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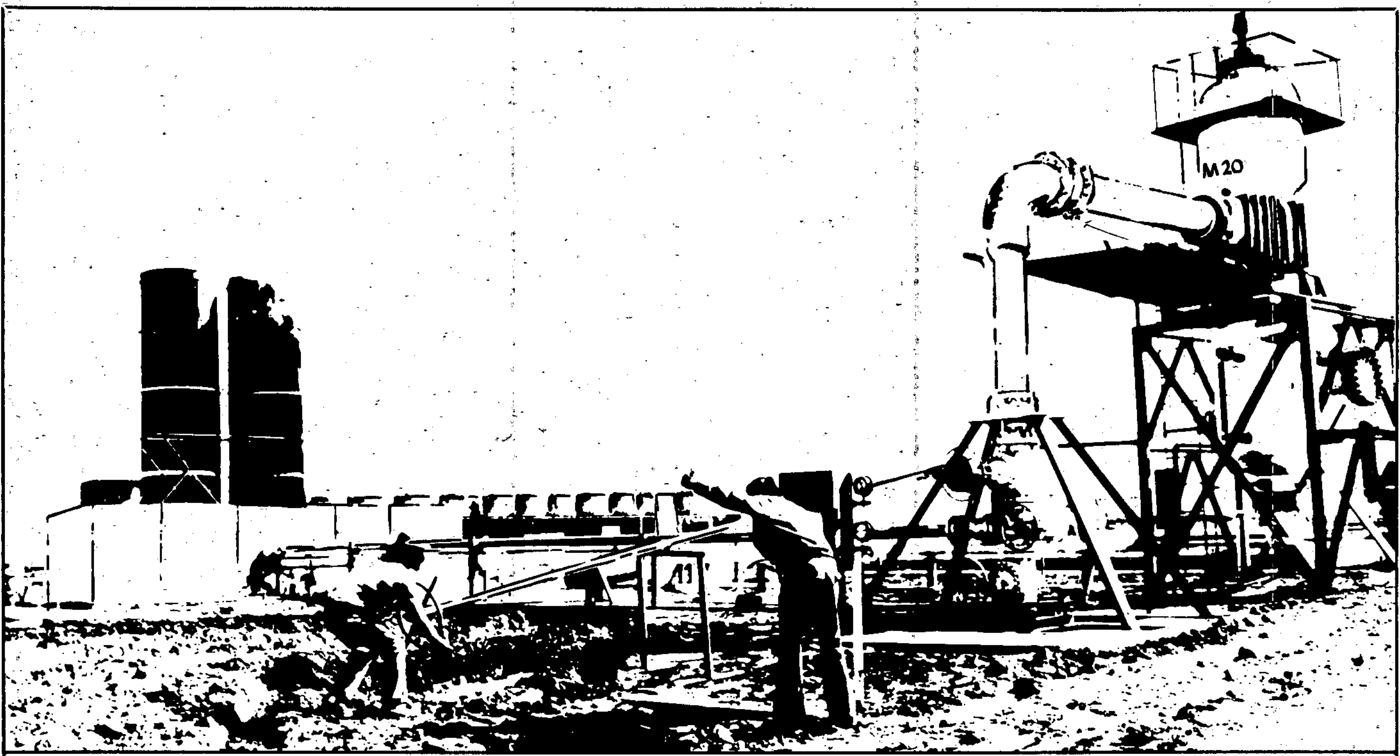

INTERSECTING FAULTS AND SANDSTONE STRATIGRAPHY AT THE CERRO PRIETO GEOTHERMAL FIELD

Stephen Vonder Haar and J. H. Howard

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ABSTRACT

The northwest-southeast trending Cerro Prieto fault is part of a major regional lineament that extends into Sonora and has characteristics of both a wrench fault and an oceanic transform fault. It apparently penetrates deep into the basement and crustal rocks in the area and serves as a conduit for both large and rapid heat flow. Near well M-103, where the Michoacán fault zone obliquely intersects a shorter northeast-southwest trending fault, large circulation losses during drilling indicate greater permeability and hence increased natural convective fluid flow. In the southern portion of the field, there is a shear fault zone in the vicinity of wells M-48, M-91, and M-101. Temperature contour maps suggest that this shear zone aids in rapidly distributing geothermal fluid away from the Cerro Prieto fault zone, thus enhancing recharge.

We have studied the distribution of lithologies and temperature within the field by comparing data from well cuttings, cores, well logs, and geochemical analyses. Across the earliest developed portion of the field, in particular along a 1.25-km northeast-southwest section from well M-9 to M-10, interesting correlations emerge that indicate a relationship among lithology, microfracturing, and temperature distribution. In the upper portion of Reservoir A of this stratigraphic section, between 1200 and 1400 m, the percentage of sandstones ranges from 20 to 55. Temperatures are 225° to 275°C based on well logs, calcite isotope maxima, and Na-K-Ca indices. Our study shows that an isothermal high in this vicinity corresponds to the lowest total percentage of sandstones. Scanning electron microphotographs of well cores and cuttings from sandstone and shale units reveal clogging, mineral dissolution, and mineral precipitation along microfractures. Our working hypothesis is that these sandy shale and siltstone facies are most amenable to increased microfracturing and, in turn, such microfracturing allows for higher temperature fluid to rise to shallower depths in the reservoir.

Ongoing research is aimed at achieving a coherent geological model that illustrates reservoir capacity, and at understanding fluid flow along major faults, lateral distribution through fault shear zones, and variable movement within deltaic clastics that have in part been microfractured.

INTRODUCTION

Geological evolution of the Cerro Prieto region (Fig. 1) has been a complex blend of rifting, rapid deltaic sedimentation, and large-scale strike-slip faulting. To understand geothermal fields in this region, it is important to be familiar with the fault intersections and with the effects of tectonism and water-rock interactions on initial sandstone porosity and permeability. In this paper, we first explore analogs for the pattern of faulting at Cerro Prieto and then focus on secondary porosity and permeability in the producing horizons.

SALTON TROUGH FAULTING

In Figure 2, a detailed compilation of faulting illustrates a number of fault intersections. These data were compiled from more than 100 published and unpublished articles with many of the specific key references shown in Figure 3. The Salton Sea area has a distinct northeast-southwest series of faults, each approximately

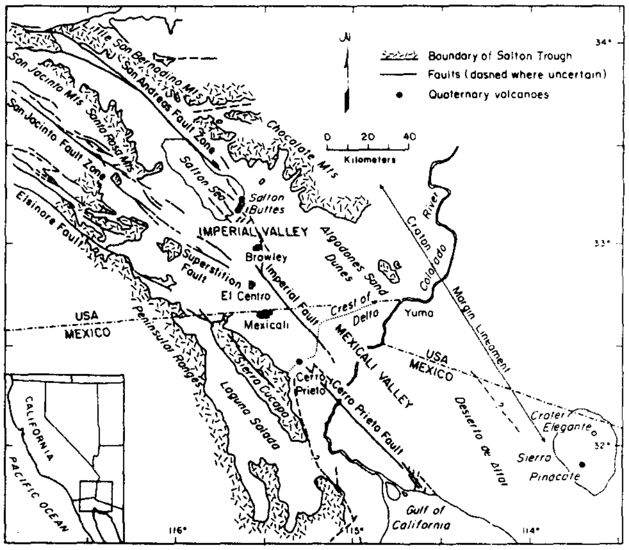

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Figure 1. Location map of the regional geology of the Cerro Prieto geothermal field.

