MODELING CALIFORNIA EARTHQUAKES AND EARTH STRUCTURES

Seismology has burgeoned into a modern science—force-fed by federal funding to advance technology for detecting underground nuclear explosions and predicting earthquakes, and by industry to improve tools for gas and oil exploration. Computers, seismic instrument systems, telemetry, and data reduction have played key roles in this growth.

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In conjunction with modern technology, the sophisticated methods of modern seismology now enable earth scientists to peer into an opaque earth. The purpose of this article is to discuss some of those tools and the information they reveal about earth processes and structures. The subject is broad; hence the focus is narrowed to several studies centered in three regions of California, the best-studied seismically active state in the nation.

The article begins with a sobering discussion of the potential impact of a major quake in California. Indeed, a disastrous shock with severe human and economic consequences is expected within the next generation, but good planning could alleviate some of the hardship. Next, for historical perspective, a few selected milestones are sketched to show how rapidly seismology has advanced in the past 25 years. In order to provide a technical perspective, the two most extensive seismic instrumentation systems in California are described, illustrating a complex system of instrumentation, telemetry, data reduction, and computers. Finally, a sampler of seismic studies that would have been inconceivable before the present era of instrumentation and computer systems is presented, centering on three regions of California (Figure 1): the Imperial Fault in the Salton Trough (site of the best-documented earthquake in history), the Long Valley Caldera east of the High Sierras (where a potentially explosive volcano threatens to cut off Owens Valley water to Los Angeles), and the Big Bend (a puzzling change in direction of the San Andreas Fault through the Transverse Ranges of southern California).

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FOREWARNED IS FOREARMED: A HYPOTHETICAL CATASTROPHE IN CALIFORNIA

Many of California's most attractive features are due to the same tectonic processes that we generally consider destructive. A geological time-lapse film, beginning around 140 million years ago, would show the Pacific Ocean lapping against the western slope of the ancestral High Sierras, a softly undulating range of low-lying mountains not at all like the lofty granite peaks of today. As millions of years roll by, leading edges of the Farallon and Pacific plates would bump and jostle offshore against the western edge of the North American plate, causing subduction of oceanic plates and crumpling and upward folding of the marginal terrain, gradually extending the continental plate by aggregation of island arcs and new mountains arising out of the sea to the west. The sea would advance and retreat repeatedly, but ultimately retreat farther and farther to the west. We would see volcanoes exploding at various places on land and offshore, and massive lava flows rushing out over the ancestral Sierras. At stages, semitropical forests would develop in central California around the marshy edges of the Great Valley leaving coal deposits, then an ice age and glaciers would appear scouring the High Sierras rising ever higher to the accompaniment of violent earthquakes. We would see the final draining of sea water from the Great Valley, the carving of the Golden Gate, and the encirclement of San Francisco Bay. What we would not see is the swallowing of the Farallon plate beneath the shores of southern and central California, an invisible process that continues today north of Cape Mendocino. But, when the present Pacific plate reached California,

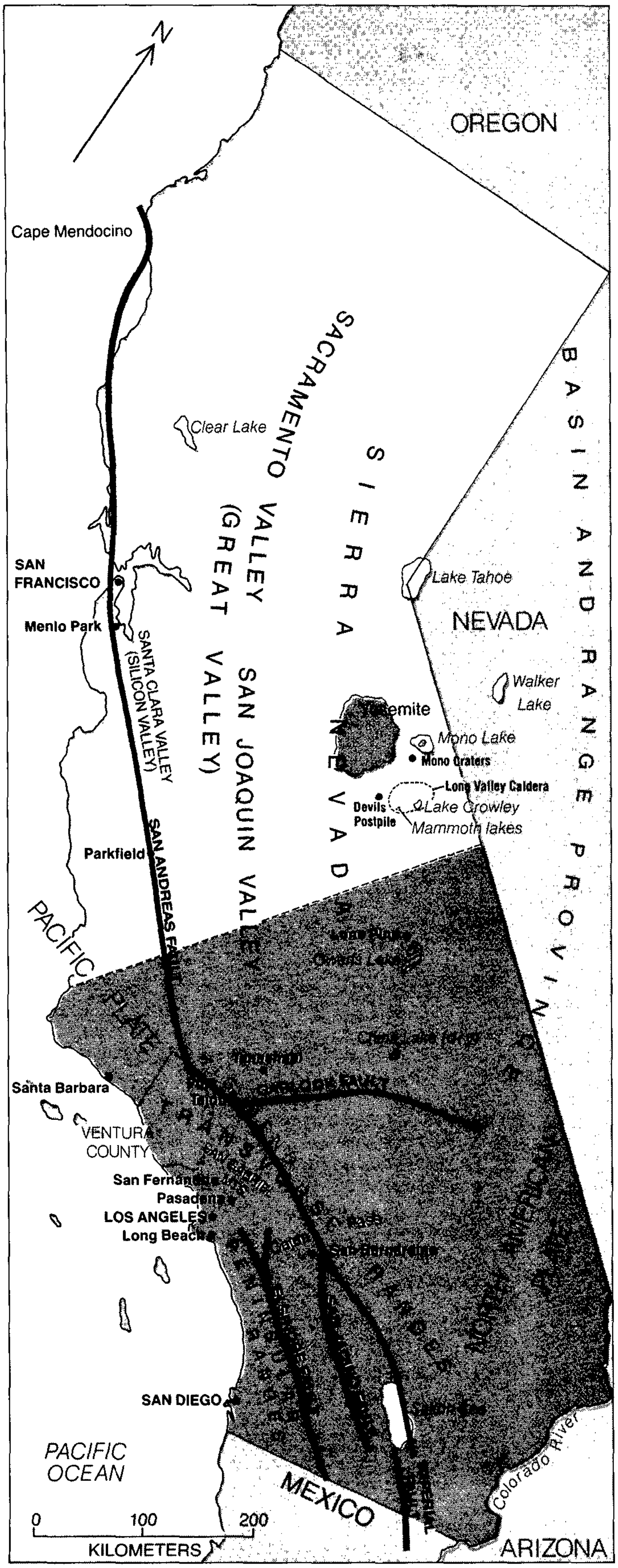
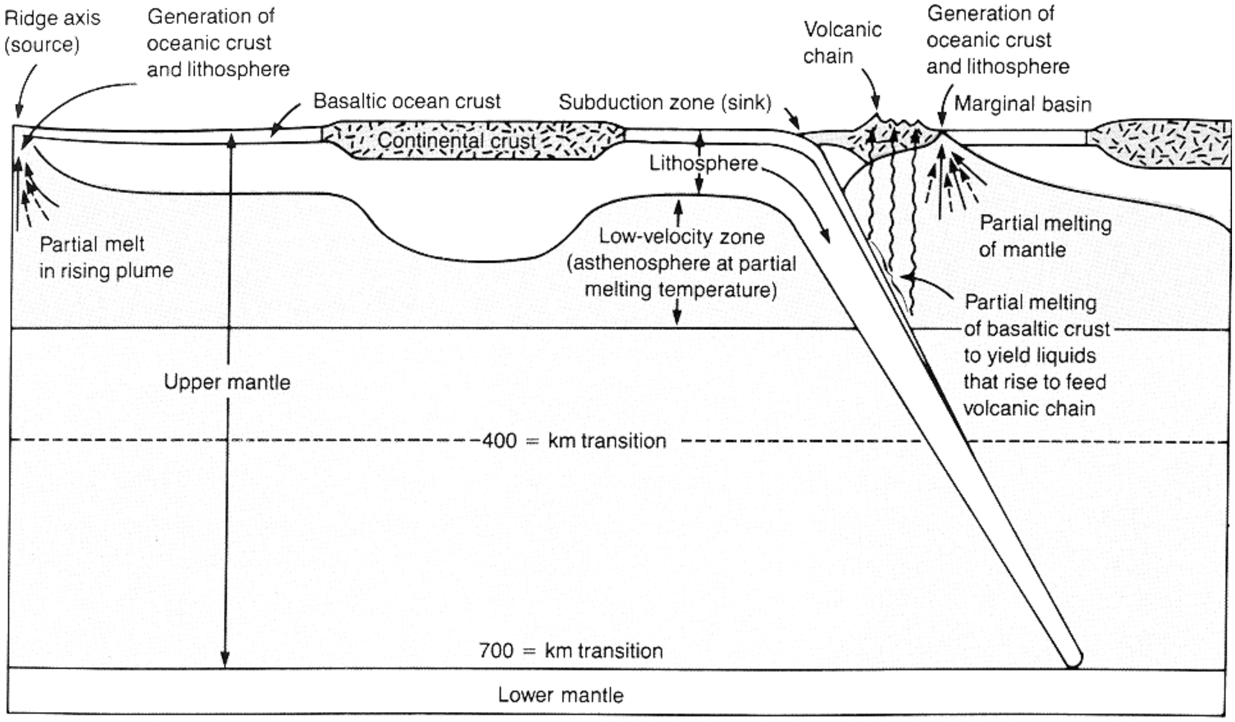


FIGURE 1. Map of California and Surrounding Landscape Showing Some Locations and Geological Features Referred to in the Text

The light background north of the Transverse Ranges approximates the region instrumented by the USGS California Seismological Network (CALNET), and the darker background to the south approximates the region instrumented by the Southern California Array, operated in cooperation by the USGS and Caltech. Owens Lake at the southern end of Owens Valley, designated in the figure as a drainage basin, was until early in the century a large body of alkaline water more caustic than Mono Lake; it has been reduced to an extensive alkali flat by diversion of the Owens River into the Los Angeles Aqueduct.

shoving the Farallon plate beneath the continent some 20 million years ago, the subduction of oceanic plates changed to horizontal slip south of Cape Mendocino, creating the highly visible San Andreas fault system. In the final sequence, we would see the edge of California west of the San Andreas gliding briskly northward (see Figure 2). The film would conclude with dramatic views of the major landmarks of California, a region justly famous for its natural resources: mountains, beaches, deserts, lakes and rivers, abundance of minerals, and fertile plains. California's beauty and wealth are due to tectonic processes. Yet even today these same relentless processes also cause the catastrophes associated with earthquakes and volcanoes.

The most famous earthquake in American history was that of 1906 in San Francisco. Two other California earthquakes at least as large also occurred within historical times, but are less well known because less damage was associated with them. The great quake of 1857, sometimes referred to as the Fort Tejon earthquake, produced approximately 350 km of faulting all the way from Parkfield in Monterey county southeast through Fort Tejon in the Tehachapis to Cajon Pass in San Bernardino county. In fact, some regions of the Tejon fault slipped as much as 11 m, compared to 7 m for the earthquake of 1906. The Owens Valley earthquake of 1872, centered near Lone Pine, may have been the largest of all. In this century, there have been



According to plate tectonics, the earth's *lithosphere* (strong outer layer) is divided into about a dozen large contiguous plates, each of which is in slow motion corresponding to convection occurring within the mantle beneath the plates flowing plastically at a rate measured in centimeters per year. Earthquakes occur when one plate scrapes against another. In special areas of the earth where plates diverge, called midocean ridges, molten material (magma) rises convectively from the earth's mantle and fills the gap between the diverging plates, creating tractions that pull the ocean ridge apart. Fresh magma flows into the cracks, where it adheres and solidifies within the ridge. When an oceanic and continental plate converge (as at the western boundary of South America), the denser ocean floor is driven (subducted) beneath the continent, creating an ocean trench associated with the line where subduction begins. As the ocean plate descends into the hot mantle of the earth, it partly melts, and lighter portions float back up toward the surface, causing volcanic eruptions and the uplift of mountains. It is a matter of debate whether convection drives the plates, or gravitational forces drive the convection by pulling down upon the uplifted ocean ridges ("ridge push") and pulling the descending slabs down ("slab pull"). Although easy to grasp in principle, the modern theory of plate tectonics was not easy to perceive and verify. Geological processes are notoriously slow, and the global patterns in which they operate become apparent only when observed systematically on a worldwide basis. (After Dewey, J.F. Plate tectonics. *Sci. Am.* (1972).)

FIGURE 2. Plate Tectonics

smaller destructive earthquakes in Santa Barbara, Long Beach, Tehachapi, San Fernando, Imperial Valley, and Coalinga.

