expedite geothermal development, new and imaginative relationships between the State and County governments were recommended.

II. ENVIRONMENTAL STUDIES

Numerous geothermal environmental studies have been performed in the County by the NSF/DOE-sponsored project, Lawrence Livermore Laboratory, which accounts for the largest bulk of studies, Union Oil Co., VTN Inc., TRW Inc., and others. Of these, only the studies by the first project are reviewed here, due to space limitations. Potential environmental effects of geothermal energy include subsidence, induced seismicity, water consumption, water pollution, well blowouts, noise, air pollution, weather modification, and land reallocation due to geothermal facilities (Pasqualetti, 1977). Of these problems, the first three were considered potentially far more serious than the others. Effects of geothermal development on subsidence and induced seismicity are largely unknown, because of lack of actual operating power plants at the time of the study. Some subsidence might have to be tolerated in marginal farming lands, such as near the Salton Sea, as a tradeoff to large scale power generation. The water problem has several aspects. For cooling water there is the choice of using fresh irrigation water from the Colorado River or of using agricultural drainage water. The latter is politically the most feasible solution. (Pasqualetti, 1977). There is also the problem of effects of geothermal water use on the level and salinity of the Salton Sea. The latter problem may be studied by computer simulation (Goldsmith, 1976a). One result indicates that use of irrigation drainage water for cooling purposes, with a 1000 MW geothermal capacity assumed, would result in a 2 1/2 foot fall in the Sea level and a 3500 mg/l rise in salinity. Given the Imperial Valley's environmental constraints, a study of the engineering feasibility of large scale geothermal development (Goldsmith, 1976b) indicates no insurmountable problems. Topics discussed included features of geothermal wells, reinjection, transmission pipes, power plant characteristics, cooling requirements, cooling water availability, production of useful water from geothermal resources and production of chemicals from geothermal resources. Among other things, the engineering study emphasized the large expense of lengthy transmission pipes--a potential detriment to direct use applications. Desalinization of geothermal brines was considered uneconomical for agriculture, but a possibility for municipal water. Production of chemicals from brines was considered technologically feasible, mainly at the Niland location, but economically risky (Hazen Research, 1975). In all, from the studies reviewed, environmental problems appear largely controllable, under the study limitations of no actual geothermal production data.

III. POLICY ASPECTS

Given domestic energy scarcities, a worthwhile goal would appear to be expeditious development of geothermal resources. In a local area, specific policy steps may be taken by the local, state, and federal governments, as well as by private industry, to bring power on line quickly, with minimal conflict. Such steps for Imperial County might include, among others, active encouragement of pilot projects, implementation of a retraining program to train County residents as geothermal workers, land use policy for population growth relative to geothermal fields, and encouragement of a broader economic base for the County (Pasqualetti et al., 1979).

Given the site-specific nature of geothermal development, can geothermal research projects be undertaken in a uniform manner or in a manner allowing transfer between sites? One solution might be a broad integrated model which uses a wide variety of standard data sources (Pasqualetti et al., 1978; Butler and Pick, 1979a, chapter 9).

CONCLUSION

There has been an unusually large number of socioeconomic and environmental studies relative to the County's ultimate geothermal electrical capacity of 2,000-6,000 MWe. The review undertaken here has only covered a fraction of the numerous studies performed. The large volume of work is accounted for by the relative novelty of this form of energy in the U.S. and by the fact that such a comprehensive study was not undertaken at the only major operational U.S. field at The Geysers.

A key question in the Imperial County studies is the extent of transferability of the research methods and results to other prospective geothermal sites, such as those in initial development stages in New Mexico, Utah, Nevada, and other parts of California. In general, methods would appear transportable, but results only transportable to a limited extent. The basic reason is that many socioeconomic/environmental effects are tied to the area of the geothermal field since, unlike fossil and nuclear resources, geothermal resources have very limited portability. Up to now, the Imperial County studies have suffered from the weakness of lack of an on-line geothermal power generation capacity. Hence, the studies are all necessarily prospective, lacking data on the operational phase of development. As a result, methodologies have been largely confined to studies of past and present County conditions, applications of analogous studies from developed geothermal resource areas, and computer simulations to project present conditions into the stage of on-line power production. Part of the benefit in all these methodologies is to elucidate development alternatives and ramifications. One example of the use of these studies is the Geothermal Element of the Imperial County General Plan, which was largely based on the NSF/DOE studies referred to. As development proceeds, into the stage of on-line electrical power generation and operational direct use applications, data will become available for greatly improved and refined socioeconomic and environmental research.

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EXPLORATION AND DEVELOPMENT OF THE HEBER GEOTHERMAL FIELD
IMPERIAL VALLEY, CALIFORNIA

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ABSTRACT

The Heber Geothermal field is located in Imperial County, California along the extension of the East Pacific Rise into the North American continent. Initial exploration in 1945 was for oil and gas but this changed to geothermal exploration when high thermal gradients were discovered in shallow holes. Several geophysical surveys were run: gravity, reflection seismic, ground noise, resistivity and spontaneous potential. However, the best data for picking the exploratory well location was provided by temperature holes up to 500 feet deep. The first geothermal well was drilled in 1972. Currently, the field is outlined by data from sixteen wells. These indicate a convective plume of hot water of 375°F or higher in a predominantly sand reservoir. A predominantly shale section provides a cap above 2,000 feet where heat flow is primarily conductive. Development, planned in zones from 2,000 feet to 10,000 feet, is expected to support a generating capacity of 500 megawatts for at least 30 years. Initial development will produce brine from zone 1 (2000-4000 feet) and zone 2 (4000-6000 feet). Producing wells will be directionally drilled to bottom hole targets in the temperature high. Cooled brine will be injected into wells located at the periphery of the reservoir. An operating unit has been formed by the leaseholders: Chevron Resources Company, Union Oil Company of California and New Albion Resources Company. Chevron is the Unit Operator and has signed a contract to supply 2-phase geothermal fluid to a 50 megawatt gross double-flash power generation plant to be built by Southern California Edison Company. Start-up for this--the first large commercial, privately financed, hot water geothermal power plant in the United States--is planned for early 1982.

INTRODUCTION

Heber is one of several geothermal fields undergoing development in the Mexicali-Imperial Valley between the Gulf of California and the Salton Sea. It is located between El Centro and Mexicali near the Mexican border (Fig. 1).

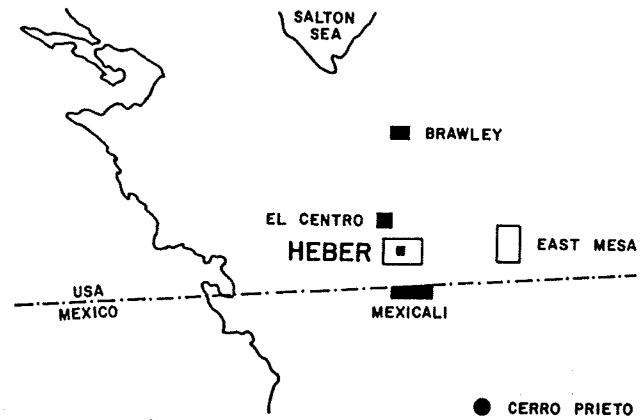

FIGURE I. LOCATION OF HEBER GEOTHERMAL FIELD.

Other geothermal fields in the area include Cerro Prieto in Mexico, East Mesa, Brawley and Salton Sea. Geologically, the area is on a tectonic trend of postulated oceanic ridge segments and transform faults which extends from the East Pacific Rise at the mouth of the Gulf of California to the San Andreas fault in the vicinity of the Salton Sea (Fig. 2).

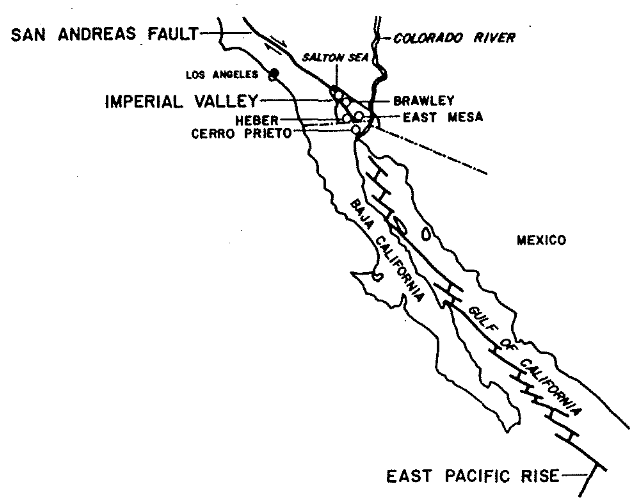

FIGURE 2. GULF OF CALIFORNIA-SAN ANDREAS FAULT TECTONIC SYSTEM.

This tectonic system has thinned the crust (Elders and others, 1972) in the Mexicali and Imperial Valleys so that regional heat flow is 2.5 H.F.U. or more (Blackwell, 1978).

EXPLORATION

Early exploration in the Heber area was for oil and gas. In 1945, Amerada drilled the No. 1 Timken to a depth of 6,637 feet just west of the town of Heber. The well did not discover hydrocarbons but there were indications that a thermal resource might exist. Large quantities of dry ice were reportedly used to cool the mud. Even so, a maximum temperature of 280°F was recorded on a Schlumberger E-log run.

Chevron conducted an extensive exploration program for oil and gas in the Imperial Valley in the early 1960's. This program included a gravity survey which indicated a positive Bouguer gravity anomaly just south of the town of Heber. In 1964, Chevron drilled several 500 foot holes in the Imperial Valley to investigate geothermal gradients. One of these holes was drilled on the Heber gravity anomaly. A gradient of 24.6°F/100 feet was measured between 400 and 500 feet and confirmed that the area was thermally anomalous. Consequently interest in Heber as an oil and gas prospect declined.

In 1970 Heber gained interest as a geothermal prospect because of the apparent success at Cerro Prieto in Mexico. A series of shallow holes (from 31 to 208 feet) drilled by the University of California (Riverside) indicated an anomaly of significant size as determined by contours of thermal gradients. Comparison of the Bouguer gravity map with the initial thermal gradient contours suggested that the gravity anomaly and the thermal anomaly were related (Fig. 3).

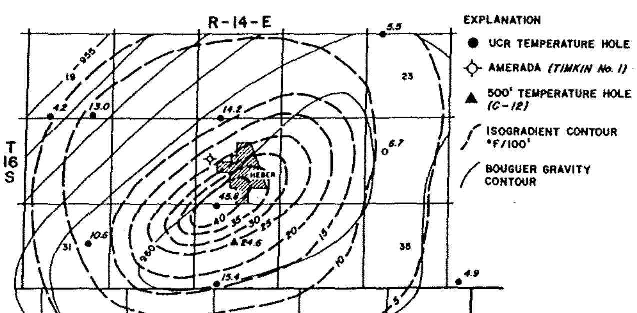

FIGURE 3. INITIAL SHALLOW ISOGRADIENTS AND BOUGUER GRAVITY CONTOURS-HEBER AREA.

However, the correlation shifted as more data became available (Fig. 4).

A north-south reflection seismic line was also shot in conjunction with the oil and gas exploration. The results were poor but suggested a very low relief, faulted, anticlinal reversal. This reversal has not been substantiated from well data but the E-log correlations used are not definitive.

Several geophysical surveys were run in conjunction with the geothermal exploration. Electrical resistivity data were obtained from a roving dipole survey, a dipole-dipole survey, and a magnetotelluric survey. The results were not diagnostic because the geothermal system at Heber does not have uniquely anomalous resistivities with respect to the one to five ohm-meter background resistivities in this part of the valley. A ground-noise survey provided an anomaly on the Bouguer gravity positive but the significance is questioned because of the generally high level of the surface noise. A weak anomaly was indicated just south of the town of Heber by a spontaneous potential survey. Unfortunately the anomaly lacked sufficient amplitude to distinguish it from other S.P. anomalies which lacked anomalous temperatures.

Early in 1972, Magma Energy, Inc. drilled the first geothermal well at Heber, the No. 1 Holtz, to a total depth of 5,147 feet. The results encouraged Magma to drill a second well, the No. 2 Holtz, a mile to the west. Chevron contributed financial support to the first well but not to the second.

Data from temperature holes, 200 to 500 feet deep, were the primary basis for locating Chevron's first deep test. A 1972 map of isotherms at 480 feet (Fig. 4) shows a well defined bulls-eye, centered at the northwest corner of Section 33.

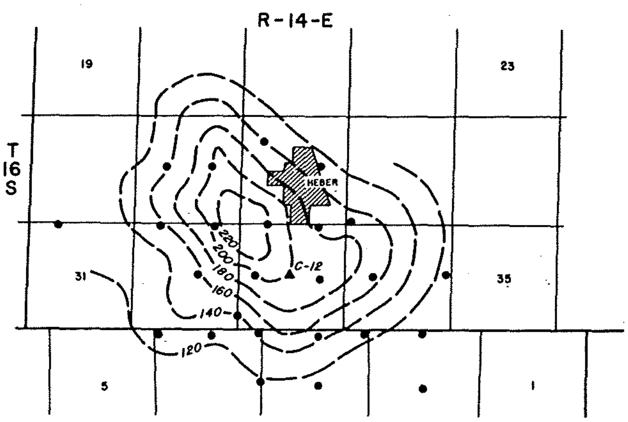

FIGURE 4. ISOTHERMS (°F) AT 480' (BLACK DOTS ARE CONTROL POINTS).

When gradient data are used to project isotherms to 5000 feet, a much broader target is seen (Fig. 5).

The gradient data suggested that the thermal anomaly shifted to the southeast with depth. Consequently, a location in the southeast part of the projected isotherm target was chosen.

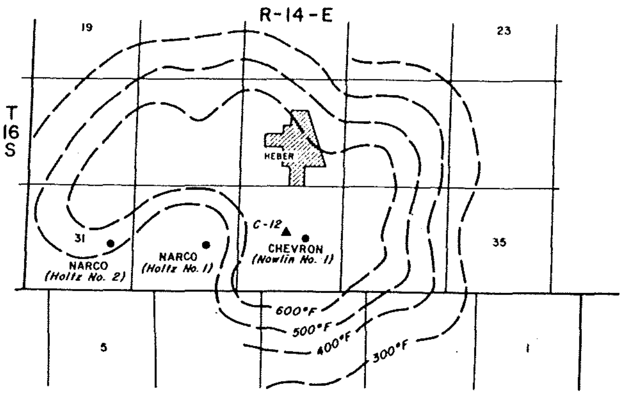

FIGURE 5. ISOTHERMS PROJECTED TO 5000' BASED ON 200' AND 500' GRADIENT HOLES. LOCATION OF CHEVRON-*NOWLIN No. 1* (CHEVRON'S FIRST DEEP TEST) IS SHOWN.