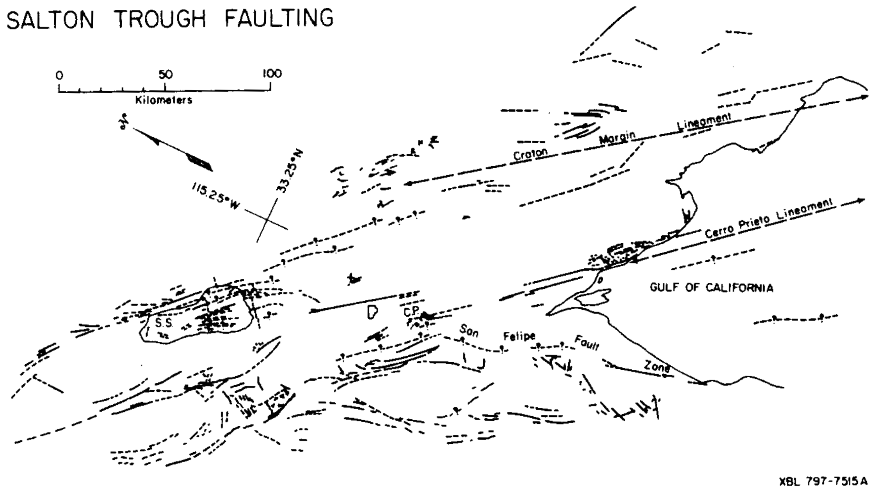

Figure 2. Salton Trough faults indicating zone of cross faulting and the major northwest-southeast hybrid transform faults.

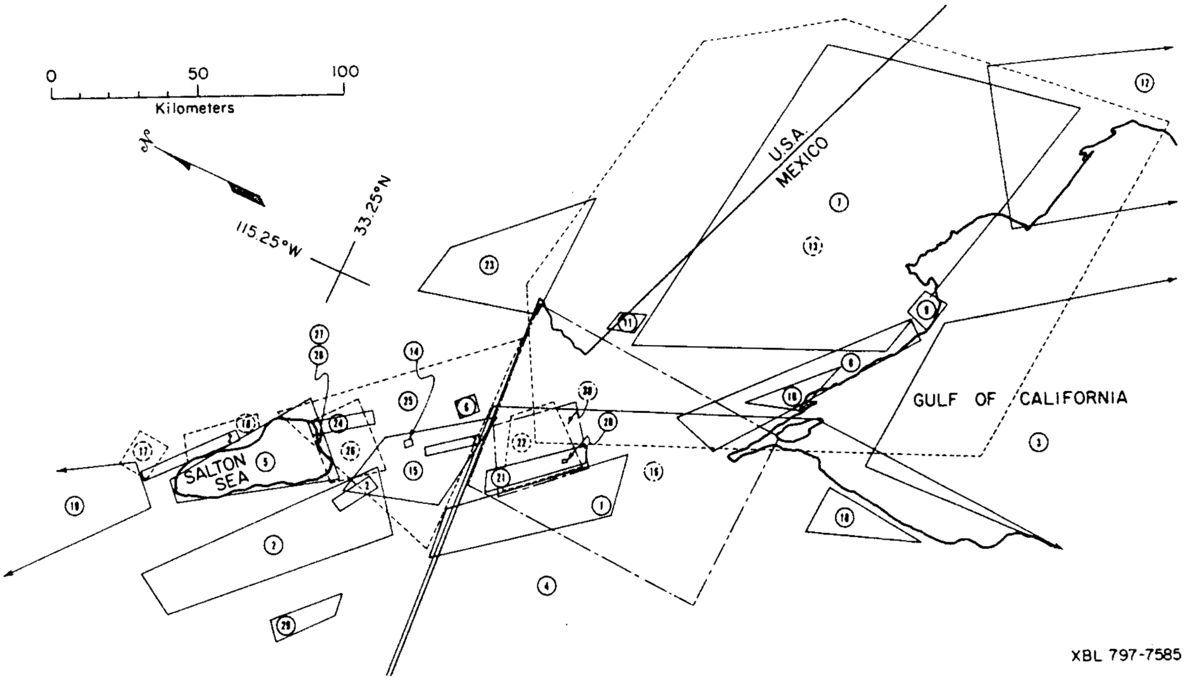

Figure 3. Key reference map to articles on Salton Trough faulting. KEY: (1) Barnard, 1968; (2) USGS, 1972; (3) Henyey and Bischoff, 1973; (4) Gastil et al., 1975; (5) Meidav and Rex, 1970; (6) Howard et al., 1979; (7) Donnelly, 1974; (8) Ortlieb, 1978; (9) Vonder Haar and Gorsline, 1977; (10) Vonder Haar and Gorsline, 1975; (11) Puente C. and Vonder Haar, 1980; (12) Gastil and Grummenscher, 1977; (13) Sumner, 1972; (14) Sharp, 1976; Johnson and Hadley, 1976; (15) Goulty and Golman, 1978; (16) De la Fuente and Sumner, 1974; (17) Sylvester and Smith, 1976; (18) Babcock, 1974; (19) Proctor, 1968; (20) Noble et al., 1977; Razo, 1976; Alonso, 1966; Reed, 1976; Mercado, 1976; Vonder Haar and Puente C., 1979; Prian C., 1979; Corwin et al., 1978; and Alonso E. et al., 1979; (21) Puente C., and de la Peña L., 1979; (22) Soto-P., 1975; (23) Crowe, 1978; (24) Kasameyer, 1976; Kasameyer et al., 1978; (25) Lofgren, 1979; (26) Meidav et al., 1976; (27) Twehey, 1977; (28) Chan and Tewhey, 1977; (29) Todd and Hoggatt, 1976; (30) Albores et al., 1979.

3 km long between the Banning/Mission Creek strike-slip fault (part of the San Andreas system) and the northern end of the Brawley/Imperial strike-slip fault (Fig. 4; also Meidav and Howard, 1979).

Similar northeast-southwest trending across faults at the Cerro Prieto field (Fig. 5) have been confirmed by recent studies (Vonder Haar and Puente C., 1979; Puente C. and de la Peña L., 1979). The northwest-southeast trending Cerro Prieto fault and a parallel fault segment, the Michoacán fault, are part of a major regional lineament that reaches into Sonora (Gastil and Krummenacher, 1977) and has characteristics of both a wrench fault zone and an oceanic transform fault (see Vonder Haar and Puente C., 1979). This major regional lineament is believed to penetrate deep into the crustal and basement rocks, which range from 7 km thick in the northern Gulf of California (Phillips, 1964) to as great as 20 km at the Mexican/United States international boundary (Biehler et al., 1964). This style of faulting, namely a deep penetrating regional fault with down-dropped blocks at fault intersections is important in connection with the occurrence of geothermal resources because they apparently serve as conduits for high heat flow. The oblique intersection of the Pátzcuaro fault zone and the Michoacán fault zone are associated with wells having greater permeability and are thus areas presumed to have increased natural convection. The prolific production of well M-103, large amounts of lost circulation, and the surface manifestations of the Laguna Volcano area southwest of well M-101, support this conclusion. (See the articles by De Boer, 1980; also Valette and Esquer P., 1979, for magnetic and geochemical data related to these fault intersections.)