Based on the observed regularity of earthquakes and other structural factors of known California fault systems, earth scientists expect an earthquake comparable to that of 1906 to strike somewhere, probably in southern California, within the next 30 years. A major earthquake near Los Angeles or Silicon Valley, on the scale of 1906, would have a terrible impact on the economy of California and on the nation. Such an earthquake is inevitable; the only question is when. Although earthquakes cannot be prevented, they can be anticipated and planned for.

The Federal Emergency Management Agency (FEMA) is responsible for developing contingency plans for responding to and planning the orderly recovery from an earthquake disaster as well as creating emergency policies in anticipation of such a disaster. Key to the planning process is a modular system of computer programs being developed to provide rapid and comprehensive analyses of earthquake impact for any designated earthquake epicenter and magnitude in California.

The programs specify the region affected by the earthquake and, for each commercial sector, estimate direct and indirect losses including (1) the physical damage caused by ground shaking; (2) the percent of loss of function including the time required to restore facilities to preearthquake usability; (3) the loss expected to arise from collateral hazards such as inundation, ground failure, and fire; and (4) the number of injuries and fatalities.

To assess the impact of a disaster on the U.S. economy, a joint supply-side/demand-side economic impact model was developed by the Engineering Economics Associates of Berkeley and is now being implemented by FEMA. It measures the economic flow between industries and various commercial sectors within the United States, as affected by the region of impact. The model is based on a classification known as the Standard Industrial Classification of the U.S. Input–Output Table Update for 1977.

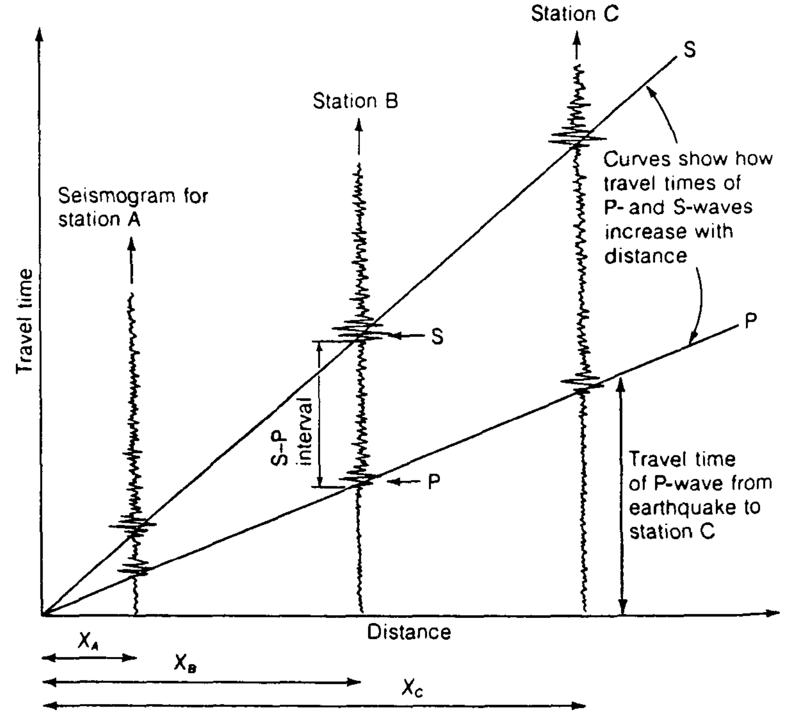
There are three major input components: (1) a ground-shaking model, provided by the USGS, to determine the geographic distribution of seismic intensity resulting from a given location and extent of faulting; (2) data on the distribution of man-made structures, including their value, economic functions, and the number of occupants as a function of time of day; and (3) an engineering model, developed by the Applied Technology Council of Palo Alto, that gives the degree of damage to each structure type as a function of seismic intensity and estimates the time required to fully recover the function of the damaged facilities.

Thus every engineering structure, every economic activity housed by every structure, and every component of regular dollar flow in California are classified and accounted for by the FEMA system. Because the system is modular, improvements in data and modeling capability may be incorporated as they become available, without adverse affect on the functioning of the overall system.

Initial scenarios are planned for developed regions in California where high probabilities exist for large-to-great-magnitude earthquakes in the near future. Preliminary studies have yielded ominous results. Steinbrugge and others (1981) found that direct property losses for a magnitude 7+ shock centered in highly developed regions of Los Angeles or in the San Francisco Bay region would be in the $40–60 billion (1980) range, an order of magnitude more damage than the worst hurricane in U.S. history (Hurricane Agnes, 1969). But that may be just the tip of the iceberg. What has not been included are estimates of the *indirect* losses, for example, unemployment and loss of supplies and services due to shutdown of factories, disruption of lifelines such as highways, water, and electric-power communications and sanitation, disruption of banking, and loss of the tax base. According to a pilot study by Bob Wilson of FEMA to assess the long-term economic impact, a major quake in the Palmdale bulge region near Los Angeles would result in indirect losses of 7 or more times the direct property losses. If this indirect-to-direct loss ratio were to hold for a magnitude 7+ in Los Angeles or the San Francisco Bay area, the total loss would be staggering: as much as $1 trillion or more. And that says nothing of the loss of human life. It is obvious from such studies that plans for preassessing and mitigating earthquake disasters should receive high national priority (see Figure 3).

A TOUCH OF HISTORY

The seeds of the modern age of computational seismology were planted on September 2, 1959. That is the date when the Advanced Research Projects Agency (ARPA) began funding research into seismic detection of underground nuclear explosions. An early ARPA objective was to stimulate the field of seismology across a broad range of topics (including improvements in seismic instrumentation and intensified studies of large earthquakes recorded worldwide, microearthquakes recorded by local networks, and earth crustal structure based on active experiments with explosive sources) and institutions (including universities, governmental research agencies, and private research corporations). When ARPA began to channel its support into studies that held the most promise of solving its limited objective of nuclear test detection, other agencies adopted promising elements of the program that supported their missions: for example, the U.S. Geological Survey for earthquake-hazard reduction (including earthquake prediction) and the National Science Foundation for engineering seismology and seismological research in support of graduate training in seismology. These programs have continued to interact strongly with each other and with parallel research programs in the petroleum exploration industry on the critical problems of instrumentation and data reduction and analysis. All have received invaluable ongoing stimulation from develop-



Earthquake locations are determined by using basic facts about elastic wave propagation. An earthquake radiates energy in the form of P-waves, which are longitudinal vibrations like sound, S-waves, which are transverse vibrations that occur only in rigid material, and surface waves, which are confined, like ocean waves, to the surface of the earth and do not travel deep within. The P-waves travel some 73 percent faster than the S-waves and arrive at surface locations first. Because the earth's elastic properties vary with depth (and to a lesser degree with latitude and longitude), P- and S-waves are refracted (bent) as they move out from the center of the quake toward distant points. For most practical purposes, geometric ray-tracing techniques may be used to plot the course of a P-wave through the earth from the earthquake source to a point on the surface. An integration along the ray path, taking into account the velocity of the wave at each point, determines the travel time. The time and location of an earthquake may be estimated either by observing P-wave arrivals timed at several (at least four) seismographic stations, and finding the point in the earth whose ray-path travel times to each seismograph are most consistent with the observed data, or by observing separations between P-wave and S-wave arrivals at three seismographic stations (see figure). Note that, for location of an earthquake, only wave arrival times are needed. The waveform itself is of no concern. If more information is required, such as the direction of slip and magnitude of the earthquake, then more of the waveform must be considered, namely, the polarity of the wave and the maximum amplitude. (From Press, F., and Siever, R. *Earth*. W.H. Freeman and Co., San Francisco, Calif., 1982.)

FIGURE 3. Locating Earthquakes

ments in microelectronics and computers that have permitted simpler, more effective solutions to old data-collection and analysis problems and have opened possibilities for comprehensive automatic data-collection and analysis systems that were hardly dreamed of a decade ago.

The introduction of computers in the early 1960s for locating earthquakes was an important step forward, but there were still serious delays in the collection and reading of seismic data for analysis. Seismograms were recorded locally at the seismometers, and phase readings or seismograms were sent by mail to a central laboratory for further analysis. Weeks or months were consumed in this process.

Computers without a convenient source of data are like Pegasus without wings. Automated instrumentation and telemetry systems are necessary adjuncts of modern seismology. Instrument arrays come in all sizes and shapes, from a few cassette recorders that can be deployed easily at the scene of a disaster to track aftershocks, to regional networks of permanently installed seismometers that transmit signals continuously via telephone lines or microwave. The instruments themselves are highly varied. There are vertical component analog seismometers, x-y-z component digitizing accelerometers, and mechanical devices that aim a wiggling light beam at an advancing film. Some historical examples of telemetered networks are mentioned in the history sidebar.

An exciting new application of computers to seismology involves microcomputers to control various components of data-acquisition systems. Electrical signals generated by a seismometer as the ground shakes must be calibrated, timed, amplified, filtered, and converted to a digital signal for processing and analysis on a digital computer. Microcomputers provide a powerful means of controlling such hardware components. Recently developed data-acquisition systems such as that developed at the U.S. Geological Survey by R. D. Borcherdt and his colleagues are designed to isolate system functions on a uniform set of hardware modules via a general computer bus. This design approach has permitted the development of a General Earthquake Observation System (GEOS) that is easily adapted to a wide variety of seismic experiments including seismic refraction studies, near-source strong motion studies, and teleseismic studies for the purpose of nuclear detection. Isolation of system functions on separate modules permits straightforward adaptation of the system to improvements in technology. This application of microcomputers has resulted in construction of data-acquisition systems that within the last two years have yielded data sets of unprecedented quality on experiments ranging from strong motion studies with ground motions as high as 1 g in acceleration to earth strain studies with motions as small as 5×10^{-11} strain units. As a result of advances of this type, the Committee on Opportunities for Research in the Geological Sciences

RANDOM HISTORICAL REFERENCE POINTS

1928: Seismological Method of Determining Earthquake Source Mechanism
Perry Byerly, at UC Berkeley, formulated the seismological method of estimating fault planes from distant recordings, enabling scientists to determine fault motions and stress patterns at distant quake locations. The method provides a mathematical foundation for modern calculations of earthquake fault mechanisms by computers.

1949: Remarkable Early Effort in Radio Telemetry
P. S. Gane led a long-term effort to study rock bursts in deep lode mines of Witwatersrand, South Africa. Data from local analog instruments, telemetered over distances of several kilometers to a central analysis station, were used to locate spontaneous explosions of distressed rocks in deep lodes.

1958: Telemetered Networks
Continuous telemetry of analog seismic data from the field to a central recording site was first introduced as a means of improving network performance and accelerating traditional analysis of the records. By 1958 a four-station telemetered network was operated by the USGS around the summit of Kilauea Volcano in Hawaii; and substantial parts of sparse regional networks operated by UC Berkeley in northern California and Caltech in southern California were on telemetry by 1961 and 1967 respectively.

1960: Computer Program to Locate Earthquakes
Bruce Bolt, now director of UC Berkeley's Seismographic Stations, in 1961 reported the use of a computer for carrying out the calculations required for locating distant earthquakes, using procedures similar to ones described by Geiger in 1910. At about the same time, J. M. Nordquist at Caltech developed a least-squares program for applications to local earthquakes; Caltech locations from 1961 to the present have used this program.

1963: Seismically Delineated Tectonic Plate Boundaries
Lynn Sykes at Lamont and Robert Engdahl at National Oceanic and Atmospheric Administration were quick to apply computers to accurately locate thousands of oceanic earthquakes around the globe. Their accurate delineation of faults beneath the seas drew early attention to the importance of midocean ridges and continental trenches as tectonic plate boundaries.

1965: Large-Scale Computer-Based Seismic Array
The first large-scale application of computer technique in the recording and analysis of large seismic networks was developed in the nuclear test detection research program for the LASA (Large Aperture Seismic Array) network in Montana. LASA was a roughly circular 300-km-wide array of 300 to 500 seismometers arranged in 21 subclusters of 16 to 25 seismometers each. The LASA network was used primarily for the detection of short-period body waves from teleseismic sources. The process was carried out digitally.

1967: Empirical Demonstration of Planar-Fault Surface
In the fall of 1965, the USGS began a detailed study of the San Andreas Fault in central California. The first seismic station was set up at Gold Hill, near Parkfield. In June 1966, a magnitude 5+ earthquake near Parkfield produced a zone of ground rupture that split right past the USGS seismic station at Gold Hill. Following the quake, eight new low-power portable stations were targeted on the southern part of the 1966 zone of surface rupture in an effort to map the fault rupture surface underground by the small aftershocks that might occur along it. The experiment, directed by seismologist Jerry Eaton, was the first in which locations were computed accurately enough to confirm that earthquakes result from slippage of the earth along a planar fault.