The Chevron No. 1 Nowlin was drilled in the fall of 1972. A maximum temperature of 368°F was recorded at 2,200 feet. This declined to 358°F at the total depth, 5,031 feet. Salinity of the water recovered from tests was fairly low (14,000 ppm total dissolved solids). Subsequent drilling has shown that if the well had been drilled in the northwestern part of the area defined by the projected isotherms at 5000 feet, it would have been well off on the flank of the deep thermal system.

FIELD DEVELOPMENT

Data from sixteen wells (including the Amerada No. 1 Timken, drilled for Oil and Gas) now define the Heber Geothermal Field (Fig. 6).

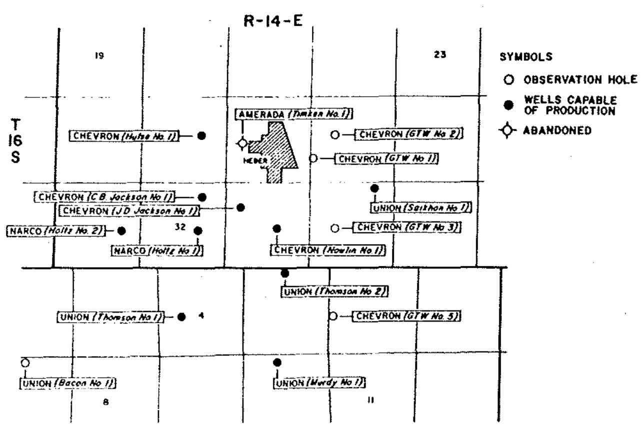

FIGURE 6. WELLS DRILLED IN THE HEBER GEOTHERMAL AREA.

The wells range in depth from 3,002 to 9,701 feet. All of the geothermal wells were drilled to evaluate and delineate the reservoir. They outline a convective plume of hot water of 375°F or higher rising from depths below 10,000 feet. A component of horizontal flow shifts the plume northerly above 4,500 feet, giving it an overall shape of a lopsided mushroom. At 2,000 feet the plume centers near the Chevron No. 1 Nowlin but shifts about 1/2 mile south at 4,000 feet (Fig. 7).

Above 2,000 feet, cap rock is provided by a generally shaley section where heat flow is predominantly conductive. Below 2,000 feet sands predominate with intergranular porosities of 15 to 30%. Only three of the wells are in suitable locations to be used as producers or injectors in the planned commercial development of the field. The others will be used as observation wells to monitor reservoir temperature and pressure as the reservoir is developed.

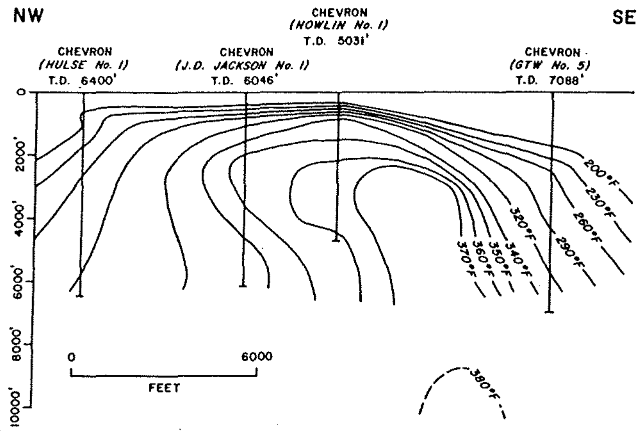

FIGURE 7. NW-SE CROSS SECTION SHOWING ISOTHERM CONFIGURATION.

Data needed to predict reservoir capacity and performance has been obtained through extensive well testing using various development schemes. The predicted reservoir capacity of 500 megawatts was established initially with a two-dimensional layered stream tube simulator model and secondly using a three-dimensional radial single phase water flow numerical simulator (Tansev and Wasserman, 1978).

The development plan was selected to optimize heat recovery and to support a generating capacity of 500 megawatts for about 30 years from the Heber thermal anomaly. Approximately 7,400 acres of land under lease to Chevron, Union Oil Company and New Albion Resources Company has been unitized with Chevron as Unit Operator. Wells will be directionally drilled for production from surface islands into the high temperature part of the thermal anomaly. Bottom hole locations will be evenly distributed in a circular pattern having a radius of about 2,000 feet. The power plants will be located near the producing islands to minimize heat loss during transit of the hot brine. Cooled brine will be moved from the power plants in pipelines, 30 to 42 inches in diameter, to injection islands on the periphery of the field. There, 1-1/2 to 2-1/2 miles from the center of the anomaly, the spent brine will be reinjected through directionally drilled wells to the present position of the 265°F isotherm. Simulated reservoir studies have shown that this production and reinjection pattern will provide the maximum economic reservoir life for the field. Imperial County has rezoned an area approximating 7,300 acres to allow the surface operations required to develop the Heber field (Fig. 8).

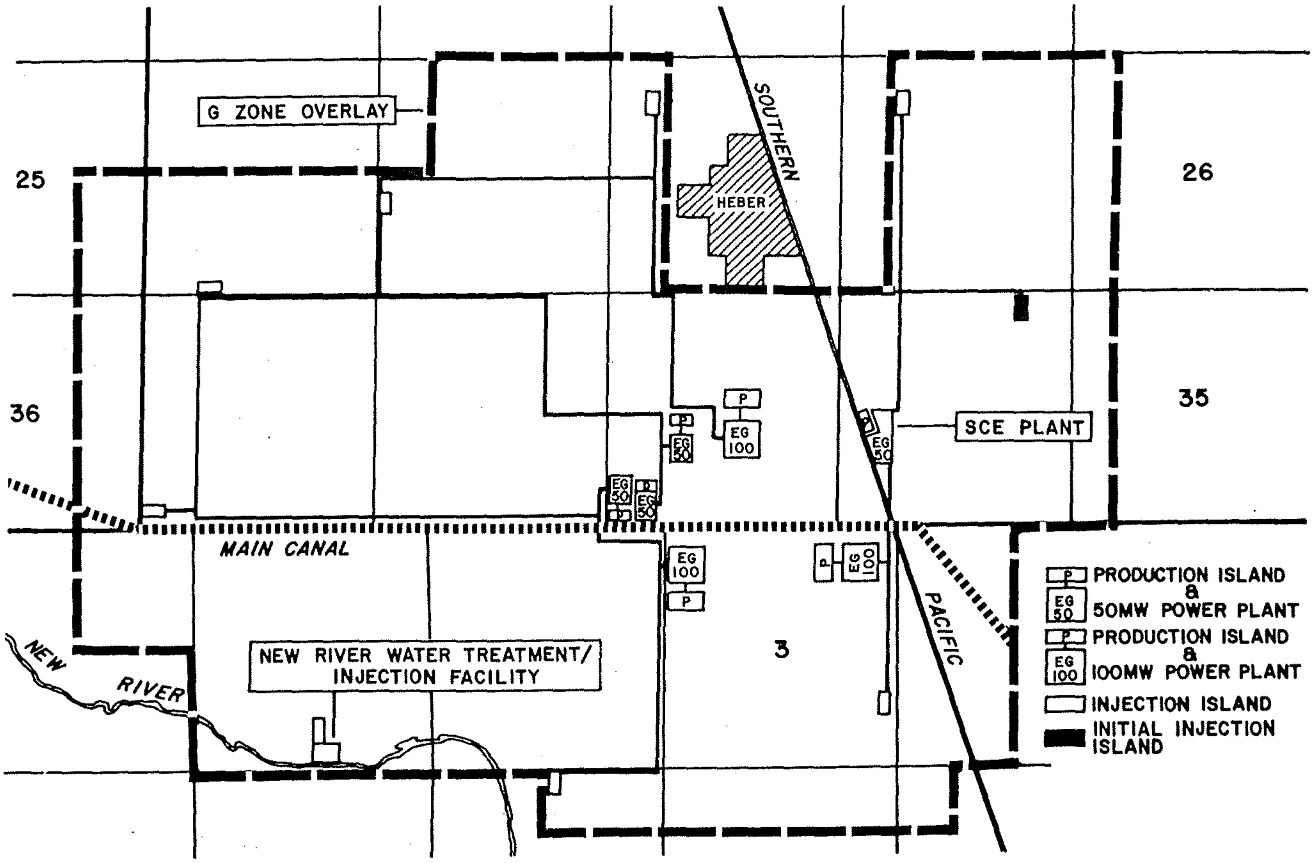

FIGURE 8. PRELIMINARY DEVELOPMENT PLAN-HEBER GEOTHERMAL FIELD.

Intervals of production and injection are limited to 2,000 feet to allow for a proper balance between the well bore and the reservoir flow capacity. Four production/reinjection zones have been defined for the 500 megawatt plan. Zones are 2,000 feet thick and extend consecutively from 2,000 feet to 10,000 feet. The first plants will use brines produced and reinjected into zone 1 (2,000-4,000 feet) and zone 2 (4,000-6,000 feet).

A fuel sales contract was signed by Chevron and Southern California Edison Company in November 1978 to supply 2 phase geothermal fluid from the Heber Unit to a 50 megawatt gross double flash power generation plant to be built by Edison. Startup is planned in early 1982 for this--the first large commercial, privately financed, hot water geothermal power plant in the U.S. Subsequent power developments are expected to occur in 50-100 megawatt increments with the total development of 500 megawatts completed in 1989.

ACKNOWLEDGMENTS

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GEOLOGY AND COMMERCIAL DEVELOPMENT OF THE EAST MESA GEOTHERMAL FIELD, IMPERIAL VALLEY, CALIFORNIA

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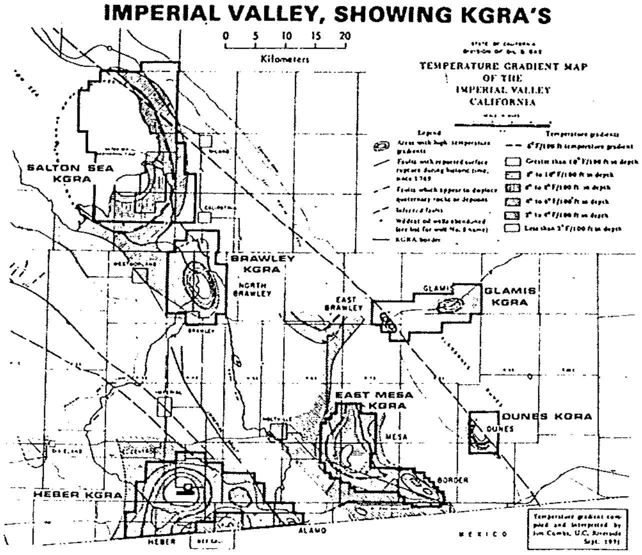
INTRODUCTION

The Imperial Valley of California is underlain by late Tertiary and Quarternary sediments that have an accumulated thickness of as great as 20,000 feet, based on seismic refraction data (Biehler, et al., 1964). Areas of anomalously high heat flow occur within these sediments and small recent volcanoes are present, dated at 16,000 years b.p. (Robinson, et al., 1976). Based upon the data obtained from some 144 shallow temperature gradient holes, Rex (1971), and Combs and Rex (1971) published maps identifying and naming the Heber, Alamo, Border, (East) Mesa, Glamis, Dunes, East Brawley, North Brawley and the Buttes (Salton Sea) thermal anomaly areas. Six of these have been designated known geothermal resource areas (KGRA's), shown in Fig. 1.

FIGURE 1

TEMPERATURE GRADIENT MAP OF THE IMPERIAL VALLEY, SHOWING KGRA'S



EAST MESA GEOTHERMAL EXPLORATION DEVELOPMENT ACTIVITIES

The East Mesa geothermal field was discovered through an investigation of the areal coincidence of a positive residual gravity anomaly with an electrical resistivity low in an area of anomalously high thermal gradient, as indicated by shallow temperature gradient holes. A summary of the significant investigations at the East Mesa geothermal field follows, together with references to the reports that detail the work done.

Heat Flow-Temperature Gradient Studies

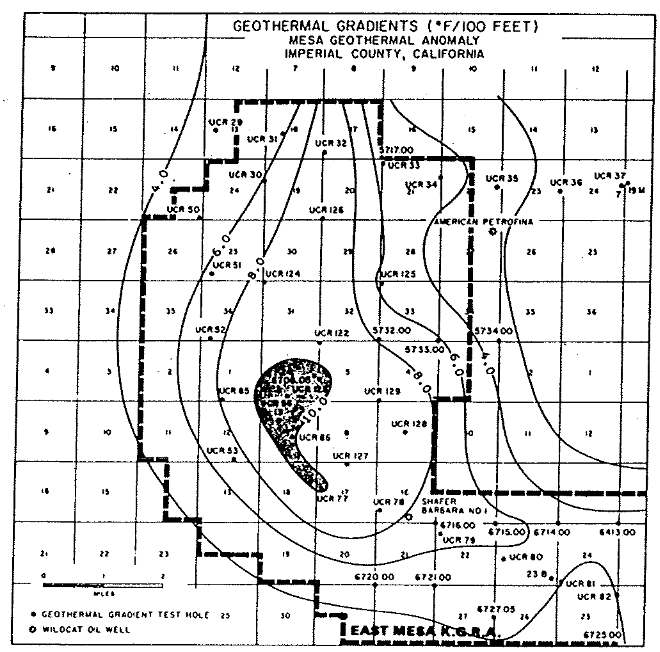
Detailed coverage of heat flow and thermal gradient data for the East Mesa area is provided by the results from 46 gradient holes drilled to depths of about 500 ft. An area of about 16 square miles is identified to have a heat flow of 5 HFU, or about five times the world average, and an area of about 25 square miles has shallow thermal gradients of over 6°F/100 ft. As shown in Figure 2, shallow gradients of over 8°F/100 ft. continue northward as a thermal ridge.

