Vol. 4, No. 5 May 1994

GSA TODAY

A Publication of the Geological Society of America

Near–Real-Time Seismology: Rapid Analysis of Earthquake Faulting

Thorne Lay, Charles J. Ammon, Aaron A. Velasco, Jeroen Ritsema
Institute of Tectonics, University of California, Santa Cruz, CA 95064
Terry C. Wallace
Department of Geosciences, University of Arizona, Tucson, AZ 85721
Howard J. Patton
Lawrence Livermore National Laboratory, MS L-205, Livermore, CA 94550

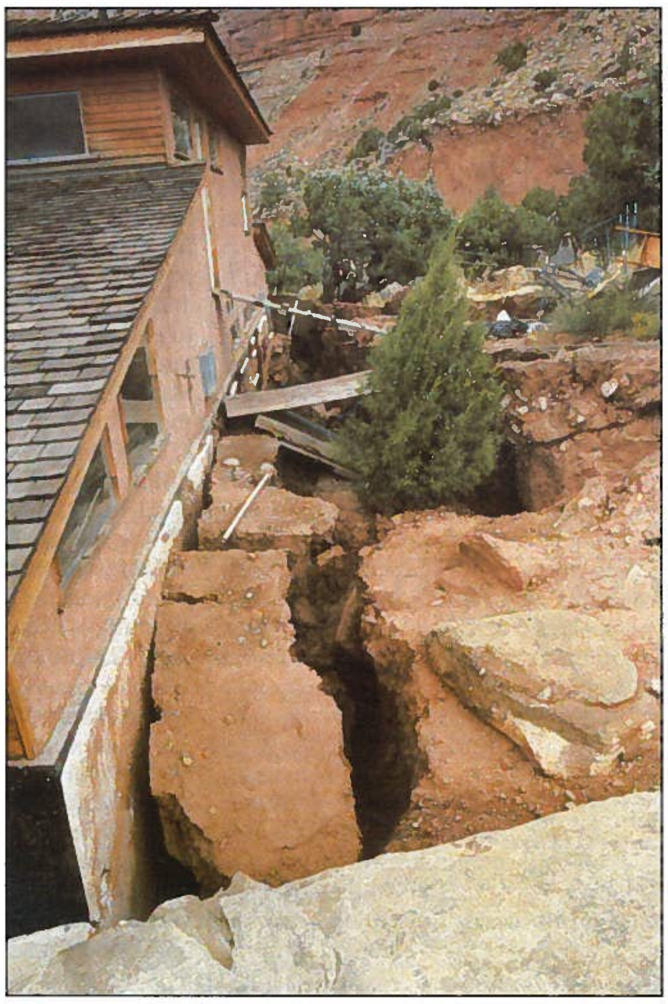
ABSTRACT

Recordings of seismic waves generated during an earthquake contain information about the energy release, fault orientation, and slip distribution on the fault. Recent technological advances in seismology enable immediate access to seismograms recorded at globally distributed seismographic stations. The availability of these data allows rapid determination of earthquake source parameters for significant events anywhere in the world from within a few minutes to a few hours after the event—a practice now being widely implemented. Using several methods, we demonstrate the ability to determine an earthquake point-source model in near real time for the St. George, Utah, earthquake of September 2, 1992 (moment magnitude $M_w = 5.6$). Identification of the actual fault plane and determination of slip distribution in near real time is demonstrated for the $M_w = 7.3$ Landers, southern California, earthquake of June 28, 1992, using a nearby small event to correct for propagation effects. Availability of quantitative faulting information soon after an event can assist emergency response activities, lend guidance to field deployments following the event, and provide a rapid assessment of the tectonic processes involved and the ensuing hazards posed by future earthquakes.