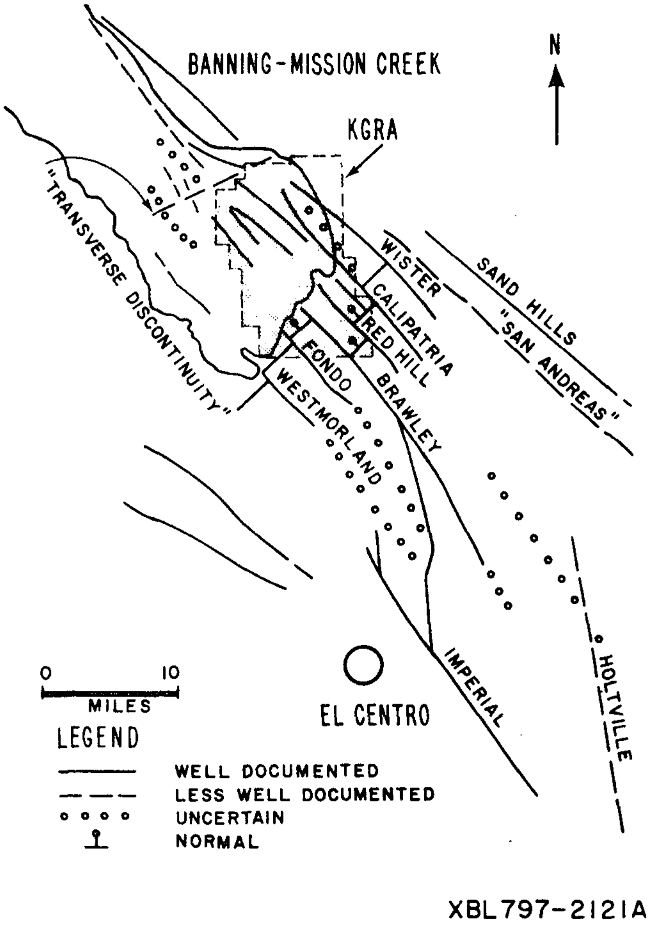

Figure 4. Structural map of the Salton Sea region based on combined geophysical data.

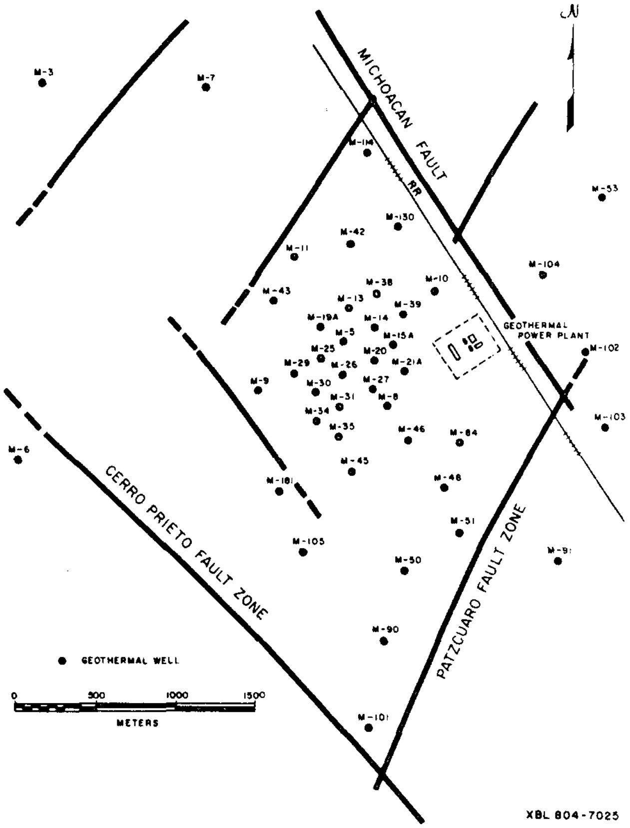

Figure 5. Faults in the vicinity of the Cerro Prieto field showing cross-faults and the very productive well M-103.

Another facet of fault intersections is their role in aiding distribution of the geothermal fluids away from a deep penetrating fault such as the Cerro Prieto fault. Such a fault is believed to be a linear or perhaps even a discreet point source at a given moment in geologic time (see Delaney and Pollard, 1980). Such a single controlling fault should lead to a field that clusters within a few hundred meters of it. However, increased permeability, recharge capacity, and storativity that result from these fault shear zones create geothermal fields on the order of 2 to 10 km widths.

A third area of cross-faulting is (Fig. 2) approximately 100 km southeast of Cerro Prieto, where the Cerro Prieto Lineament enters the Gulf of California. These faults have been confirmed by field studies (Ortlieb, 1978). Although there is an en echelon style to the Cerro Prieto fault zone in this area, flooding frequency and duration data (Vonder Haar and Gorsline, 1979) indicate that saline surface waters would hamper ground-level geophysical surveys and drilling of shallow wells for heat flux data. Presumably a geothermal resource is present at depth.

Still another facet of faulting in the Salton Trough may pertain to the origin of Cerro Prieto volcano and the adjacent geothermal field. Both may be the result of yet another fault intersection, namely the meeting of the basin bounding San Felipe fault zone (Fig. 2) with the Cerro Prieto Lineament.

There are other indications of fault intersection in the Salton Trough/Upper Gulf of California area. Magnetic data suggest reactivation of earlier rifting faults (see de Boer, 1980) and regional gravity data indicate that the Gila Lineament extends into the Salton Trough from Arizona to near the Imperial fault's southernmost end.

TECTONIC ANALOGS TO CERRO PRIETO

The Dead Sea rift zone, oil-producing basins in southern California, and the Afar region in Africa, among others, provide stimulating comparisons to the Cerro Prieto region. However, perhaps the most useful models for faulting for Salton Trough geothermal fields come from the detailed observations by deep diving submersibles along transform faults and hydrothermal centers in the FAMOUS area of the mid-Atlantic ridge and in the Gulf of California.

Underwater exploration of transform fault "A" in the FAMOUS area is summarized in a three-dimensional block diagram (Fig. 6), on a scale appropriate to the Cerro Prieto field. As shown further in Figure 7, cross-faults and normal faults extend for up to 5 km on both sides of the present zone of active transform movement, which was located in a 200-m-wide central zone. Hydrothermal activity (Fig. 8) was noted in this zone, as were numerous step faults with as much as 250 m of cumulative displacement.