Gravity Studies

The results of more than 3,000 gravity observations in the Salton Trough were reported and interpreted by Biehler, et al., (1964). Biehler

FIGURE 2

SHALLOW TEMPERATURE GRADIENT MAP, EAST MESA KGRA (COMBS, 1971)



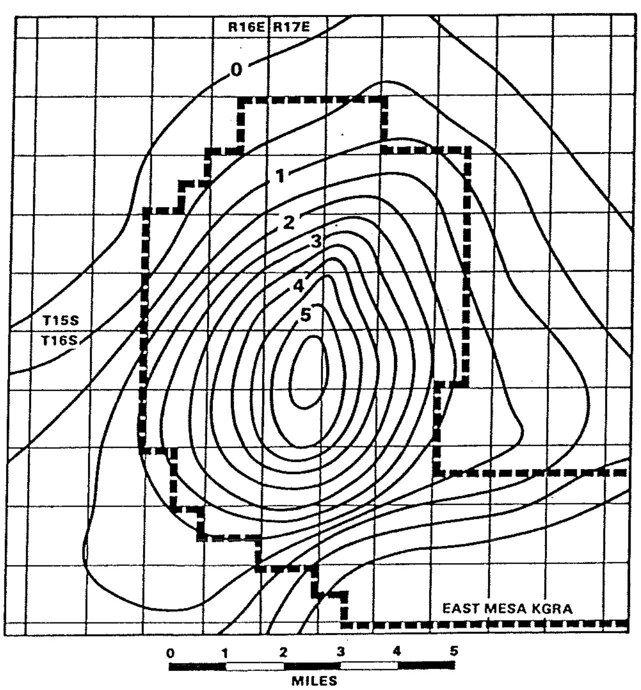
subsequently added hundreds of additional gravity stations to further detail the areas of thermal significance in the Imperial Valley. The complete Bouguer anomaly map of the Imperial Valley, which Biehler published in 1971, has proven to indirectly indicate the general location of almost all of the presently known thermal anomalies in the Valley. Seven of the thermal anomalies, including the East Mesa field, are areally associated directly with seven distinct and prominent gravity maxima with closures of from 2 to 22 milligals.

A detailed interpretation of the gravity maximum associated specifically with the East Mesa field was made by Biehler (1971). The interpretation includes the compilation of a complete Bouguer anomaly map of the field, and a calculation of a quadratic surface regional gradient map of the surrounding area. A residual anomaly map (Figure 3) was produced and a comparison of this anomaly with the thermal anomaly indicates that there is an excellent correlation between the areas of high near-surface thermal gradient and the center of the gravity maximum.

The explanation for the casual relationship between the high thermal gradients and the positive gravity anomaly is that high temperature formation waters in these areas have deposited silica and carbonate from solution into the intergranular porosity of the sediments as the solutions migrate and cool, thereby increasing the density of those sediments.

FIGURE 3

RESIDUAL GRAVITY MAP OF THE EAST MESA GEOTHERMAL FIELD (BIEHLER, 1971)



(CONTOUR INTERVAL 0.5 MILLIGALS)

Electrical Resistivity Studies

Meidav and Rex (1970), and Meidav and Furgerson (1972), report the results of resistivity depth soundings made in the Imperial Valley. The conclusion reached is that there is a gradual regional resistivity increase toward the southeastern part of the Valley caused by a gradual decrease in groundwater salinity. Superimposed on this regional change are local decreases in resistivity which are attributable to the effects of local geothermal anomalies.

The East Mesa geothermal field is clearly indicated to be a local low resistivity anomaly (Meidav and Furgerson, 1972). The anomaly is shown to increase in areal extent at greater depths below the ground surface.

Microseismic Studies

A series of microearthquake investigations of the East Mesa geothermal field has been reported by Combs and Hadley (1973) for the period June-July 1973, and by Combs (1975) for the period December 1974 to December 1975. These studies were used to suggest the probable location of an active (Mesa) fault associated with the geothermal anomaly at East Mesa. McEvilly and Schechter (1977a, 1977b, 1978) have more recently reported on a similar type of microseismicity study continuously conducted at East Mesa during the last 186 days of 1977. The major result of this latest study is that no local events were detected within the East Mesa field for those six months, although a significant number of events with hypocenters located elsewhere in the Imperial Valley were recorded by the six station instrument array positioned at East Mesa.

Drilling Activity

The first two deep wells drilled near the East Mesa geothermal field were drilled as wildcat oil wells. The Shafer Barbara No. 1 (16, T16S,R17E) was drilled to 8,017 feet in 1960, and the American Petrofina No. 27-1 (27,T15S, R17E) was drilled to 10,550 feet in 1966 (see Figure 4).

Between 1972 and 1974, five deep geothermal wells were drilled in the East Mesa KGRA by the United Sates Bureau of Reclamation. These wells, with their locations having been suggested by the (previously discussed) surface geophysical studies, confirmed the existence of the deep thermal anomaly at East Mesa with their bottom-hole temperatures of 300° to 400° F.

In late 1975 and early 1976, Republic Geothermal drilled 3 deep geothermal wells in the northern part of the East Mesa field. These wells successfully confirmed the presence of at least 330° to 360° F waters at their locations, and their high observed flow rates indicated that improved reservoir conditions could be expected in this northern portion of the field. Republic then proceeded to make the first application for

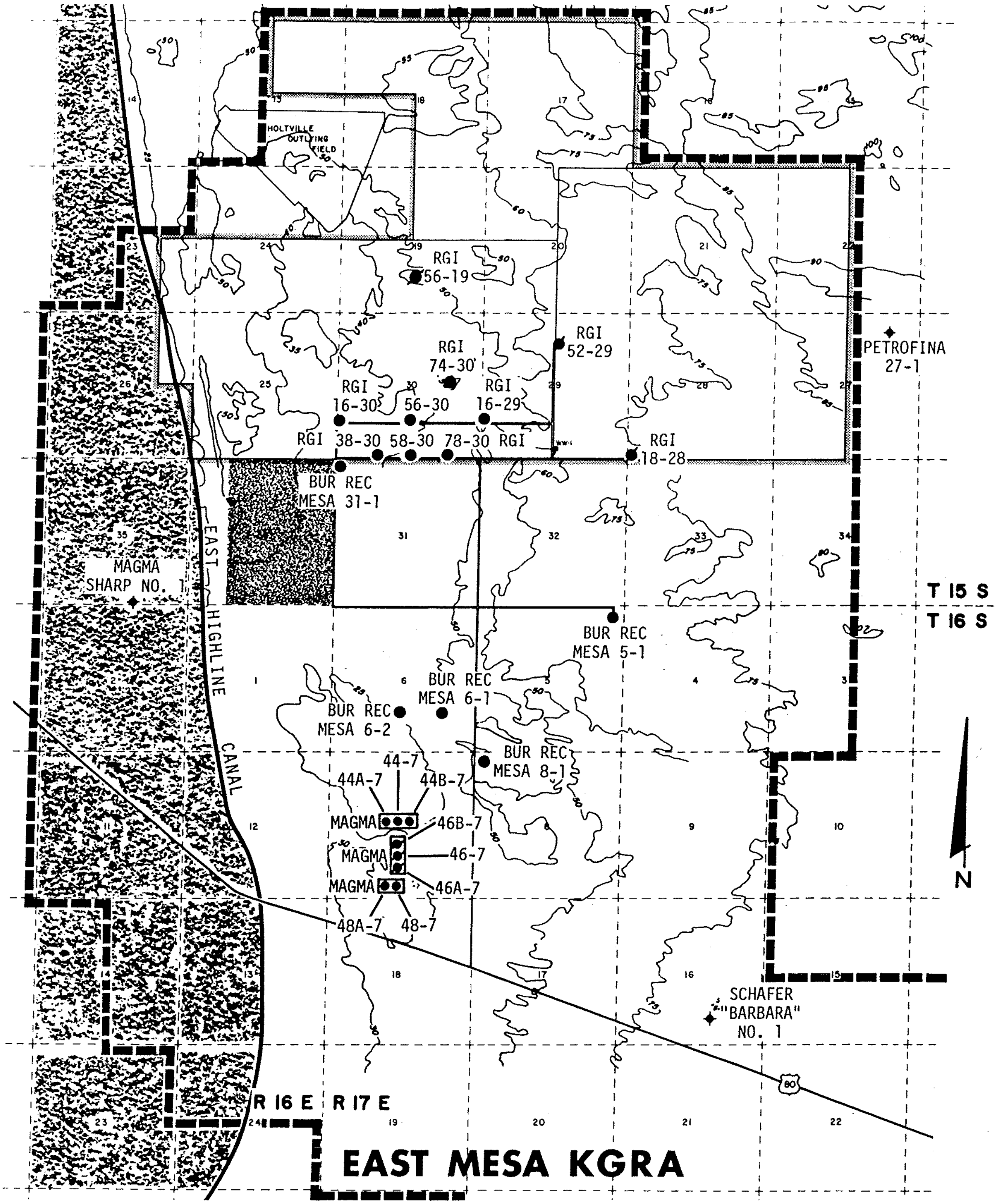


FIGURE 4 WELLS DRILLED AT EAST MESA

a Federal Geothermal Loan Guaranty, and following approval of that application in May 1977, seven more wells have been drilled to increase the present Republic total to 7 production wells and 3 peripherally located injectors.

Meanwhile, starting in mid-1976, Magma began the deep development well drilling on their lease at East Mesa, which is located south of the Bureau of Reclamation wells. By September 1979, they had completed 5 production and 3 internally located injection wells.

All of the deep wells at East Mesa have been electrically logged. Detailed lithologic descriptions have been made on the ditch cuttings of USBR No. 6-1 (Fournier, 1973) and USBR No. 6-2 (Fournier, 1976; Hoagland, 1976). The logs, cuttings and cores show that the first 10,000 feet of stratigraphic section at East Mesa is a sequence of deltaic clastic sediments that includes abundant amounts of fine to medium-grained sandstones, fine to coarse-grained siltstones, and lesser amounts of mudstones. Coarse sandstones are commonly present only in the upper 2,000 feet. Mineralogically, the sandstone grain composition averages about 70-75% quartz, 20% lithic fragments, with 5-10% feldspars and accessories. These sands are compositionally equivalent to Colorado River delta sands (Hoagland, 1976). The siltstones consist of quartz, feldspars, calcite and dolomite, montmorillonite, illite and kaolinite, plus pyrite (Fournier, 1976; Hoagland, 1976).

Post depositional alteration at East Mesa is generally restricted to depths below 2000-3000 feet. The alterations are principally the addition of authigenic carbonate and overgrowths and veinlets, and the conversion of the detrital phyllosilicates to illite and chlorite.

Geochemical Studies

Detailed studies of the waters of the East Mesa Field suggest a moderately complex stratification and distribution. There appear to be at least two, and possibly three, major water types present in the field. A saline chloride-rich water ranging from 11,000 to 24,000 ppm salinity occurs in the deep zone of USBR well 6-1 and Magma well 44-7, one mile south of 6-1. The majority of the other Bureau of Reclamation wells contain a much lower salinity range from 1,500 to 6,000 ppm with characteristically intermediate sodium to calcium ratios.

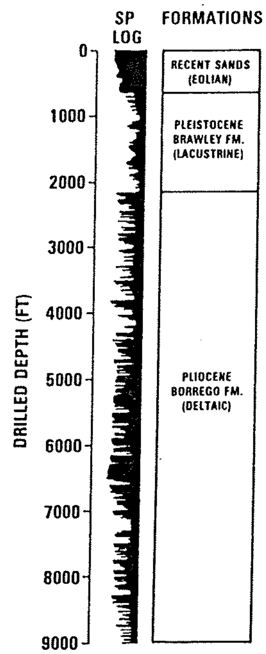
Another major type of water at East Mesa has extremely high sodium to calcium ratios, and salinities ranging from 1,800 to 2,200 ppm. The Republic wells and the USBR well 31-1 contain this type of fresh water.

Detailed Stratigraphic and Structural Studies

Within the northern part of the East Mesa field, the stratigraphic units present to a depth of 9,000 ft. have been examined in detail. The basic stratigraphic sequence, as shown in Figure 5, is about 600 ft. of recent Eolian dune sands overlying 1,200-1,500 ft. of Pleistocene lacustrine units that are mainly siltstones and mudstones. Below this is a thick deltaic sequence composed predominantly of sandstone units, which are the reservoir rocks of the field, interbedded with thinner silt and mudstone layers.

FIGURE 5

REPUBLIC GEOTHERMAL, INC.
"EAST MESA" NO. 38-30
SEC. 30, T15S, R17E

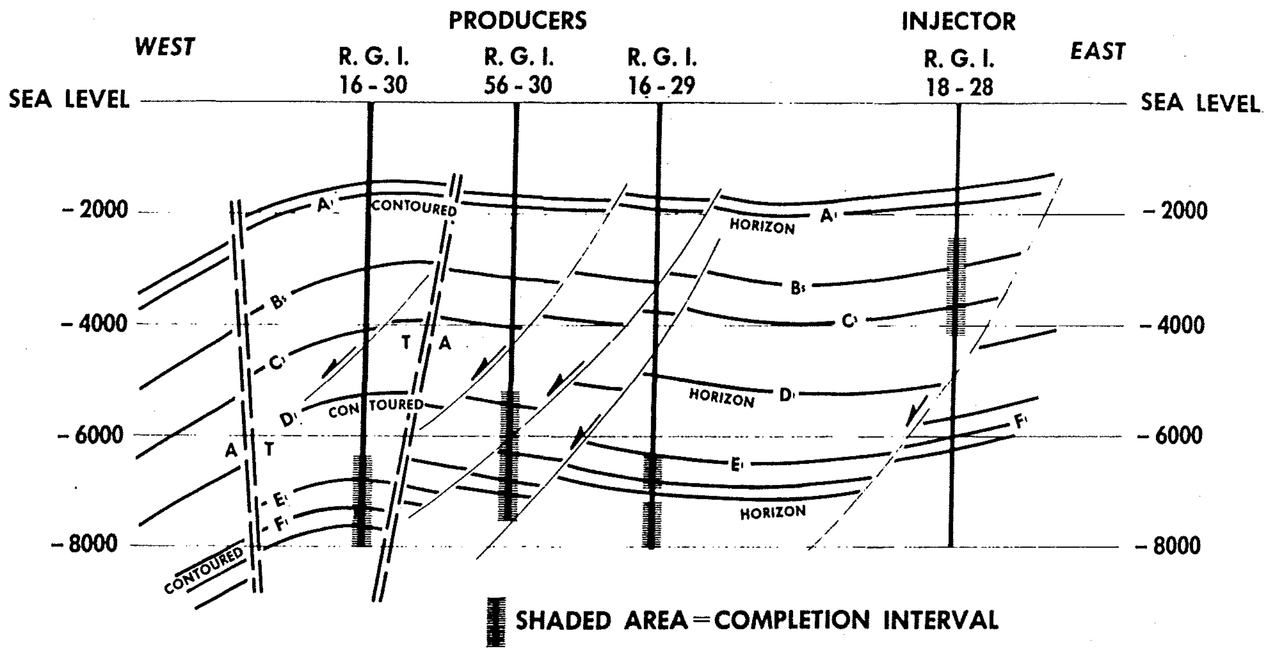


A study of the electric logs from all of the 11 deep production/injection wells in this area indicates that the deltaic sandstone reservoir units have lateral stratigraphic continuity. To examine this interval in more detail, a series of correlative horizons has been recognized and selected. The top of the first sand of the deltaic sequence occurs at depths between 1800-2100 ft., and this horizon is designated A1. Successively lower horizons that are also easily correlated were arbitrarily designated B1, C1, D1, E1 and F1. The depth of F1 varies between 6800-7000 ft., which is near the bottom of the reservoir as presently developed. Next, 53 additional stratigraphic horizons that occur between the 6 fundamental correlations were recognized and similarly designated.