INTRODUCTION: EMERGENCE OF A NEW SEISMOLOGICAL CAPABILITY

During the past two decades, seismologists have developed a broad suite of methods for analyzing ground-motion recordings produced by earthquake faulting (e.g., Aki and Richards, 1980). Analysis of these seismograms provides fundamental information about the source process, including the location, origin time, fault orientation, style of faulting, and slip distribution on the fault. Those characteristics involving only the overall geometry and temporal history of the rupture are represented in a point-source model of the event, typically as a double-couple or moment tensor representation (equivalent force systems associated with the shear dislocation). Finite-source models include the spatial slip characteristics of the faulting and require specification of the actual fault surface, thus eliminating the ambiguity of the two possible fault orientations intrinsic in point-source earthquake models. Recordings of body waves (P and S waves) and surface waves (Rayleigh and Love waves) at different distances are processed to determine a source model. Variations in wavefield complexity as a function of distance and wave period have led to development of diverse inversion procedures that exploit separate portions of the seismograms in different period ranges. Many earthquake studies are regularly conducted to develop an understanding of faulting, but these studies typically take months to complete.

As earthquake faulting is a transient process, often having serious consequences for society, it is desirable to have quantitative information about the source process as quickly as possible.



Landslide damage in southern Utah caused by the St. George, Utah, earthquake. Photo courtesy of Gary Christenson, Utah Geological Survey.

Seismology *continued on p. 132*

Donald M. Davidson, Jr., Named New Executive Director of GSA

Keeping in mind that the Executive Director of GSA must be an earth scientist with managerial experience, be familiar with GSA programs, and have a knowledge of the publication business, the Executive Director Search Committee selected Donald M. Davidson, Jr., to replace F. Michael Wahl, who will retire in June after 12 years of service. Davidson will assume his new duties at GSA headquarters in Boulder, Colorado, on July 1, 1994.

For the past four years, Davidson has been Assistant Provost for Resource Planning, Northern Illinois University, De Kalb, where he is responsible for the administration of an $84 million budget, space allocation, new building construction, remodeling, and strategic planning within the Academic Affairs Division. In addition, he oversees the operations of Cooperative Education, Media Services, the Lorado Taft Outdoor Education Campus, and the Northern Illinois University Hoffman Estates Education Center. Immediately prior to his present position, he was chair and professor of the Department of Geology.

He has held positions as chair and professor, Department of Geological Sciences, University of Texas at El Paso, and professor, Department of Geology, University of Minnesota at Duluth. Outside of academe, he supervised a multidisciplinary research group as senior research specialist and group leader, Satellite Imagery Section, Exxon Production Research, Houston, Texas. He also spent several summers as a consultant involved in metallic and nonmetallic deposit exploration and as a staff geologist mapping for the Minnesota Geological Survey.

Davidson became a GSA member in 1964 while working on his Ph.D. at Columbia University. In 1980 he was elected to Fellowship. He has served the GSA North-Central Section as treasurer for the 1985 Section Meeting, as chair of the Student Awards Committee, and as a member of the Education Committee at the section level. Most recently he has served as a SAGE liaison volunteer.

For the past eight years, Davidson has been treasurer of the Society of Economic Geologists, the SEG Foundation, and the Economic Geology Publishing Company. He previously held the position of Business Manager for the Economic Geology Publishing Company, which publishes the journal *Economic Geology*. In his spare time he has served as a reviewer of grant proposals for the National Science Foundation and National Research Council of Canada, as well as reviewing several geology and mining geology programs.

Davidson received his undergraduate degree from Carleton College, Northfield, Minnesota, and earned his graduate degrees at Columbia University, New York. His areas of professional interest are in resource geology, structural geology, Precambrian geology, and remote sensing. His recent work has focused primarily on strategic planning, space allocation analysis, and financial projections.

Davidson, who is 54, and his wife Mary have two sons. The older son, Rob, will pursue a graduate degree in creative writing following a two-year Peace Corps assignment with his wife. Mark, a third-generation geologist, is studying for a master's degree in geophysics at Purdue University, Indiana.

The five-member Executive Director Search Committee, chaired by GSA Vice-President Dave Stephenson, screened applications and interviewed finalists in January. ■

Seismology *continued from p. 129*

For more than a decade, regional and global earthquake monitoring systems have been developing automation capabilities for rapid determination of source locations and magnitudes of earthquakes worldwide. Primarily, these capabilities exploit telemetry of seismic recordings to central facilities where automatic event detection and location algorithms are running continuously (Lee, 1981). Most of the monitoring instrumentation in such systems has usually recorded a narrow range of high-frequency ground motions that provide good time resolution for accurate event location but are not well suited to characterizing other source parameters.