Drilling at the mouth of the Gulf of California by the Deep Sea Drilling Project (DSDP) (Geotimes, July 1979) resulted in a hypothesis about the opening of the Gulf that bears on interpretation of the structural geology in the vicinity of the Cerro Prieto field. The sequence began approximately 20 m.y. ago with weathered granite and alluvial outwash gravels. Perhaps by the late Miocene (5 to 10 m.y. ago) a rifting stage took place with listric faults (concave upward with a decrease dip angle at depth) in the basement. Around 4.5 m.y. ago, subsidence was active and the opening of the gulf began, with a transform-fault-related opening of the present gulf around 3.5 m.y. (see also Terres and Crowell, 1979). To date, geophysical studies near Cerro Prieto have not revealed listric faults in the basement. However, rotational faults related to early rifting may be

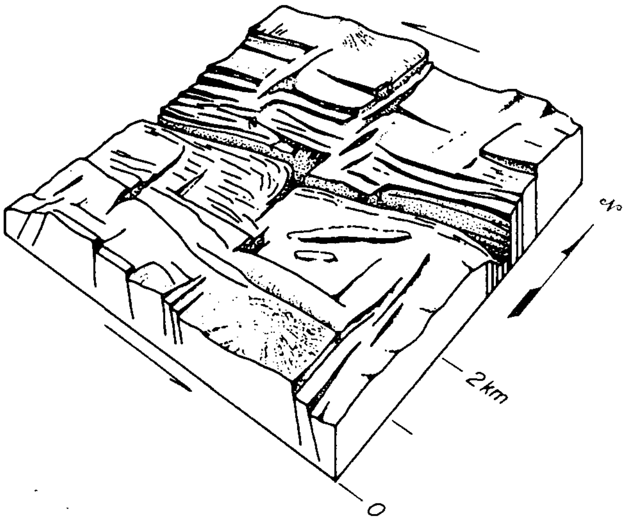

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Figure 6. Interpretive block diagram of a portion of the oceanic transform fault "A" in the FAMOUS area of the Mid-Atlantic Ridge (after Choukroune et al., 1978). The intersecting faults and 200-m-wide active zone of strike-slip movement within a 4-km-wide trough suggest the possible complexity of faulting along the Cerro Prieto fault and within the production field.

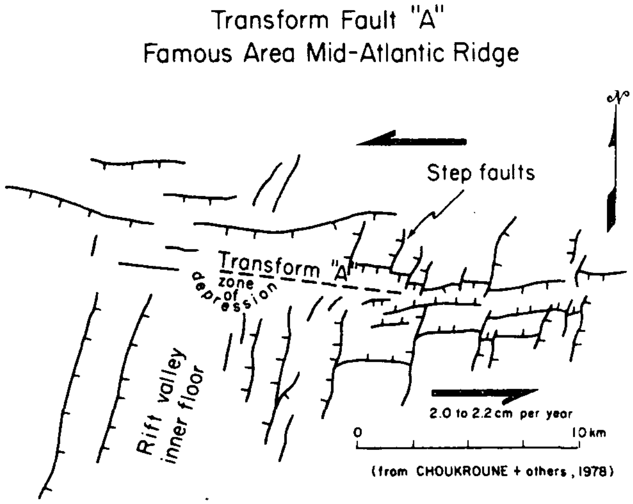

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Figure 7. Diagram illustrating the complex faulting near an oceanic transform fault; a possible analog to Salton Trough faults.

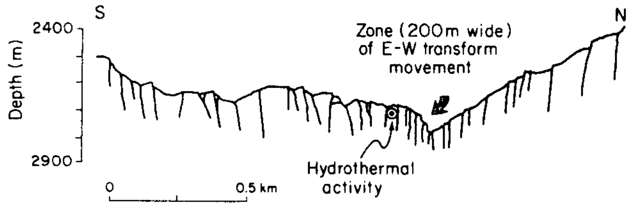

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Figure 8. Section across the oceanic transform fault "A" based on deep-submersible dives showing active fulating within a wider fault zone.

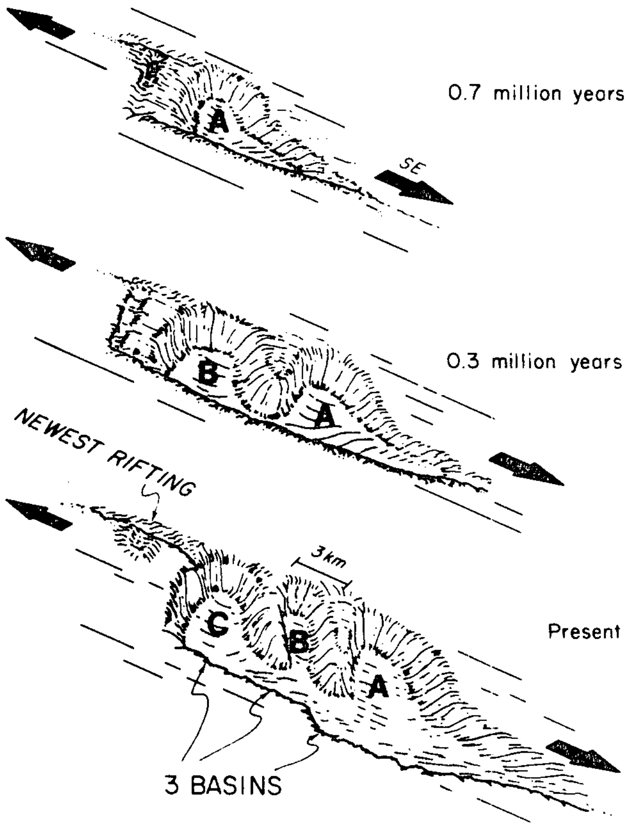
confined to areas 50 km or more west and southwest of the geothermal field (see Gastil et al., 1979; Dokka and Merriam, 1979). It is important for a geological model of Cerro Prieto to include older basement faults that may couple with more recent strike-slip generated faults. Such coupling would increase the potential fluid flow network along fractures thus extending the area of maximum energy available for production.

Submersible studies in the Guaymas Basin in the central Gulf of California (Lonsdale and Lawvor, 1980) are also interesting when considering the geology of the Cerro Prieto field. They show a transform fault that has a shear zone approximately 1 km wide. Cross-faults cover an area 1 to 2 km wide, and the seabed has hydrothermal minerals, which oxygen isotopes indicate precipitated between 220° and 240°C.

Earlier investigations in the Gulf of California by Sharman (1976) provide yet another important possible model (Fig. 9) for the zone between the Imperial and Cerro Prieto faults. As drilling progresses at Cerro Prieto reservoir modelers should consider that multiple basins separated by upraised blocks were formed sequentially. Perhaps such an arrangement of basins represents episodic shifts of the heat source on a scale of 5 to 20 km.

Another aspect of faulting related to spreading centers is indicated in Figure 10. The intersection angle between main fault and cross fault need not be 90°. Thus the geometry of the basins east of the present Cerro Prieto field can have margins as much as ±20° from normal or parallel to the major regional fault.

Figure 11 represents one of many possible modes of evolution of oceanic transform faults and spreading centers. These "cartoons" are intriguing for they suggest patterns that may fit regional geophysics data. For example, the Tule Check geothermal area 15 km northwest of Cerro Prieto could be an abandoned fracture zone, as seen in Figure 11 (D) with a remnant heat anomaly that is now cut off from the main Cerro Prieto and Imperial pull-apart system.



after SHARMAN ,1976

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Figure 9. Interpretation of the evolution of the Carmen Basin in the Gulf of California; a possible analog to pull-apart basins in the Salton Trough. Note the assymetry and multiple-basin formation between two transform faults.

