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Earthquakes, Active Faults, and Geothermal Areas in the Imperial Valley, California

Abstract. *A dense seismograph network in the Imperial Valley recorded a series of earthquake swarms along the Imperial and Brawley faults and a diffuse pattern of earthquakes along the San Jacinto fault. Two known geothermal areas are closely associated with these earthquake swarms. This seismicity pattern demonstrates that seismic slip is occurring along both the Imperial-Brawley and San Jacinto fault systems.*

The Imperial Valley region in southern California has sustained more moderate to small earthquakes than any other section along the San Andreas fault system. The California Institute of Technology catalog of earthquakes in southern California from 1932 through 1972 shows a dense pattern of earthquakes with a magnitude of 4 or greater within the Imperial Valley and along the San Jacinto fault to the northwest (*1*). Nine earthquakes above magnitude 6 have occurred along the San Jacinto fault since 1890; in addition, two earthquakes of magnitude 6 in 1915 and one earthquake of magnitude 7.1 in 1940 have occurred along the Imperial fault (*2*).

In April 1973 a 16-station seismograph network was installed in the Imperial Valley to improve the resolution of earthquake locations in this region of known geothermal resources and high tectonic activity. Four stations were added to the network in February 1974 as a small, special-purpose array south of El Centro. This network is part of a cooperative effort between the U.S. Geological Survey and the California Institute of Technology (Caltech) to investigate (i) the relation between microearthquake activity and known geothermal fields, (ii) the location of active faults as determined from the distribution of microearthquakes, and (iii) the tectonic processes as a basis for earthquake prediction and hazard reduction. This report summarizes the results obtained from the network for its first year of operation (June 1973 through May 1974). Details concerning the array and a catalog of earthquakes for this period are given elsewhere (*3*).

