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Crustal Spreading in Southern California

The Imperial Valley and the Gulf of California formed by the rifting apart of a continental plate.

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More than 45 years ago Wegener, as part of his comprehensive scheme of continental drift, proposed that the Gulf of California formed by separation of the peninsula of Baja California from mainland Mexico (*1*). This proposal, ignored for several decades during which the concept of continental drift was found unacceptable by many geologists, has now been revived (*2*). The idea is particularly appealing in the light of later ideas on sea floor spreading (*3*), which put continental drift in a wider context and gave birth to the newer, unifying theory of plate tectonics that is currently revitalizing geology (*4*).

The northeast Pacific Ocean appears to be a flank of the East Pacific Rise modified by the westward boundary of the North American plate (Fig. 1) (*5*). Marine geophysical studies both in the Gulf of California and in the adjacent ocean strongly support the interpretation that the gulf originated in the spreading apart of the continental crust. It appears that the Gulf of California is part of the active boundary between the North American and Pacific plates (*6*).

In this article we discuss geological and geophysical evidence for crustal spreading for the Salton trough, the landward extension of the gulf into North America (*7*). Patterns of magnetic, gravitational, and thermal anomalies, together with geodetic measurements, strike-slip faulting, and young volcanism suggest that the continental crust is rifting apart, as part of the dynamic system that includes the southern part of the San Andreas and related faults in the Salton trough. In the Imperial Valley of California, at the northern end of the trough, where our work has been concentrated (*8*), the high heat flow associated with this active tectonism is potentially a major energy resource (*9*).

Structure of the Valley

The Mexicali-Imperial Valley, the northern extension of the Gulf of California, is a broad, structural trough partly filled with lacustrine and deltaic silts, sands and gravels of late Tertiary age, and by great thicknesses of Quaternary alluvium and lake sediments. It is a complex rift valley bordered by mountains consisting of Mesozoic, and older, granitic and metasedimentary basement rocks, with subordinate Tertiary volcanic rocks (*10*). The oldest sedimentary rocks cropping out in the valley may be as old as Miocene, but most of the sediments were probably deposited by the Colorado River during the last few million years (*11*).

A preliminary investigation of the basement configuration under the valley north of the Mexican border shows that the Imperial Valley has steep, step-faulted margins and a broad, relatively flat basement floor 6 to 7 kilometers deep (*12*). Numerous subsidiary blocks and basins are aligned along the major faults. This trough is comparable in shape and size with the deeper submarine basins of the southern part of the Gulf of California, but it is partly filled here by the vast accumulation of sediments of the Colorado River Delta (*13*).

The major faults in the region are shown in Fig. 2. The map also shows three newly inferred faults, named the Brawley, Calipatria, and Holtville faults, which apparently transect the valley south of the Salton Sea (*14*). Together with the Sand Hills fault they may be part of the San Andreas fault system.

We believe that the Salton trough formed by a combination of tensional and right-lateral strike-slip movements associated with the opening of the gulf as Baja California was transferred from the North American to the Pacific lithospheric plates (*13, 15*).

A complete Bouguer anomaly map of the Salton trough (*16*) 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. 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 (Fig. 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

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(*16*), a density model of the sediments of the Imperial Valley was constructed and used for the gravity calculation (dashed lines in Fig. 3A). If the effect of the low-density sediments in the Imperial Valley is removed by gravity stripping, crust-mantle models can be computed. The offshore gravity data and crustal seismic refraction data have been used for control (*17*).

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 (*18*). 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.

Thermal Anomalies

Typical oceanic spreading centers are characterized by ocean ridge topography; high heat flow; linear, symmetrically arranged, magnetic anomalies; and transform faults. On land, however, the search for spreading centers is rendered difficult by the thick, sedimentary cover. This insulating blanket allows temperatures to rise above the Curie point. Consequently, patterns of linear magnetic anomalies characteristic of the ocean floor are not generated (*19*), and other lines of evidence must be used to recognize spreading centers beneath the continents. Among these might be heat flow anomalies.

Although heat flow along the East Pacific Rise in the ocean is quite variable, ranging from 0.14×10^{-6} to 8×10^{-6} calorie per square centimeter per second, the average value along the crest is about 3×10^{-6} cal cm^{-2} sec^{-1}, nearly twice the oceanic average (*20*). Numerous thermal anomalies with computed heat flow values in the upper range of those on the East Pacific Rise are present in the Imperial Valley, south of the Salton Sea (*21*) (Fig. 2). Another thermal anomaly occurs on the southwest side of the Imperial fault in the Cerro Prieto geothermal field, 20 km south of Mexicali, Mexico (*C* in Fig. 1) (*22*).

These thermal anomalies coincide with low-amplitude positive residual gravity anomalies with closures of 2 to 22 mgal. The pronounced, northeast-trending thermal anomaly between Calexico and El Centro is a good example, extending at right angles to the San Jacinto fault (*23*). The anomalous temperature gradient is accompanied by a long, narrow and shallow, positive gravity anomaly of 2 mgal. These geophysical anomalies have no geological expression at the surface. 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.

