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SCIENCE

Transversely Aligned Seismicity and Concealed Structures

Alignments of earthquake epicenters reveal underlying structural complexities not seen at the surface.

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In studying seismicity and tectonics, both on the local and on the global scale, it has been usual to accept linear alignments of epicenters as the expression of active structures. Locally, they are expected to show the position of active faults; on the global scale they are taken to indicate the general trend of an active zone, within which individual faults may have divergent trends.

This procedure has met with some conspicuous successes. One of the most notable is identification of the mid-oceanic ridges as active structures, which began with the pioneer work of Tams (*1*), on the mid-Atlantic ridge, and later was extended to other oceans by numerous investigators (*2*). On the continents, the procedure has added new information, especially where active structures are buried under deep alluvium and sedimentary rock, as in Turkmenia and northern India.

The method is neither infallible nor universally applicable. In continental areas where epicenters of small earthquakes have been located over many years, the resulting maps often show a general scatter from which it is difficult to pick out the major active structures. Good examples are in the Caucasus and in parts of central Asia. For Japan, maps showing epicenters of small earthquakes recorded in recent years are somewhat less informative than those showing only areas heavily shaken by major earthquakes in the last few centuries. In southern California, on mapping epicenters of earthquakes that have occurred in the past 40 years, the phenomenon is very evident. If this were a submarine area, erroneous inferences might well be drawn, for the mapping gives little indication of the major San Andreas fault, while, of the other principal faults, only the San Jacinto is indicated by aligned epicenters.

Epicenter mapping on a world scale is of most value in exhibiting the principal active tectonic belts, but where seismicity is low the method is difficult to apply. The major disappoinment of this kind has been Antarctica, where even the intensive program during the IGY failed to identify local earthquakes which might add to our knowledge of Antarctic tectonics (*3*).

In this article I chiefly consider epicenter alignments that are transverse to the evident surface structures, or that at least intersect them at a high angle. It should be remembered that active structures exist in three dimensions and do not necessarily dip vertically. This truism is generally admitted, but its implications are nevertheless often neglected.

Three chief types of observations are discussed, distinct in kind but occasionally difficult to separate: (i) transverse belts of deep-focus earthquakes; (ii) transverse boundaries to seismicity in the active belts, including transverse limits to areas of aftershock epicenters; and (iii) epicentral alignments demonstrably or hypothetically associated with concealed structures having a transverse or divergent trend.

Deep and Intermediate Earthquakes

Most earthquakes in the deep and intermediate classes show satisfactorily regular relationship to active tectonic arcs. The occurrence of earthquakes at intermediate depths directly under chains of active volcanoes is often of assistance in tracing the active tectonic surface downward. Alignments of epicenters of deep shocks are frequently parallel to, and presumably associated with, lines of shallow shocks near the circumference of the arc, as well as parallel to the lines of intermediate shocks just noted.

The most conspicuous deviation from these regularities is the belt of shocks at depths from 300 to 400 kilometers that runs transversely beneath the Japanese island of Honshu (Fig. 1). Southward, this belt rather closely parallels a zone of small volcanic islands, submarine troughs, and epicenters of shallow shocks, including all the characteristic arc features, except for arcuate alignment, which is more evident farther south. The northward course of this belt, under Honshu and the Japan Sea, diverges progressively from the major arc of eastern Honshu, with which it is usually thought to be associated. It passes transversely under the generally east-west structures of Honshu, including the Median Tectonic Line. So does the northward extension of the active arc of the Ryukyu Islands; volcanoes and intermediate earthquakes help to trace it across Kyushu and into the Japan Sea. A similar tectonic situation, with less divergent trends, appears in the North Island of New Zealand, where block structures with active faulting cross evident arc structures at a low angle.

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Shallow Earthquakes and Related Structures

Shallow earthquakes are related to processes going on in the earth's crust. Transverse alignments of epicenters, especially on land, are often readily correlated with observed structures which interrupt or cross the main trends. Such are the east-west Transverse Ranges in southern California, which cross and appear to offset the northwest-southeast-trending San Andreas system of faults. In Japan, the zone involving the Neo Valley fault associated with the Mino-Owari earthquake in 1891 cuts transversely across Honshu and apparently offsets the Median Tectonic Line. The large active Atera fault has a similar trend; both show left lateral strike slip (*4*). East of these, and not quite parallel to either, is the transverse zone of the Fossa Magna; it is not a locus of epicenters, but it separates eastern and western Japan into two regions of different tectonic history, with past large relative displacement. In New Zealand the structures of the two main islands are separated by the transverse zone of Cook Strait.