1970–: Large-Scale Dense Regional Networks
Large regional telemetry networks were developed under the Earthquakes Hazard Reduction Program and its close antecedents during the 1970s. The number of telemetered stations in the USGS northern California network (Calnet) and the cooperative USGS-CIT southern California array rose to 189 and 94 respectively by 1975, and to 303 and 211 respectively by 1982. Data from these large dense networks overwhelmed traditional methods of analysis and forced the development of more effective, computer-based methods for recording and analyzing the data.

The first large-scale effort to develop automatic processing for a dense regional network was carried out on the northern California telemetered network by Sam Stewart in the early 1970s. Stewart's system employed a CDC-1700 to analyze 110 stations in real time. Detection and timing of events, collation of data from stations across the network to distinguish earthquakes from noise, and calculation of the earthquake hypocenters were carried out on this one machine. Though successful as a prototype, this system was not sufficiently flexible and economical to expand to cover the much larger seismic network that then existed in northern California.

1982: First Regional Digitally Telemetered Microearthquake Array
The Anza array monitors the San Jacinto fault region in southern California. It comprises 10 three-component seismometers that continuously transmit digital signals via microwave to a seismological laboratory at UCSD's Scripps Institution in La Jolla. Seismic signals are recorded with a broader frequency bandwidth and dynamic range many times that possible in an analog system. The goal at Anza is to use the entire waveform to unravel the source properties of each earthquake and synthesize them into a composite picture of the evolving forces that drive the fault.

WHAT IS SEISMOLOGY?

Seismic waves bend, reflect, scatter, slow down, speed up, and fade in response to the media through which they propagate. Although such behavior seriously distorts earth imagery and complicates analysis, it is this very sensitivity of seismic waves to inhomogeneities in the earth that makes them carriers of valuable hints of the materials and structures through which they have traveled.

Wave probes are produced randomly by earthquakes and volcanoes, or purposefully by explosions or shaking machines (as in gas and oil exploration). To detect them, networks of seismic instruments serve as sensors to measure and record ground motion at select points of the earth's surface. The data may be either collected on magnetic tape then physically transported to a central processing location, or telemetered directly via phone lines or microwave, for reduction and computer analysis.

The primary tools of analysis are *forward methods* and *inverse methods*: Forward methods compute a simulated response of the earth to a given wave source, based on hypotheses about elastic properties of the intervening earth and rupture properties of the seismic source. To a first approximation, the laws governing P- and S-wave propagation are very similar to the laws of geometric optics, with the P- and S-wave velocities taking the place of the index of refraction in optics. Hence, usually, the methods of geometric optics may be used. In more exacting studies, the elastic wave equation may be used to model propagation more accurately, usually requiring a great deal of computation. The resulting waves are called *synthetics*. With either rays or synthetics, the computed wave behavior depends on the earth and source hypotheses. A comparison of the simulated response and the empirically measured ground response is made to support or reject the hypotheses.

Nonlinear inverse methods assume that the earth structure and seismic source under study are reasonably well known, so that corrections to the a priori model may be determined from the data by linear inverse theory. Although inverse methods are elegant in theory and efficient computationally, they often require more a priori knowledge of the earth than do the forward methods.

It is interesting to note that in many studies only the wave travel times are of interest: The waveform itself is discarded. When more information is required, relatively more of the wave may be used. In some advanced studies (as in Archuleta's study reviewed below), in which fine-grain details of earth structure or fault rupture are sought, much of the waveform may be simulated.

It is clear that computers are necessary to carry out the massive calculations required by seismology. But, equally important, seismic imaging is an underdetermined problem, which means that similar results could be achieved by more than one set of hypotheses for the earth and rupture. Hence great amounts of accurate data are needed to constrain the possibilities within reasonable bounds. That is why automated instrumentation systems have become so important in modern seismology.

(1983) has recommended the development of a national instrumentation resource for the earth-science community, comprising as many as 1000 instruments for studying the continental lithosphere, and expansion and improvement of the worldwide network. The microcomputer offers the possibility of developing hardware modules that can be configured in a variety of ways to serve these as well as most seismic data-acquisition needs.

TWO SEISMIC NETWORKS: CALNET AND THE SOUTHERN CALIFORNIA ARRAY

Before moving on to a sample of seismic studies centered in the three California regions, we will briefly describe the two largest regional seismic networks in California: the USGS Northern California Seismological Network, known as Calnet, and the Southern California Array. Most of the instruments in these two networks are inexpensive single-component (vertical) seismometers that transmit analog signals continuously via phone lines to their respective data-reduction centers: the USGS in Menlo Park or the Caltech Seismological Laboratory in Pasadena. Although neither network exhibits advanced instrumentation, each is extraordinarily useful because of the large amounts of regional data obtained and the automated data-reduction techniques employed.

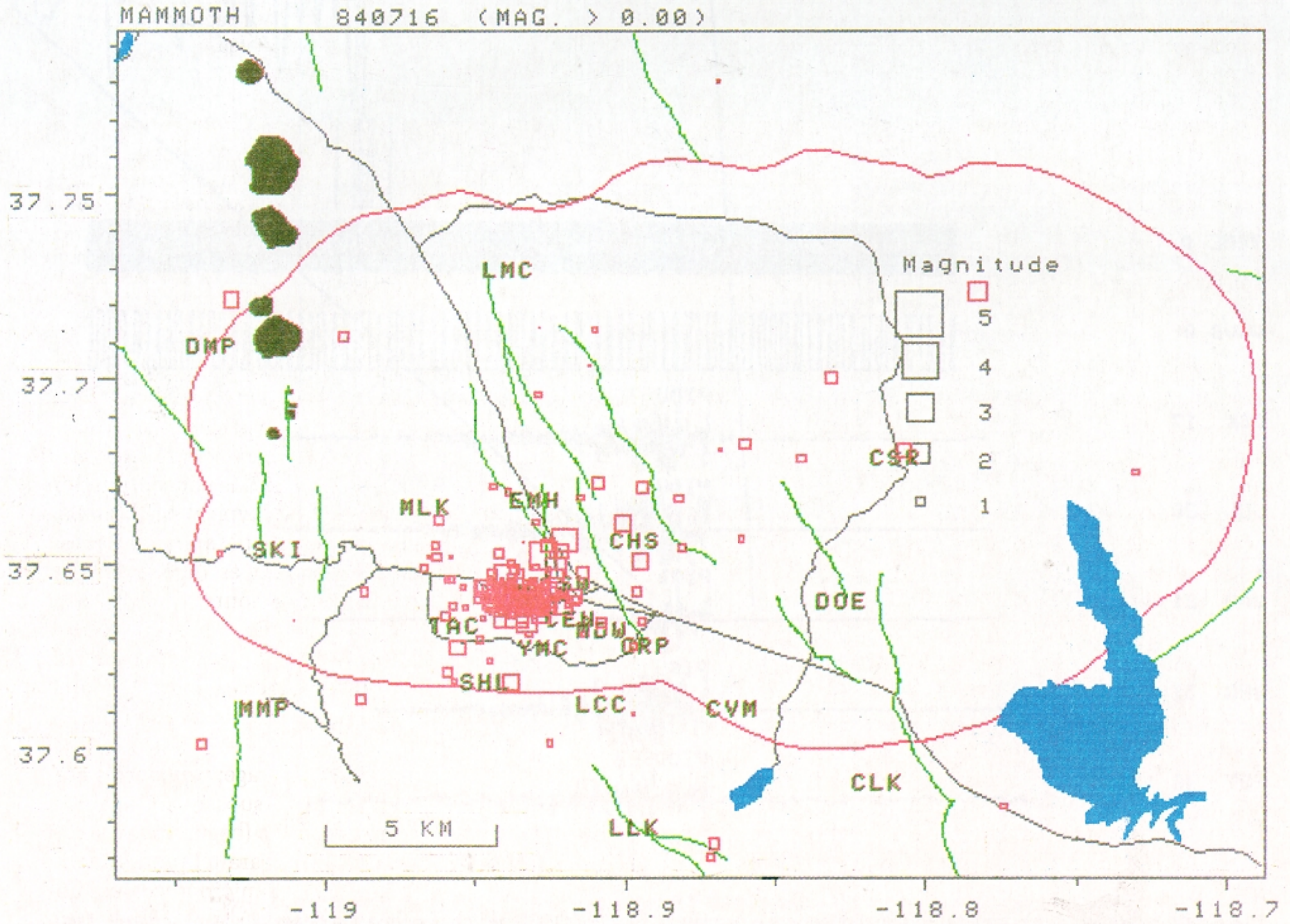
Calnet currently uses approximately 400 instruments, 264 of which feed signals continuously by phone lines to the RTP (real-time picker) computer system in Menlo Park, where signals are immediately digitized, earthquake P-waves are picked automatically, and earthquake locations and magnitudes are computed and displayed within minutes. Calnet covers the terrain north of the Transverse Ranges and is concentrated in regions of high seismicity. During typical earthquake swarm activity, such as occurred at Mammoth Lakes (see below) or at Coalinga, as many as 1200 to 1400 events may be plotted in a single hour.

The primary purpose of Calnet is to monitor potentially hazardous situations. Accordingly, emphasis is placed on efficient real-time detection and graphics display of seismic activity at any designated region throughout the net. RTP saves only an abstract of each earthquake event for archival storage; waveforms are discarded and cannot be used for subsequent analysis.

Built by Rex Allen and Jim Ellis (beginning in 1977), the core of RTP is a homegrown parallel processing system of 33 16-bit TI-9900 based microprocessor subsystems. With one exception, each of the subsystems processes the data from eight instruments. Significant alterations in the signal from any one instrument trigger deposit of critical data from that instrument into a ring buffer shared by all of the subsystems where it is allowed to remain for three minutes. The exceptional subsystem acts as an *associator*. When a fresh record has been placed in the ring buffer, the associator searches through the ring buffer for other records that correlate in time and space with the fresh one. If there is a sufficient number of simultaneous events at neighboring seismometers, RTP signals that an earthquake has occurred and passes the relevant reports to a minicomputer (PDP-11/70) for computing the location and plotting the earthquake in the context of a regional image (see Figure 4).

In the days before RTP, when locating earthquakes required manual intervention, days, weeks, even months could be lost before locations of earthquake swarms were plotted and interpreted. Now scientists need only wait for an automatic, digitized-audio phone call from RTP to be advised within minutes that significant activity is taking place. A smaller version of RTP has been installed at Caltech's Seismological Laboratory in Pasadena to monitor swarms that are occurring in the vicinity of the dormant Coso volcanic field adjacent to the Naval Weapons Test Range at China Lake in southern California.