Globally distributed networks of seismic stations with more complete ground-motion recordings have existed for several decades, but the data were not generally available for significant lengths of time—up to months—after an event. An ongoing upgrade of global international seismic systems, exploiting technological developments for both extremely broad band ground-motion sensitivity and high-dynamic-range recording systems, has been accompanied by improvements in rapid access to the globally distributed data (Romanowicz et al., 1991; Boschi et al., 1991; Incorporated Research Institutions for Seismology [IRIS], 1992). This has involved primarily telephone dial-up access, where specific time windows of ground-motion recordings can be remotely retrieved from the site (IRIS, 1992) Additional broad-band stations, such as those in the Berkeley Digital Seismic Network, have continuous telemetry to regional monitoring centers. By linking global monitoring operations, which determine initial earthquake locations and approximate magnitudes, to automated dial-up data-retrieval systems, both regional and global seismic recordings can be obtained soon after an earthquake occurs, typically within the few minutes to few hours that it takes for all primary body waves and surface waves to travel to regional and global stations, respectively.

Using these new capabilities, high-quality broad-band seismic data are assembled in near real time and made generally available on-line via Internet computer connections at major seismic data centers such as the Incorporated Research Institutions Data Management Center (IRIS-DMC); the Caltech TERRAscope Data Center, the Berkeley Digital Seismic Network (BDSN) Data Center, and the University of Tokyo pre-POSEIDON Data Center. This immediate access to global and regional data sets suitable for waveform inversion enables rapid quantification of important earthquake source parameters as well as prompt investigation of unusual sources, such as volcanic eruptions.

Inversion of rapidly retrieved global seismic data can also be automated, but this requires careful assessment of the resolution and reliability of various procedures, particularly given the limited numbers of signals available in real time. Each of the seismic wave analysis procedures has limitations and advantages for resolving distinct source attributes. Since earthquakes of all sizes and locations, with various data availability, are of interest, a wide variety of seismic analysis techniques is warranted. Some methods exploit signals from a single station, others require at least several regional observations, and yet others utilize global coverage (e.g., Ekström et al., 1986; Ekström, 1993; Fukushima et al., 1989; Dreger and Helmberger, 1991; Ritsema and Lay, 1993; Thio and Kanamori, 1992; Giardini et al., 1993).