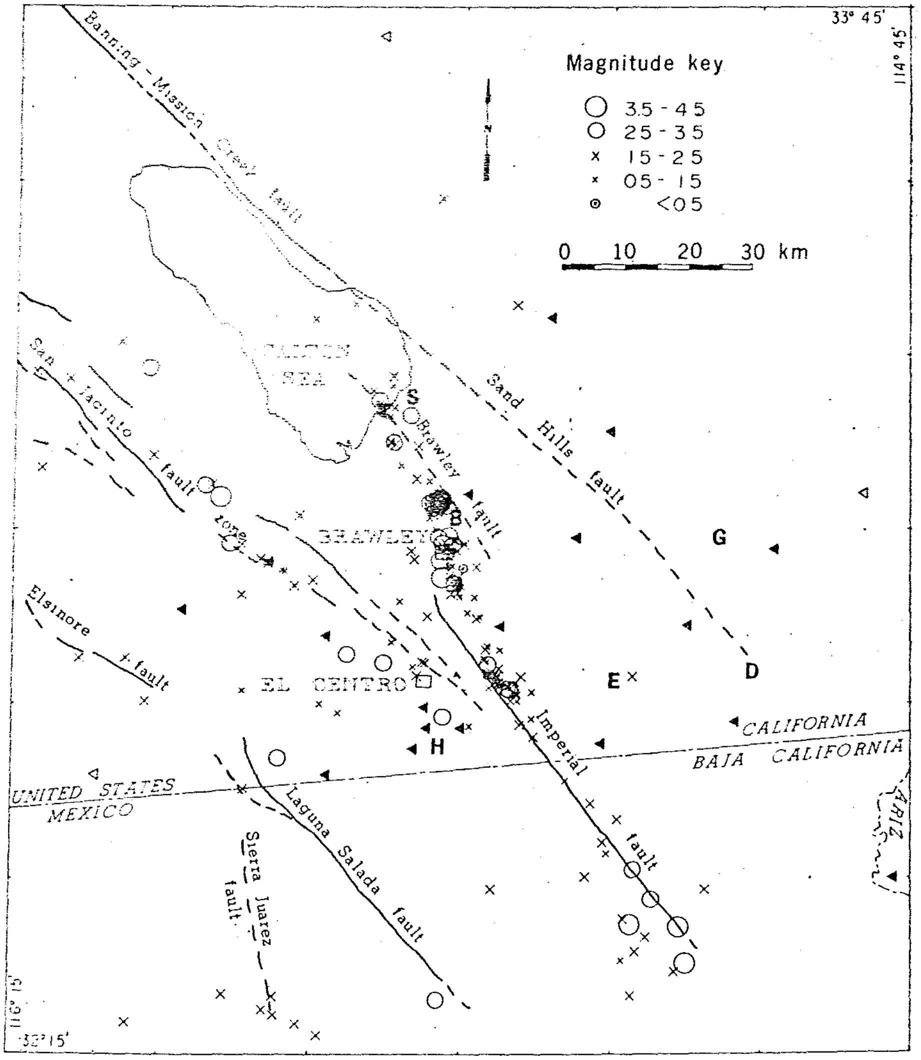

Fig. 1. Location of earthquakes in the Imperial Valley region with respect to major faults and geothermal anomalies. The smallest and largest earthquakes plotted have magnitudes of 0.5 and 4, respectively. Solid triangles represent locations of seismograph stations in the Imperial Valley network; open triangles correspond to locations of Caltech regional seismograph stations. Known geothermal resource areas are indicated by capital letters as follows: *B*, Brawley; *D*, Dunes; *E*, East Mesa; *G*, Glamis; *H*, Heber; and *S*, Salton Sea. Summaries of the geophysical and geological setting of the Imperial Valley and Salton trough are given in (*7, 17, 22*).

Figure 1 shows the location of all earthquakes recorded at four or more stations in the network for the period considered. Many earthquakes with magnitudes of 1 or less are included, but, because of high noise levels in the cultivated sections of the valley and intermittent instrumental problems, coverage is not uniform for earthquakes with magnitudes less than about 2.

The most striking aspect of the seismicity pattern is the linear concentration of epicenters in the central part of the valley. These epicenters coincide closely with the northern segment of the Imperial fault and extend northward through Obsidian Buttes at the southeastern end of the Salton Sea in a diffuse pattern nearly coincident with the inferred location of the Brawley fault (*4*). Most of the activity along this trend occurred in a series of four earthquake swarms between 20 June and 17 July 1973. A second, more diffuse pattern of epicenters extends from the central part of the valley to the northwest along the San Jacinto fault zone. Also noteworthy are the low level of activity east of the Imperial fault and the absence of earthquakes in the vicinity of the Sand Hills fault. Scattered earthquakes occurred near the Imperial and Sierra Juarez faults in Baja California, but, because these events are outside the network, their locations are poorly constrained. Except for the swarms in June and July 1973, the seismic activity developed in a fairly uniform manner with time.

The swarm sequence began on 20 June with a series of earthquakes of magnitude 2 to 3 along a 15-km stretch of the Imperial fault just north of the border. [This activity is nearly coincident with the surface break of the 1966 earthquake of magnitude 3.6 on the Imperial fault (*5*).] On 21 June seismic activity was observed 25 km to the north with a shock of magnitude 2.8 followed 4 minutes later by a shock of magnitude 4.0, both of which were located about

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m north of Brawley. Activity dropped low level in both areas after 22 June to be interrupted by a 24-hour flurry arthquakes in the vicinity of Obsidian tes and the Salton Sea on 1 July. Fi- ly. on 8 July, a swarm began near the thern end of the Imperial fault, par- ly filling the gap between the first two arms. Activity in this area had generally sided by 11 July, but sporadic activity tinued in all three swarm areas until roximately 17 July.

The shock of magnitude 4 in the wley swarm was the largest earthquake orded in the network during the year, hough three additional earthquakes of gnitude 4 occurred just outside the net- rk (one along the San Jacinto fault zone two in Baja California). The relative mber of shocks of a given magnitude to se of a larger magnitude in the swarms essentially the same as that reported by eman *et al.* (*1*, *6*) for earthquakes in the perial Valley region between 1932 and 2.

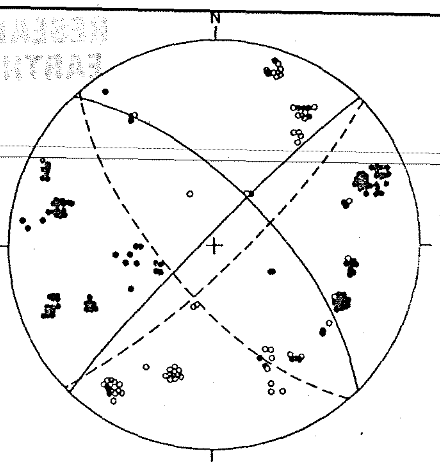

Fig. 2. Composite focal mechanism for 30 events in the 21–22 June swarm 8 km north of Brawley on an equal-area, lower-hemisphere projection. Solid circles represent compressional P wave first motion; open circles represent dilatation. Two fault-plane solutions are plotted (solid and dashed lines) to suggest the range of possible fault-plane solutions for individual events in the swarm.

The composite focal mechanism based 30 events from the swarm north of wley, shown in Fig. 2, indicates that the rm activity involved predominantly -lateral slip on planes nearly parallel h the Imperial fault. Left-lateral motion conjugate fault planes, however, cannot ruled out. Composite focal mechanisms the two southern swarms show similar t less well developed patterns.