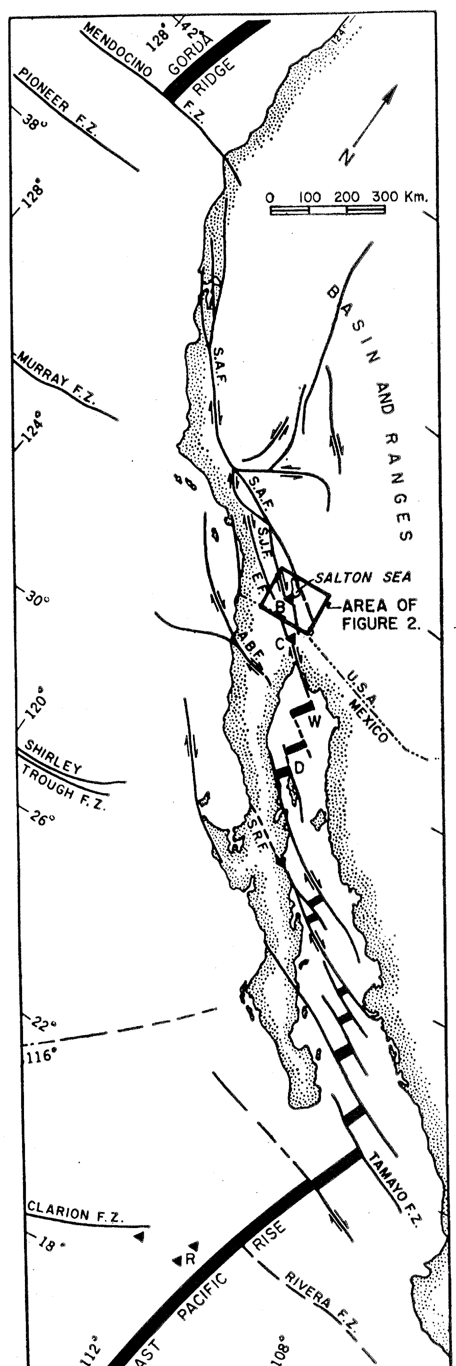

Fig. 1. Fractures and spreading centers along part of the Pacific Coast of North America between the East Pacific Rise and the Gorda Ridge (*6, 41, 43, 50*). Oceanic fracture zones (*F.Z.*) and continental faults (*F.*) are solid black lines, dashed where uncertain. *S.A.F.*, San Andreas fault; *E.F.*, Elsinore fault; *S.J.F.*, San Jacinto fault; *A.B.F.*, Agua Blanca fault; *S.R.F.*, Santa Rosalia fault. Postulated spreading centers in the Gulf of California are shown in black: *W*, Wagner Basin; *D*, Delfin Basin. The black triangles are Holocene or Recent volcanoes: *B*, Buttes; *C*, Cerro Prieto; *R*, Revillagidego.

An extrapolation of the measured gradients suggests that temperatures sufficient to cause melting of granitic rocks may be reached within the basement beneath the valley. The most complete temperature data available to us for depths greater than 200 meters are from the Buttes geothermal field at the southern end of the Salton Sea (*24, 25*). Figure 4A shows the locations and depths of nine holes drilled into this anomaly. Superimposed are Bouguer gravity values and estimates of the depth contours for the 300°C isotherm based on temperature gradients measured in the wells. The temperature gradients are plotted as solid lines in the upper left of Fig. 4B. They show that temperatures in excess of 350°C exist at depths less than 2 km. An examination of rock cuttings and cores from several wells shows that a progressive change to greenschist facies mineralogy begins at a depth of only 1 km (*26*). This contrasts markedly with the depth of 5 km usually assigned to the conditions under which greenschist metamorphism begins (*27*).

The observed temperature gradients become flatter with depth, probably because of convective flow of hot brine in fractures in the surrounding rocks. The wide range of temperature gradients and the high values of the estimated heat flow observed in the Imperial Valley require that heat transfer in the upper part of the sedimentary pile must be largely due to advective flow of brine. We have extrapolated the observed gradients monotonically on this assumption. Our estimates suggest that temperatures of 400°C are reached at a depth of only 3 km in the Buttes area (Fig. 4B).

In order to bracket the temperatures below 3 km, we further note that borehole logs indicate that the porosity and permeability of the rocks decrease rapidly below this depth. As heat transfer by rising plumes of brine becomes less efficient, the geothermal gradients must increase. If we assume that advection of water is negligible at greater depth, the temperature gradients depend only on thermal conductivity.

The computed heat flow for the center of the Buttes thermal anomaly is 7.1×10^{-6} cal cm^{-2} sec^{-1} (*28*). If steady-state conditions and no divergence are assumed, the boundary conditions for deeper extrapolation of geothermal gradients are easily calculated. Using values of the thermal conductivity for various appropriate rocks (*29*), we can estimate a range of possible geothermal gradients. The thermal conductivity of shale gives the steep gradient of 280°C per kilometer, that of granite or basalt gives 140°C per kilometer, whereas the high conductivity of greenschist gives a gradient of 100°C per kilometer.

Reported for comparison, in the upper left of Fig. 4B, are the temperatures reported in the log of the Wilson No. 1 well, drilled to a depth of 4 km in a relatively cooler part of the valley, 15 km south of the Buttes thermal anomaly (*30*). If our extrapolations of the geothermal gradients are valid, temperatures high enough to melt rocks should occur at quite shallow depths. To the right of the diagram are shown curves for the onset of melting of three different kinds of rocks: basalt, which is typical of the Pacific Rise, and tonalite and a granite, which represent rocks likely to be found in the granitic basement locally (*31*). The pressure in kilobars appropriate to each depth is plotted on the right-hand axis, under the assumption that the water vapor pressure equals the total pressure. Assuming greenschist metamorphism of the sediments, we note from the appropriate temperature gradient that a granite, with adequate water present, would begin to melt at a depth of about 6 km (*32*). In spite of the uncertainty in the extrapolations of the temperature gradient, it seems certain that melting should occur in or even above the regional basement during the present temperature regime.

Volcanism

Volcanism is another characteristic of some oceanic spreading centers. The volcano Bárcena on the island of San Benedicto in the Revillagigedo group on the flank of the East Pacific Rise (*R* in Fig. 1) erupted in 1952 (*33*). Several young volcanoes also occur in the gulf and along its landward extension. In the Mexicali-Imperial Valley volcanoes occur at Cerro Prieto, 30 km south of Mexicali, and also at the southern end of the Salton Sea. At the latter locality there are five small rhyolite domes, known as the Buttes, trending along a northeast line (*34, 35*). Because of the structural setting of these domes in relation to a high heat flow anomaly, a detailed study was undertaken in an attempt to determine the origin and nature of the rhyolite magma.