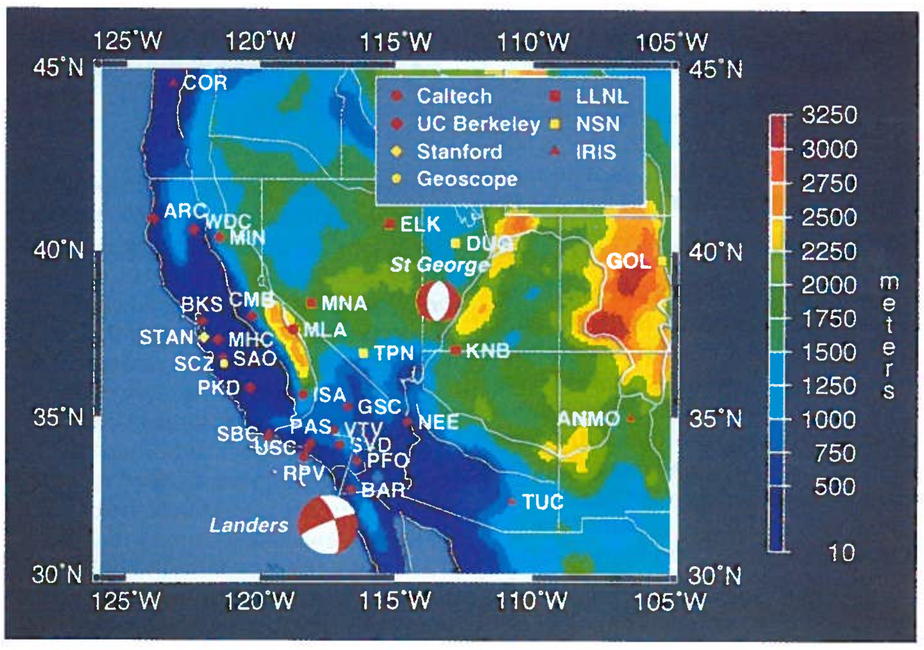


Figure 1. Map of the western United States showing the location of the two earthquakes discussed in this article, along with the location of broad-band seismographic stations with real-time data accessibility now operating in the region. The background color indicates the surface topography. Graphics software was provided courtesy of Paul Wessel and Walter Smith.

ST. GEORGE, UTAH, EVENT OF SEPTEMBER 2, 1992: RAPID DETERMINATION OF A POINT-SOURCE MODEL

An important recent earthquake for which a variety of different near–real-time procedures were applied and compared is the September 2, 1992, St. George, Utah, earthquake ($M_w = 5.6$) (Pearthree and Wallace, 1992). Located within the transition zone between the Basin and Range and Colorado Plateau in southwest Utah (Fig. 1), this is the largest seismic event in Utah and its border regions since 1975. This moderate-sized earthquake produced signals recorded at broad-band stations in the western United States (locations of those with real-time access are shown in Fig. 1) as well as globally, making it well suited for comparing results from different procedures. We applied a variety of seismic analysis procedures to quickly estimate double-couple or moment tensor point-source models for this event and compare the resulting source mechanisms (Fig. 2). The solutions are quite consistent, and all indicate normal faulting at a depth of 10–15 km.

A conventional P-wave first-motion solution (Fig. 2A) was obtained (Pechmann et al., 1992) from regional short-period stations of the University of Utah seismographic network and other arrays in adjacent states, and these data also provided an accurate source location. In this case, the station coverage is sufficient to provide a well-constrained solution, as the event is surrounded by stations from various networks. Researchers at Harvard University produced the solution in Figure 2B by the "quick" centroid-moment tensor (CMT) inversion (Ekström, 1993), which used teleseismic body wavetrains from six stations with periods longer than 45 s. For recent large events of interest, near–real-time data are used to automatically obtain preliminary CMT inversions, and the solutions are broadcast to seismological research groups (Ekström, 1993). These solutions are usually very similar to the final CMT solution obtained months later after more extensive data become available. The CMT procedure uses seismic waves that take several hours to reach stations around the world. More rapid source analyses (yielding a source solution within 20 min or so) can be performed using regional distance recordings 50–1500 km from the source.

We employ four regional distance techniques that vary in the wave types and period range of ground motions used. A modified CMT procedure, using regional distance body and surface-wave ground motions (Ritsema and Lay, 1993), was applied to signals from six regional broad-band stations with good azimuthal distribution around the St. George epicenter (Fig. 2C). This procedure requires very little preprocessing, as it involves inversion of the complete waveform, usually about 10–15 min long, filtered to retain periods longer than 50 s. At these periods, a laterally uniform Earth model is sufficient to account for propagation effects. Only the latest generation of high-dynamic-range, broad-band seismometers provides on-scale, long-period signal recordings at regional distances for earthquakes larger than magnitude 5.5.

Intermediate period (10–50 s) regional distance surface waves can be analyzed for a source model when a suitable, heterogeneous velocity model is available. Results of one procedure for the Utah earthquake are shown in Figure 2D. In this procedure, fundamental mode Rayleigh and Love waves are isolated by windowing; the spectra are computed and corrected for path-specific propagation effects due to variable crustal structure and then inverted for the source mechanism (Patton and Zandt, 1991; Thio and Kanamori, 1992; Pasayanos and Romanowicz, 1992). The correction procedure requires a modest amount of time and can be automated in the future. The source model in Figure 2D was obtained within a few hours of the event.