The Southern California Array, operated in partnership by the USGS and Caltech, includes approximately 250 instruments, distributed fairly evenly throughout southern California from the southern Sierras to the Mexican border. Analog data are transmitted continuously into the CUSP data-reduction and storage system at Caltech. Unlike RTP, CUSP was designed for efficient storage of ground-motion data for subsequent analysis rather than for real-time display. The success of CUSP can be seen in the fact that the USGS, with an operational staff of four, is now recording and cataloging 25,000 earthquakes per year, most of a magnitude less than 2.0 in southern California. Compared to pre-

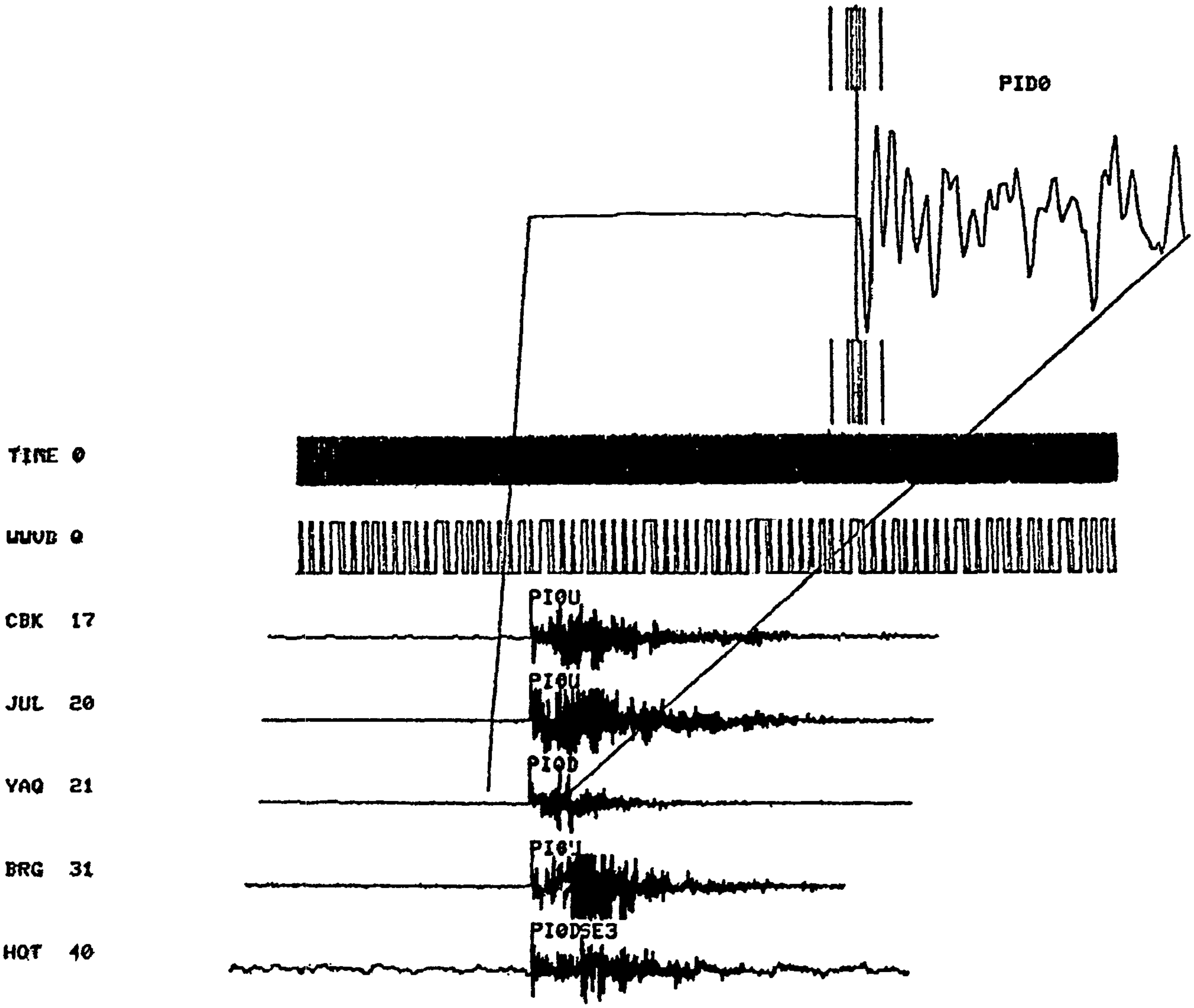


RTP uses graphics terminals to display Calnet seismic activity. At any time any terminal may be used to display seismicity on any subnet. A map of the region is displayed with green traces delineating known faults. Events are depicted by circles on a background map of the region, appropriately colored to indicate how recently they occurred (red for within 24 hours, blue for older than 24 hours). Magnitude is indicated by the proportionate size of the circle. RTP is coupled to an automatic phone dialing system to advise scientists when an earthquake of magnitude 4.5 or greater is detected. (Data provided by Rob Cockerham and Rick Lester, U.S. Geological Survey, 1985.)

FIGURE 4. RTP Display of Long Valley

CUSP productivity, this amounts to a tenfold increase in the number of events and a fourfold increase in the number of stations processed, while significantly increasing accuracy and reducing overall staffing requirements. In the design of CUSP, considerable thought was given to automating just those aspects of data reduction that are best done by computers. Interactions are executed through well-designed graphics tools (see Figure 5).

The CUSP design is predicated on a novel combination of a process sequencer coupled with a relational database in such a manner that the body of earthquake data is "self-evolving." Events enter the system in an arbitrary initial state and are carried through required



An operator sitting at a computer terminal observes a display like that in the figure and, if necessary, may correct automatically generated picks of seismic wave arrival times at select seismic stations indicated by three-letter codes on the left-hand side. The topmost window of the figure, called the *precision timing window*, provides an expanded view of the indicated portion of a seismogram, enabling the operator to verify or improve the accuracy of the pick. The individual picks are labeled by short character strings, such as PIOU or PIODSE3, which describe the onset of seismic energy. The two time codes, WWVB and TIME, represent an international standard and a locally generated observatory time, respectively. The seismograms have been automatically shifted into alignment by a theoretical calculation of P-wave arrivals based on the epicentral distances displayed in kilometers following the corresponding station names on the left; misalignment would indicate an erroneous pick.

FIGURE 5. Interactive Display of CUSP in Event-Timing Mode

processing using a sequence of state transitions resulting eventually in their inclusion in a research database. This approach is particularly appropriate for the reduction of seismic network data since it provides the flexibility required to deal with various analysis requirements that vary spatially and with earthquake magnitude. The CUSP paradigm stands in sharp contrast to earlier methods (sometimes referred to as the cattle prod approach) in which all discrete steps in the analysis must be individually initiated through some human intervention.

Carl Johnson, while a graduate student at Caltech in 1975, began developing CUSP in order to study a large ensemble of small-magnitude earthquakes in the Imperial Valley. Now working for the USGS in Pasadena, Johnson has been improving the system and adapting it to current technology. A CUSP system with a capacity of about 500 stations and a sample rate of 100 Hz has been set up in Menlo Park on Calnet. As in the south, the system will be used to prepare accurate earthquake catalogs and to preserve digital archives of both reduced data and seismic traces for further study.

A new CUSP system was installed this year at the USGS Hawaiian Volcanic Observatory on the island of Hawaii. This system, comprising two VAX-11/780s (VMS operating system) installed at the summit of Kilauea volcano, provides the additional capability of picking and locating volcanic earthquakes as they occur and has resulted in a 20-fold increase in analysis productivity. A unique aspect of the Hawaiian system is the provision for volcanologists to tap into the real-time data stream for tremor analysis and microearthquake counting, without disrupting the routine real-time processing.

We turn now to an exhibit of seismic studies conducted recently in three regions of California. The underlying theme is that these studies could not have been performed without the aid of modern instrumentation and computer systems and the attendant innovations in data reduction and analysis methods.

EARTHQUAKES AS A SOURCE OF SUBSURFACE ILLUMINATION

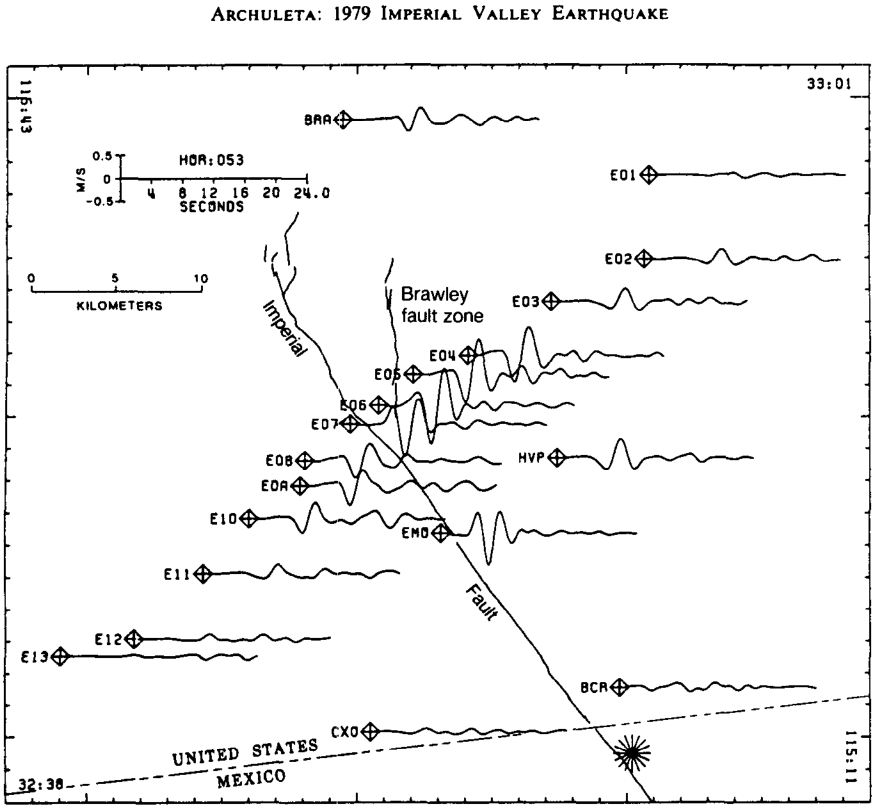
The Imperial Valley region in southeastern California has been called the birthplace of the San Andreas fault system. It lies within the Salton Trough, a tectonic rift zone, in which a portion of the earth's crust is stretching and thinning out, creating a valley depression along the upper surface and an opposite upward bowing along the lower surface. Crustal extension and apparent intrusions of magma into areas of the lower crust explain the presence of hot springs and three small volcanoes at the southern shore of the Salton Sea. The Imperial Fault lies on the boundary between the Pacific Plate to the southwest, and the North American Plate to the northeast. Geologists have long recognized the region as earthquake country, especially after a magnitude 7.2 that occurred in 1940.

The best-documented earthquake in history occurred on the Imperial Fault on October 15, 1979 (see Figure 6). For the first time, strong ground shaking in the near source region of a large-magnitude (6.5) earthquake was well documented. The first recordings from a dense differential array were used for studying fault-rupture dynamics (Spudich and associates), and an instrumented building provided the first well-documented observation of failure of a modern engineering structure. In addition, the Geological Survey maintained 18 accelerographs that surrounded the most-affected region north of the epicenter. Each instrument recorded three orthogonal components of motion: one vertical and two horizontal. Thus complete timed records of ground motion were available. Moreover, the region previously had been the subject of an extensive seismic refraction survey (see seismic-refraction-study sidebar), which provided a detailed velocity structure that made accurate analysis possible.

The time was ripe for studying the temporal and spatial evolution of the faulting process. The information to be determined included (1) precise delineation of the fault surface; (2) the amount of slip at each point on the fault; (3) the direction, rate, and duration of slippage for each point; and (4) the speed at which the fault rupture (crack tip) advanced—that is, the rate at which the slip region spread out from the initial point of rupture.

Several outstanding studies, notably those of Olson and Apsel, and Hartzel and Heaton, have analyzed these issues using inverse methods. Here we discuss another method by Ralph Archuleta of UC Santa Barbara, which uses a forward method and illustrates the use of synthetics. We present Archuleta's work because the detailed results and straightforward analysis yield direct insight into the inner workings of an earthquake. Although Archuleta's method was straightforward, the results were not achieved without cost; the large number of iterations and extensive computation required unusual tenacity.

First, it was assumed that slip (motion of one side of the fault relative to the other) occurred on a fault surface, the exact position of which was to be determined. The surface was dissected into small rectangular cells, and adjustable parameters were assigned to each cell to define the slip motion of the points within each cell. The parameters included the starting time, direction, rate, and duration of slip for each cell. Any complete selection of parameters would constitute a discretized model of the fault plane and rupture behavior. Second, it was necessary to compute the ground motion that would be caused by such a rupture throughout the surrounding region, particularly at the location of each accelerograph; as will be discussed, the technical core of the work resides in how this was accomplished. Third, by laborious trial and error, a tentative slip model was specified, the theoretical effects of such slippage were computed for each accelerograph location, and the computed ground motion was compared with the actual ground motion observed during the earthquake. The objective was to iteratively readjust all of the parameters until a good fit was obtained. After several months and nearly three hundred executions of his



(a) Archuleta's Map of Imperial Valley

Low passed 323° horizontal component of particle velocity superposed on a map view of the Imperial Valley. (From *J. Geophys. Res. 89*, B6 (June 10, 1984), 4563.)