Probably different in character from the other instances here cited are the transverse offsets of mid-oceanic ridges, now being generally attributed to transform faulting.

Examples of three-dimensional superposition at shallower depth, and usually on a smaller scale, can be identified only where structures and seismicity have been investigated in close detail, as in California. A well-studied active structure which is relatively simple at depth but has a complex surface expression is the Inglewood-Newport tectonic zone in southern California (*5*). At depth this is a fairly continuous zone of horizontal shearing and large vertical displacement, but in reaching the surface through deformed sedimentary strata the feature appears as a series of fractures aligned en echelon with respect to the main trend, and further complicated by very recent thrusting.

There are at least two well-known examples of active faulting at depth having produced earthquakes felt sharply at the surface, where the topography is that of a featureless plain: the Panhandle area of Texas (*6*) and the vicinity of Krasnovodsk near the Caspian Sea (*7*).

Observations of a sort which might be expected in other regions were made by the Soviet Caucasus expeditions, in a highland area southeast of Akhalkalaki. Here the expeditions found epicenters of numerous small shocks, but these originate beneath a thick blanket of Quaternary lavas, so that elucidation of the active structure would call for intensive geophysical exploration (*7*).

Boundaries of Active Areas

Less attention has been given to data suggesting relatively sharp boundaries for areas that include mapped epicenters, whether of long-term seismicity in a given region or of aftershocks following a large event. The possibility of recognizing such patterns depends on the completeness and precision of the data. A few mislocated epicenters of small or imperfectly observed shocks, entered on a general map, can entirely obscure the effect. Takeo Matuzawa for many years emphasized the confinement of aftershock epicenters to limited areas; a good collection of data for Japan is to be found in his book (*8*). He believes that the area of epicenters is generally elliptical. His maps show that, especially for earthquakes that have occurred in recent years, for which locations are more reliable, fairly definite lateral boundaries appear. He has also emphasized the point that, in a large majority of instances, the epicenter of the main shock is near one side of the aftershock area; this indicates a tendency toward unilateral rather than symmetrical extension of faulting, which appears to be characteristic of earthquakes in many regions (*9*).

The great Assam-Tibet earthquake of 15 August 1950 was followed by many large aftershocks. Epicenters for most of these, as well as for the main event, are given in the *International Seismological Summary* (*10*) (see Fig. 2). For convenience, the workers who prepare the *Summary* refer any later shock to an epicenter previously located, unless the times plainly do not fit; nevertheless, epicenters listed in the *Summary* for shocks in the Assam-Tibet region during the few months immediately following the earthquake spread over a definitely bounded area. The main shock is placed at 28.7°N, 96.6°E; this is near one boundary. The aftershock epicenters are located between 91.9°E and 97.4°E. The eastern limit is notably rectilinear, with trend transverse to the structural grain of the region, from 32.0°N, 95.0°E to 25.9°N, 96.8°E. (One spot represents a few shocks placed a little farther to the east, at 27.3°N, 97.4°E.) Shocks on 31 October at 32.0°N, 97.0°E and on 2 November at 30.5°N, 97.5°E began to define another transverse alignment, which was extended by other shocks in February and March. To the northwest, at 30.5°N, 91.5°E, is the epicenter of a very large earthquake that occurred on 18 November 1951, with one large located foreshock and many aftershocks.

The area spotted over by epicenters of aftershocks of the large Aleutian earthquake of 4 February 1965 has very sharp transversely trending limits both to the east and to the west. The authors of the report (*11*) comment upon this and conclude that it indicates a longitudinal subdivision of the Aleutian arc structure into blocks (see Fig. 3).