Regional body waves also can be used to estimate first-order properties of the seismic source (Wallace and Helmberger, 1982; Dreger and Helmberger, 1991). P waves in the period range 5–30 s are relatively insensitive to variations in crustal structure and

continued on p. 133

Grants Available for Collaborative Work

The Office for Central Europe and Eurasia of the National Academy of Sciences is offering travel and host grants to U.S. scientists who would like to engage in collaborative research with colleagues from Central and Eastern Europe and the former Soviet Union. Grants will fund two programs: the Collaboration in Basic Science and Engineering (COBASE) and the Radioactive Waste Management Program. COBASE offers short-term development grants to $2200 for hosting a European or Asian colleague for two weeks to prepare a collaborative research proposal for submission to the National Science Foundation or other funding organization. Long-term grants of $3600–$12,100 would support hosting or visiting a foreign researcher for one to six months to become familiar with research and prepare results for publication.

Deadlines for short-term grant applications are June 24 or December 9. Applications for long-term grants are due by June 24. The Radioactive Waste Management Program, funded by the U.S. Department of Energy, would support researchers who wish to host colleagues from the former Soviet Union for 6–12 months for research on managing radioactive waste. Grant levels range from $16,000 to $30,000. Deadlines for applications are March 30 or September 30. Applicants must be U.S. citizens with a Ph.D. or research equivalent. Foreign colleagues, who must also have a Ph.D. or equivalent, must be citizens of participating countries in Eurasia. For an application or additional information, please contact: Office for Central Europe and Eurasia, National Academy of Sciences, 2101 Constitution Ave., N.W., Washington, DC 20418, (202) 334-3680, fax 202-334-2614, E-mail ocee@nas.edu.