Hypocenter solutions for earthquakes in swarms, as well as other earthquakes ated within the network, give focal pths between 5 and 14 km with an uncer- inty of roughly ± 5 km (*3*). An inter- etation of secondary P wave arrivals ob- rved on most stations from shocks in the arm north of Brawley, however, sug- sts that these earthquakes may actually cur near the base of the sediments at pths of 4 to 5 km (*7*).

Earthquake swarms are relatively com- on in the Imperial Valley. Richter (*8*) has scribed several swarms including one ar Brawley in December 1955, with ocks up to magnitude 5.4; Brune and Al- (*9*) recorded up to 75 microearthquakes day near Obsidian Buttes over a 5-day riod in July 1966. Recent activity in- des a minor swarm in August 1974 at northern end of the Imperial fault and major swarm in January 1975 near awley with shocks up to magnitude 4.7) that received wide coverage in the s media. The Imperial fault is capable producing both earthquake swarms and ge earthquakes (magnitude 7.1) accom- ied by normal aftershock sequences.

On a global scale, most earthquake rms appear to be closely related to magmatic processes. Swarms in the oceans usually occur in crustal spreading centers along mid-ocean ridges, and swarms on the continents usually occur in areas of recent or current volcanism and geothermal activity (*11*). Clusters of microearthquakes or earthquake swarms are regarded as promising signs in geothermal resource prospecting (*12*).

Two of the known geothermal resource areas in the Imperial Valley (the Salton Sea and the Brawley geothermal areas) are closely associated with the earthquake swarms that occurred in June and July. The Salton Sea geothermal area includes a site of recent volcanism; the Obsidian Buttes rhyolites erupted between 16,000 and 55,000 years ago (*13*). A swarm of microearthquakes was also recorded under the East Mesa geothermal anomaly in June 1973, on a tight array of six portable seismic stations of the University of California at Riverside (*14*). Most of these earthquakes, however, were too small to be recorded on four or more stations in the Imperial Valley network. To date, there is no evidence of microearthquake activity associated with the Dunes and Glamis geothermal anomalies in the vicinity of the Sand Hills fault (*15*).

The common occurrence of earthquake swarms in active spreading centers along mid-ocean ridges, the frequent swarms in presumed spreading centers in the northern part of the Gulf of California (*16*), and the close association of swarm activity in the Imperial Valley with geothermal anomalies and the Obsidian Buttes volcanic area are all consistent with earlier suggestions that the tectonic regime of the Gulf of California extends as far as the Salton Sea and that one or more spreading centers may exist under the Imperial Valley (*17*). The swarm pattern illustrated in Fig. 1, however, indicates that such spreading centers are more subtle features than the idealized pictures showing northeast-trending zones bounded by normal faults (*17*). One can easily imagine, for example, that the swarms near Brawley and the Brawley geothermal anomaly are associated with a spreading center between the Imperial and Brawley faults. The dimension of this spreading center perpendicular to the faults, however, is only about 10 km, or less than half the crustal thickness in this region (*18*). This, together with the composite fault-plane solution for events in the swarm, suggests to us that the opening of the spreading center takes place in a diffuse zone of en echelon strike-slip faults (leaky transform faults?) rather than along short normal faults perpendicular to the Imperial and Brawley faults.

The pattern of seismicity described above emphasizes that release of tectonic strain as seismic slip in the Imperial Valley is presently occurring along two zones: (i) a narrow zone that coincides with the Imperial fault in the central part of the valley and extends northward beneath Obsidian Buttes and the Salton Sea along the inferred location of the Brawley fault (ii) and the broader and historically more active zone extending from the central part of the valley to the northwest along the San Jacinto fault system (*2*). The relatively broad zone of aftershocks that occurred after the Borrego Mountain earthquake of magnitude 6.8 in 1968 (*19*) supports the evidence presented here that the San Jacinto fault is a wider, more complex fault zone than the Imperial fault and sections of the San Andreas fault in central California (*20*).

Independent evidence for a narrow zone of continuing right-lateral deformation along the Brawley fault near Obsidian Buttes is provided by repeated triangulation measurements at the south end of the Salton Sea between 1934 and 1972 described by Savage *et al.* (*21*). These measurements show that the benchmark at Alamo, 3.7 km northeast of Obsidian Butte, has been moving to the southeast at a steady rate of 0.5 cm/year with respect to the benchmark on Obsidian Butte. Both the seismic and triangulation evidence for continuing displacement north of the Imperial fault suggest that strain is accumulating along the Banning–Mission Creek fault between Desert Hot Springs, where an earthquake of magnitude 6.5 occurred in 1948, and the Salton Sea. Although this stretch of the Banning–Mission Creek fault has had no earthquakes above magnitude 4 since at least 1932 (*1*), it clearly has the potential for producing moderate earthquakes in the future.