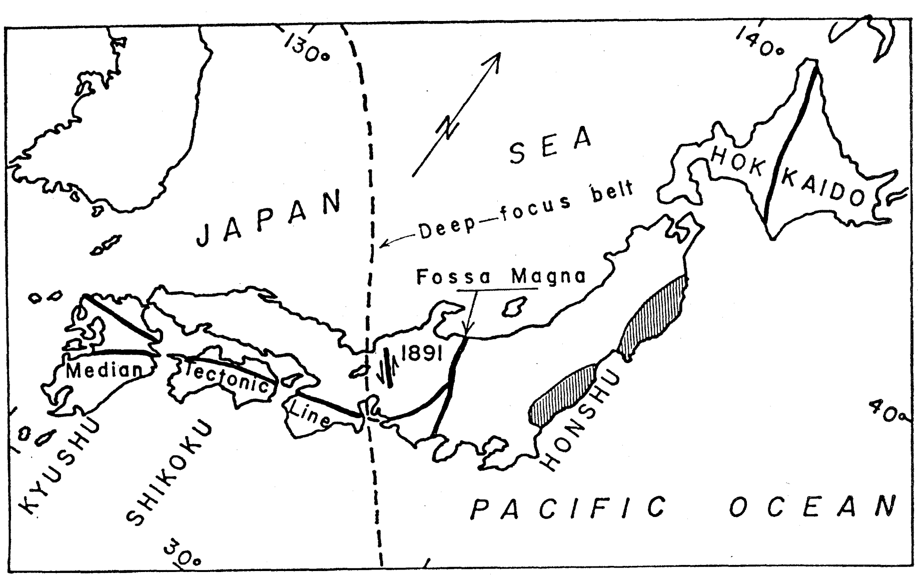


Fig. 1. Map of Japan, showing major tectonic lines and transverse belt of epicenters of deep earthquakes.

Epicenters of the immediate aftershocks of the Kern County, California, earthquake of 21 July 1952 were distributed over a quadrilateral area (*12*) (see Fig. 4). Initially the northwest boundary was quite definite, following the surface trace of the White Wolf fault, where fracturing reached the surface; adjacent epicenters chiefly represented shocks originating on the southeastwardly dipping fault surface, with a few at higher levels within the overthrust block. (Alignment farther to the northwest represents shocks beginning on 29 July.) For the present discussion it is noteworthy that the main shock was initiated on a part of the White Wolf fault which is deeply blanketed by the alluvium and sedimentary rocks of the southern San Joaquin Valley; even in its further course the fault, though previously identified at the surface, was largely obscured by landslides. The area of epicenters is bounded on the east by a line running roughly north-south, which corresponds to no known structures and is not sharply defined; small shocks in earlier and later years originated beyond it. The southwestern boundary of the area is comparatively definite and follows a known fault; although the San Andreas fault is only a few miles beyond this limit, the 1952 aftershock activity did not extend to it.

Similar examples can be cited from the now abundant data for the U.S.S.R. (*7*, *13*). The principal mapped activity of the Caucasus (Fig. 5) has a roughly northwest-southeast trend, parallel to the large structures, but it is fairly well bounded on the northwest by a transverse active zone, extending from east of Grozny to the vicinity of Akhalkalaki. The active zone in the Black Sea, off the Crimean coast, has sharp transverse limits to east and west. In Central Asia an alignment of epicenters near 79°E appears as an eastern boundary to an area of high seismicity, although the principal trans-Asiatic seismic belt extends much farther, to beyond 120°E.

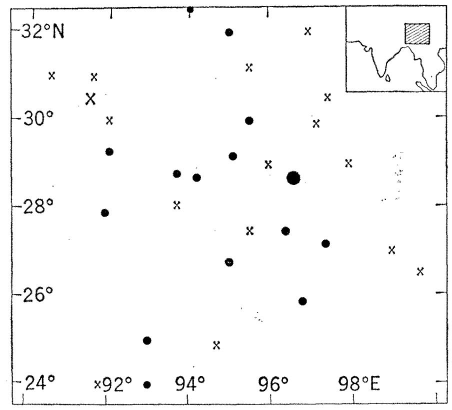


Fig. 2. Epicenters of earthquakes in Assam and Tibet, 1950–51. (Solid circles) Events of August and September 1950; (crosses) events of October 1950 through December 1951; (large circle) main shock (magnitude 8.7), 15 August 1950; (large cross) later large shock (magnitude 8), 18 November 1951. [Data from *International Seismological Summary*]