The subsurface stratigraphic interpretations just described provide the essential basis for a detailed structural interpretation of this portion of the East Mesa field. Figure 6 is an east-west structural cross-section through the northern line of Republic wells showing the series of normal faults, dipping to the west (basinward), that disrupt the stratigraphic units which are folded into a broad syncline and anticline before they dip more steeply westward into the basin. Also shown in the section are

FIGURE 6

EAST MESA
STRUCTURAL CROSS SECTION



the locations of two near-vertical strike slip faults that are interpreted to be present based upon structural, stratigraphic and reservoir testing data.

The total available subsurface data, including modern reflection seismic data, well correlation points and dipmeter data have been combined to produce a series of subsurface structure contour maps. The structure map made on the A1 horizon, found at the top of the deltaic reservoir section near a depth of about 2,000 ft., shows the interpreted location of a broad structural high just north of the Republic wells (Figure 7). The normal faults strike about N30E, dip NW, and the two lateral faults are indicated to be a conjugate pair. Reservoir buildup- drawdown pressure tests in these wells indicate that the normal faults do not provide a barrier to communication, but that the lateral faults apparently do. This may be because the normal faults, developed early as essentially growth faults, form in response to a tensional environment, while the lateral faults are developed due to later near-horizontally directed compressional forces.

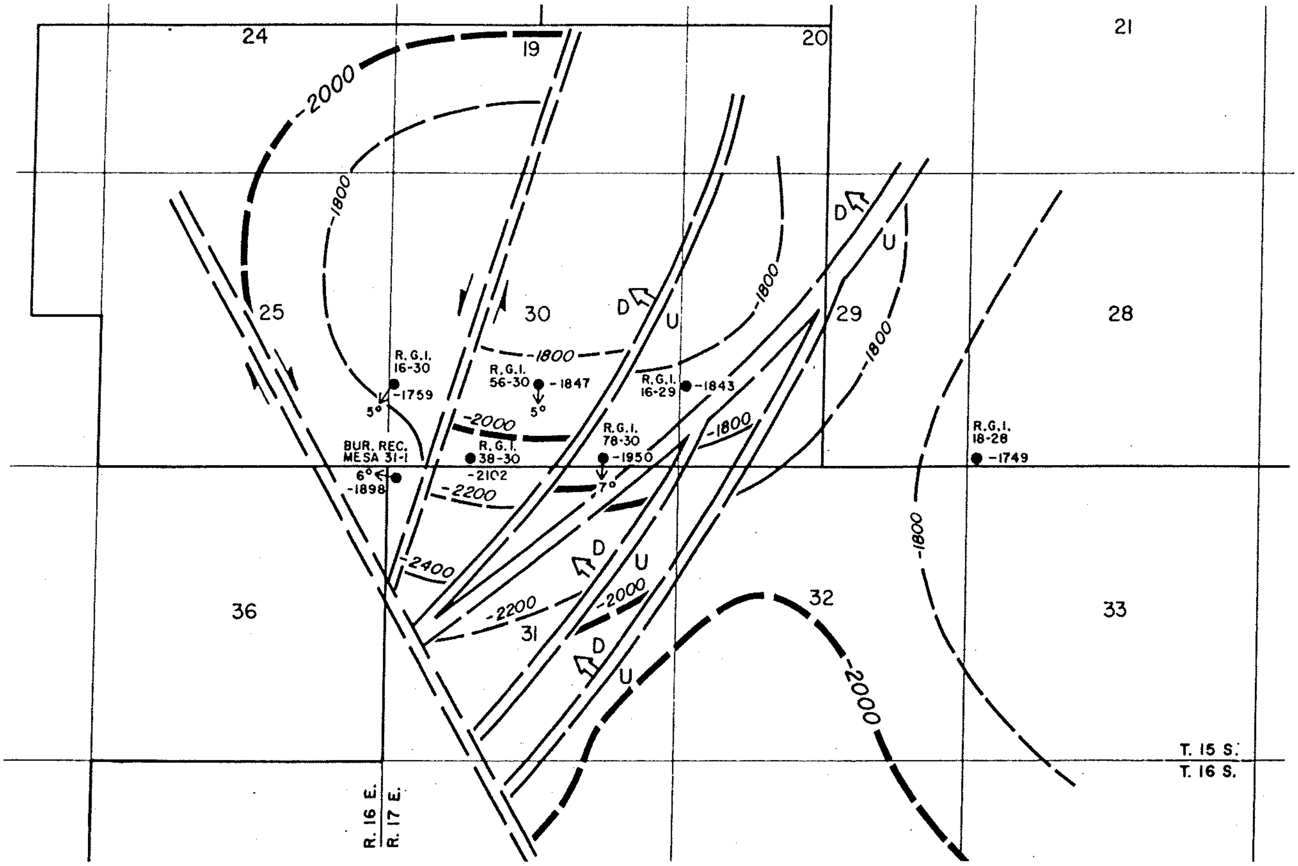
RESERVOIR EVALUATION AT EAST MESA

Subsurface Temperature Distribution

Static temperature surveys have been run in all the East Mesa wells. These temperature measurements are made while the well is shut-in, and under conditions such that the data is as representative as possible of the reservoir temperature at each depth surveyed. An examination of the shape of the plotted temperature profiles clearly indicates that starting from a surficial base temperature of 78-80° F, each well has a relatively high thermal gradient down to a depth of about 2,000 ft. These upper-zone gradients are essentially linear, which describes the low conductive heat transfer and low vertical permeability through the predominantly claystone-rich lacustrine sediments that are immediately above the sand-rich deltaic section. Within the deltaic section the thermal gradients become reduced, illustrating the overall more convective nature of this reservoir interval. The maximum observed subsurface temperature at East Mesa, to date, is 400 °F at 8,030 ft. in USBR Well #6-1.

Isothermal surface contour maps covering essentially all of the East Mesa field have been made by using the static temperature survey data from 7 Republic wells combined with that available from the 5 U.S. Bureau of Reclamation wells and from 2 wells drilled by Magma. The shape of these surfaces is essentially dome-like, centered near the center of the shallow thermal anomaly and the center of the positive residual gravity anomaly. The depth of the 300° F surface varies from about 2,000 ft. to about 5,000 ft. in the area of drilled production wells (Figure 8).

FIGURE 7



EAST MESA
STRUCTURE CONTOUR MAP
A_1 HORIZON

Produced Fluids

Three substantially different purposes are served by chemical studies of the geothermal fluids that flow or are pumped from the production wells: (a) characterization of the fluid as a component of the geologic formations, (b) description of the chemical factors which must be accommodated in the engineering design and operation of the power plant and injection facilities, and (c) assessment of the environmental impact of the development.

The summary description of the geothermal fluids, considering these three aspects, is (a), that the water is relatively fresh, compared to reservoir fluids from other geothermal fields; (b), the two significant engineering considerations are to prevent carbonate scale buildup, by using chemical inhibitors, and to make the normal power plant equipment designs that take into consideration the carbon dioxide (noncondensable) gas content in the flashed fluid; and (c), the produced fluids are so environmentally benign that the USGS does not consider their anticipated production to be of major impact or concern.

The results of 37 chemical analyses of reservoir water samples obtained from Republic production and injection wells at East Mesa are available. These analyses represent the composition of a liquid sample mixture of reservoir fluids produced from sands distributed through the (typically) long completion interval of each well. In addition, analyses of produced reservoir waters from Bureau of Reclamation wells and from one of the Magma wells are available for comparison purposes.

The first six major components of the reservoir water analyses listed in Table 1 together comprise 99+% of the dissolved materials present in these waters. Four minor components, defined as those others present in concentrations generally above 1 ppm, are listed next. Trace materials are the remainder, which are generally below 1 ppm in concentration.

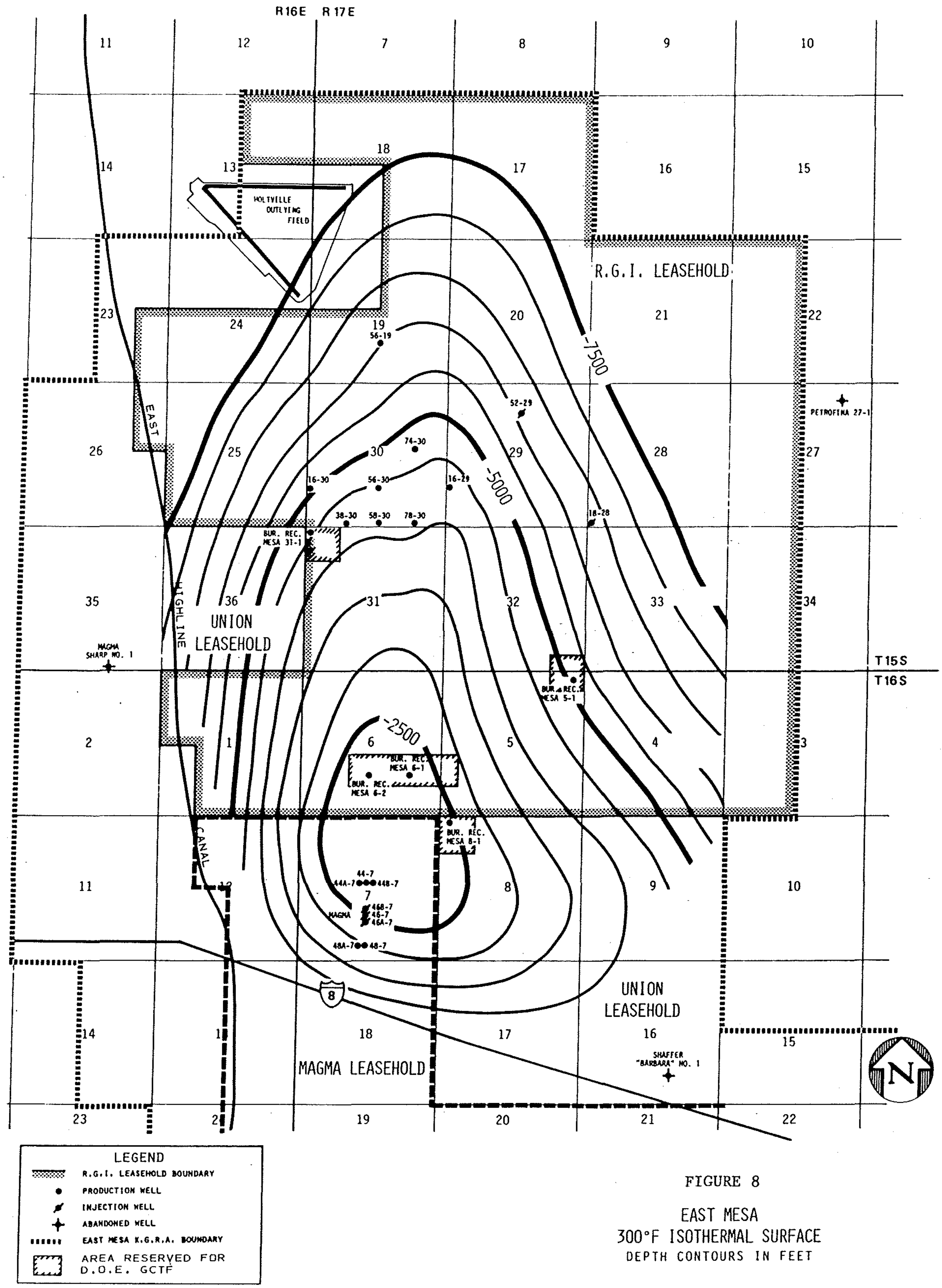


FIGURE 8

EAST MESA
300°F ISOTHERMAL SURFACE
DEPTH CONTOURS IN FEET

TABLE 1

COMPOSITION OF THE

EAST MESA RESERVOIR WATERS,

IN mg/l

	1.	2.	3.	4.
Major Components:				
Sodium	575	7,000	1,328	1,710
Chloride	475	12,000	1,845	6,588
CO_3+HCO_3	454	95	627	365
Sulfate	165	25	169	NA
Silica	181	291	205	289
Potassium	30	721	129	NA
TDS	1,880	21,650	4,090	17,200
Minor Components:				
Calcium	9.	816.	10.1	17.3
Fluoride	4.	1.6	2.8	NA
Boron	2.2	14.3	7.8	NA
Ammonium	4.	38.	13.	NA

1. Avg. Republic Well, ±6,000-7500' Depth Interval
2. USBR Well 6-1, 6496-8018' Depth Interval
3. USBR Well 6-2, 4567-5455' Depth Interval
4. Magma #44-7, 5147-7320' Depth Interval

Porosity and Permeability Distribution

An analysis of the geophysical logs run in the Republic wells at East Mesa has been completed by Intercomp. The principal results of the analysis were a determination of porosity, permeability, and net sand present at each well location, versus depth. The permeability and porosity log relationships were calibrated with composite core data from USBR Well 5-1 and RGI Well 78-30, and properties were calculated using a theoretical shaly sand correlation technique. This procedure provides consideration for the calcareous cement present in the sand sequences, for variations in hole size, and for intervals of thick mudcake; thereby greatly enchancing the resolution of the petrophysical parameters relative to previous efforts.