The Buttes rhyolites were extruded onto the sediments of the valley floor. Abundant hyaloclastic material and the presence of wave-cut benches on their side suggest that the volcanoes were erupted under water during a high

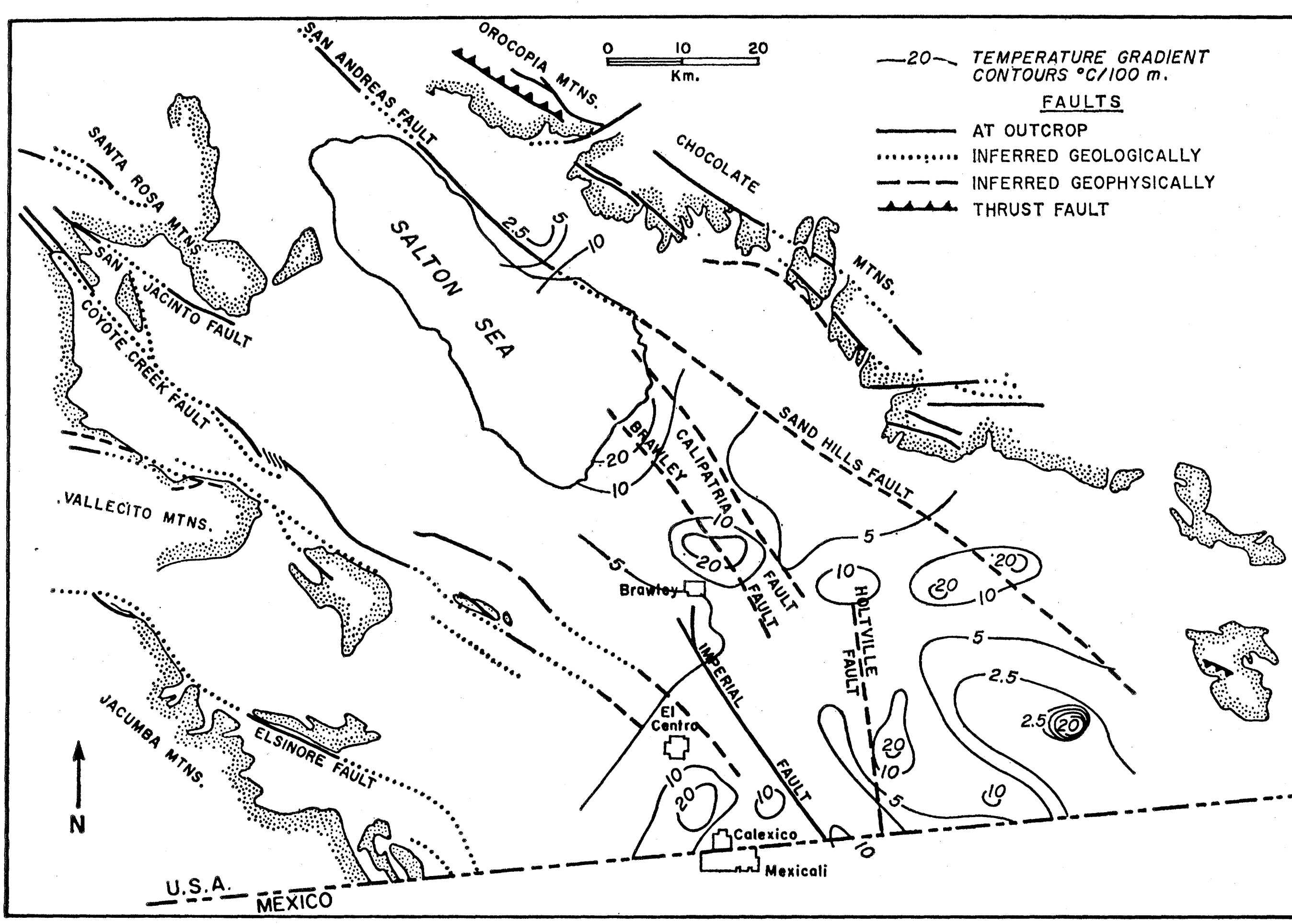

Fig. 2. Faults and geothermal areas in the Imperial Valley (*21*). Outcrops of basement rocks are indicated by the dot pattern. The contours indicate temperature gradients in degrees centigrade per 100 m, measured in approximately 100 shallow wells.

stand of the ancestral Salton Sea (Lake Cahuilla), between 16,000 and 55,000 years ago (*26*). They are alkaline, with potassium and sodium comprising 8.5 percent by weight of the total oxides. They contain iron-rich pyroxenes and amphiboles as the ferromagnesian silicates. Compared to soda rhyolites from the islands of the East Pacific Rise (*33*), they are slightly higher in silica and in potassium (*36*). Two determinations of the ratio of strontium-87 to strontium-86 indicate that the lavas have relatively primitive values of 0.704 and 0.705 (*37*).

Numerous xenoliths in these volcanic rocks provide a grab sample of the rocks beneath the valley, much like a dredge haul from the sea floor. The most common varieties are basalt, granite, sandstone, and mudstone (*36*). The sedimentary rocks are presumably accidental fragments, plucked from the walls of the volcano as the lava erupted through the deltaic sediments. The sandstone blocks range in size up to 2 m across. Most of these sandstone and mudstone xenoliths show little reaction with the lava, which suggests that they originated at shallow depths beneath the valley. A few of the mudstone xenoliths have incipient development of chlorite and epidote, similar to the greenschist mineralogy reported at depths of 1 to 2 km in wells in the Buttes geothermal field (*26*).

The most abundant inclusions consist of subangular blocks of basalt up to 30 cm across. These are low-potassium tholeiites composed of labradorite, clinopyroxene, and iron oxides. They are medium- to coarse-grained rocks presumably derived from dikes and sills intruded into the sedimentary pile beneath the valley. Griscom and Muffler (*35*) report that such dike rocks were encountered in two of the wells shown in Fig. 4A. The mineralogy and chemistry of these basalts are very similar to those of basalts erupted along the crest of the East Pacific Rise (*33, 38*).

Almost equally numerous are xenoliths of granitic rocks, which range from a few centimeters up to 2 m in diameter. They are coarse-grained quartz diorites and alkali granites composed chiefly of sodic plagioclase, quartz, and potassium-feldspar. Mafic minerals, probably formed by the dissociation of biotite, are ferro-augite, hedenbergite, fayalitic olivine, and garnet. Most xenoliths have well-developed granophyric textures and show incipient melting along fractures and grain boundaries. Patches of undersaturated glass up to 2 cm across also occur. Although variable in composition, most are soda granites with higher silicon and lower potassium than the enclosing rhyolites. These granite xenoliths are similar mineralogically and chemically to some of the plutonic rocks exposed in the basement outcrops bordering the valley, especially to the east. We infer therefore that they were derived from a similar source at depth.