EARTHQUAKE DATA

A map of epicenters and magnitudes for the Salton Trough (Fig. 12) indicates a high degree of tectonic activity. A story is shown by a regional plot of microseismic events (Fig. 13). Our interpretation of these events, most of 1 to 3 Richter magnitude, is that they are predominantly a series of northeast-southwest cross-faults that link the Imperial and San Andreas faults. Over 800 events are plotted in Figure 14 with major concentrations at 4 to 6 km depth. The error on these depths could be as much as ±2 km, (G. Fuis, 1978, personal communication; see also Fuis et al., 1977a,b,c, 1978a,b,c).

The fact that depths of occurrence are shallow is important evidence of repeated activity that maintains fracturing and allows fluid flow through fractures at geothermal production depths in the

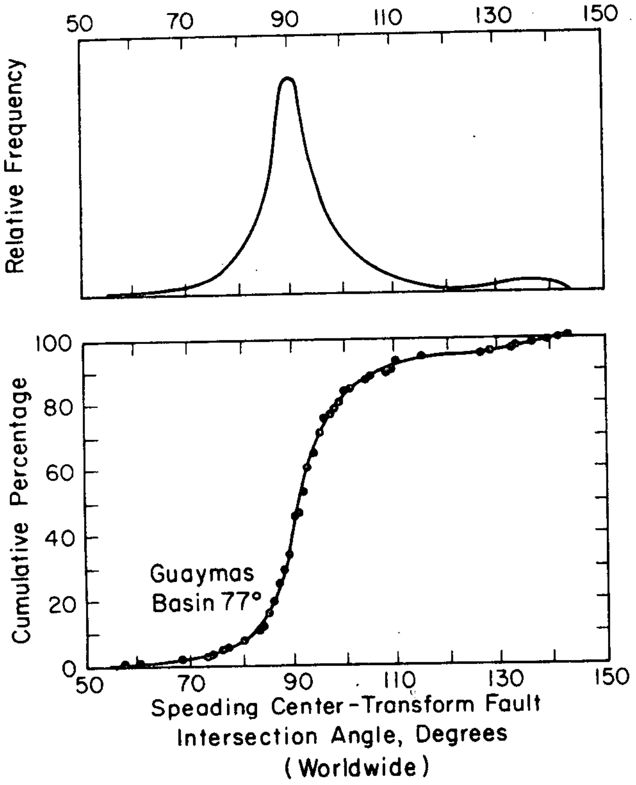

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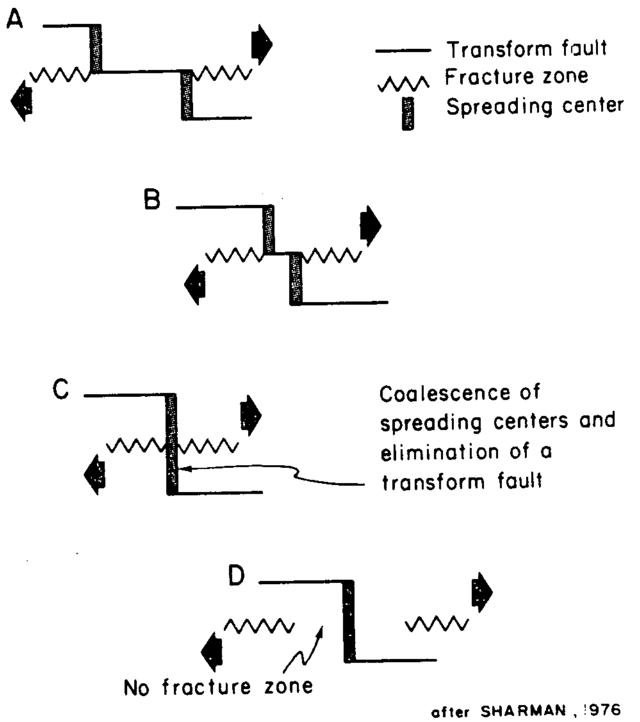
Figure 10. Confirmation of the concept that transform type faults need not be at 90° to spreading centers (after Sharman, 1976).



after SHARMAN, 1976

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Figure 11. A cartoon of the possible evolution of the San Andreas, Imperial, and Cerro Prieto faults illustrating where fracture zones should exist if these faults are pure transform types.

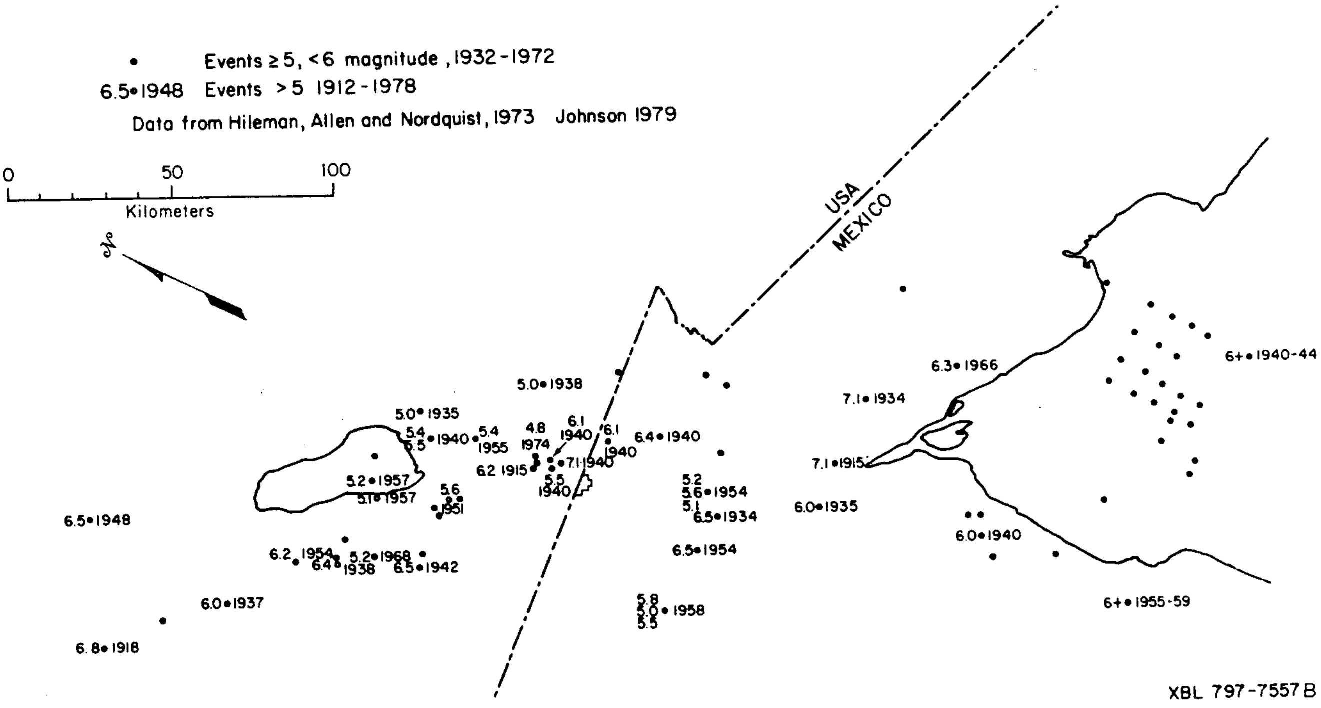

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Figure 12. Earthquake epicenters and recorded magnitudes in the Salton Trough for events of Richter magnitude ≥ 5.