Table 2 is a summary of the average reservoir properties for two major depth intervals. The data generally shows an excellent amount of sand development in the wells, with a decrease in reservoir properties below a depth of 7,000 feet. The porosity, net sand and permeability values in the interval from about 5,000 to 7,000 feet are sufficiently high to permit large flow rates with relatively small pressure drawdowns. The relative validity of these calculations has been confirmed by both pressure buildup analyses and by interference testing.

An observed lateral variation of reservoir properties is also illustrated in Table 2. The 5 wells shown are selected and arranged to represent a west to east line of section. Within each depth interval the porosity and permeability values tend to first decrease eastward from Well 38-30, reaching a minimum at Well 78-30 or 16-29, and then increase at Well 18-28. Realizing that different stratigraphic units are included to some degree in each depth slice, the lateral porosity and permeability variations have been examined in more detail between correlative stratigraphic horizons. These results demonstrate more consistently the same trend of a central area with reduced reservoir character, centered on the location of the northern axis of the positive residual gravity anomaly.

TABLE 2

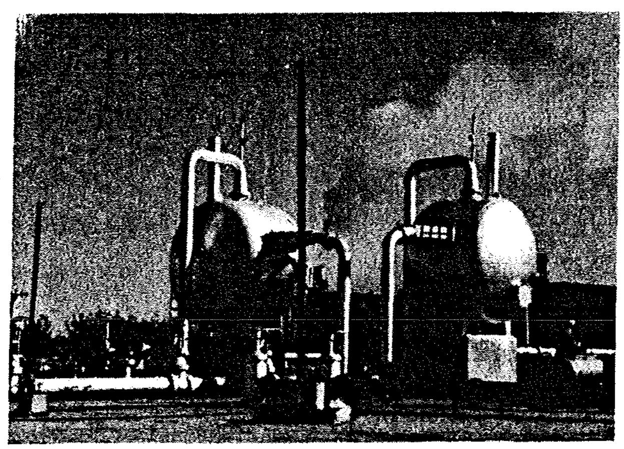
LOG ANALYSIS SUMMARY OF SELECTED

REPUBLIC EAST MESA WELLS

WELL:	#38-30	#56-30	#78-30	#16-29	#18-28
5000-7000 Ft. Depth Interval					
Sand Percent	72.4	66.1	77.9	69.0	60.4
SS Porosity	28.3	25.2	25.0	23.2	28.9
SS Perm. (md)	514.8	118.8	79.1	68.8	941.3
7000-8000 Ft. Depth Interval					
Sand Percent	40.3	13.6	46.8	37.2	37.4
SS Porosity	22.6	16.3	16.1	20.5	24.1
SS Perm. (md)	50.6	3.9	3.8	16.0	117.1

PRODUCTION AND COMMERCIALIZATION

The maximum stable natural flow rates observed for the Republic wells have ranged between 150,000 and 1,100,000 lb/hr. Increased production rates for those wells with relatively lower natural flow rates have been realized by using lineshaft turbine pumps. Maximum stable pumped rates have ranged from 350,000 to 780,000 lb/hr, with the major constraint being the pump capacity and the capacity of the subsurface injection (water disposal) system.



REPUBLIC GEOTHERMAL WELL TEST
FACILITY AT EAST MESA, CALIFORNIA

The general system of utilizing the geothermal resource at East Mesa will consist of pumping the deep production wells and and transporting the produced water through 12 to 24" insulated steel flow lines to a power plant facility. At the power plant, separators operating at 56 psia will first separate steam from water with the steam then directed into the power plant to drive a turbine-generator to produce electricity. The initially separated and diverted hot water will be flashed at a second (17 psia) separator and the steam produced will enter the same turbine-generator at a lower pressure inlet. The cooler waters from the 2nd stage separators and that resulting from the condensation of steam having passed through the turbine will then be gathered and piped to be reinjected back underground into the reservoir. Republic Geothermal is currently planning to have its first such 50 Mw dual-flash power plant on line in 1982, using about 30 production and 15 injection wells.

Magma Power is in the final construction stages of their 11.2 Mw power plant located in the southern part of the East Mesa field. This demonstration plant will utilize a dual binary cycle conversion system, which involves using pumped production well water to heat first isobutane and then propane within heat exchangers, and then sending the resulting hydrocarbon gases to drive a turbine-generator. A large cooling pond supplies water to condense the turbine outlet hydrocarbons, which are then recycled to the heat exchangers within a closed system.

The total developed potential of the East Mesa geothermal field is currently estimated to be about 350 Mw for 30 years, which is equivalent to the amount of electricity that would alternatively be generated by the burning of about 124,000,000 barrels of oil.

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Hybrid Transform Faults and Fault Intersections in the Southern Salton Trough Geothermal Area, Baja California, Mexico*

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Abstract

Analysis of 55 wells drilled at the Cerro Prieto Geothermal Field and a suite of geological and geophysical studies throughout the southern Salton Trough from the Mexican-United States border to the Gulf of California clarify two concepts important to geothermal development: 1) increased natural convective fluid flow and better permeability should occur at intersecting faults both regionally and within a producing field, and 2) the Cerro Prieto and Imperial faults are best conceived of as hybrid types having features of both San Andreas style wrench faults and oceanic transform faults.

Introduction

Study of fault intersections and a merging of concepts on San Andreas type wrench faulting with oceanic transform fault theory aid in explaining geothermal resources in the southern Salton Trough. This wedge shaped region (Fig. 1) from Mexicali to the present Gulf of California is bounded on the east by the Craton Margin Lineament which trends approximately N 30°W and on the west by the San Felipe fault zone. The latter fault zone trends N 15° ± 10°W from the city of San Felipe, along the Ometepec Salina where it has 1.5 m of recent vertical offset, and then follows the east side of the local mountain ranges (Sierra Mayor and Cucapa) until intersecting the Cerro

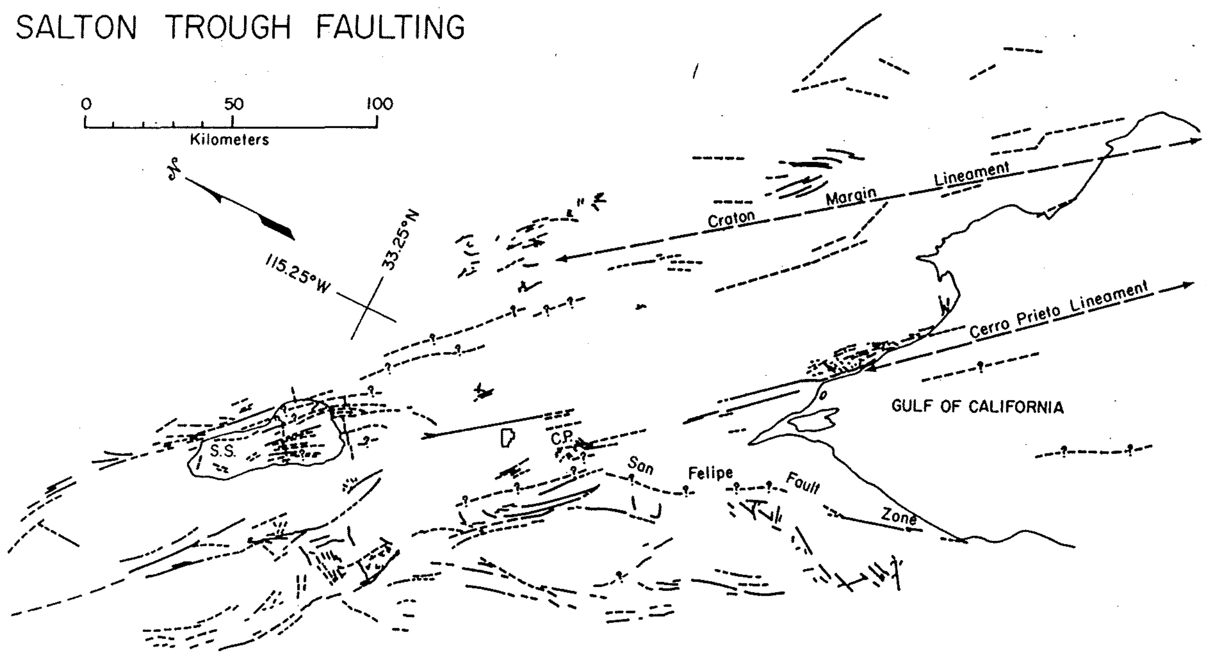

Figure 1: Compilation of faults in the Salton Trough showing the Cerro Prieto Lineament as a major hybrid transform fault zone. Note the prevalent and long NW-SE trending faults with much shorter intersecting faults of NE-SW trends. Faults indicated by lines, dashed where discontinuous or subsurface; - ? - indicates uncertain location. Critical data evaluation from published work; paper in preparation by the authors; S.S. indicates Salton Sea; C.P. is the Cerro Prieto geothermal area (from Vonder Haar and Puente, 1979).

*This paper is an augmented version of an earlier report by the authors (Vonder Haar and Puente, 1979).

Prieto Lineament 6 km north of the Cerro Prieto Volcano. Research by Gastil and Krummenacher (1977) in Sonora has shown the Cerro Prieto fault zone lineament to be a major regional feature. The San Felipe fault zone and the Cerro Prieto Lineament, which trends N40° ± 50°W are confirmed by seismic reflection data (publication in progress by Cerro Prieto, C.F.E.). The Cerro Prieto geothermal field is currently producing 150 megawatts and is 12 km southeast of this major fault intersection.

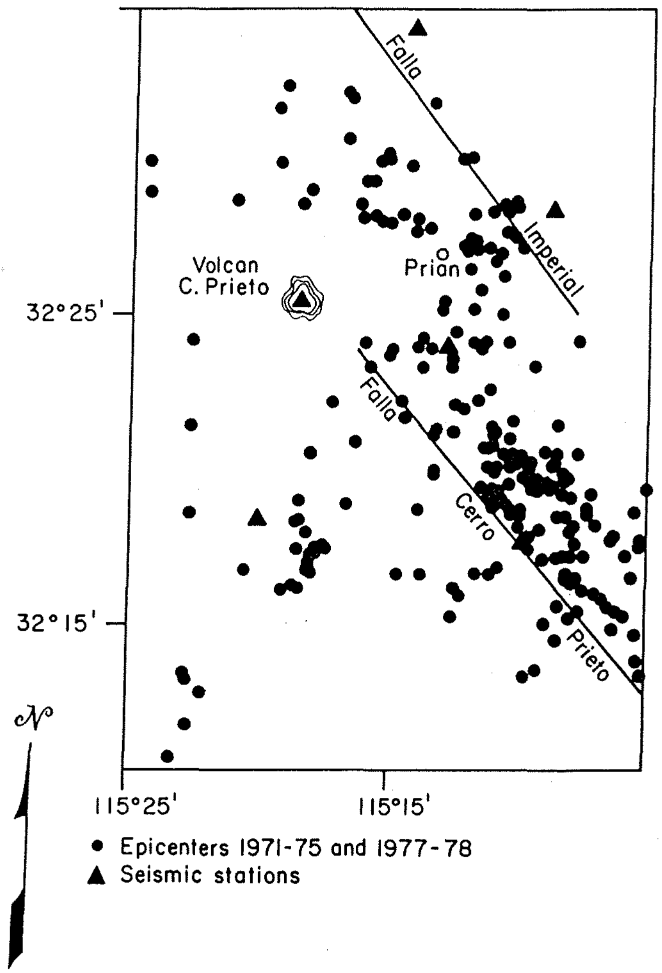

Figure 2: Microseismic studies illustrating the active movement along the northwestern terminus of the Cerro Prieto hybrid transform fault and the north to northeasterly shift to the Imperial hybrid transform fault (data from Albores and others, 1979).

Fundamental to the regional geothermal history is the idea that the Cerro Prieto fault and the Imperial fault exhibit characteristics of both wrench faults and oceanic transform faults; hence they are informally termed hybrid transform faults. Freund (1974) discussed in detail 16 differences between wrench faults and transform faults. Important characteristics of hybrid transforms are: a) episodic strike-slip movement, b) obliquely intersecting shorter normal faults, often in clusters of fault shear zones, c) a tendency to be linear rather than curved, d) an active shear zone up to 200 m wide in the basement yet only 10 m near the surface, e) a lack of splayed fault segments at their terminations. They have no equivalent of oceanic fracture zones (i.e. a non-active fault extension), and they do not link clearly defined spreading centers. Such faults are capable of deep penetration into the crust to serve as conduits for heat flow. Thickness of the crust ranges from 7 to 11 km in the northern Gulf of California (Phillips, 1964) to as great as 32 km at the Mexican-United States border. (Biehler and others, 1964).

The Cerro Prieto hybrid-transform and its intersection with the San Felipe basin and range style fault zone has three important features: 1) a shift in regional tectonic activity from the locked end of the Cerro Prieto fault to the Imperial fault, which is 11 km to the northeast and trends N 36°W, 2) formation of fault blocks along the hybrid transform as well as in the region between them, and 3) localization of a major geothermal field i.e. Cerro Prieto at the intersection of the hybrid transform and crosscutting faults. Microseismic studies, as shown in Figure 2, and a self-potential survey (Corwin and others, 1978) support a north to northeasterly trending fault between the Cerro Prieto and Imperial faults. (Fig. 3).