The volcano Cerro Prieto, south of Mexicali, consists of gray to dark reddish-gray dacite with phenocrysts of andesine, hypersthene, and iron oxides. It is calc-alkalic with significantly lower silicon and potassium and higher iron and calcium than the rocks of the Salton Sea domes (*34, 35*). Thus, the composition of this lava is similar to that of the batholithic rocks of the Peninsular Ranges, and it could be derived anatectically by the remelting of such rocks. However, the bulk composition and isotopic ratios of the Salton Sea rhyolites suggest that they are more likely to have formed by the fractionation of a more primitive basaltic magma derived from the mantle. The occurrence of basaltic xenoliths suggests just such a genetic relationship. However, the presence of inclusions of partially melted granite and xenocrysts, together with the high potassium content of these lavas compared with typical soda rhyolite from oceanic environments, implies that some contamination by crustal materials has occurred (*39*).

Origin of the Valley

The Imperial Valley is an example of a rift valley or structural trough. Figure 5 is a simple two-dimensional model relating the rifting of the valley to magma generation. 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 expansion 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 sedi-

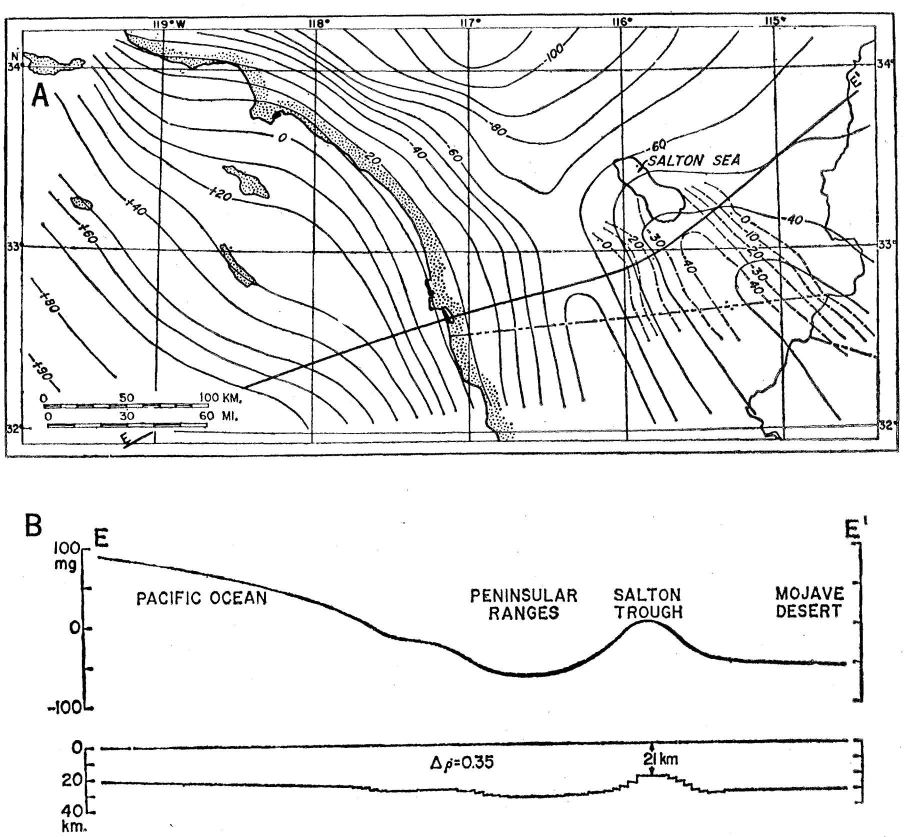

Fig. 3. (A) Regional Bouguer gravity anomalies of southern California from the continental borderland to the Colorado River. The solid lines are isogal contours. The dashed lines, south of the Salton Sea, represent the gravitational effect of low-density sediments in the Imperial Valley. (B) A crust-mantle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

ments. 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, rhyolitic volcanoes bring up fragments of basalt, metamorphosed sediments, and granitic basement.

Whether derived from the mantle or from remelting of the basement, the magmas in the Imperial Valley are generated in an environment of crustal spreading. The areal extent of the gravitational and thermal anomalies suggests that perhaps a batholith is forming in the basement at the southern end of the Salton Sea.

In these two-dimensional models we 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, obliquely 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.

Crustal movements in the Imperial Valley are currently active. The valley is lengthening by right-lateral slip, and the center is sinking relative to the walls. This is demonstrated by topographic surveys by the U.S. Coast and Geodetic Survey. Triangulations begun in 1931 were repeated in 1941, 1954, and 1967, and first-order leveling was carried out in 1931 and 1941 (*40*). Figure 6 synthesizes the relative movements suggested by measurements. In the figure, changes of elevation are referred to a single station east of the Salton Sea and west of the San Andreas fault. However, in reducing the data on horizontal position it is necessary to assume a baseline, and the stations *A*, *B*, and *C*, indicated in Fig. 6 were chosen for this purpose. Nason (*40*) suggested that the pattern of vectors can be made more reasonable geologically if it is assumed that the baseline lengthens by *B* and *C* moving away from *A*. The horizontal position vectors then progress as shown.

Overall, where survey lines crossed faults they tended to be rotated in a clockwise direction consistent with a right-lateral shear of 1 part per million per annum. The most notable defor-