FIGURE 6a. Data Used in Archuleta's Study of the Imperial Valley Earthquake of 1979

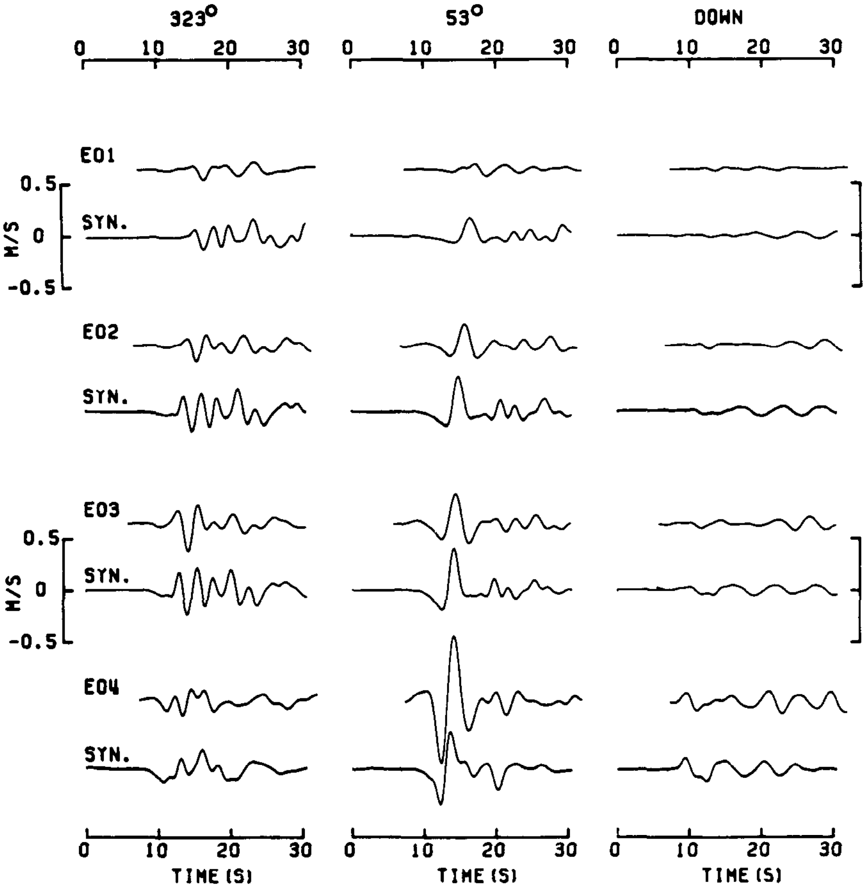
program on a VAX-11/780 (VMS operating system), Archuleta acquired the insights needed to obtain a solution.

The method used by Archuleta to compute ground response as a function of a given slip model illustrates a common feature of modern seismology. To accurately predict wave behavior throughout a region, it is first necessary to construct a model of local inhomogeneities in the earth's crust that can affect wave motion. The process can be compared to calibrating a lens to compensate for the effects of distortion. Typically the required information is obtained from seismic refraction experiments (see sidebar).

Fuis and associates, using seismic refraction methods, had carefully constructed a velocity profile of the Imperial Valley, which Archuleta incorporated into a computer program to simulate the elastic properties of the Imperial Valley. The program permitted Archuleta to compute the response of the earth throughout the Imperial Valley to impulse excitations at various cell positions within his fault model. This was like determining the regional effects of a hammer blow at selected points on the fault. Thus it was possible to determine (Independently of the slip model!) Green functions for Imperial Valley, quantitative descriptions of ground shaking at each accelerograph location induced by an impulse located anywhere on the Imperial Fault. By combining Green functions to simulate the effects of any given slip model, Archuleta was able to synthesize the response of the earth to any one of his fault models.

Here are the results: The Imperial Fault plane was found to incline 10° from the vertical. Slip occurred to a depth of nearly 13 km and at a distance 35 km north from the epicenter lying to the south of the border with Mexico. Slip was almost entirely horizontal with a slight vertical component in sediments at the northern end. The largest slip rates were confined to depths between 5 and 13 km with maximum speeds of about 1 m per second, the duration of slip for a particle was less than 1.9 s, a period considerably shorter than the rupture time (approximately 12 s) for the entire quake. Rupture speed on the Imperial Fault was highly variable, on the average moving slower than S-wave velocity.

In addition to motion on the Imperial Fault, it was known from surface measurements that the Brawley Fault had slipped. The questions were *when* (the surface measurements were not made until 24 hours after



(b) Data and Synthetics

Comparison of three components of synthetic particle velocity time histories with the data at stations E01, E02, E03, and E04. All components are plotted to the same amplitude scale. For stations where absolute time was available (E01, E02, and E04), the synthetics have been aligned accordingly; for stations where absolute time was not available (E03), the synthetics have been shifted for the best fit. This shift is generally less than 1.0 s from the trigger time of nearby stations. Stations E01 and E02 were not used to constrain the faulting model. (From *J. Geophys. Res. 89*, B6 (June 10, 1984), 4570.)

FIGURE 6b. Some Results of Archuleta's Study of the Imperial Valley Earthquake of 1979

AN EXAMPLE OF A SEISMIC REFRACTION EXPERIMENT

Recently Gary Fuis and associates at the USGS in Menlo Park completed an extensive (10 man-year) seismic refraction survey of the Imperial Valley region. Their preliminary data, published in 1982, were used by Archuleta to model seismic velocity variations in the Imperial fault zone. To gather data, one hundred portable seismic instruments were arranged linearly at approximately one-km intervals. An explosive charge was fired, sending P-waves down into the earth along ray paths that curved and resurfaced at points within a radius of 200 km. Any particular instrument thus received a signal that had passed through some portion of the earth's surface. Generally, a ray detected far away may have traveled to greater depth than one measured closer to the source, or both rays may have grazed a structural discontinuity—such as a layer of harder soil, shale, or compacted gravel—been diffracted along the same boundary for some distance, and radiated back up toward the instrument. In any case, each ray provides a sample of subsurface elastic properties. The experiment was repeated 40 times with various shot points and alignments of the linear array of instruments. By trial-and-error perturbation of velocity models running on a Honeywell Multics system, calculation of ray paths, and analysis of arrival times of rays to each of the one hundred instruments, it was possible to construct a model of wave velocities as a function of depth throughout the Imperial fault region. The information thus acquired, combined with data from bore samples throughout the valley, enabled Fuis and associates to construct a stratigraphic model of the Imperial fault region. Ray tracing describes an approximation of true wave motion and works well only for wavelengths that are significantly shorter than the size of typical inhomogeneities and in circumstances where the velocity gradient does not change rapidly. In regions where ray-tracing methods are not applicable, full solutions of the wave equations must often be developed by either finite difference or finite element methods and may require considerable computer power. Such complications arise frequently in gas and oil exploration, where the earth is typically layered in complex strata with sharply differing wave velocities or is crushed and convoluted as in a fault zone. These complications do not arise within the Imperial fault zone.

the main shock) and *how much.* Archuleta found that he could not fit the data without including a slip model for the Brawley Fault. The Brawley quake was quite substantial (of magnitude 5.7), and judging from the timing of the rupture, it must have been triggered by rupture on the Imperial Fault. The Brawley Fault was 10 km long and 8 km wide. Although it contributed less than four percent to the total energy release, it had a large impact on local accelerations.

The most dramatic discovery was that the synthetics could not be matched to the true data without rejecting a common assumption, namely, that the rupture must advance more slowly than an S-wave. To obtain a good fit, it was necessary to allow the rupture to race at an apparent velocity exceeding the P-wave speed. This was an especially satisfying result. As early as 1972, Robert Burridge, a mathematician at the Courant Institute, suggested theoretical conditions under which a rupture could become transonic, that is, exceed S-wave speed. The idea was that, because the two sides of a fault are slipping in opposite directions, the P-wave radiation from the crack tip can induce a substantial shear on the fault ahead of the rupture. If such a shear happened to occur at a point on the fault already stressed at a level near its yield point, it could trigger a new earthquake there before the arrival of the original rupture. Burridge's result has a maximum rupture velocity equal to the P-wave speed. D. J. Andrews of the Geological Survey and Steven Day of Systems, Science and Software later demonstrated the feasibility of the idea with a computer model of a transonic crack tip. Although transonic rupture velocities had been inferred for other earthquakes, because of the paucity of data and theoretical basis, the results were generally discounted. The result has important implications for seismic engineering, because if rupture velocity is near a wave speed, radiated energy can be strongly focused in the direction of rupture.

Archuleta's work involved the direct computation of seismic waves; hence his technique falls into the category of forward modeling (see the sidebar on seismology). As mentioned, other authors studied the same earthquake by linear inverse methods. An advantage of inverse methods, besides being efficient computationally, is that they place bounds on how well each parameter is determined. An advantage of forward methods, despite the fact that they may entail vastly more computation than inverse methods, is that they allow greater flexibility in exploring models that depend nonlinearly on one or more parameters. Archuleta has shown that ground response is very sensitive to the rupture propagation speed, a highly nonlinear variable.

It is indicative of present-day seismology that each of the Imperial Valley studies has offered only a kinematic model. Each has specified motions on a fault without attempting to describe the stresses that induced them. A dynamic model of a real earthquake—a model taking account of the stresses—may be the next step forward in earthquake modeling.

LONG VALLEY CALDERA: A POSSIBLE LINK BETWEEN VOLCANISM AND EARTHQUAKES

Long Valley is a popular recreational area on the east side of the Sierra Nevada about 40 km southeast of Yosemite Valley. Famous for its Mammoth Lakes ski area, fishing in Lake Crowley, and numerous hot springs, it has become a vacation and summer residential spot for thousands of Californians. Long Valley also has the distinction of standing at the headwaters of the Owens River, long submerged in political controversy as a major water supply for Los Angeles. Since 1978 Long Valley has been shaken by a series of intense and unusual earthquakes. Each of the larger quakes, ranging in magnitude from 5.7 to 6.3, was associated with swarms of thousands of smaller quakes during the preceding or following weeks. The unusual nature of these quakes has been puzzling earth scientists and has prompted a wide variety of monitoring and research activities in the area.

Typical California earthquakes consist of one large quake, called the main shock, usually followed, and occasionally preceded, by many smaller events; then a subsequent long period of calm. The smaller events commonly occur upon the same fault plane as the main shock. But in Long Valley the pattern is different. Instead of calm, there seems to be a trend toward recurring episodes of large quakes. In this recent episode of activity, the first large quake occurred in October 1978—a magnitude 5.7. Between May 25 and May 27 of 1980, four magnitude-6 events occurred. In January 1983, three magnitude-5.0–5.7 events were followed by thousands of smaller earthquakes. On November 23, 1984, a magnitude-5.7 earthquake occurred. And dispersed among these larger events have been smaller short-lived swarms of hundreds of events each. Furthermore, the swarms associated with the larger quakes do not appear to occur on a plane. They are confined to a restricted volume, as though the crust were snapping at random locations within the volume, rather than slipping along a well-defined fault plane.

Long Valley sits in the midst of an area of intense prehistoric volcanism. In the early 1970s, geologist Roy Bailey, during the course of mapping supported by the Geological Survey's geothermal research program, proved that 730,000 years ago Long Valley was the site of a giant volcanic explosion. To compare it with a cataclysm of our time, Mount Saint Helens spewed 0.25 cubic km of ash onto the surrounding region, but the explosion at Long Valley hurled 600 cubic km of ash, burying 1500 square km of countryside under incandescent deposits of hot, steaming ash and spreading airborne ash over the entire southwest and east as far as Kansas, leaving a caldron-shaped depression 17 km long by 32 km wide. Major eruptions continued intermittently within the caldron, the last occurring about 50,000 years ago. Now somewhat cooled and apparently mellowed with age, the caldron's interior has softened into scenic Long Valley. Because of a broad domelike uplift in its center, Long Valley is known as a resurgent caldera. Many older calderas of similar kind have been identified in North America, but two young ones of similar age include the Yellowstone Caldera, Wyoming, and the Valles Caldera, New Mexico. Five km southwest of Long Valley is Devils Postpile National Monument, where spectacular vertical stone columns were created by a cooling of lava flow. Immediately northwest of Long Valley are the Inyo Domes and Mono Craters, where violent volcanic explosions occurred as recently as 550 years ago. Long Valley is in fact surrounded by evidence of active volcanism: black lava mountains, red cinder cones, obsidian domes, pumice layers, and youthful explosion craters, ample evidence that similar eruptions could occur in the future.

One difficulty in understanding Long Valley seismicity arises from the volcanic deposits themselves. The region is shot through with a complex pattern of magma dikes and covered by thick accumulations of volcanic ash, lava flows, and welded ash deposits. In addition the earth's crust beneath the valley is interpenetrated by a network of aquifers that conduct superheated water and steam from volcanic chambers deep in the crust to thermal springs at the surface. In such intensely fractured and variable terrain, earthquake waves are scattered and attenuated unpredictably. It is difficult to interpret seismic waves passing through the caldera and to compute earthquake locations with precision. In a sense, volcanic regions tend to hide themselves behind a dark veil of geologic complexity.