Internal Transverse Alignments

Besides those transverse epicentral alignments that appear as limits to active areas, there are some that trend across belts which are active on both sides. In examining maps for such features it is not easy to eliminate the element of accident. Obviously, if a number of spots are placed at random on a series of roughly parallel lines, transverse alignments are likely to appear. In the earlier Soviet literature some such alignments, which did not then seem to be accidental, were referred to as "earthquake paths." As more and better data have become available, these, as might have been expected, have tended to disappear. However, the large *Atlas* (*13*) and other regional maps still afford a few examples. One perhaps is the alignment near 79°E noted above. Another alignment crosses the seismic zones of the Caucasus region (Fig. 5) from near Erevan to the coast of the Caspian Sea at about 42°N. A transverse zone which, in part, is a boundary to activity trends northeast-southwest from a point southeast of Grozny, crossing the Great Caucasus and passing northwest of Tbilisi (Tiflis), extending to the epicenter of the large Akhalkalaki earthquake of 1899. In its western section it is traceable as a surface feature designated the Abul-Samsar fracture. It has been suggested that the numerous shocks southeast of Akhalkalaki may indicate a parallel active fracture. Another such feature, the Megrel fracture, has the same general trend; it was originally identified from study of the epicenters of a swarm of small earthquakes in 1941. Later its existence was confirmed by seismic exploration and by borings near Poti.

In Central Asia the epicenters of locally strong earthquakes in the Fergana basin form a northwest-southeast-trending zone paralleling known active faults about 150 kilometers distant but not close to any identified tectonic feature. Vvedenskaya (in *7*) notes this seismic zone as unexplained.

The "earthquake path" type of alignment is by no means restricted to the U.S.S.R. Wilson and O'Halloran (*14*) pointed out an interesting northeast-southwest alignment of historically known earthquakes in the central United States, where no corresponding structure can be identified with confidence. In a pioneer study of California earthquakes, Wood (*15*) indicated a roughly east-west transverse alignment which he called the Mare Island-Nevada-Carson line. After major earthquakes, with faulting, occurred in Nevada in December 1954, several writers drew attention to the remarkable alignment with adjacent zones in which faulting developed in 1915 and 1932, noting that the trend of individual faults diverged from that of the active zone as a whole. This zone can reasonably be extended to include the region of the great Owens Valley earthquake of 1872. Ryall, Slemmons, and Gedney (*16*) have called it the "Ventura-Winnemucca" zone, implying further extension, through the area of the Fort Tejon earthquake of 1857 (on the San Andreas fault), all the way to the coast near Ventura. This prolongation appears improbable and is not clearly indicated by the data.

In California there are instances of transverse alignment where the evidence is more precise. One such is provided by the Manix earthquake of 1947 and its aftershocks (*17*). Correlation of recorded times at stations in different azimuths led to the finding of a roughly north-south alignment of aftershock epicenters, whereas the surface structures, including the previously described Manix fault, trend roughly east-west. Small surface displacements along the Manix fault at the time of the earthquake were probably of secondary character, attributable to shaking or to local readjustment of stresses.

The Kern County earthquakes of 1952, referred to above, provide another instance of transverse alignment. Northwest of the White Wolf fault and roughly parallel to it, in the vicinity of Bakersfield, is a line of epicenters for shocks which began on 29 July, 8 days after the major event (see Fig. 4). This line passes through an area in which the surface and near-surface structures, well known from oil exploration, trend nearly at right angles to it. The only surface feature which might imaginably be associated with it is the gorge of the Kern River, which parallels the active line at a distance of a few miles.