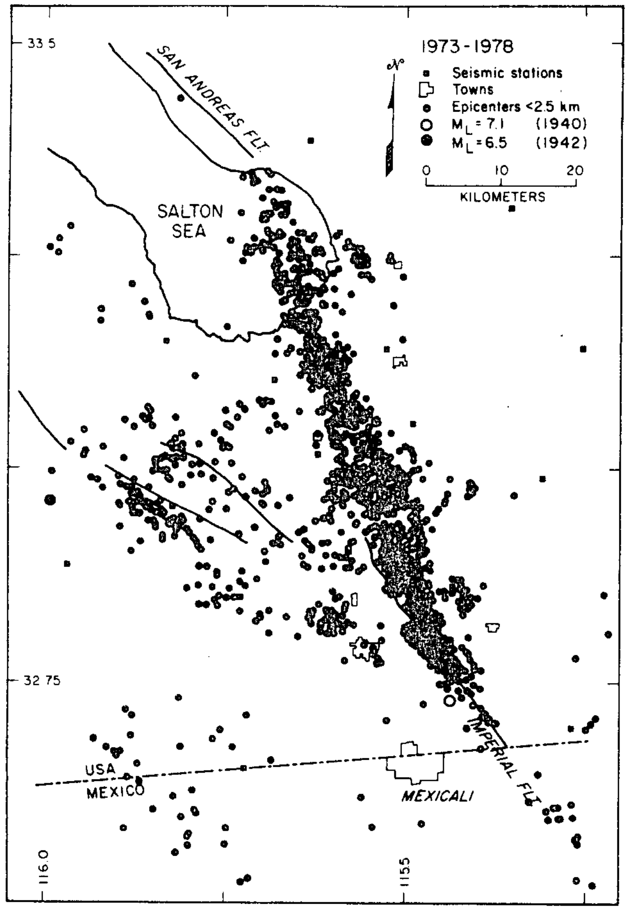

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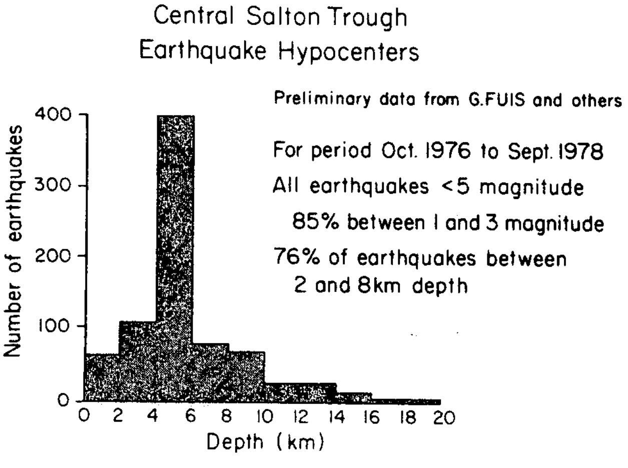
Figure 13. Central Salton Trough epicenters showing the connecting activity between the Imperial and San Andreas faults (data from Johnson, 1979). Epicenter location error less than 2.5 km. M_L refers to local Richter magnitude.



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Salton Trough. More refined data on depths of earthquakes are needed for the Cerro Prieto area (Fig. 15) in order to document whether these events are in the production zone or at the interface of the deltaic sediment and the basement of granodiorite, volcanics, and metasedimentary rocks.