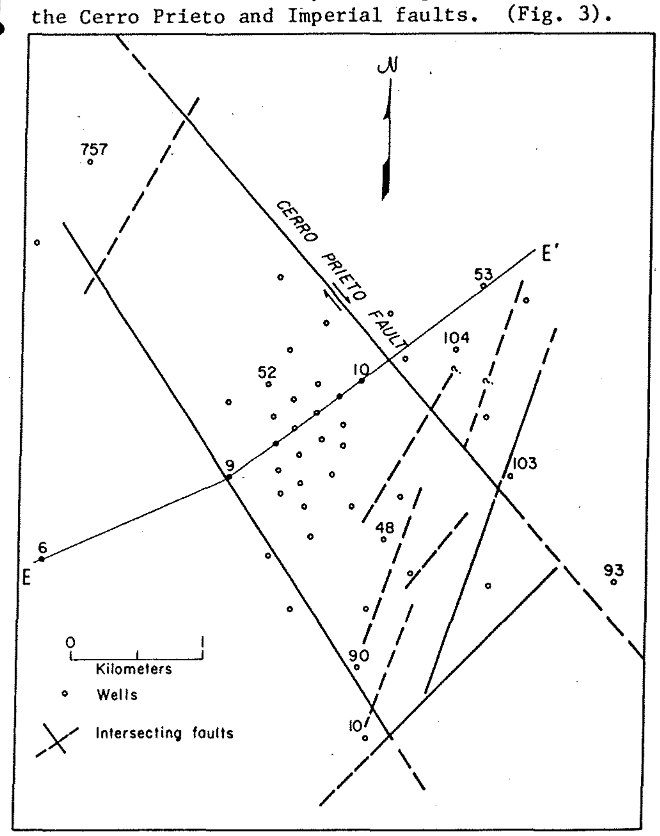

Figure 3: Intersecting faults and well locations at Cerro Prieto. Also shown are the very productive well 103 and the line of section E-E'.

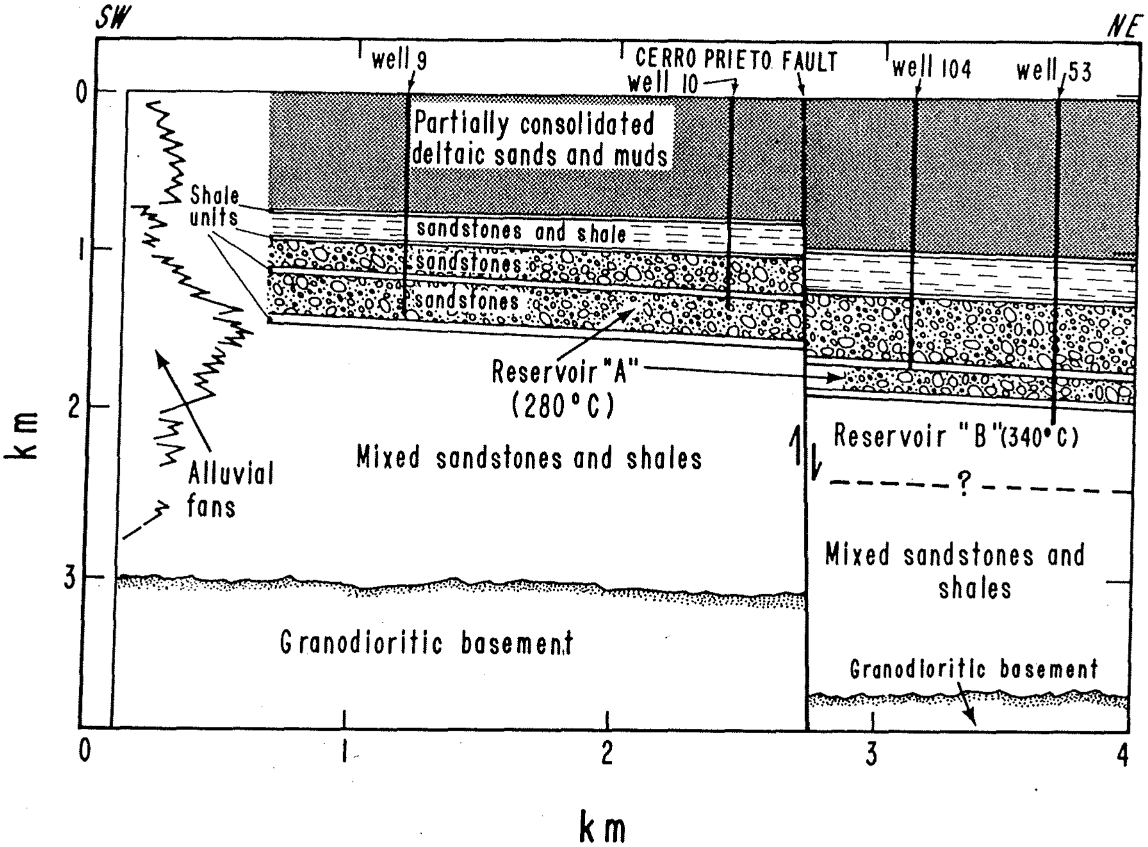

Figure 4: Simplified geologic section (E-E') across the earliest developed portion of the Cerro Prieto Geothermal field, Baja California, Mexico. Interpretation based on well logs and geophysical surveys.

The 65 wells drilled at the Cerro Prieto geothermal field and the geophysical interpretations provide details on both the role of fault intersections, and on the hybrid transform fault shift that is occurring today. Well No. 103 is very productive, hot, >350°C, and lies at the intersection of one of the NE-SW faults and the Cerro Prieto fault (Figure 3). There are at least 7 similar faults in the Cerro Prieto Field spaced 200 to 300 m apart with vertical displacements of 40 to 250 m. A simplified geologic section through the field (Figure 4) indicates 400 to 600 m of vertical offset across the Cerro Prieto fault. Mylonitized granodioritic basement was reached at 2547 m and 2722 m in two wells west of the main field and at 1478 m in one well to the southwest. Subsurface stratigraphy gives clues to the role of faulting. For example, well No. 757 drilled through a lithologic sequence, at a depth between 600 m and 934 m, that is not found in the main production field 3 km to the southeast. These units were: 85 m of siltstone, underlain by 95 m of 50% siltstone and 50% silty sandstone units 3 to 9 m thick, followed by 145 m of nearly pure sandstone. The upper siltstone was highly densified by mineral precipitation and the well bottom temperature in the sandstone was approximately 100°C. Such a sequence suggests a rapid infilling of an actively subsiding block.

The following figures are presented to emphasize the important role of faulting in the geothermal field. Figure 5 is a two-dimensional dipole-dipole resistivity model SW to NE along section E-E' of Figure 3 (Wilt, 1979). Note the more resistive block of 4.0 ohm-meters that corresponds to the main production zones. Also note the apparent boundary fault near well M-6 and the Cerro Prieto fault between wells M-10 and M-53. Figure 6 shows the temperature data for this section across the main production field measured from the wells. Note the plume-like movement up and away from the Cerro Prieto fault between wells M-10 and M-53 (Mercado, 1976). Finally Figure 7 illustrates the close relationship between high temperature, high resistivity and hydrothermal alteration along the same section (Elders, et al 1978).

Earlier ideas of pull-apart basins in the Salton Trough (see Elders and others, 1972; also Dibblee, 1977) can thus be refined. Fault blocks between the hybrid transform faults that occur en echelon appear to be 1 to 4 km on a side. Oblique inter-

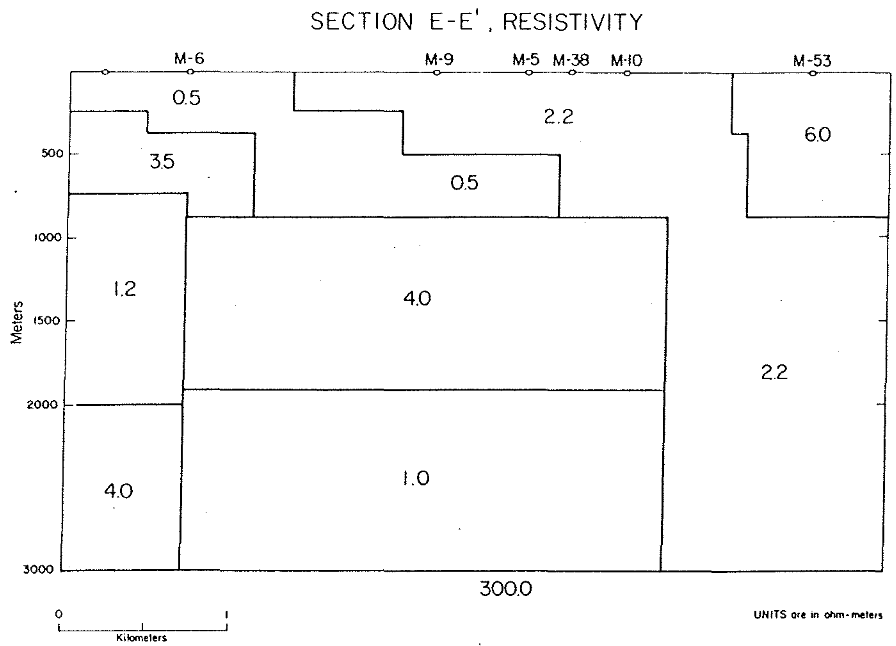

Figure 5: Two-dimensional dipole-dipole resistivity model, SW to NE along section E-E' across the Cerro Prieto geothermal field. (Data from Wilt, 1979).

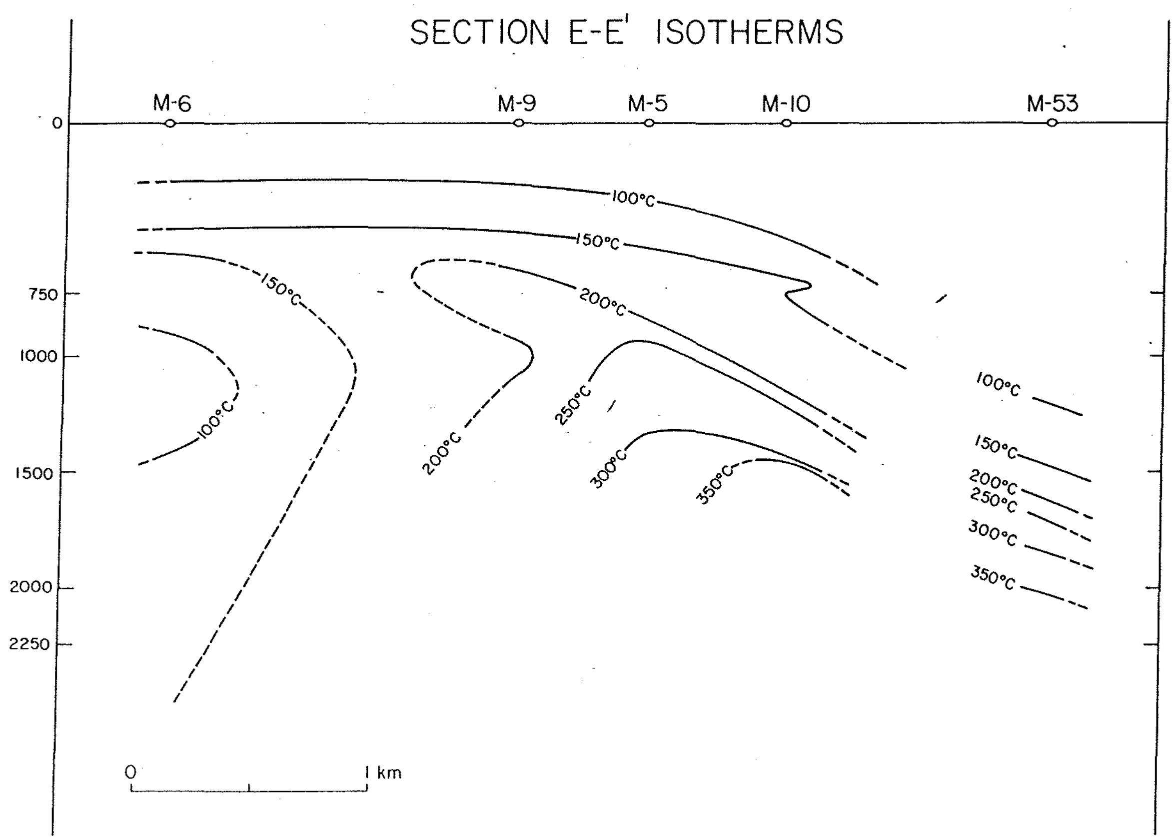

Figure 6: Isotherms across the section E-E' based on temperature logs from the wells. (Data from Mercado, 1976).

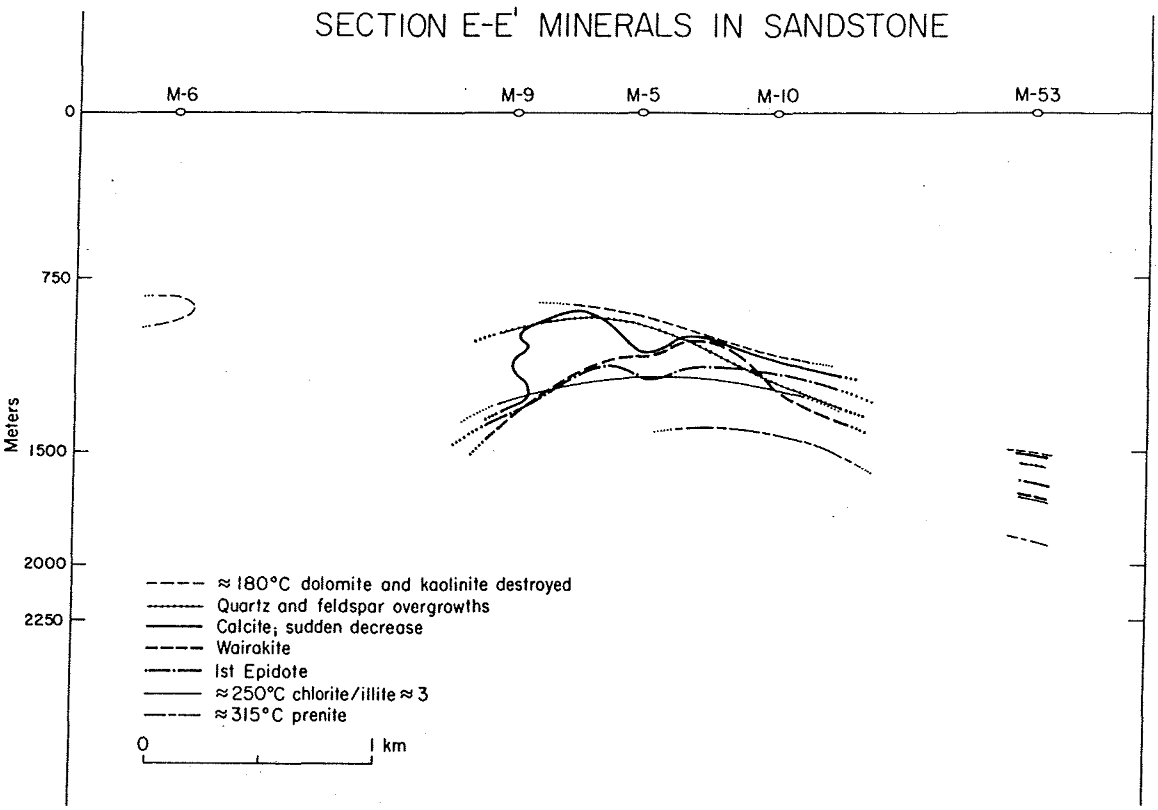

Figure 7: Hydrothermal mineralization along section E-E'. Compare with Figure 6. For prenite read prehnite. (Data from Elders et al, 1978).

section of major faults, such as the Imperial and Cerro Prieto, with fault shear zones may indicate sites for the most productive wells. However, these wells may be located in downthrown blocks with appropriately hot production zones 1 km or more deeper than in wells within a few hundred meters of the hybrid transform fault. Ongoing research and continued drilling between the Cerro Prieto and Imperial faults will clarify ideas presented herein. There are also suggestions of major fault intersections with shorter faults near geothermal areas at East Mesa, Desert Hot Springs, Coso and Roosevelt Hot Springs.