Brune, Arabasz, and Engen (*18*) have investigated numerous small earth-

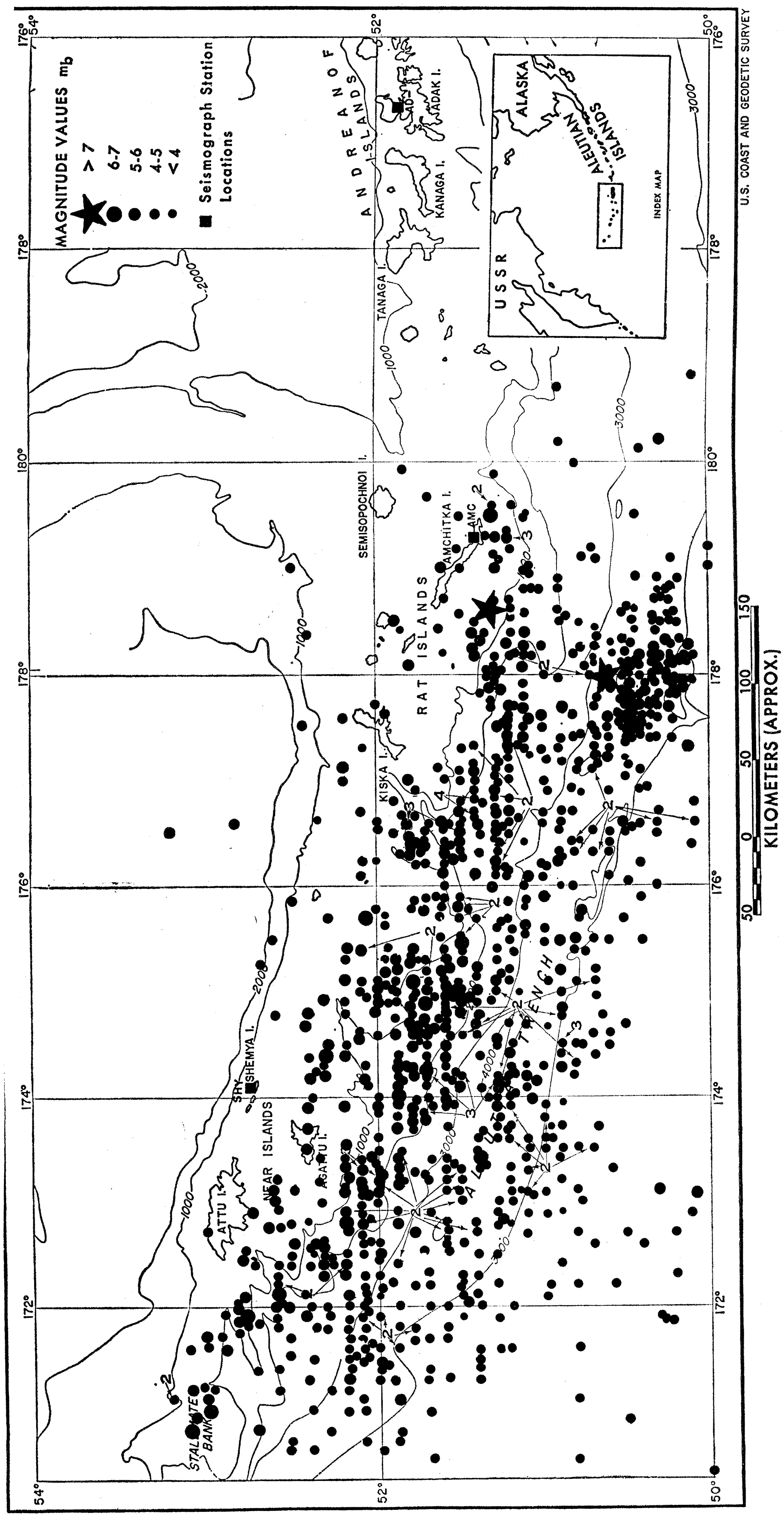


Fig. 3. Epicenters of the Rat Island (Aleutians) earthquake of 4 February 1965 and aftershock sequence through 20 April 1965. [Courtesy Environmental Science Services Administration and Coast and Geodetic Survey]

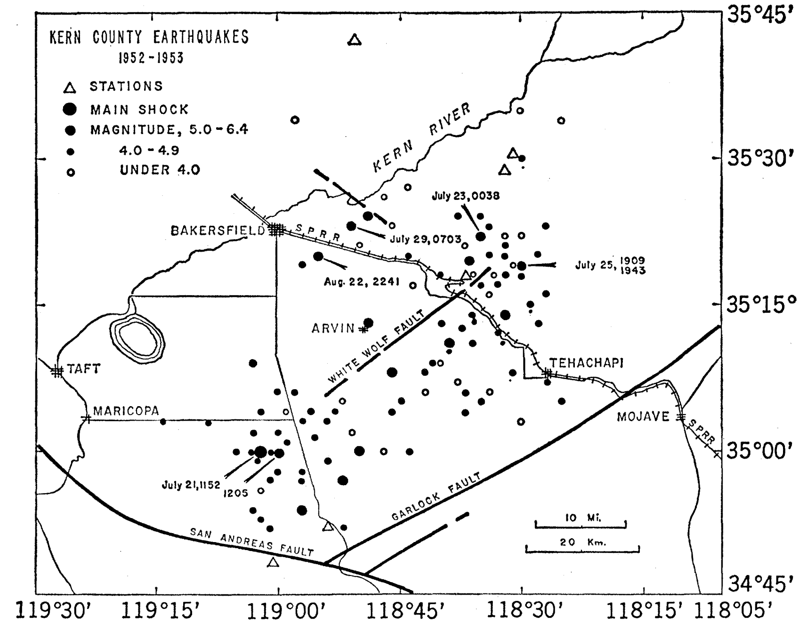
quakes in the Anza area of the San Jacinto fault zone. Most of these can be correlated with surface structures, but there is one alignment of epicenters for shocks at depths near 5 kilometers along which no fault or other significant structure could be identified, even after careful study on the ground.