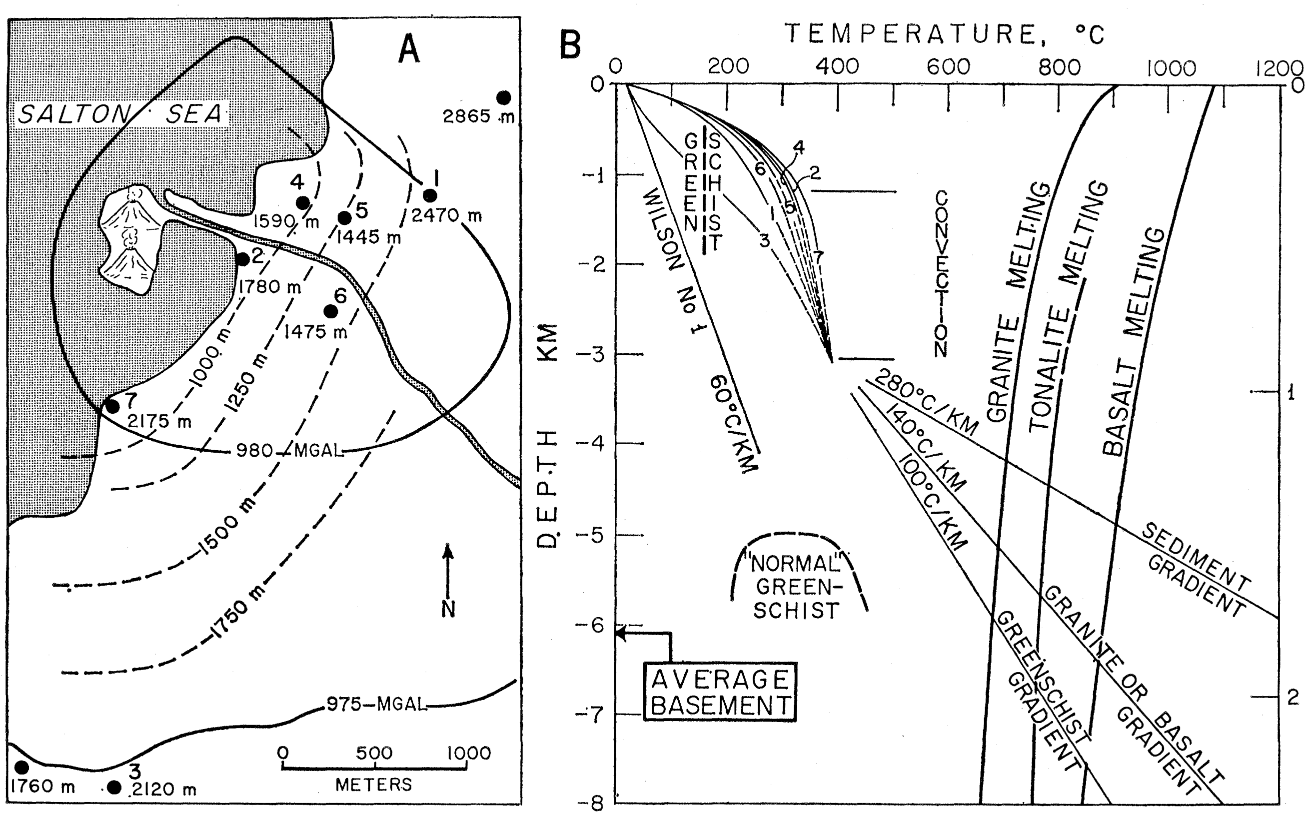

Fig. 4. Thermal effects in the Buttes geothermal area at the southern end of the Salton Sea. (A) Map of the volcanic domes on the Red Hill peninsula. The locations and depths of wells in which temperature gradients were measured are indicated. The dashed contours are the depths of the 300°C isotherm; the solid lines are Bouguer anomaly isogals. Modified from (*24*, figure 6). (B) Depth of metamorphism and melting in the Buttes thermal anomaly. The temperature gradients measured in the seven numbered wells of (A) are indicated in the upper left. These are extrapolated to 3 km under the assumption of heat flow by circulation of brine at least to this depth. Below the zone of convection, a range of linear geothermal gradients is shown, for different values of thermal conductivity. We assume steady-state heat flow and ignore the effects of radiative heat transfer and melting on the temperature gradient. Polybaric solidus temperatures for three wet rocks are shown to the right. Granite saturated with water could begin to melt at the average depth of the sediment-filled trough.

mations of the survey net are associated with the earthquake of Richter magnitude 7.1, which occured in May 1940 on the Imperial fault. There were also several earthquakes of magnitude 5 to 6 during the intervals between surveys.

The vectors for the period 1934 to 1941 indicate 3 m of right-lateral displacement on the Imperial fault at the international border. The magnitude of this right-lateral displacement falls off rapidly away from the fault and averages about 1 m in the southern part of the area. The maximum vertical displacement between 1931 and 1941 also appears to be related to the Imperial fault. Right-lateral strain appears absent north of the Imperial fault in this period. Instead, basement outcrops northeast and southwest of the Salton Sea appear to have moved toward each other.

Between 1941 and 1954 right-lateral shear appears to have propagated north from the Imperial fault, and Nason (*40*) suggested that this northward migration is an aftereffect of the 1940 earthquake. During the third period between surveys the average deformation was less, but a small right-lateral shear is again apparent, particularly in the southern part of the net.

Because of the ambiguities introduced by possible changes in the length of the baseline, exact strain parameters are still uncertain. However, the total displacements from 1934 to 1967 indicate a differential right-lateral, regional shear of about 2 m for the southern part of the net, which is equivalent to 5 cm/year. Most of this occurred in the 1940 earthquake. Whatever the long-term rate of deformation, it is clear that on the whole the valley is undergoing right-lateral motion and the center is sinking relative to the walls. It appears to us that there is a steady right-lateral creep and dilation in the Imperial Valley, punctuated by strong earthquake motion. During these earthquakes, the uplifted and tilted valley walls may be triggered to slide toward the valley.

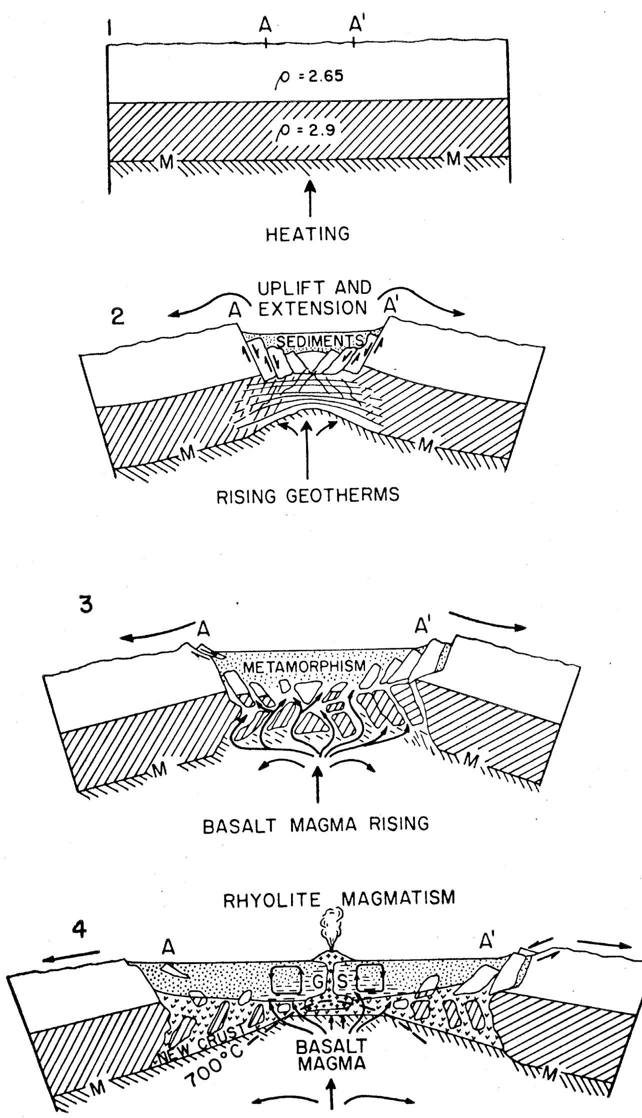

Fig. 5. Model of rifting and magma generation during growth of a graben. The sections are drawn parallel to strike-slip faults. (Stage 1) Two layers of crust overlie a hot zone in the mantle. *M*, Mohorovičić discontinuity; *A* and *A'*, reference points for later movements. (Stage 2) Upward and lateral 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.