Another difficulty is due to the fact that Long Valley lies at the boundary between two very different geological provinces, the Sierra Nevada to the west and the Basin and Range to the east. The former is a massive granite batholith with a solid root extending to a depth of 45–55 km. The latter is a broad, shallow-crusted, rift zone.

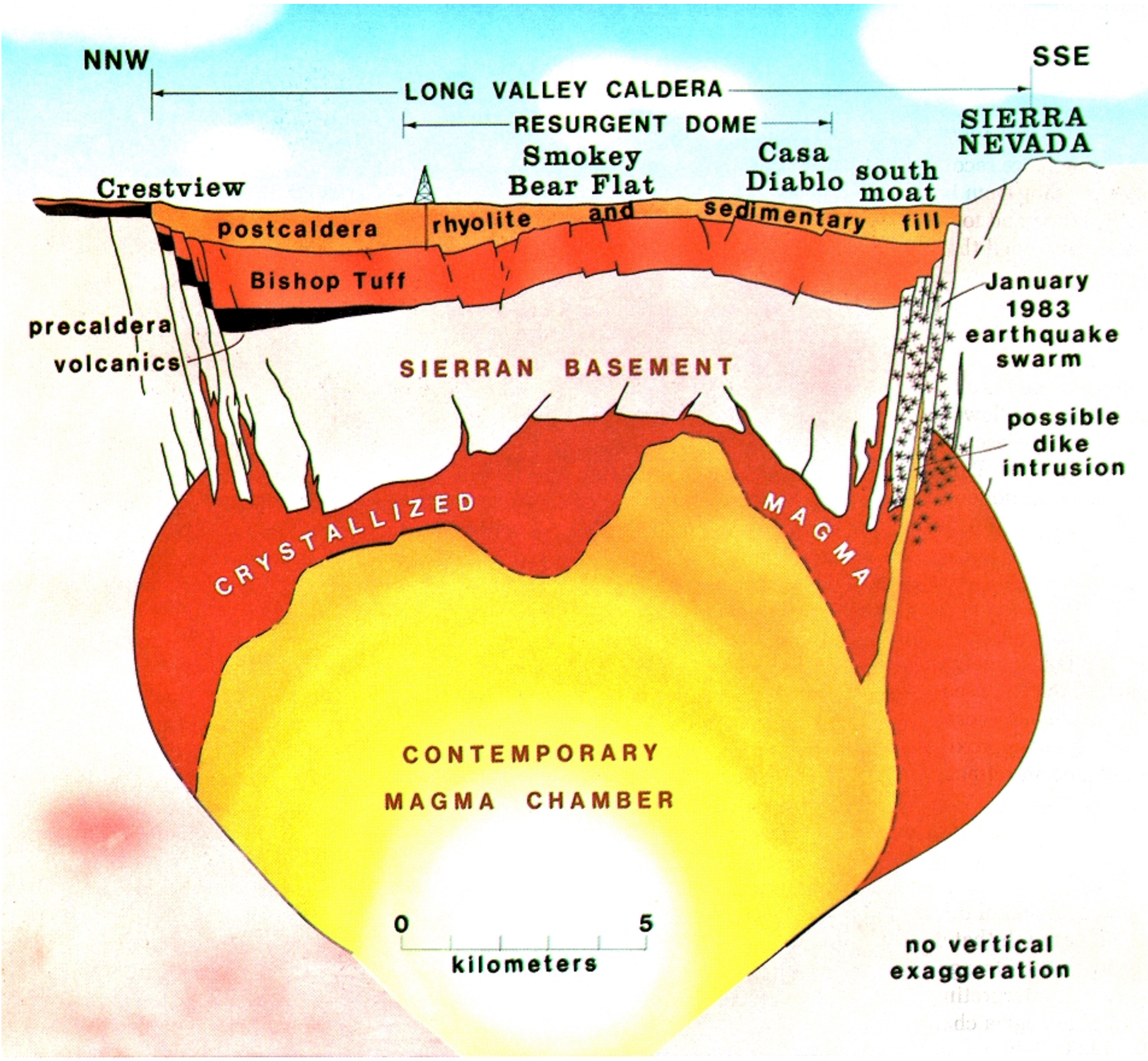
One of the largest earthquakes in California history occurred 140 km south of Long Valley centered near Lone Pine on the eastern escarpment of the Sierra Nevada in 1872. Earthquake scarps throughout the region show that large earthquakes have regularly accompanied the regional uplift that continues to hoist the Sierra Nevada. Earthquakes at Long Valley can be related to any number of causes: to Sierran uplift and the inevitable grinding conflict between the adjacent provinces, to cracking of the crust by extensional rifting, or to the forceful intrusion of magma into dikes, sills, or magma chambers. Most geologists would agree that any of these could be the cause of quakes in Long Valley. In sum, there is increasing evidence that the magma chamber beneath Long Valley's resurgent dome has become reactivated, with the possibility of an eruption in the near future.

Geologists are well aware of the possible dangers and are watching developments at Long Valley carefully. It was not too long ago that similar swarms of tremors beneath Mount Saint Helens gave hints of the impending explosion. The sciences of seismology and volcanology are too young to make claims of predicting California earthquakes and volcanic eruptions with certainty. Earth scientists must forever seek to balance the possibility of errors in prediction against the consequences of failing to advise the public of an impending catastrophe. We certainly will not try to resolve that complex debate here—the scientific as well as the political issues are intractably controversial. Here we merely review some of the evidence for potential volcanism, using it as a means of exhibiting some of the modern tools of seismology.

Early in the 1970s geophysicist Art Lachenbruch and his colleagues, while participating in the Geological Survey study of Long Valley as a possible source of geothermal energy, noted that the magnitude of the observed heat flow in the area required an intense heat source at depth. Lachenbruch speculated on the likelihood of an active magma chamber lying beneath the valley. By determining the thermal flux as measured in specially drilled bore holes, he was able to place constraints on where such a chamber might lie. As part of this multidisciplinary geothermal research effort, seismologist Dave Hill and his colleagues conducted a seismic refraction study of Long Valley, similar in kind to the one discussed for the Imperial Valley (see sidebar), but smaller in scope. The objective was to model the velocity structure of the crust and, working in concert with field geologists and geochemists, determine the stratigraphy and structure of the region. Unexpectedly, on one of the refraction lines Hill discovered a secondary reflected phase possibly from the top of a 7-km-deep magma chamber. At the same time Hill's colleagues, Don Steeples and H. Iyer, found that P-waves arriving from distant large earthquakes were delayed by as much as a third of a second if they passed through certain parts of the caldera. They postulated that molten rock to depths as deep as 15 km were slowing down the P-waves. Thus, beneath the region mapped as a resurgent dome by Bailey, and speculated by Lachenbruch as the site of the necessary heat source, Hill, Steeples, and Iyer found seismological evidence strongly supporting the existence of molten magma.

Early in 1980 Alan Ryall, taking note of the 1978 magnitude-5.7 quake and subsequent swarms, predicted that a large quake could be expected in the region within the foreseeable future. In May of 1980 four quakes of magnitude 6 occurred within hours, followed by a magnitude 5.9 in September 1981, and three magnitude-5.0–5.2 quakes in January 1983 within a swarm of thousands of smaller quakes. Repeated geodetic surveys of the region have shown that the resurgent dome has been stretching laterally and has been lifted vertically approximately 50 cm since 1979. Jim Savage and Malcolm Clark of the Geological Survey have mathematically modeled the swelling as due to expansion of a spherical chamber at a depth of 10–11 km beneath the resurgent dome by the injection of 0.15 cubic km of magma (see Figure 7).

In 1983 Chris Sanders, working at the Seismological



Long Valley Caldera was produced by eruption of Bishop Tuff 730,000 years ago, which fills the caldera above the subsided Sierran basement block. Partial emptying of the upper part of the chamber during these eruptions caused collapse of the roof of the chamber and sinking of the Sierran block about 2000 m into the magma below. Subsequent renewed magma pressure caused arching of the caldera floor to form the resurgent dome about 700,000 years ago. Since then the magma chamber has been cooling and crystallizing from the walls inward (red), gradually reducing the size of the partially molten chamber (yellow-orange). Recent (1979–1985) renewed rise of the resurgent dome (0.5 m) and surrounding earthquake activity indicates renewed filling of the chamber with magma from depth and possibly injection of a dike along the caldera ring fracture below the south moat. The shallower cupola (hump) of magma on the right, based on Sanders's seismic attenuation studies, appears to be the center of the current uplift. The heavier lines at the upper left and lower right margins of the contemporary magma chamber mark the location of seismic phase transitions detected by Hill, Leutgert, and colleagues. (Cross section prepared by Roy Bailey and Dave Hill, U.S. Geological Survey, Apr. 30, 1985. Publication by permission of the American Geophysical Union.)

FIGURE 7. Cross Section through Long Valley Caldera and Its Inferred Subjacent Magma Chamber

Laboratory of the Mackay School of Mines in Nevada, used the Nevada seismic network and seismic modeling programs on a PDP-11/70 to analyze S-wave energy received from Long Valley earthquake swarms as a means of locating regions of apparent partial melt beneath Long Valley. The concept is that, because elastic solids are capable of transmitting shear waves but liquids are not, the shear-wave characteristics of crisscrossing ray paths through Long Valley can be used as magma sensors: The more completely molten the region, the more attenuated the shear waves passing through it. With enough rays in different directions, it should be possible to identify regions that have no melt and those that are partially or completely molten. Sanders analyzed 1200 ray paths from 281 small earthquakes that were recorded by a high-density seismic array spreading from Long Valley in eastern California to Lake Tahoe and to Walker Lake in western Nevada. Sanders concluded that two shallow magma bodies appear to lie in the central and northwest caldera, both lying partly beneath the resurgent dome, as well as two smaller, more diffuse magma areas in the southern caldera and beneath Crowley Lake. The top of the central magma body is as shallow as 4.5 km, and the northwest body as shallow as 5.5 km. At depth the two bodies probably coalesce and extend to at least 13 km beneath the surface. This is the first direct evidence of large bodies of molten rock in the caldera, since only a liquid will affect S-waves in such a drastic manner. It is also the first detailed subsurface map of such a body. This study provides new evidence indicating magma as shallow as 4.5 km, compared to the 7–10-km depth originally suggested by other studies.

In 1983 James Luetgert and Walter Mooney at the Geological Survey used seismic refraction profiles from eight earthquakes north of Mammoth Lakes in the depth range of approximately 5–8 km to complement Hill's explosion refraction study with additional velocity information at greater depth. An unusual, possibly unique, feature of the study is that the dense array of seismic instruments used for recording data was the same as that used in the earlier shot-charge study, enabling comparison of information derived from deeper earthquakes with that derived from shallower explosions. By noting strange secondary arrivals on these profiles and interpreting them as reflections from the bottom of a magma chamber, Leutgert and Mooney were able to define a possible lower boundary for the region of partial melt, thus complementing Sander's upper and lateral boundaries. Combining their results with those of Sanders, they estimated that the magma body in the southcentral caldera must have lateral dimensions of about 10 km × 5 km and a height of about 12 km, and they deduced a volume of partial melt on the order of 600 cubic km.

As noted earlier, because of the complexity of the volcanic formations in Long Valley, the seismic data are especially difficult to interpret. Nevertheless, there is increasing suspicion, if not consensus, among geologists, geophysicists, and seismologists that an active magma chamber is stirring beneath the resurgent dome. One additional line of reasoning in support of this suspicion has been provided by Bruce Julian of the Geological Survey.

Julian has noted inconsistencies in interpretations of seismic data from Long Valley and has proposed an interpretation that suggests that the recent earthquakes may have been magmatic in origin. To understand Julian's thesis, note that seismologists are often satisfied with determining just a few basic facts about an earthquake, such as the location, direction of fault slip, orientation of the plane of faulting, and magnitude. Observed from a distance, it is almost impossible to distinguish finer features. In principle, given data from a number of distant seismic stations, a trial-and-error forward method could be used to determine a rupture location, orientation, and average distance of slip, consistent with the observed seismograms. But, because at large distances, the data cannot distinguish between small slips on a large surface and large slips on a small surface, the same results would be obtained by increasing the slip surface and proportionately decreasing the slip distance. The features thus described, understood as an average, provide a phenomenological description of a source and are referred to as an earthquake mechanism.