In Memoriam

George Biemesderfer
Bethlehem, Pennsylvania
May 29, 1993

Phillip Guild
Bethel, Arkansas

John M. Kellberg
Knoxville, Tennessee
July 14, 1993

Harold Kirkemo
Sun City, Florida

Louis Heyman
Amarillo, Texas
February 10, 1994

Robert F. Legget
Ottawa, Ontario, Canada
April 17, 1994

Heine Lowenstam
Pasadena, California
June 7, 1993

Gordon B. Oakeshott
Walnut Creek, California
December 27, 1993

Fred B. Phleger
Solona Beach, California
December 14, 1993

William G. Pierce
Cupertino, California
January 31, 1994

Carl B. Richardson
Tucson, Arizona

Austin A. Sartin
Shreveport, Louisiana
November 21, 1993

James R. Townsend
Los Angeles, California
November 27, 1990

John W. Wells
Washington, D.C.
January 12, 1994

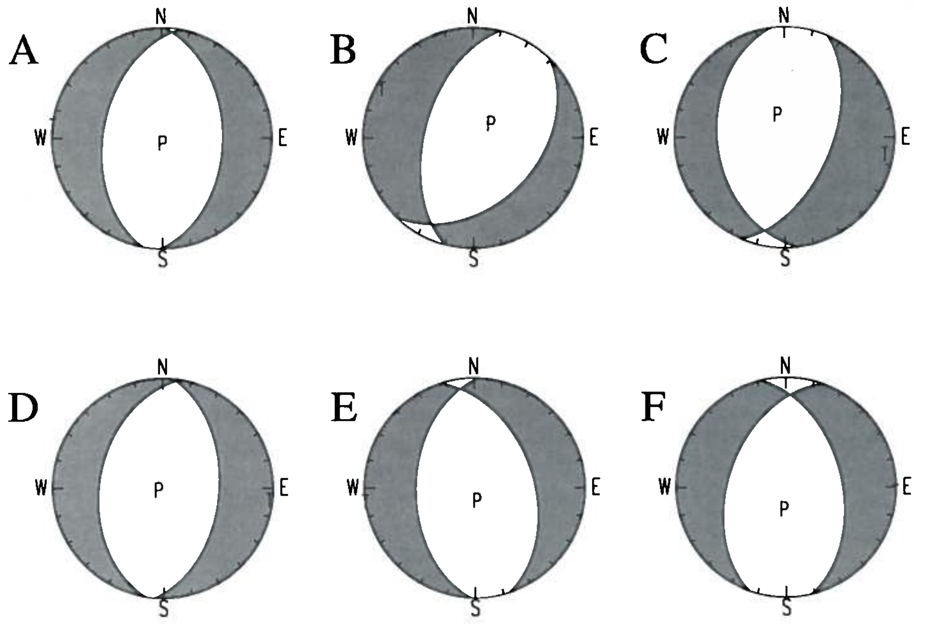


Figure 2. Source focal mechanisms determined using different near–real-time procedures for the 1992 St. George, Utah, earthquake. Each plot is a lower-hemisphere, equal-area projection of the best double-couple solution from the various methods. Compressional (P) and tensional (T) strain axes are plotted; shaded regions correspond to P wave first-motions away from the source. The two curves in each projection represent the fault plane and the auxiliary plane, with independent (aftershock) data indicating that the westward-dipping plane is the actual fault plane. All solutions involve almost pure normal faulting; differences between solutions arise from the limitations of each technique. A: P wave first-motion mechanism. B: Quick CMT solution. C: Regional-CMT solution. D: Regional short-period surface wave solution. E: Regional P wave inversion from multiple stations. F: Regional P and S wave inversion from a single station.

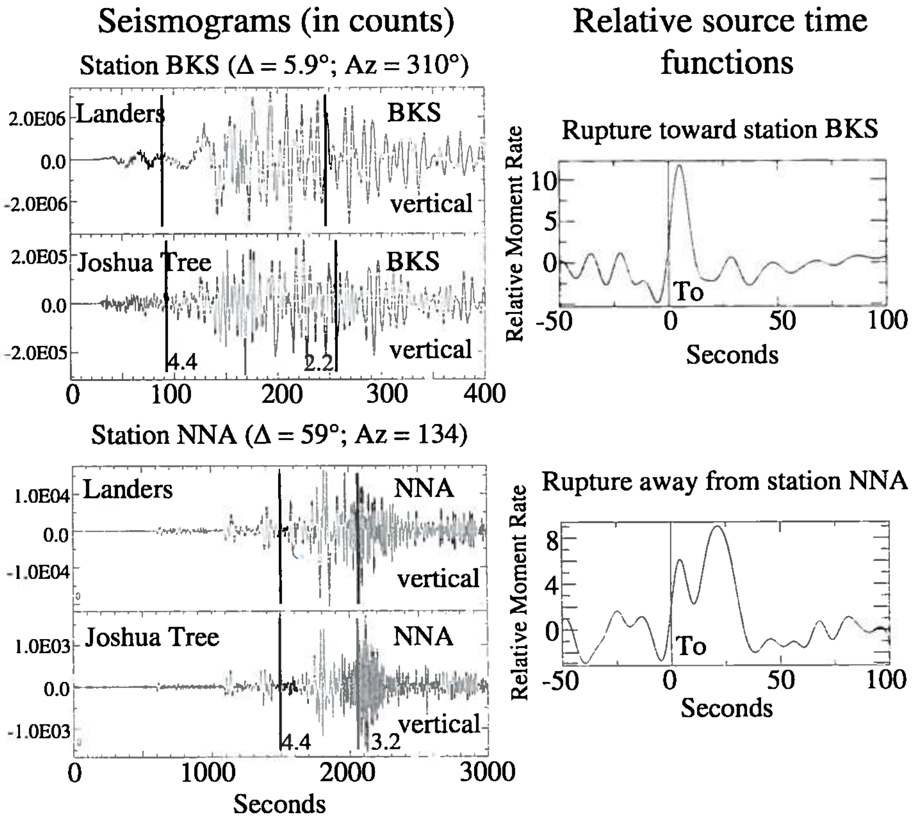


Figure 3. Examples of propagation correction by deconvolving signals from a small event from the corresponding signals from a large event. The data on the left are Rayleigh wave recordings at two broad-band stations of the magnitude 7.3, June 28, 1992, Landers, California, earthquake and the magnitude 6.1, April 23, 1992, Joshua Tree event. The signals share common propagation complexity but differ due to the greater rupture complexity of the Landers event. Deconvolution of the Landers records by the Joshua Tree records yields the relative source time functions shown on the right, which contain information about the spatial-temporal rupture history for the Landers event. Note the great reduction in complexity of the signals achieved by removing the propagation effects. Stations BKS (Berkeley, California) and NNA (Naña, Peru) are at opposite azimuths along the rupture plane, and the differences in the relative source functions reflect the finite rupture of the Landers event as it ruptured northwestward toward BKS. The Landers event involved two subevents, apparent as the double peak at southern station NNA, in which northward rupture resulted in a Doppler shift causing the pulses to overlap, making a single pulse at northern station BKS.