Spreading Centers and Faults

How does a rift valley originate by strike-slip faulting? This problem was discussed by Carey (*2*) 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 (Fig. 7A). The spreading centers postulated in the Gulf of California (see Fig. 1) fit this model remarkably well as they coincide with submarine depressions (*6*). The idea is particularly appealing in the case of the southern part of the gulf.

Young volcanic rocks occur at Consag Rock immediately northwest of the Wagner Basin (*W* in Fig. 1). Thatcher and Brune (*41*) described a swarm of earthquakes that occurred in 1969 near Consag Rock (over 70 shocks with magnitudes between 4.0 and 5.5 in a 6-hour period). The swarm was characterized by a shallow hypocentral depth and predominantly normal faulting, which is typical of earthquake activity on spreading ocean ridges (*42*). Thatcher and Brune (*41*) also suggested that the seismicity of the Wagner Basin is coupled with that of the Delfin Basin about 150 km to the south (*D* in Fig. 1) and that these basins are related by a transform fault system.

Lomnitz and his coauthors (*43*) have suggested that a similar pattern of spreading centers and transform faults is found farther north (Fig. 7B). However, the seismic coupling between the Wagner Basin and the spreading centers which they postulate at Cerro Prieto and Obsidian Butte has not yet been demonstrated. Nonetheless, the location of the Cerro Prieto volcano and geothermal field between the San Jacinto and Imperial faults fits the model of Fig. 7A. Spreading centers may also occur at the northern end of the Imperial fault at the Brawley geothermal anomaly and at the Buttes volcanic domes geothermal anomaly (*44*).

As an explanation of the numerous active faults diverging northwest from the Salton trough, Lomnitz *et al.* (*43*) suggested that the rates of spreading on the individual spreading centers decrease progressively northward, as shown schematically in Fig. 7A. Thus, 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 Fig. 7A, 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 Fig. 7A) 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.* (*43*), 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 (*45*).

The simple conceptual model shown in Fig. 7B 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.

The segments of spreading centers suggested in Fig. 7B are at least an order of magnitude smaller in scale than those normally suggested for the oceans. The thermal anomalies shown may be simply plumes of ascending hot brine, localized along faults and other permeable zones. Thus, their positions may reflect thermal inhomogeneities in the upper mantle only indirectly. Thermal signals from the mantle are modulated by the thick, thermally insulating, continental crust, which may itself contain heat sources and sinks. On the other hand, until the fine structure of spreading centers in the oceans is better known, it may be reasonable to assume that the details of faulting and heat flow on the ocean floor may be at least as complex as those reported here.

It is now widely accepted that the border between the North American and Pacific plates was initiated after the consumption of the Farallon plate and adjacent spreading center, which occurred 30 million years ago south of the Mendocino fracture and 11 million years ago off much of Baja California (*46*). However, there are a number of problems requiring further study.