Acknowledgements

We would like to thank our many Mexican and United States colleagues who have worked with us. Special thanks to Margot Harding for creative drafting and Susan Miller for work coordination while under hot geothermal pressure. Funding was provided by Comisión Federal de Electricidad, Mexico, and the U.S. Department of Energy under Contract W-7045-ENG-48.

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SAN DIEGO GAS AND ELECTRIC COMPANY GEOTHERMAL ACTIVITIES

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Abstract

This paper discusses the role of geothermal resources in meeting SDG&E's electrical energy needs of the next decade. A brief historical overview of today's utility environment will highlight the importance of pursuing geothermal energy in an aggressive, prudent manner. Uncertainty, as an obstacle to early full-scale commercial development of geothermal resources in Imperial Valley, will be addressed, and a strategy to minimize potential economic consequences resulting from uncertainty will follow.

Introduction

San Diego Gas & Electric, like other electric utilities, is obligated to provide a reliable and economic supply of power to its customers. SDG&E's service territory extends from the Mexican border northward to include a small portion of Orange County, and eastward along the Riverside County line to points approximating the Imperial County line. The Company's total sources of firm electrical power include four fossil-fired steam plants, 19 combustion turbine units, one nuclear plant (20% share of San Onofre Unit No. 1), and contracts with other electric producers.

In order to meet our obligation of supplying power, we are pursuing all available energy resources. Given the environmental safety and fuel supply restrictions affecting the development of proven resources, it is essential to consider new and promising sources of energy such as geothermal.

The Role of Geothermal Energy

Geothermal resources are expected to help meet California's incremental electric energy needs in the next decade. The total actual amount of electric production from Known Geothermal Resource Areas (KGRA's) is still uncertain, but virtually all major California utilities are developing plans to construct commercial-sized plants or demonstration facilities through the 1980-1990 time frame.

Since 1960, the rate of population growth in SDG&E's service territory has been about three times the national average. This increase continues to have a dramatic effect on electric energy demand. Consistent with our optimistic conservation forecast, the peak demand requirement during the early 1980's is expected to be met with committed resources. In the mid-1980's, however, the peak demand requirement will begin to erode the reserve margins established for reliable electric supply. The deficit could be reduced in part by demonstration geothermal plants, planned for construction at the Heber, Niland and East Mesa reservoirs in the Imperial Valley.

Since May of 1976 SDG&E has been operating a test facility near Niland, California which is jointly funded by SDG&E and the U.S. Department of Energy. The objective of the Geothermal Loop Experimental Facility (GLEF) is to determine the technical and economic feasibility of generating power from the Salton Sea Known Geothermal Resource. Reservoir operations are supplied by Imperial Magma.

The Geothermal Loop Experimental Facility (GLEF) was originally designed based on information available in the early 1970's. The original process was based on transferring the geothermal heat from the brines to a clean working fluid which could be used to drive a turbine/generator (flash/binary cycle). The facility began operations in this mode (excluding the turbine) in mid-1976 and continued for approximately two years.

An evaluation of the two-year test data using the original cycle was performed. Data was not as expected in several key areas, which indicated that the original cycle selection may not have been optimum. Using this data, a feasibility and risk study identified the dual stage flash cycle as optimum with brine scale, corrosion and injection as major remaining risks. The facility was modified to evaluate the major remaining risks. Results to date indicate that effective techniques are available to resolve these areas.

We have signed letters of intent with Magma Electric and Republic Geothermal for purchasing power from proposed plants at Niland and East Mesa respectively. We are also investigating the possibility of constructing several of our own 50 MWe flash demonstration units. Cycle studies, economic evaluations and risk analyses are being conducted on both the Niland and Heber sites to provide a sound basis for our first demonstration plant. Consideration is also being given to a 50 MWe binary demonstration plant, but a schedule has not been established at this time. In addition to our generation plans, we intend to construct a 500 KV transmission line to Imperial Valley by 1983.

The Threat of Uncertainty

Vapor-dominated resources are generating power commercially in Northern California at the Geysers. However, liquid-dominated resources, such as those in the Imperial Valley, require further research and development. Before the commercial potential of these resources can be realized, the technical, environmental and institutional uncertainties must be identified and reduced.

The technical uncertainties of the liquid-dominated geothermal option are associated with the brine resource and its integration with the power plant. The primary uncertainties in the environmental area are the geologic questions of brine production and injection, the impact of airborne effluents and the source of water for power plant cooling and other uses. Institutional uncertainty stems from changing regulatory processes and other related activities.

Several demonstration plants are planned by various utilities and resource developers for operation in the early 1980's. These demonstration facilities are essential to assess the cost, to establish the reliability and, most of all, to minimize the overall risk of full-scale development.

Commercial Development Strategy

To provide support for its initial demonstration plants, SDG&E has formed an engineering organization under the heading of the "Expanded Geothermal Program." The primary purpose of this program is to help identify and reduce the uncertainties of liquid-dominated geothermal technology. Concurrently with SDG&E's expanded program activities, other institutions, resource companies, equipment manufacturers, and utilities are pursuing their own geothermal research and development activities. Many of these activities will continue to benefit our Company's expanded program directly as they have in the past. SDG&E is coordinating its geothermal programs with those of EPRI, DOE and others to ensure that the activities of these entities and SDG&E do not overlap.

Following is a discussion of SDG&E's current expanded program projects.

a. Cooling Water Rights Acquisition and Source Evaluation

The principal purpose of this project is to obtain long-term supplies of geothermal power plant cooling water. SDG&E is attempting to obtain rights from the State Water Resources Control Board. All of the potential Imperial Valley cooling water sources will be evaluated for quality, pretreatment requirements and availability.

b. Salton Sea Injection Project

Studies are being conducted to determine the economic and technical feasibility of injecting Salton Sea water into the Niland reservoir. This approach could have merit as a backup to using condensate or agricultural waste water, or as a vehicle for possible reduction of salinity in the Salton Sea. If the feasibility studies are promising, a full-scale testing program would be required to confirm the preliminary results.

c. Component Development

This part of the expanded program concentrates on further development of component designs critical to plant operability and efficiency. Through close cooperation with manufacturers of valves, pumps, controls, heat exchangers, etc., improved production designs are expected to emerge.

In March of this year, work began on a direct contact heat exchange unit to be installed and tested at the Niland Geothermal Loop Experimental Facility. If the tests are successful, capital equipment costs will be lowered and cycle efficiencies will be improved for future binary geothermal applications.

d. Solid Waste Disposal

The goal of this project is to expedite the development of a site in Imperial County to accommodate the wastes generated during geothermal development. SDG&E has been meeting with Imperial County representatives to reach agreement on a cooperative effort for establishing this disposal site.

e. Economic/Risk Assessment of Geothermal Development

SDG&E is continually reassessing the busbar cost of geothermal power production as additional information regarding power plant construction and operation becomes available.

As mentioned before, precise information about the cost of power from liquid-dominated geothermal power plants is uncertain, due to the lack of commercial-scale power plant operating experience with this type of resource. Demonstration plants are needed to remove this uncertainty regarding cost, which continues to impede large-scale development.

Work is under way at SDG&E to determine a probabilistic cost estimate of the busbar electricity from commercial-size geothermal power plants at Imperial Valley reservoirs. The cost information will be followed by a probabilistic risk analysis of large-scale geothermal development. The computer programming of a cost estimating methodology for geothermal busbar costs has been completed and the results of sensitivity studies indicate that plant capacity factor and fuel (brine) cost escalation rates have primary influence on the busbar cost of power.

f. Airborne Effluents Assessments

A bioenvironmental assessment program is being developed to study the potential impacts of cooling tower drift and noncondensible gases. Since agriculture forms the basis of Imperial County's economy, it is expected that commercial-scale geothermal development will not be allowed to affect this industry adversely. Thus, efforts must be made to evaluate potential consequences of geothermal development and to implement measures which will reduce agricultural impact.

In addition to the project already described, SDG&E's Expanded Geothermal Program includes cycle efficiency improvement analyses and cooling water reduction efforts. To date, SDG&E has devoted minimal attention to these projects, but anticipates greater involvement in the near future.

In summary, we are confident that our plans for commercial geothermal power plant development will be assisted by information derived from the proposed demonstration plants supported by our Expanded Geothermal Program projects. San Diego Gas & Electric recognizes the potential for meeting electrical demands through development of geothermal energy conversion technology. We are committed to provide a reliable and economic supply of power to our customers, and we believe that their needs can be satisfied in part by geothermal energy. Data obtained from demonstration plants in the mid 1980's will enable SDG&E to formulate plans for subsequent large-scale commercial development.

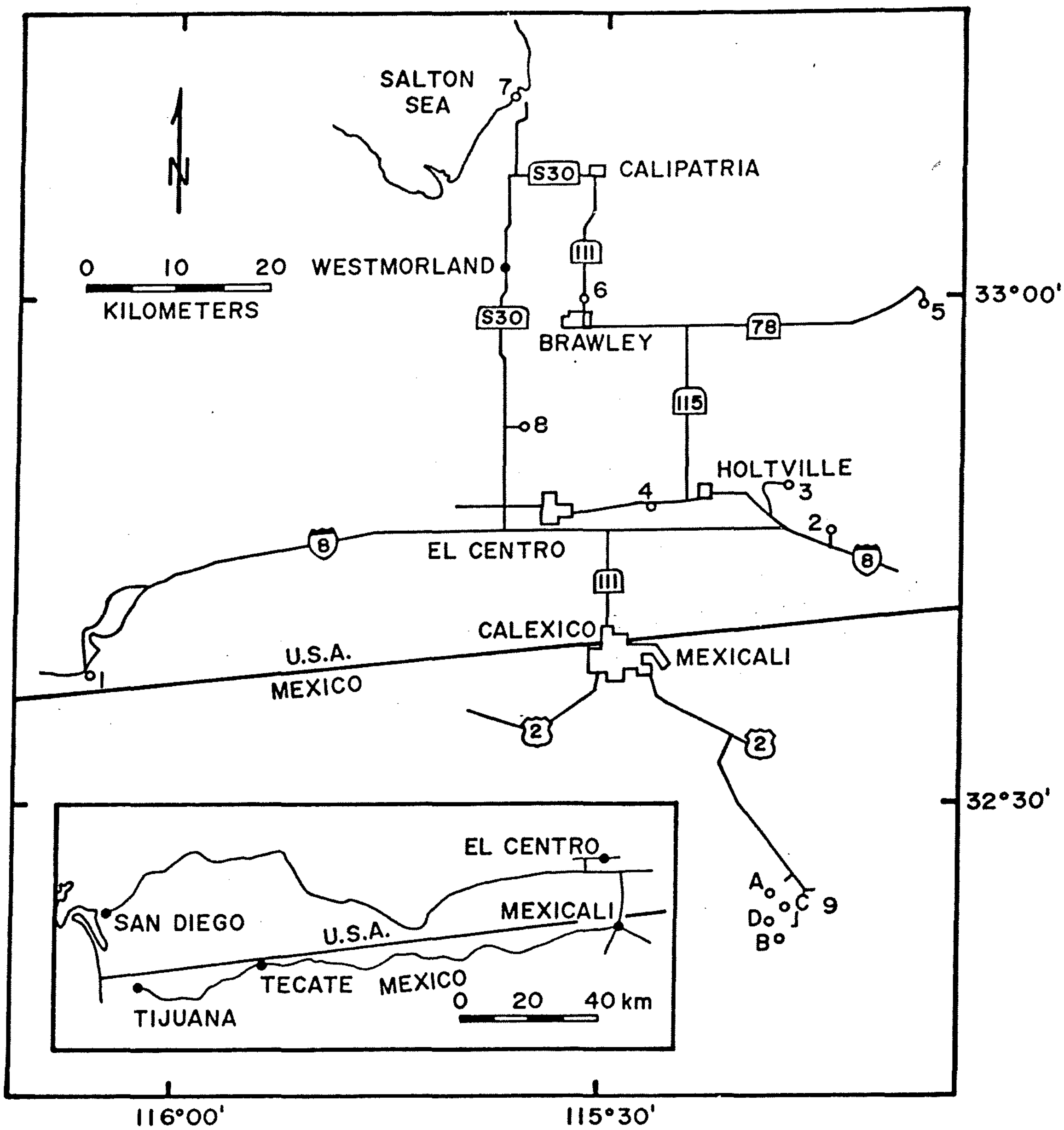
GEOLOGY AND GEOTHERMICS OF THE
SALTON TROUGH

Leaders: W. A. Elders and Shawn Biehler, University of California, Riverside, A. De La Pena, Comision Federal De Electricidad, Mexicali

Itinerary of the field trip November 3-4, 1979 (See Footnote)