Seismology *continued*

can be modeled simply and quickly. Inversion of 12 regional P waveforms from six western U.S. stations gave the source model in Figure 2E. The P and S wave information in a single, three-component regional seismogram is sometimes adequate to resolve the source as well (Fan and Wallace, 1991; Dreger and Helmberger, 1990); the result of inversion of a single set of recordings from a broad-band station in Berkeley, California, is shown in Figure 2F. Use of broad-band data in the body wave and short-period surface wave frequency band improves resolution of the source depth relative to standard location capabilities.

Each of the methods used in Figure 2 has associated error estimates, but the average parameters for the event are strike, 188° ±10°; dip, 46° ±4°; rake, –89° ±14°; depth, 15 ±5 km; and seismic moment, 2.2 ±0.6 x 10^{24} dyne-cm. The general consistency of the point-source characteristics of this event, all obtained within a few hours of the rupture, indicate that near–real-time quantification of earthquake processes is viable and robust using a variety of methods. Additional methods exist for rapid analysis of teleseismic body waves (Kanamori et al., 1992) as well as very close-in strong motion recordings (Kanamori et al., 1990; Uhrhammer, 1992), and these can be implemented depending on data availability. Some procedures will be more successful for smaller events, while others will be useful for larger events, and the distance range of the available data will also influence the procedures that can be used. A point-source characterization is sufficient to assess the overall nature of faulting and energy release.

Although the point-source inversions discussed above can routinely recover the seismic moment and overall faulting geometry, none of them provides a unique choice of the fault plane or variations in the slip function on the fault. For the St. George earthquake, the only basis for identifying the fault plane (believed to correspond to the west-dipping Hurricane fault in this case) is the distribution of small aftershocks (Pechmann et al., 1992). Point-source parameters are retrieved using seismic wavelengths longer than the source dimensions, and the period range limits the temporal resolution of the source energy release. Resolving greater details of the finite spatial-temporal rupture history requires use of shorter period wave energy, but this in turn requires an increasingly accurate Earth model to account for wave propagation effects.

In regions of dense instrumentation and seismic activity, there are ongoing efforts to "calibrate" the propagation paths, developing catalogs of models or propagation transfer functions that can be used for rapid or routine source model investigations (e.g., Ho-Liu and Helmberger, 1989; Dreger and Helmberger, 1991). Similarly, steady improvements in global aspherical Earth models provide better propagation models for long-period body and surface waves, but these have been used primarily to improve point-source inversions (Velasco et al., 1992).

1993 LANDERS, CALIFORNIA EARTHQUAKE: RAPID DETERMINATION OF A FINITE FAULT MODEL

For near–real-time analysis of finite source characteristics of earthquake ruptures applicable on a global scale, we have adapted a procedure called "empirical Green's function analysis," historically applied mainly to small, locally recorded events. The essence of this technique is to use the seismic wavefield produced by a small earthquake located near a larger event of interest to empirically account for propagation effects on each path (Ammon et al., 1993; Nakanishi, 1991). This technique works best for colocated events with identical fault mechanisms that have a large difference in rupture duration (involving at least a magnitude unit difference in size). The signals from the smaller event are treated as the Earth's impulse response and are deconvolved from the signals of the larger event to remove common propagation effects. The deconvolved signals are relative source functions containing the isolated spatial-temporal energy release information of the larger event (Fig. 3). Since an empirical path correction usually has much greater accuracy than that provided by existing aspherical Earth models, this procedure greatly extends the period range of seismic signals that can be used to study the source, particularly for surface waves.