The details of how Baja California was transformed from the American

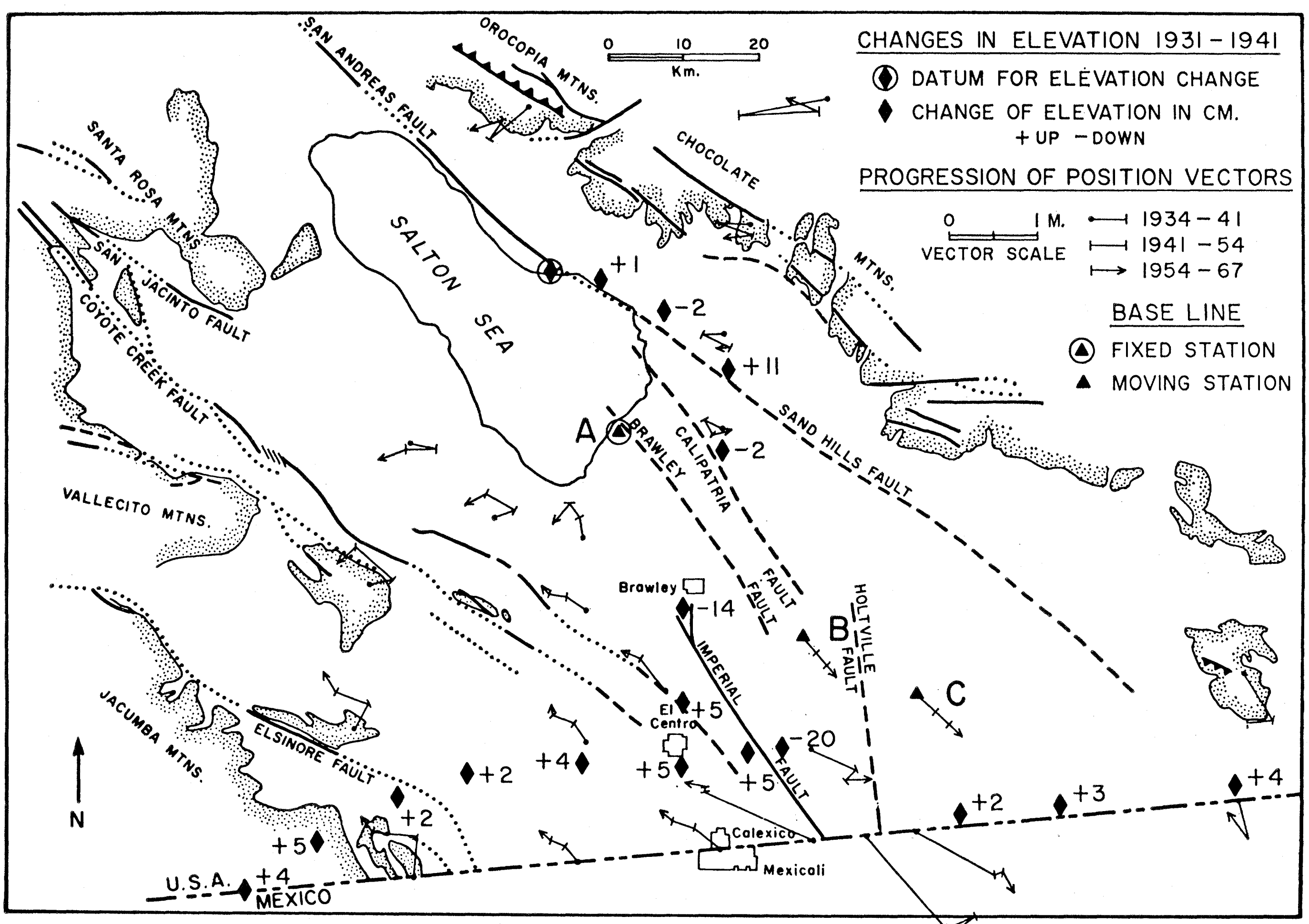

Fig. 6. Geodetic measurements in the Imperial Valley. Compiled and adapted from (*40*). Stations A, B, and C indicate the baseline for the reduction of data on position vectors. The horizontal vectors were computed by assuming that A is fixed and that AB and AC expanded 5×10^{-6} from 1934 to 1941, $4 \times 10^{+6}$ from 1941 to 1954, and 3×10^{-6} from 1954 to 1967 [after Nason, in (*40*)]. The fault pattern is as shown in Fig. 2.

to the Pacific plate remain enigmatic. Magnetic profiles at the mouth of the Gulf of California indicate that the protogulf began spreading to its present width about 4 million years ago. About 260 km of displacement has occurred since that time (*6*). North of the gulf, postulated displacements in southern California have about the same magnitude. For instance, Crowell (*47*) reported evidence suggestive of 250 km of displacement on the San Andreas fault north of the Salton Sea. This makes it difficult to accept the hypothesis that we are dealing with a spreading system that propagated from south to north unless most of the offset on the San Andreas fault predates the opening of the gulf. Similarly, it remains to be demonstrated whether the transform faults that separate the en echelon ridge segments in the central and southern part of the gulf have offset Baja California shortening the peninsula from south to north.

Geothermal Resources

The broad range of geophysical, geochemical, geologic, and economic problems in the Imperial Valley has led us to establish a broadly based research project. These studies will provide scientific support for the new technology of geothermal energy (*9*).

We estimate that the sediments in the Imperial Valley contain 10^4 km^3 of geothermal brines, a potential resource of remarkable dimensions. Nearly all of these brines appear to be less saline than seawater, except for those in the old Salton Sink salina, which are saturated with sodium chloride. We are currently studying the potential of the geothermal brine of low salinity for supplying steam for the generation of electricity and hot water for desalination. It is, therefore, necessary to determine the ratio of nonmetalliferous brine of low salinity to metalliferous brine that is highly saline. Studies of electrical resistivity have shown that a regional salinity gradient exists in the Imperial Valley (*48*). The regional salinity is lowest near the Colorado River at Yuma and increases northwestward toward the Salton Sea. This should be tested by exploratory wells.