Until recently, a forward method was used to compute earthquake mechanisms. In its most efficient implementation, it could easily consume 20 minutes or more on a VAX-11/780 to compute the mechanism of a single earthquake. In 1971 geophysicist Freeman Gilbert formulated a powerful mathematical tool that has drastically reduced computation times to seconds: the seismic moment tensor. The essence is that an elastic medium responds linearly to a moment tensor mechanism, that is, the parameters that enter into the definition of the moment tensor operate linearly upon the earth model, so that the efficient inverse methods of linear algebra may be applied to derive the moment tensor from the observed data. The moment tensor has been an important innovation, not only numerically, but conceptually as well, for it provides a concise description of a variety of different possible earthquakes, not just of those that arise from lateral slip on a fault, but also of those arising from explosions.

Julian has underscored the fact that the moment tensor may also be used to describe earthquakes caused by the forceful intrusion of magma into the earth's crust. Such magma intrusion yields no net material expansion, but does incorporate simultaneous expansion and contraction along orthogonal axes. Although this fact had been noticed before, Julian was first to apply it to the Long Valley caldera earthquake data. Other investigators, when calculating mechanisms, constrained the moment tensor to be equivalent to a fault-slip model and arrived at inconsistent results, depending on which set of seismograms was being analyzed. But Julian sought the best-fitting unconstrained tensor and arrived at an intrusion model that reconciles the data.

Whether alleged magmatism beneath Long Valley is indeed the cause of the recent earthquakes or is instead an effect of tectonic rifting that cracks the crust and opens it to magmatic intrusion is still very much a matter of controversy. Julian's conclusions have been disputed, but his work demonstrates that the seismic moment tensor can be used effectively to study intrusion models as a cause of earthquakes.

I want to mention one further seismic study conducted at Long Valley even though it has nothing to do with magmatism. Seismic-reflection data have been used extensively by the petroleum industry to construct images of geological strata in prospecting for structures that accompany deposits of gas and oil. The method exploits the fact that the wave equation is reversible in time. This means, in particular, that recordings of excitation of a free boundary by incoming waves may be used in reverse as a source of waves that are identical, but opposite in direction, to the incoming waves. Thus, when a shot charge is fired and waves that are reflected by subsurface strata are recorded by a sufficiently dense array of instruments, the data may be propagated backward into the earth through a programmed solution of the wave equation. By plotting the results at various time steps, the wave front may be observed to converge upon subterranean structures. The seismically detected structures are the clues used by geologists to determine whether gas and oil may be present. There are numerous technical difficulties caused by refraction, diffraction, and multiple reflections, as well as limitations in the data. Nevertheless, reflection seismology has proved to be a tool of immense importance to the petroleum industry—an industry that has purchased more than a dozen Cray and a small number of CDC Cyber-205 supercomputers for a variety of applications including reflection work.

George McMechan of the Texas University Center for Lithospheric Studies is the first to use seismic-reflection techniques to construct an image of an earthquake source (see Figure 8). Working with colleagues at the Geological Survey, McMechan used reverse propagation of earthquake data from a dense array of instruments located in Long Valley. Selecting three quakes from the January 1983 swarm, McMechan reversed the data for each quake through a finite difference implementation of the wave equation. Beginning with the waves recorded at the surface of the earth, he reversed the propagating direction such that the wave field converges to reconstruct an approximate image of the earthquake source. The important aspect of McMechan's work is the imaging of the seismic source rather than earth structure as is normally done in the petroleum industry. The black dot indicates the location of the source as computed by more traditional means.

REFINING IMAGES OF THE INNER EARTH: THE BIG BEND AND THE MINIPLATE

Plate tectonics has provided a global understanding of processes that create continents and cause volcanoes and earthquakes. Now, using massive amounts of high-quality data and sophisticated processing techniques, earth scientists are beginning to fill in details of plate structure and to understand finer points of the physical processes that create regional topography.

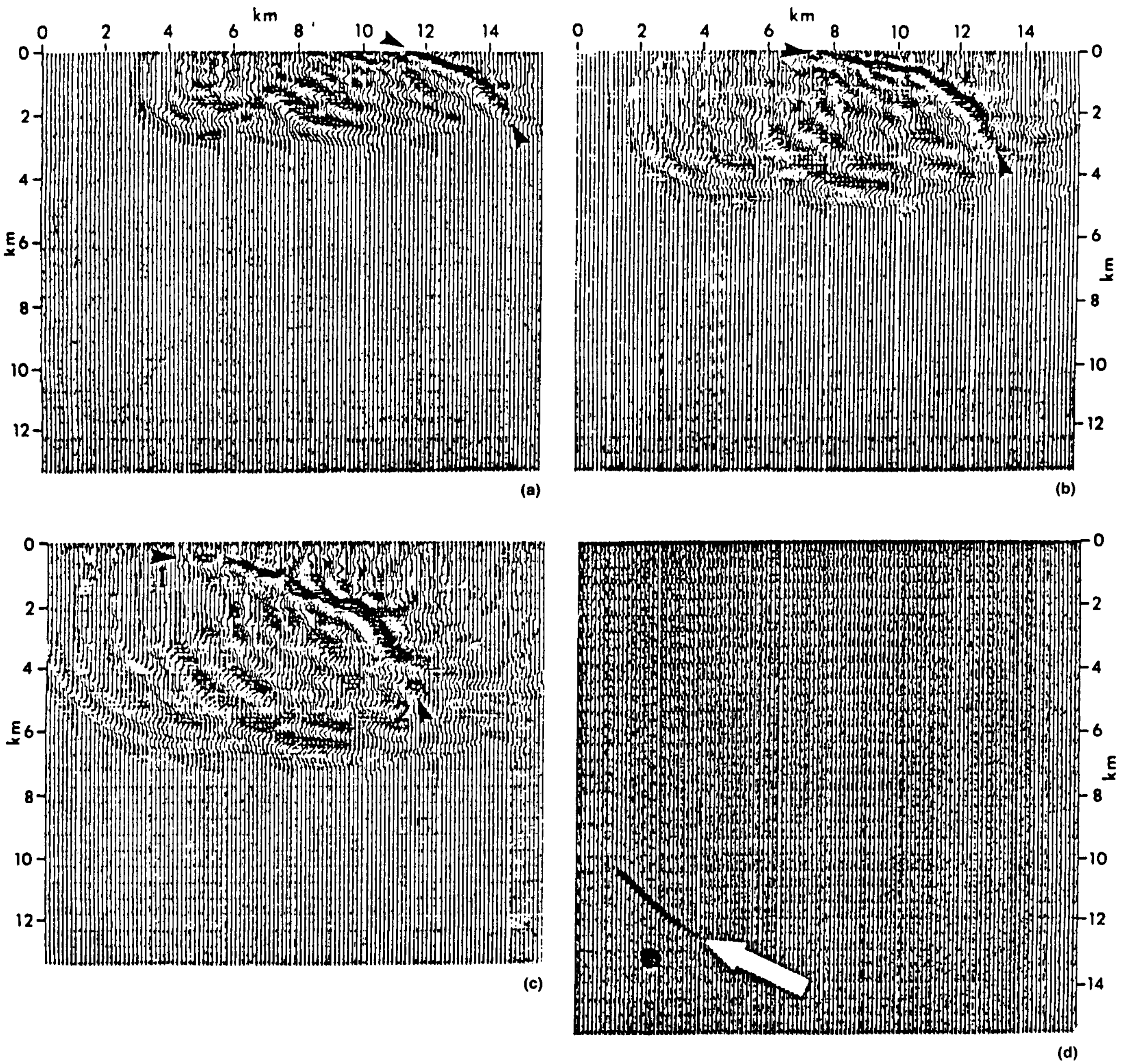
Southern California is a good example. Take a look at the map of the San Andreas Fault. For most of its length, the San Andreas trends north by northwest. But note that where it approaches the southern end of the San Joaquin Valley the San Andreas swings eastward past San Bernardino, where it resumes a north by northwest trend into the Salton Trough. The extraordinary deflection of the San Andreas through the Transverse Ranges is called the Big Bend.

The Big Bend is a puzzle for geologists: What is it doing there? If the Pacific Plate west of the San Andreas is moving northerly in a direction parallel to the general trend of the San Andreas, how does it manage to slip around the Big Bend? Some interesting proposals have been put forward by scientists at Caltech that may help to explain the Big Bend and resolve other puzzles as well.

The major tool is tomographic seismology, which is related to tomographic image reconstruction used in medical CAT scanning. In the latter, a patient lies still while a movable X-ray beam sweeps in a plane at right angles to the long axis of the patient's body. One full revolution of the sweeping beam about the patient's body thus provides sufficient information to reconstruct an image of one slice (or *transverse section*) of the body. Imagery of adjacent sections can be adjoined in order to reconstruct an image of, say, the patient's head or spine.

The basic idea of medical tomography is to imagine that a transverse section of heterogeneous matter is divided into a checkerboard of discrete elements, each of uniform size. A typical X-ray beam, as it passes through a line of such material elements, will be attenuated by an amount that depends only on the total mass strung along that line. The attenuation (and, indirectly, the total mass encountered) is measured at the point where the beam reemerges from the patient's body: The greater the cumulative amount of matter traversed by the beam, the greater the reduction of intensity of the beam. Obviously it is not possible to reconstruct the density of individual elements along a single ray path without more information. But, if there are enough rays (beams) in different directions or, more precisely, if there are typically more rays of varied directions through each element of area than there are elements along a typical ray path (such that there are more independent equations than unknowns), then in principle, a least-squares algebraic method can be used to estimate the density of each material element. Several computationally efficient methods are now available to solve this problem, the most common being ART (Algebraic Reconstruction Technique). A related method called SIRT (Simultaneous Iterated Reconstruction Technique) is also used.

Tomography may also be applied to determine the variation of seismic wave speeds within the earth. Since wave speeds correlate with temperature and density of the earth, the method has become an important research tool in modern geology. The idea is to subdivide a region of interest into congruent rectangular bricks that are as small as possible, but large enough to be resolved by the data. Material within each brick is assumed to be uniform, so that the elastic properties are identical throughout any one brick. The time required by a seismic wave to traverse the brick is inversely proportional to wave velocity within the brick and directly proportional to the length of the ray segment within the brick. To determine the travel time



Extrapolation of an observed (seismogram) wave field backward in time produces an image, in both time and space, of the source. Four time steps in the process are displayed showing the numerically reconstructed wave field at (a) t = 3.00 s, (b) t = 1.50 s, (c) t = 0.75 s, and (d) t = 0.00 s, where the inferred time of earthquake at the source is arbitrarily set equal to zero. The round black dot in (d) is an estimated hypocenter computed by a standard method using regional network travel times. (Figure from McMechan, G.A., Leutgert, J.H., and Mooney, W.D. Imaging of earthquake sources in Long Valley Caldera, Calif., 1983. Undated manuscript provided by Walter Mooney at USGS in Menlo Park, Calif.)

FIGURE 8. Backward-Extrapolation Image of the Source of an Earthquake of January 1983 in Long Valley Caldera

of a wave from an earthquake source to a seismograph station at the earth's surface, it is only necessary to compute the ray path from the source to the station and add up the traversal times of the ray through each brick in its path. As in the case of medical tomography, the measurement made for one ray is inadequate to resolve the character of each brick along the ray path, but if there are enough rays in enough directions through each brick, then an average wave velocity for each brick can be determined.

A complication for tomography in seismology is that the data arise from random earthquake sources and cannot be controlled to provide uniform coverage from all directions. Until the advent of instrument networks and semiautomatic processing of earthquake records, the data were too sparse for tomographic methods. But in recent years the CUSP system has gathered adequate data from the Southern California Array to make tomography feasible for studying the crust and upper mantle beneath southern California.

At Caltech Rob Clayton and his associates have adapted medical tomography to study the geology of southern California. They have used an SIRT program on a VAX-11/780 (UNIX® operating system). In order to "see" through the earth's crust to determine the character of the earth's mantle, it is necessary first to understand the structure of the crust. For his thesis, Tom Hearn applied tomography to data from thousands of regional earthquakes to determine the P-wave velocities and crustal thickness variations beneath southern California. He analyzed both Pg- and Pn-wave arrivals recorded at approximately two hundred seismographs of the Southern California Array. Pg-waves are P-waves that originate at an earthquake source within the crust and propagate directly to the seismic station without ever leaving the crust. Pn-rays are P-waves that descend to the bottom of the crust from an earthquake's source within the crust, run at high speed along the upper mantle, radiating rays back upward through the crust at reduced speed to the surface.