Smith and Nordquist (*19*) find that epicenters for a swarm of minor shocks in the Santa Barbara Channel that occurred from June to August 1968 outline an area whose major elongation is transverse to the channel, and consequently to the trends of structures in the adjacent ranges on land to the north, as well as in the islands bounding the channel on the south. However, there are submarine ridges in the epicentral area which show the same transverse trend.

An apparent conflict of evidence with regard to the Nacimiento fault in west-central California should be noted here (*9*, *20*, *21*). The fault marks an important stratigraphic and tectonic boundary. Field geologists, until very lately, have been nearly unanimous in finding no surface evidence of displacement since the Miocene. On the other hand, a number of small-to-moderate shocks have originated in the general area, and one earthquake of magnitude 6, which occurred on 21 November 1952, was located both from instrumental data and from field observations in the vicinity of Bryson, close to the Nacimiento zone. This location is subject to more than the average uncertainty for the general region because of the unfavorable situation with respect to established seismological stations. The lack of surface evidence for current faulting may be explained by supposing that displacements are going on at depth but that their expression at the surface is very complicated and reduced.

Complementary Tectonic Trends

Explanation of features in a given area with two trends roughly at right angles is possible on the basis of simple assumptions—indeed, of assumptions which are probably too simple. In southern California three principal trends are evident, all associated with



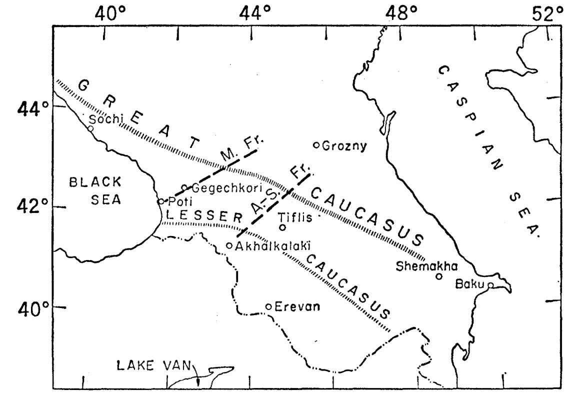


Fig. 4 (left). Epicenters of earthquakes in Kern County, California, 1952–53. The dates and times of the larger events are indicated. Fig. 5 (right). Location map of the Caucasus region, U.S.S.R. Abul-Samsar fracture (*A.-S. Fr.*); Megrel fracture (*M. Fr.*).

seismicity. The major trend, that of the San Andreas fault and some of its associated faults, is near N30°W to S30°E. Some other important faults, such as the Garlock, Big Pine, and White Wolf faults, trend about N60°E to S60°W. Still others are associated with the roughly east-west lineament of the Transverse Ranges. Regional shearing, implying north-south compression, is in agreement with the observed right-hand displacement on the San Andreas system of faults, the left-hand displacement on the Garlock and White Wolf faults, and the north-south thrusting in the Transverse Ranges. Both main diagonal trends can be seen in the faults and structures of the Mojave Desert area; the phenomenon of the Manix shocks could be interpreted to mean that, until comparatively late geological time, the stresses in that area favored development of northeast-trending fractures, while more recently a change in stress, not necessarily very great, has given preferential development to northwest-trending fractures, such as already exist west of the Manix area. This change in fracturing presumably is expressed chiefly at depth and has not yet broken its way up to the surface.

Two complementary trends are also observed in Japan, particularly in the zone of block faulting bordering on the Japan Sea. There, northeast-trending faults show right-hand displacement, and northwest-trending faults show left-hand displacement. In the Tango earthquake of 1927, faulting with both trends broke the surface. These observations, and other details of tectonics in Japan, also fit an assumption of general regional shearing. This is in agreement with general east-west compression, but it is in disagreement with some details of the Pacific arc structure, and particularly with the strong evidence of past north-south thrusting across the Median Tectonic Line.

The tectonic configuration of Japan should not be looked upon as merely a mirror image of tectonics in the California region; such treatment is rather misleading. For one thing, there is no longitudinal fault system in Japan that has the dominating significance of the San Andreas fault. A more valid comparison is one between California and New Zealand: the Alpine fault of the South Island (with northeast trend and right-hand displacements) is in many ways analogous to the San Andreas fault zone (*22*, *23*).