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7. The secondary P wave arrivals follow the first arrivals by a constant interval of about 2 seconds at distances up to 60 km. Both sets of arrivals have apparent velocities of about 6.0 km/sec. In the interpretation in terms of focal depth it is assumed that the later arrival is reflected from the surface and then critically reflected at the basement-sediment interface. Gravity and seismic refraction data indicate that the sedimentary fill is as much as 6 km thick in the central part of the valley [S. Biehler, R. L. Kovach, C. R. Allen, *Marine Geology of the Gulf of California*, T. H. van Andel and G. G. Shore, Eds. (American Association of Petroleum Geologists Memoir 3, Tulsa, Okla., 1964), pp. 126–143.
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HL-A LD (Lymphocyte Defined) Typing: A Rapid Assay With Primed Lymphocytes

Abstract. *When human lymphocytes are cultured for 9 to 14 days with stimulating cells of a family member differing by a single HL-A haplotype they become "primed" to recognize specific HL-A LD (mixed lymphocyte culture) antigens. These primed lymphocytes respond specifically and rapidly when "restimulated" with cells of a person that contain the same LD antigens as those of the priming haplotype. Specific HL-A LD antigens can be detected within 24 hours by this primed LD typing.*

Rejection of a transplanted tissue or organ is initiated when the graft recipient's immune system recognizes genetically controlled "foreign" antigens on the grafted tissue. In humans a single genetic region, called HL-A or the major histocompatibility complex (MHC), appears to control the majority of strong antigens important in graft rejection (*1*). Minimizing antigenic disparity between donor and recipient (matching) for the MHC increases the probability that the transplant will survive.

Two methods are commonly used for detecting antigens associated with the major histocompatibility complex: (i) serological testing for HL-A SD (serologically defined) antigens, and (ii) mixed lymphocyte culture (MLC) tests that define disparity at an HL-A LD (lymphocyte defined) locus (or at several loci). In MLC tests, lymphocytes from one individual (the "responder") are cultured for 4 to 7 days with "stimulating" lymphocytes from another individual. To prevent their proliferation, stimulating cells are treated with mitomycin C or x-rays before they are mixed. When the stimulating cells are from unrelated persons or family members whose MHC is different from that of the responder, the untreated lymphocytes proliferate; this proliferation is assayed by incorporation of tritiated thymidine into the proliferating cells. All SD and LD loci are closely linked genetically, and within families they are inherited as a unit called a haplotype. However, since the SD and LD loci are genetically separable (*2*), both the serological and MLC tests are necessary in the evaluation of the MHC relationship between two individuals.

In transplants between SD matched persons who are not related, the frequency and severity of rejection generally have been much greater than in transplants between siblings with identical MHC's (*3*); moreover, most unrelated individuals who are SD identical are LD disparate when tested by the MLC assay. There is some evidence that MLC matching for HL-A LD antigens may be useful for predicting the success of a transplant (*4*).

Two major obstacles prevent the widespread use of MLC tests for transplant matching. (i) The result cannot be obtained in less than 4 to 5 days—a time that exceeds the limits for cadaver kidney preservation. (ii) Although MLC tests can identify individuals that are matched for their LD antigens, it does not indicate which specific LD antigens the two persons bear; therefore lymphocytes from all potential donors must be tested in MLC with lymphocytes from all potential recipients. This last problem would be alleviated by an "LD typing" method (analogous to serological typing that has been done for blood groups and HL-A SD antigens) that would identify specific LD antigens. Because LD typing would preclude the necessity of the recipient and potential donor being present in the same MLC-testing laboratory at the same time, the LD type of any potential tissue donor could be determined, and the donor organ or bone marrow could be sent to an LD matched recipient at any center in the world.

One approach to LD typing has been MLC testing with stimulating cells homozygous for an LD haplotype (*5*). Such cells should fail to stimulate cells of individuals bearing the LD antigens of the homozygous haplotype, since no foreign antigens are presented. LD antigens can be identified in this manner, but a homozygous cell donor must be found for every identifiable LD haplotype; rare LD haplotypes will be particularly difficult to obtain in homozygous form. Moreover, this test also requires several days. In other approaches to LD typing antiserums are used (*6*) in an attempt to define LD serologically. However, it is not clear whether these antisera actually detect the LD antigens.

We have developed an LD typing method, designated primed LD typing (PLT), that seems to have some advantages over these other methods. (i) PLT appears to recognize LD. (ii) Results are obtained in less than 2 days, usually within 24 hours. (iii) Even very rare LD haplotypes can be conveniently typed. This method is based on the finding (*7*) that lymphocytes stimulated in a primary MLC exhibit an accelerated secondary response when stimulated 14 days later.

PLT cells are prepared in MLC; cells of individual A are "primed" by stimulating