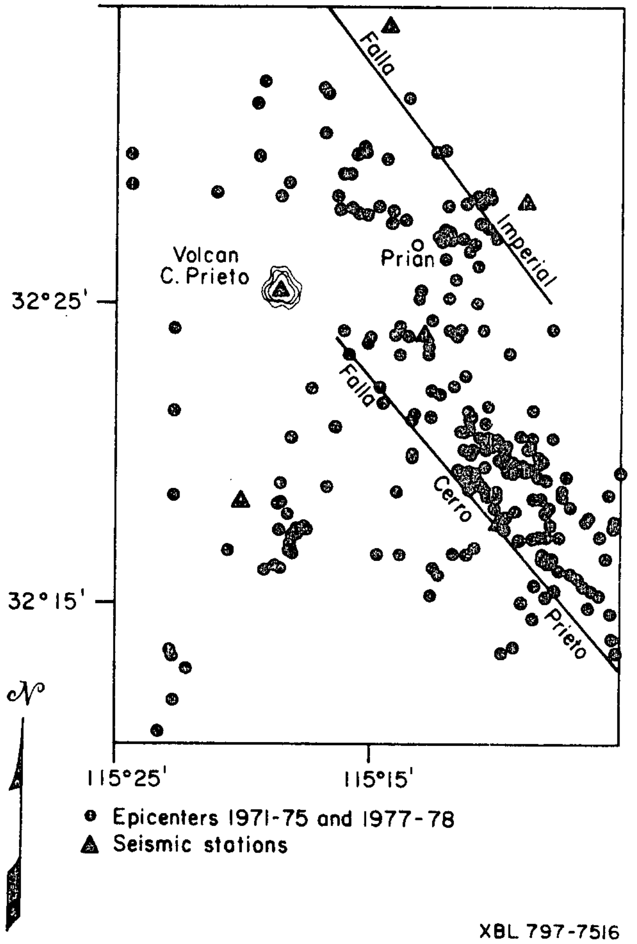

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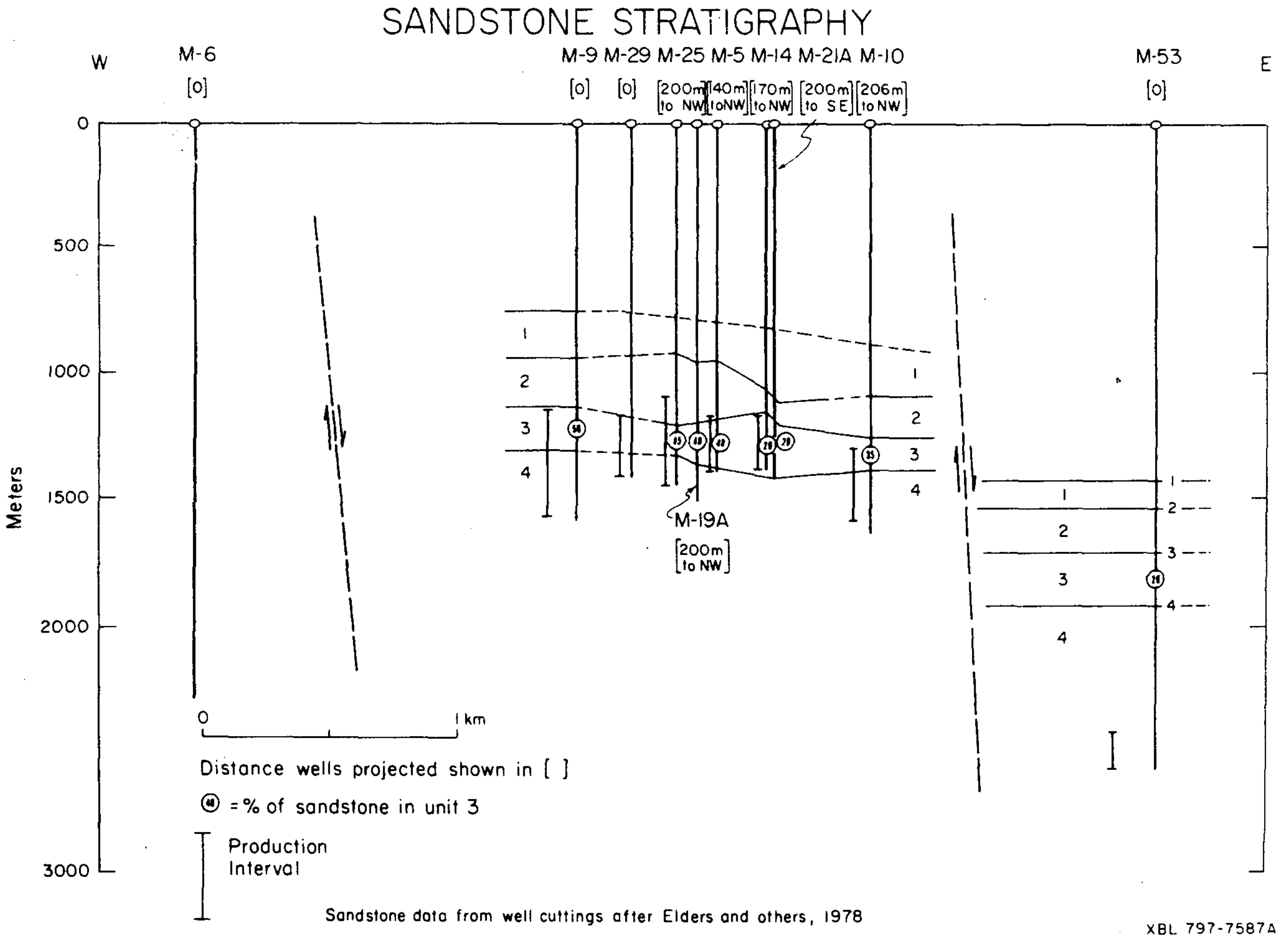
Figure 15. Earthquake epicenters in the vicinity of the Cerro Prieto and Imperial faults; data from Albores et al., 1979. Tectonic interpretations of recent movement between major en echelon faults are supported by these data and similar data along the north-trending zone between the Imperial and San Andreas faults.

Figure 14. Earthquake depths in the Salton Trough north of the Mexican-U.S. border, although difficult to quantify in the Salton Trough, show a concentration near geothermal fields in a zone from 2 to 6 km. (Richter magnitudes, local).

SANDSTONE POROSITY

Figure 16 represents the basis of a working hypothesis, namely that zones of lower total sandstone percentage, approximately 20% to 50%, are better for geothermal production than zones of, say, 80% total sandstone. This hypothesis has two corollaries: (1) secondary porosity caused by geothermal fluids is spotty throughout a field, and (2) fracture porosity is relatively greater in siltstones, shales, and sandstones that have been densified. Detailed comparison of sandstone percentage, lithofacies types, mineral data, and resistivity are in progress but available information support the hypothesis (Elders, 1980, personal communication; Wilt, 1980, personal communication).

Scanning electron microphotographs of well cuttings and cores reveal mineral dissolution and mineral precipitation, clogging of pore throats, and apparent phases of overgrowth. Selected photographs present an idea of these features. A laminated siltstone in well NL-1 at 1888 m (Fig. 17) shows little porosity and little densification, while deeper samples in NL-1 at 2720 m in the production region (Figures 18, 19, 20) illustrate clogging and precipitation. Figures 21 and 22 at 3209 m in the same well document a dramatic change to a metamorphosed zone with reduced secondary porosity. Well M-38 samples at 1215 to 1372 m show clay and framework minerals (Figs. 23 and 24) and M-3 at 2203 m (Fig. 25) is a spectacular example of silica mineral precipitation adjacent to clay minerals.



Sandstone data from well cuttings after Elders and others, 1978

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Figure 16. Sandstone units defined by relatively continuous major shale zones. Within the production reservoir the sandstone percentage, as in unit 3, varies from 20% to 50% with a minimum near well M-14 (see Fig. 5 for well locations).

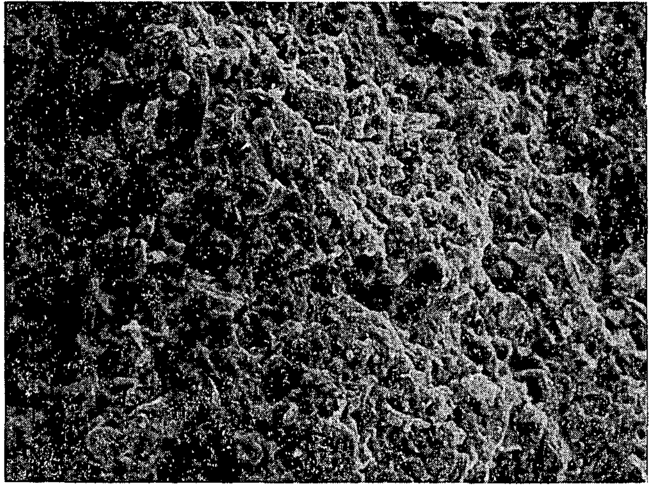

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Figure 17. Low-porosity laminated deltaic siltstone from well NL-1 at 1888 m depth; field of view across the SEM photograph is 0.2 mm.

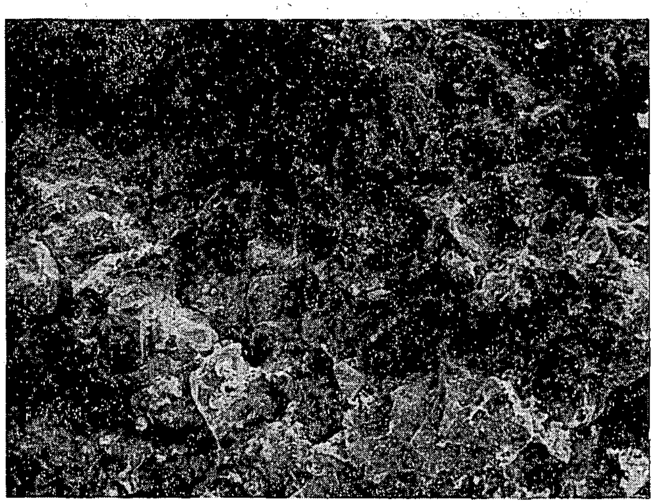

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Figure 18. Sandstone showing mixed secondary porosity and newly precipitated hydrothermal minerals from production zone of well NL-1 at 2720 m depth. Field of view across the SEM photograph is 0.2 mm.