Conclusions

Alignments of epicenters transverse to obvious structural trends, and the bounding of epicentral areas by limits also transversely oriented, are probably explainable in the same way that complementary trends of faulting are, as discussed above. They may be described in the familiar terms of diagonal shearing in two roughly orthogonal directions, belonging to a single system of stress and strain. Objectors have regularly pointed out that the angles between conjugate systems of this kind are usually not those observed in the fracture of laboratory specimens. Quite apart from questions of scale, and of proper application of the principles of mechanical similitude, there is here a tacit but improblable assumption—namely, that the stresses now acting to cause strike-slip displacements along active faults are of the same character, and have the same orientation, as those which originally produced the faults. There is not much ground for insisting that the present orientation of principal axes of stress and strain, or the present directions of crustal displacements, must be identical with those of 50,000 years ago, much less with those of a million years ago.

Present dislocations in old structures are probably taking place along lines of weakness originally developed in remote geological time and now rejuvenated by the development of local strains sufficient to overcome accumulated resistance. Simple relations of present strain axes with the ancient fractures are, then, hardly to be looked for.

Significant changes in comparatively late geological time are suggested by at least three instances in which major faults appear to have been offset by faulting with the complementary trend. (i) Hill and Dibblee (*24*) identify the Big Pine fault as an extension of the Garlock fault, offset along the San Andreas fault. (ii) The Median Tectonic Line of Japan, along which there has been not only strong thrusting but also apparently recent right-hand strike slip (*25*), has a left-hand offset in Ise Bay, where it crosses the extension of the Neo Valley fault system associated with the great earthquake of 1891. (iii) The

Alpine fault of New Zealand, with generally right-hand strike slip, appears to have a left-hand deflection (*23*). These and other indications of contemporary tectonic change are discussed elsewhere (*26*).

Summary

Earthquake origins are distributed in three dimensions, but ordinary mapping displays only two. Lines of epicenters often trend transversely with respect to the larger surface structures. This is true not only of deep-focus earthquakes but also of ordinary shallow shocks.

Such transverse alignments are often associated with transversely trending boundaries of active areas, defined by all known events during an interval, or by the aftershocks of a given large earthquake.

Both types of transverse trends are presumably due to fractures cutting across the principal structures. In many areas they parallel alternative trends evident elsewhere in the general region, which is then characterized by two principal trends crossing at a high angle. Such conjugate trends are often taken as expressing alternative directions of shearing under approximately uniform regional stresses. As such, they need not conform closely to present strains and tectonic dislocations; rather, they represent established zones of weakness of considerable geologic antiquity. Such zones of weakness may have originated under conditions differing widely from the present ones, but they will still determine the lines along which current dislocations are taking place.

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Computer-Assisted Design of Complex Organic Syntheses

Pathways for molecular synthesis can be devised with a computer and equipment for graphical communication.

E. J. Corey and W. Todd Wipke

Introduction

This article is concerned with the general theory of chemical synthesis and with the application of machine computation to the generation of chemical pathways for the synthesis of complicated organic molecules. The basis for the approach which has been developed comes in large measure from the methods used by chemists in the solution of certain types of synthetic problems. It is appropriate, therefore, to begin with a brief description of the general processes by which chemical syntheses of organic molecules are devised.

The number of discrete organic chemical compounds which are capable of existence as stable entities can be described conservatively as astronomical. The simple formula $C_{40}H_{82}$, which is "saturated" by univalent hydrogen so that only chains of atoms are possible, has been calculated to permit the joining of carbon atoms in 63,491,178,805,831 different ways with regard to topology in two dimensions (*1*). The number of possible and distinctly different molecules of formula $C_{40}H_{82}$ is actually far greater because of the three-dimensional (stereochemical) characteristics of organic structures. For instance, the fact that four single bonds to a carbon are normally tetrahedrally directed in space allows any four unlike groups to be attached to that atom in two different ways. The profusion of organic structures becomes still more impressive when consideration is given to three additional molecular characteristics: first, that organic molecules can contain many thousands of atoms; second, that a large number of the known elements can bond to carbon and to each other in a molecule; and third, that cyclic connections within molecules can lead to a prodigious variety of rings or networks of atoms.

A large majority of the millions of

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