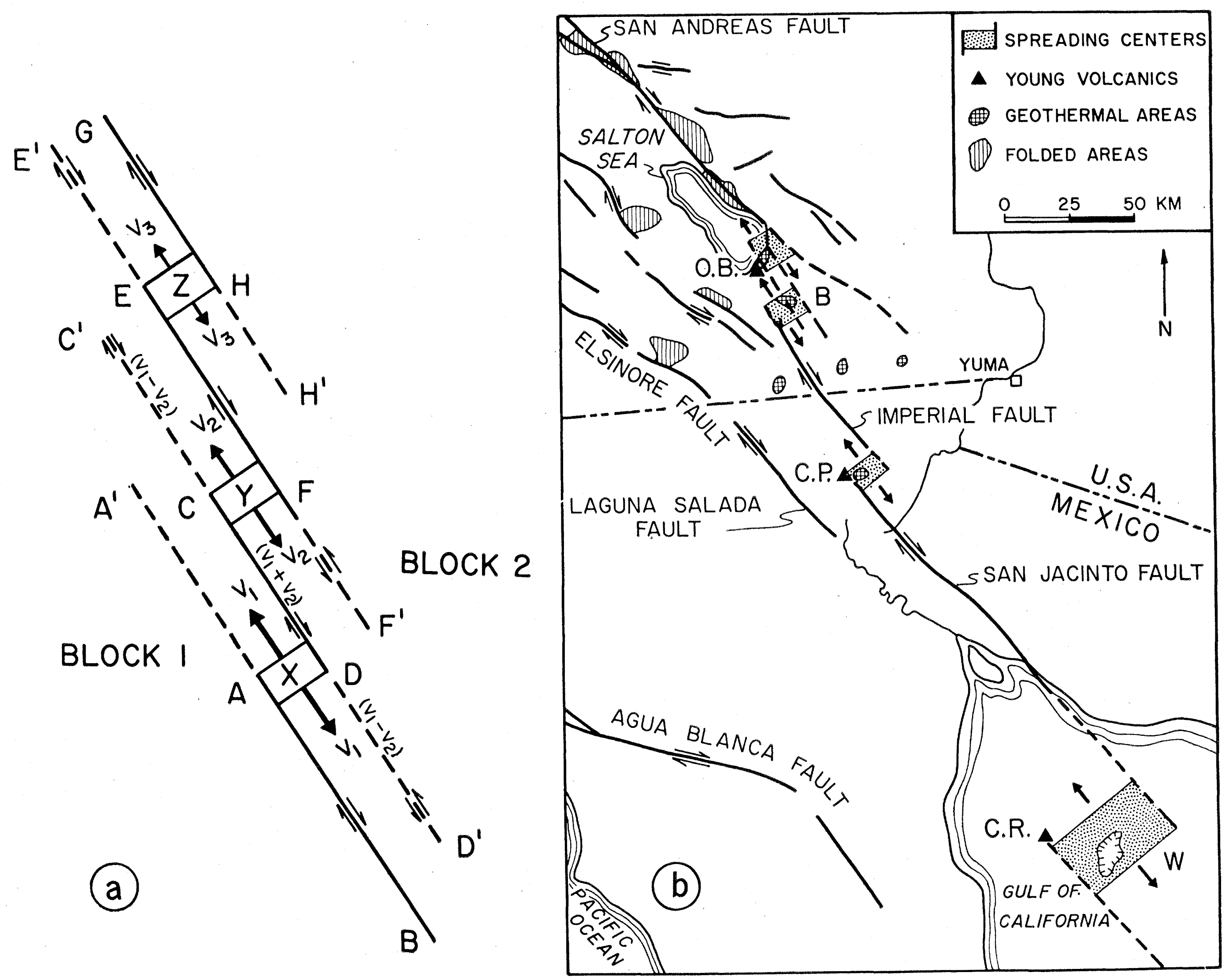

Fig. 7. Possible relations between strike-slip (transform) faults and spreading centers in the Salton trough. (a) Tensional zones or rhombochasms between en echelon strike-slip faults. *X*, *Y*, and Z are spreading centers between faults *AB*, *CD*, *EF*, and *GH*, with right-lateral motion. If these 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) Postulated spreading centers, young volcanics, geothermal areas, and zones of intense folding and compression in Cenozoic sediments. *O.B.*, Obsidian Butte; *B*, Brawley geothermal area; *C.P.*, Cerro Prieto; *C.R.*, Consag Rock; *W*, Wagner Basin. Adapted from Lomnitz *et al.* (*43*, figure 3).

The highly saline brines contain abundant iron and manganese chlorides, plus small amounts of copper, silver, zinc, and lead, but no sulfate or free hydrogen sulfide. These brines constitute ore-forming fluids readily accessible for study and may have an economic potential themselves.

We are also concerned with the influence of temperature on earthquake mechanisms in the valley. Recent laboratory results of Brace and Byerlee (*49*) indicate that the transition from stick-slip to creep movements in rocks is strongly dependent on temperature. Perhaps the present area of creep on the Imperial fault is characterized by steep temperature gradients, whereas stick-slip motion predominates in colder areas. If further studies verify these preliminary observations, it might suggest that if the cooler, shallow portions of the faults are warmed by hot brines from deeper levels, stick-slip might convert to creep motion.

Summary

The current excitement among geologists and geophysicists stemming from the "new global tectonics" has led to a widespread, speculative reinterpretation of continental geology. The Gulf of California and its continuation into the Imperial Valley provide an excellent opportunity for studying the border zone between the North American and Pacific plates, and an interface of continental and oceanic tectonics. The Salton trough, the landward extension of the gulf, is a broad structural depression, comparable in size with the deeper marine basins of the southern part of the gulf, but here partially filled with sediments deposited by the Colorado River.

We propose a model in which the continental crust is being thinned beneath a deepening and widening rift. Dilation is accompanied by high heat flow and magmatism. The trough forms as successive sections of the crust are sliced off along strike-slip faults. These slices move northwest and are transferred from the North American to the East Pacific plate. Our studies relate to the present nature of a small part of the plate boundaries, and the details of the evolution of the whole system in the last few million years are still unclear.

The model is an 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 localized melting in the basement beneath the sedimentary pile, (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 32 km in the north to a maximum of 22 km in the south with apparent upwelling of the mantle under some of the geothermal anomalies, (vii) geodetic measurements, and (viii) seismic studies in the northern gulf.

We intend to test and refine our model by further investigations, including drilling. The pace of tectonic activity in the Imperial Valley is rapid enough to make studies of time dependence meaningful. The Imperial Valley is an accessible natural laboratory for studying sea floor spreading, plate boundary tectonics, ore formation, and a wide range of geothermal phenomena. A series of geophysical, geochemical, and geological studies are presently under way as part of a program to investigate the scientific and economic potential of geothermal energy in the Imperial Valley.

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Carrier-Mediated Ion Transport

Electrical relaxation experiments give insight into the kinetics of ion transport through artificial lipid membrane.

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Biological membranes have a thickness of about 100 angstroms, and they are made up of lipids and proteins in a more or less ordered arrangement. The lipid molecules are oriented in such a way that their polar head-groups are in contact with the aqueous phases, whereas the hydrocarbon chains form the interior of the membrane. Because hydrocarbons have a low dielectric constant, the energy required to bring a small ion, such as sodium or potassium, from the aqueous medium into the membrane is many times the mean thermal energy. This means that the lipid portions of the membrane represent an extremely high barrier for the passage of these ions.

Nevertheless, biological membranes are permeable to alkali ions, and therefore one must assume that mechanisms exist by which the activation energy of the ion transport is drastically reduced. One possible mechanism is represented by a mobile carrier molecule that binds the ion at one membrane-solution interface, then migrates to the opposite interface and releases the ion into the aqueous solution. The concept of a carrier that facilitates the transport of ions and small hydrophilic molecules such as sugars and amino acids across the cell membrane dates back to the experiments performed by Osterhout (*1*) in 1933. This concept has since been worked out in great detail (*2*), but the existence of ion carriers in biology remained hypothetical until such compounds as valinomycin, monactin, and enniatin B were isolated and characterized [for reviews see (*3, 4*)]. These compounds are produced by certain microorganisms and possess antibiotic activity. Valinomycin and enniatin B are depsipeptides, that is, they are built up by α-amino acids and α-hydroxy acids in alternating sequences (Fig. 1). Monactin and the other macrotetrolides (nonactin, dinactin, trinactin) are cyclic compounds which contain four ether and four ester bonds. All these substances share a common property: they are macrocyclic molecules in which one side of the ring is hydrophilic, the other strongly hydrophobic. These compounds form complexes with alkali ions in organic solvents with a high degree of specificity (*3–5*); for instance, the stability constant of the potassium complex of valinomycin in methanol is larger by a factor of about 10^4 than the stability constant of the sodium complex (*6*). Valinomycin and the macrotetrolides may be used to extract alkali ions from water into an organic phase (*7, 8*).

The structure of the valinomycin-K^+ complex has been studied by spectroscopic methods (nuclear magnetic resonance, infrared spectroscopy, optical rotatory dispersion) as well as by x-ray diffraction (*3, 9*). The oxygen atoms of

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