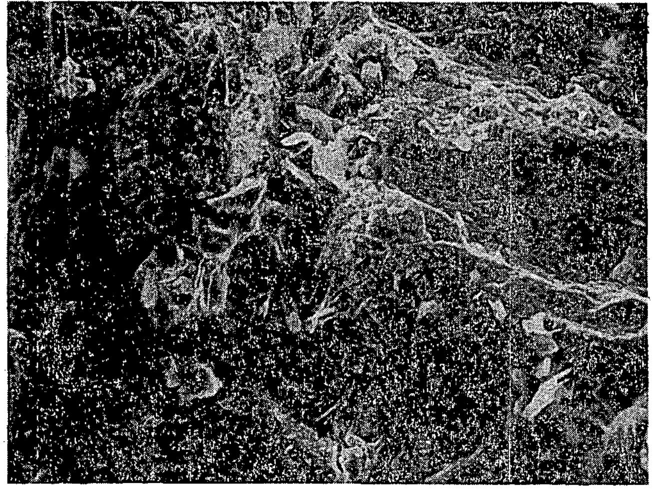

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Figure 19. Sandstone; closeup of the same sample as Figure 18. Note the long hairlike crystals (illite?) and wafer-shaped clay or zeolite minerals partially filling a pore throat between sand grains. Sample taken at 2720 m depth from well NL-1. Field of view across the photograph is 0.2 mm. This is an example of altered secondary permeability effects.

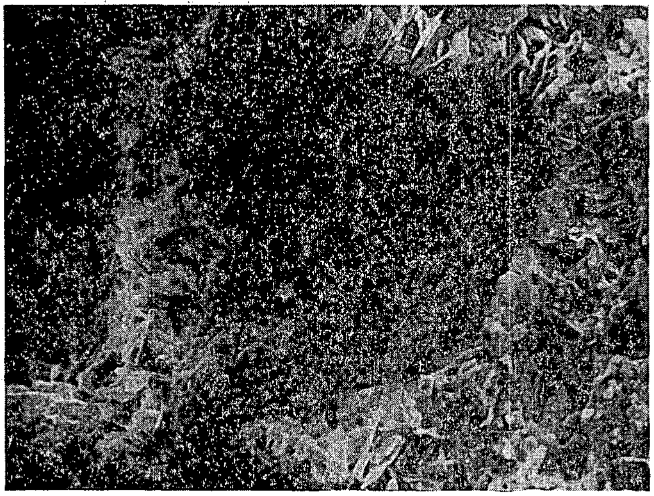

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Figure 20. Sandstone; closeup view of a portion of Figure 18. During sample preparation a grain was plucked leaving behind the hydrothermally precipitated clay cement. Sample from 2720 m depth in well NL-1. Field of view across the SEM photograph is 0.2 mm.

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Figure 21. Metamorphosed very dense sandstone from well NL-1 at 3209 m depth. Field of view is 1.0 mm. This is an example of a super-mature secondary porosity zone susceptible to microfracturing.

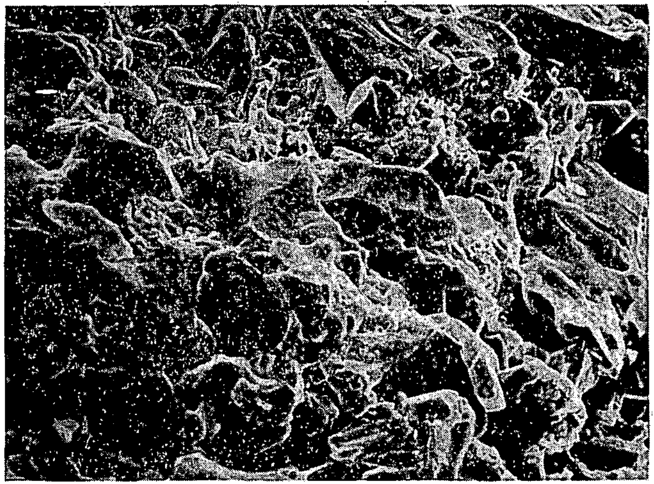

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Figure 22. Closeup of Figure 21 showing reduced porosity due to precipitation of framework minerals. Note how grains were broken durng sample preparation compared with Figure 18. Sample from well NL-1 at 3209 m depth. Field of view across the SEM photograph is 0.5 mm.

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Figure 23. Clay and framework minerals, or mineral overgrowth in a pore space. Sample taken from well M-38, at depths from 1215 to 1372 m; field of view across the SEM photograph is 0.1 mm.

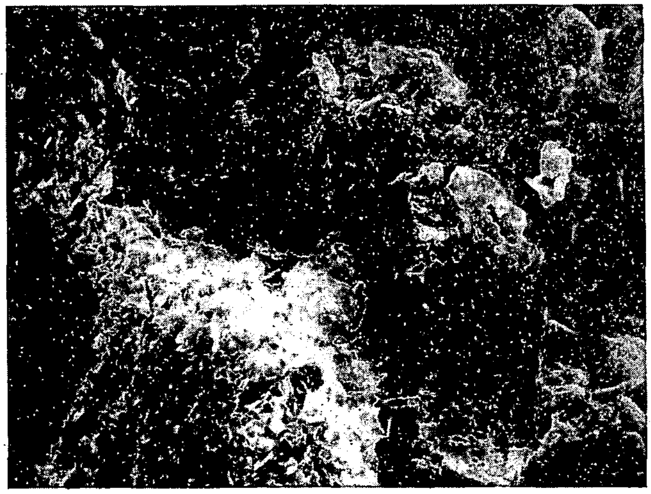

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Figure 24. Leaching of a crystal face and a massive clay mineral agregate. Samples taken from well M-38 at 1215 m depth. Field of view in the SEM image is 1.0 mm.

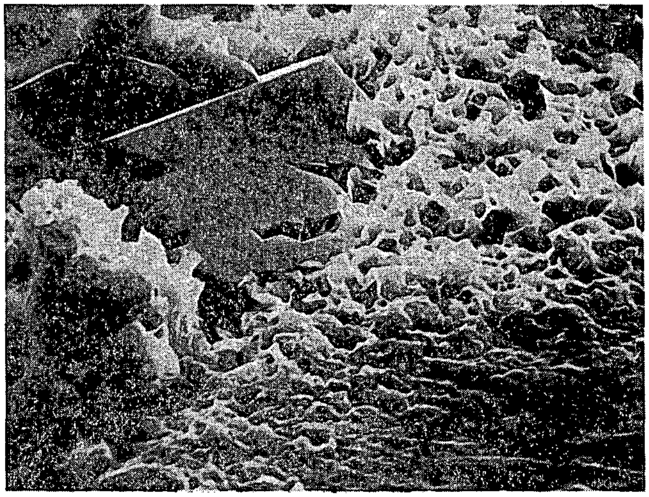

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Figure 25. Nearly pure silicate minerals (EDAX scan shows only Si) adjacent to honeycomb clays (Fe, Mg, Al rich) overgrowths. Both features greatly reduce permeability. Sample from well M-3, at 2203 m depth. Field of view across the SEM photograph is 0.05 mm.

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