Analysis of Pg-arrivals yielded a velocity map that reveals spectacular discontinuities across several of the major faults of southern California (for example, the San Andreas, Garlock, San Jacinto, and Elsinore faults) demonstrating the existence of regional blocks divided along fault boundaries. A somewhat puzzling result is that the velocity profiles beneath the Transverse Ranges and the Peninsular Range are slow like that of the surrounding terrain rather than fast like that of the mountains themselves, indicating that the mountainous material does not extend downward beneath the level of the surrounding terrain. This is puzzling because most mountains have a root that is deep enough to compensate for the elevated part, much as an iceberg floats partly submerged to provide buoyancy for the part that rises above sea level. One hypothesis is that the roots were shorn from beneath the mountains by a *detachment* fault, the plane of which is parallel to the earth's surface. Presumably the region now beneath or surrounding a mountain has flexed downward to support it. Another hypothesis, perhaps complementary to the first, is that part of the force that sustains the mountain may be generated dynamically by tractions due to mantle convection underneath causing convergence of the crust from opposing sides of the mountain. The latter type of sustaining force is called *dynamic compensation.* We shall see below that, for the Transverse Ranges at least, there is good reason to believe that dynamic compensation is involved. But first it is important to know more about crustal thickness.

Pn-rays were used to determine the thickness of the crust and variations of P-wave velocities in the upper mantle. Hearn's analysis of Pn-arrivals resulted in a profile of crustal thickness (Moho depth) throughout southern California and a profile of upper mantle wave velocities. The crust is thinnest (20 km) in the Salton Trough near the Colorado River and thickest (34 km) farther northwest in Ventura County. In fact, the regional topography of the boundary between the lower crust and upper mantle, known as the Moho, is quite complicated, reflecting the complexity of the surface topography.

Having obtained knowledge of Moho depths throughout southern California, as well as an average crustal velocity, it became possible for scientists to trace and time ray arrivals from distant earthquakes with greater accuracy than ever before. In this respect, Hearn's crustal study serves a purpose like that of a seismic refraction experiment carried out on a much larger scale. Because an inhomogeneous crust distorts imagery through wave refraction, Hearn's work made it possible to remove the distortions. Gene Humphreys, working with Clayton, used Hearn's results to refine a tomographic image of the P-wave velocity in the southern California mantle, derived from teleseismic events (distant earthquakes) recorded by the Southern California Array. Humphrey's early work was done on a Prime computer, but subsequently a VAX-11/780 (UNIX) was used. As before, the region of interest (this time the underlying mantle) was dissected into rectangular blocks, each of supposedly uniform elastic properties. The earthquake sources were sufficient in number and variable enough in location to obtain a well-resolved image of the upper mantle using SIRT, the same tomographic technique used by Hearn (Figure 9).

The results are fascinating. A slow region was found beneath the Salton Trough. Assuming that wave velocity is a decreasing function of temperature, the result implies that this mantle is relatively hot and less dense than the surrounding material. Because the mantle is presumed to flow plastically in geological time, it is reasonable to infer that differential density of material in the mantle must induce upwelling beneath the Salton Trough and that resulting basal tractions on the crust cause the thinning and extension known to occur in that region. A more remarkable result, however, is that there is a large block of relatively fast-velocity material directly beneath the Transverse Ranges. Assuming a lower temperature in the block (and therefore higher density) compared to the surrounding mantle, it is reasonable to believe that the block is downwelling. If that is so, then upper mantle material, drawn in from opposite sides to replace the top of the downwelling block, must exert tractions upon the overlying crust,

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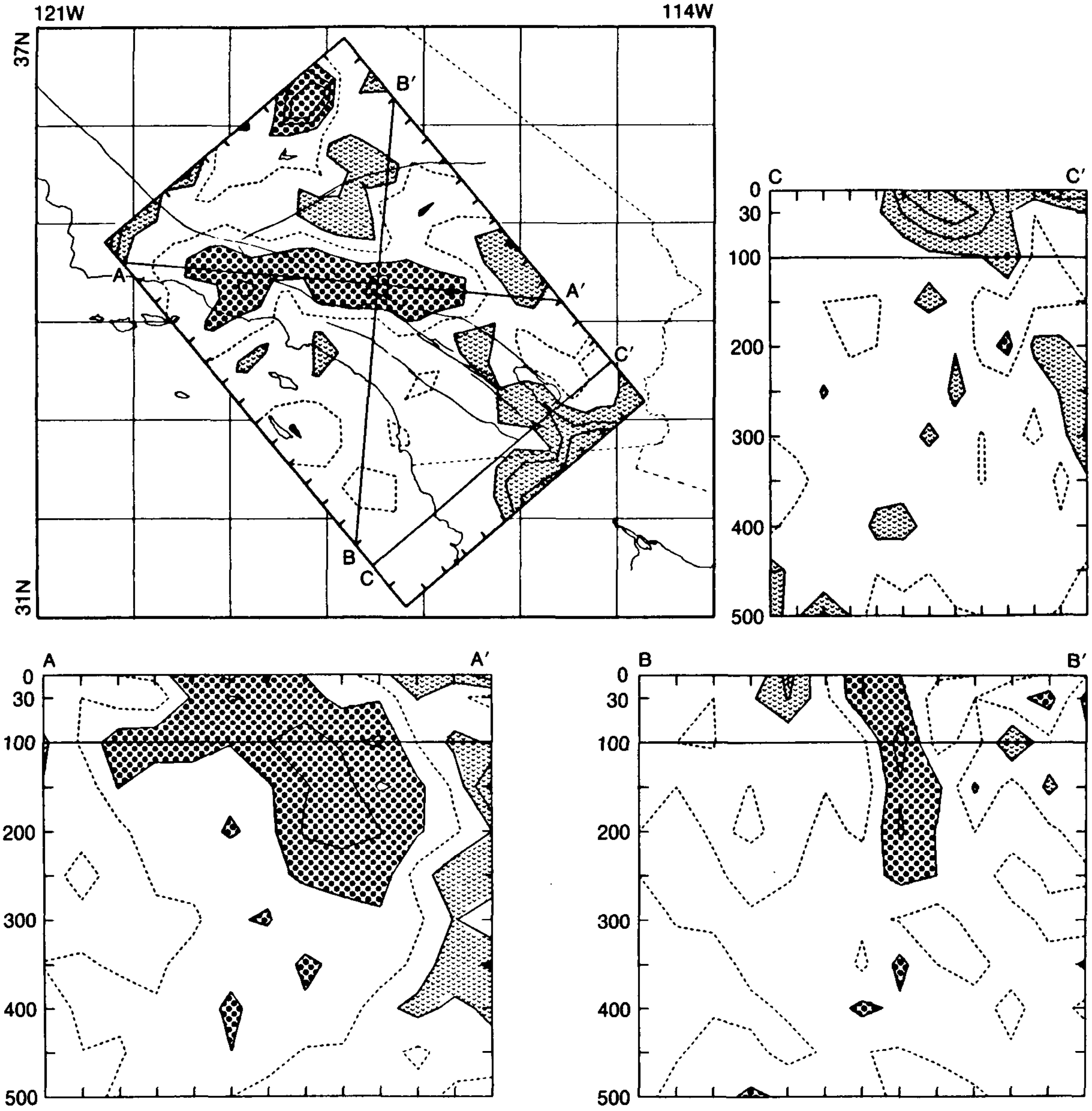

Results of the inversion of teleseismic P-delays. In the upper left panel, a horizontal section at a depth of 100 km is shown superimposed on a location map of southern California. The locations are shown for the three cross sections (A–A', B–B', and C–C') that are displayed in the other panels. The tick marks surrounding the horizontal section show the locations of the block centers used in the inversion. All panels are displayed with no relative exaggeration. The contour interval is 1.5 percent relative velocity deviations, with > 1.5 percent indicated by dotted areas and < −1.5 percent by the hatched areas. The zero contour is dashed. In the lower left panel, a W → E cross section (A–A') through the Transverse Range anomaly is shown. In this projection the anomaly appears as a wedgelike feature that is deeper on the eastern side. A S → N cross section (B–B') through the Transverse Range anomaly is shown in the lower right panel. The anomaly appears as a slablike feature that dips slightly to the north. In the upper right panel, a SW → NE cross section through the Salton Trough anomaly is shown. The anomaly is about 2–4 percent slow and extends down to 75–125 km. (From *Geophys. Res. Lett. 11*, 7 (July 1984), 626.)

FIGURE 9. A Tomographic Image of Mantle Structure beneath Southern California

causing the kind of convergence mentioned above that could dynamically support a rootless mountain. Although the mechanisms are not yet completely understood, such tractions appear to be aligned in such a way as to maintain the curvature of the Big Bend.

In order to test the self-consistency of dynamic compensation. Brad Hager and Gene Humphreys employed a finite-element simulation of viscous flow driven by a mantle density gradient. Their programs were run on a variety of computers, including a VAX-11/780 (UNIX operating system), Prime (Primos Operating System), and Ridge (UNIX operating system). At present Hager is using a Celerity (UNIX operating system) for some of his work. Assuming density differences commensurate with the tomographically inferred velocity variations beneath the Transverse Ranges, they were able to show that the seismically inferred density anomalies would result in viscous flow supportive of the Transverse Ranges. Further support for dynamic compensation is given by the fact that the flow models predict variations in gravitational potential equal to the empirically measured regional gravity field.

It is interesting to note in passing that Clayton, Hager, and their colleagues are experimenting with concurrent processing; they are converting some of their finite-element convection modeling programs and finite-difference seismic modeling programs for execution on the *Mark II* hypercube, a parallel computer with 16–128 processing elements, each based upon an Intel 8086/8087 chipset and 256 Kbytes of memory, under development jointly at Caltech and NASA's Jet Propulsion Laboratory in Pasadena.

Additional understanding of the Big Bend is being gained by kinematic studies of southern California. Geodesic trilateration measurements made by the USGS have yielded accurate relative motions between benchmark points throughout southern California. Ray Weldon of the USGS, working with Humphreys, has considered that such motions must be simultaneously consistent with geologically measured slip rates of known faults in southern California and measured extension rates of the Basin and Range province east of the Sierra Nevada. Their conclusions are that the Sierra Nevada and Great Valley block is moving westward against the San Andreas Fault north of the Big Bend, driven by the Basin and Range extension. That extension, combined with the basal tractions described by Hager and Humphreys, is driving a counterclockwise rotation of southern California about a point that is approximately 650 km southwest of the San Andreas Fault in the Big Bend. Thus Weldon and Humphreys assert that southern California must occupy its own miniplate, situated between the North American Plate and the Pacific Plate. In theory, the Big Bend and the southern portion of the San Andreas Fault are simply the outer arc along which the miniplate rotates. As attractive as the theory may be, not all scientists agree. Thomas Jordan of MIT and his associates, who are studying satellite ranging measurements made by NASA's Crustal Dynamics Project, do not believe that a miniplate is needed to account for the kinematics of southern California. Undoubtedly data from NASA's highly accurate new Global Positioning Satellite system will help to clarify plate motion in southern California. Although the problems posed by the Big Bend will continue to stir debate, earth scientists are unlimbering powerful tools that may soon provide the answers.

CONCLUSION

I have tried to show, by presenting a few contemporary examples, that modern computer and instrumentation systems have catalyzed the rapid growth of seismology over the past three decades, leading to increasingly accurate knowledge of the structure and physical processes of the Earth's interior. In effect, we are peering into the opaque Earth, not with crystal clarity yet, but in more than just a shadowy, suggestive way. The rapid progress of recent years has been astonishing. Networks of seismic instruments, automated data-reduction systems, efficient database storage of huge volumes of data, and rapid and flexible computer analysis techniques have each played a part; and they have all come about within one generation. Most of the key systems and analytical techniques described in this paper either came into being or were generally known only after 1970. Without these technical innovations, the studies reviewed here concerning the Imperial Valley earthquake, the Long Valley Caldera, and the tomography of southern California would have been impossible.

Our knowledge of the Earth's interior will continue to advance rapidly, in pace with developments in graphics, parallel computation, expert systems, computer networks, and instrumentation systems. Hopefully that knowledge will not only illuminate science, but also permit society to plan for and mitigate the effects of inevitable earthquake disasters.

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