Saturday by W. A. Elders

Time	Miles	Stop 0	
7:00AM	0		Depart, Town and Country Convention Center, San Diego, via Interstate 8. The route soon leaves the coastal plain and traverses the Peninsular Range. There are many fine exposures of the Southern California Batholith, with typical desert land forms.
8:45AM	74 mi	Stop 1	Desert View Overlook An opportunity to become oriented to the geography of the Salton Trough (See Elders, 1979, preface to this volume).
9:00		Depart	Descending to the valley we traverse West Mesa and on crossing West Side Main Canal we enter the intensely irrigated area and pass El Centro. The irrigated area is left behind at the Highline Canal as we reach East Mesa. Presumably the valley floor, before being so highly modified by farming, resembled West and East Mesas.
10:15AM	58 mi	Stop 2	East Mesa. Imperial Magma Co., and Magma Electric Co. Facilities. Leaving the freeway at Van de Linden Road, we reach the first operational geothermal power plant in the Imperial Valley (see Hinrichs, 1979, this volume). Other activities on East Mesa include the Department of Energy, Geothermal Test Facility, operated by Westec, Inc. and the developments of Republic Geothermal, Inc. further north (see Smith, 1979, this volume). A dual-flash 50 MW power plant is to be constructed by 1982 by Republic Geothermal, Inc.
11:00AM		Depart	We return to the irrigated area and follow Highline Road north to reach the northern end of the geothermal field.
11:15AM	10 mi	Stop 3	Holtville Drag Strip. Here on the abandoned runways of a World War II military airfield we can observe plate tectonics in action. The concrete slabs of the runways are being deformed, exhibiting spreading, transform faulting and subduction (and obduction). Babcock (Geol. Soc. Amer. Bull. Vol. 82, p. 3189-3196, 1971) decided this was due to faulting on what he proposed to call the "Holtville Fault". We think that thermal expansion and contraction of concrete may be a better explanation.
11:45AM	10 mi	Stop 4	Imperial Valley Country Club. Buffet Lunch.
1:00PM		Depart	We go north on Highway 115. Note the two levels of drains for irrigation. The higher level brings in water from the Colorado River. The lower level carries the effluent to the Salton Sea. We leave the irrigated area on highway 78, going east across the Highline and Coachella Canals.
1:40PM	29 mi	Stop 5	Osborn County Park, Sand Dunes. The sand hills which have been called the Algodones dunes form a belt which is 75 km long in northwesterly direction and 5-10 km wide. Some of the individual dunes are 60-90 m. high. The northwest trending front of the dunes and its sharpness has lead to the inference that the dune formation is fault controlled. From the top of the dunes the entire Imperial Valley can be observed. (Sharp, 1979, Bull. Geol. Soc. America, Vol. 90, No 10, pp 908-916).

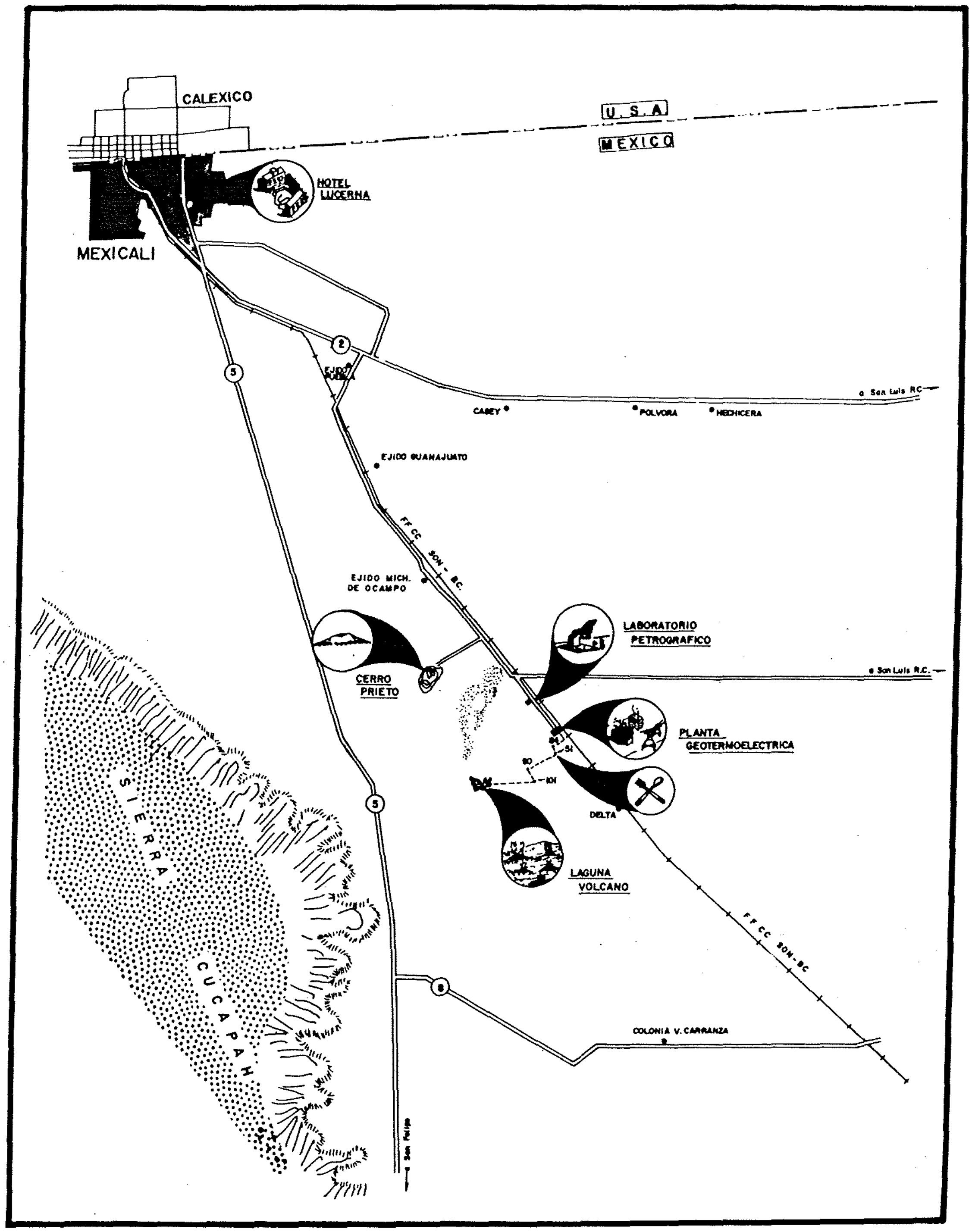


Route of the field trip November 3rd and 4th, 1979.

Time	Miles	Stop	
2:00PM		Depart	Returning to the agricultural portion of the Imperial Valley, the route leads west to Brawley and then north on Highway 111.
2:30PM	26 mi	Stop 6	Union Oil Co. Operation at Brawley. Union Oil Company has been developing their leases on 1,500 hectares near Brawley since 1975. More than a dozen deep wells now penetrate the reservoir which contains brines of 100,000 mg/L and temperatures of 295°C. Southern California Edison Co. is building a 10 MW plant, at a cost of $16 million, to be operational in 1980.
2:55PM		Depart	North across the New River, to Calipatria where we turn west and then north again to the Salton Sea geothermal field.
3:25PM	22 mi	Stop 7	Red Hill Volcano. This is one of the five small rhyolite domes in the Salton Sea Geothermal Field. For a discussion of the petrology and chemistry of the volcanoes see Elders, 1979 (this volume). Similarly hydrothermal alteration in the reservoir is discussed by McDowell and Elders, 1979 (this volume). Its structural setting is described by Meidav and Howard, 1979 (this volume). The Salton Sea Geothermal Field is the largest and hottest of the geothermal fields in the Salton Trough and has the longest history of development. Although the resource is large and temperatures exceed 365°C, technical problems associated with treating brines of salinity 280,000 mg/L T.D.S. have hindered development. San Diego Gas and Electric Co., together with the Department of Energy, have been operating a Geothermal Loop Experimental Facility since June 1976 (See Wagenen, 1979, this volume) in an effort to resolve these problems. Similar attempts are being made by Lawrence Livermore Laboratory (Locks, Owen and Quong, 1979, this volume) and the U.S. Bureau of Mines has a facility testing mineral recovery from the brines. Southern California Edison and Union Oil Co. are planning a 10 MW plant to go into operation in 1982. Recent developments suggest that the field extends southwest towards Westmoreland. Republic Geothermal Inc., in partnership with MAPCO-Geothermal Inc., plan to drill 19 wells there to supply a 55 MW plant of Southern Calidornia Edison. This project would cost $40 million and has received a $29 million loan guarantee from the Department of Energy.
4:00PM		Depart	We return south to Westmoreland and follow Forester Road towards El Centro.
4:35PM	26 mi	Stop 8	Superstition Hills Fault-New River. The New River gorge was formed in a period of less than two years (1906-1907) when the Colorado River flooded (see Elders, preface to this volume). In June of 1906 the entire Colorado River was emptying into the Salton trough. The channel to the Gulf had become completely dry. The presence of the Superstition Hills fault has been exposed in this location because of the erosion of the New River. Here up-turned beds of Quaternary and Pleistocene deposits form an angular unconformity with recent lake and alluvium deposits. This area indicates some of the complexities of structure which underlie the apparent flat valley floor, and make the interpretation of geophysical and geological data very difficult.
4:55PM		Depart	Our route joins Interstate 8 again and then turns south on highway 111 to the border city of El Centro. Immediately west of Highway 111 is the Heber Geothermal Field being developed by Chevron Resources Co. (see Salverson, 1979, this volume). Together with Southern California Edison they are developing plans for a 50 MW unit scheduled for completion in mid-1982.
5:30PM	22 mi		Calexico. Border crossing to Mexicali.
6:00PM	3 mi		Hotel Lucerna, Mexicali.

Time	Miles	Stop	
Sunday	by Ing. A. De la Pena and W. A. Elders		
8:00AM		Stop 0	Depart Hotel Lucerna. Mexican Highway 2, through Ejido Puebla to microwave tower on Cerro Prieto.
8:40AM	22 mi	Stop 9A	The volcano Cerro Prieto, 30 km south of Mexicali rises 260m above the valley floor. It is a typical calc-alkaline rhyodorite (see Elders, 1979, this volume). From it we can obtain a general view of the Cerro Prieto Geothermal Field and Laguna Volcano.
9:40AM			Depart. We return to the highway and pass the Cerro Prieto Geothermal Power Plant. The geology of the field is described in De la Pena and Cruz, 1979 (this volume) and Vonder Haar and Cruz, 1979 (this volume). Aspects of the hydrothermal alteration are treated in Elders, et al, 1979 (this volume). The first shallow wells were drilled in 1959 and 1961 and the first deep wells in 1964. Drilling of production wells began in 1966 and the first stage of the plant began generating 75 MWe in 1973. The second stage which doubled the capacity went on line in April 1979. In 1976 a major program of exploration and development began. Currently some 30 wells supply the plant which uses 1500 metric tons of steam per hour. A 30 MW low pressure turbine is under construction. The ultimate capacity may reach 400 MWe.
10:00AM		Stop 9B	Laguna Volcano. This large area of hot springs, geysers, mudpots, funaroles, mofette, and cold springs first drew attention to the geothermal potential of Cerro Prieto. As production from the field continues, these manifestations are declining. Their chemistry is complex and reflects water/rock interaction, boiling, condensation, dilution by rain, and evaporation.
10:40AM		Stop 9C	Visit to the steam field and to a drilling rig.
11:20-11:50AM		Stop 9D	Visit to the Geothermal Electric Plant.
11:50-12:30AM		Stop 9E	Visit to the Geological Laboratories.
12:30-2:00PM		Stop 9F	A typical Mexican meal served in the open air at well M-51.
2:00PM			Depart for Mexicali. From here we take Mexican Highway 2 west across the Peninsular Range to Tijuana. The route again crosses the batholith.
2:40PM	0 mi		Mexicali.
3:45PM	45 mi		La Rumorosa.
4:40PM	85 mi		Tecate (population 13,500) well known for its brewery.
5:30PM	34 mi		Tijuana. Transfer to buses to return to San Diego.
6:15PM	16 mi		Arrive at Convention Center.

This itinerary will be changed in the light of the October 15, 1979, earthquake of magnitude 6.4 on the Imperial Fault.



Route of the field trip to Cerro Prieto, November 4, 1979.

ERRATA

Geology and Geothermics of the Salton Trough

Page iv: left hand column, second line from bottom: for "Mighigan" read "Michigan"

Page 9: right hand column, fourth line from bottom: for "Riviera" read "Rivera"

Page 11: left hand column, line 14: for "Figure 7B" read "Figure 6B"

right hand column, fourth line of second paragraph: for "busidence" read "subsidence"

Page 13: left hand column, fourth line from bottom: for "In contrast is..." read "In contrast to..."

Page 15: left hand column, third line, second paragraph: for "see Figure of Vonder Haar..." read "see Figure 2 of Vonder Haar..."

right hand column, line 12: for "a maximum of 22 km in the south" read "as little as 10 km in the Gulf."

third paragraph, replace sentence beginning "This implies a half spreading rate..." with "This implies a total spreading rate of about 5 cm/year (V in Figure 6). This would require between only 200,000 to 300,000 years to form the gap."

Page 15: Third paragraph, line 16: for "half" read "total"

Page 16: The second to last sentence should read "If aseismic slip has proceeded at 4 cm/year..."

Page 17: left hand column, line 10: before the word "spreading" insert "half"

Page 18: Reference to Minster *et al*., the last two author's names are "Molnar" and "Haines"

Reference to Olmstead *et al*., the last author's name is "Ireland"

Reference to Rex *et al*., Meidav's initial is "T"

Page 19: The date of Wilson and Wood's paper is "1979"

Page 14: left hand column, line 4: for "well sand" read "wells and"

Page 107: line 6: for "rhyodorite" read "rhyodacite"

Stop 9B, second line: for "funaroles" read "fumaroles"

Geothermal Fields of the Salton Trough. S-Salton Sea, W-Westmoreland, B-Brawley, H-Heber, G-Glamis, E-East Mesa, D-Dunes, BO-Border, T-Tulecheck, C-Cerro Prieto, P-Panga de Abajo, MA-Mesa de Andrade, and MS-Mesa de San Luis.

Skylab Imagery courtesy NASA