Earthquakes that rupture over a significant spatial (>20 km) and temporal (>10 s) extent often produce readily observable variations in the source time functions, which are azimuthally dependent functions of the spatial-temporal rupture history. Thus, analysis of the azimuthal variation of relative source time functions can reveal the spatial-temporal faulting complexity. This works best if the rupture progresses unilaterally down a fault in one direction, as this maximizes the azimuthal pattern. For a bilateral rupture it may not be possible to determine the actual fault plane.

A near–real-time determination of a finite fault model was performed for the $M_w = 7.3$, June 28, 1992, Landers, southern California, earthquake, the largest event to occur in the contiguous United States in 40 yr (Kanamori et al., 1992; Henyey, 1992; Harris and Simpson, 1992; Stein et al., 1992). As soon as a preliminary point-source solution was obtained for this event by the CMT procedure (Fig. 1), we searched for nearby smaller events with the same mechanism with high-quality signals at the same stations. The small event used for empirical path corrections in this case was the April 23, 1992, Joshua Tree earthquake, which had a magnitude of 6.1. Both events involve right-lateral strike-slip faulting. In general, we exploit the large CMT catalog for all significant earthquakes since 1977 (more than 10,000 CMT solutions are included) to find a suitable small event close to a large event of interest. Then, on-line databases at various data centers are searched for common path seismograms for use in the deconvolutions. Very broad band data are available on-line only for events in 1989 and later, whereas digital data are available from the Harvard data center back to 1977. All of this data collection and deconvolution can be performed in a few minutes.

Upon deconvolving the surface wave recordings for the Landers event using the Joshua Tree signals, we immediately detected strong azimuthal patterns in the deconvolved source functions that revealed north-northwestward rupture of the fault (Ammon et al., 1993). The Landers rupture involved two main pulses of energy release, each lasting about 10 s, with a 10 s separation between the subevents. These pulses arrive closer together at stations in the direction of rupture due to the Doppler shift effect of rupture directivity, so the relative source functions are single pulses toward the north, while clear double pulses are observed toward the south (see Fig. 3). Having determined the fault plane, we assume unilateral rupture to arrive at the slip model shown in Figure 4, which is compared with actual surface-break slip measurements (Sieh et al., 1994). By detecting systematic azimuthal patterns in the relative amplitude of the two pulses for seismic waves with different radiation patterns, we were also able to invert for a change in strike between the subevents, involving a 12° counterclockwise rotation (Fig. 4). This corresponds well to the transfer of slip from north-striking to north-northwest–striking faults observed in the surface breaks (Sieh et al., 1994).

Most events around the world with magnitudes >7.0 can be analyzed for details of the source rupture process as long as suitable data for a small event are available. This generally proves to be the case, and we have analyzed several other large events in or offshore of California in 1991 and 1992, uniquely identifying the rupture plane in each case. Deconvolution has also proved advantageous for determining overall

Seismology *continued on p. 134*

Seismology *continued from p. 133*

time histories of rupture for very large events, such as recent ones that produced destructive tsunamis in Nicaragua and Japan.

SUMMARY

Procedures for real-time determinations of earthquake faulting parameters are in their infancy, but this is clearly an emerging capability that will expand in the near future. The advantages of rapid quantifications of source properties include possible guidance for emergency response activities, rapid assessment of the tectonic processes involved by identification of the actual fault, and anticipation of ensuing hazards from future events such as aftershocks or the triggering of adjacent faults, as well as tsunami warning applications. Detailed knowledge of the fault depth, mechanism type, and rupture plane can guide post earthquake studies, including searches for surface offsets and deployment of geodetic and seismic instruments in the source vicinity. In addition, there is great value in rapid analysis, because unusual events will not be overlooked or forgotten as readily, a common occurrence in the past given the transient nature of earthquake activity and the formerly slow rate of data accumulation.

ACKNOWLEDGMENTS

We appreciate the rapid distribution of information about earthquake source parameters provided by researchers at Harvard University, California Institute of Technology (Caltech), and University of California, Berkeley, along with the general seismological research community. The on-line data resources provided by the Data Management Center of the Incorporated Research Institutions for Seismology (IRIS-DMC) are indispensable for these new capabilities, along with on-line data centers at Caltech, UC Berkeley, and the pre-POSEIDON data center of the Earthquake Research Institute of Tokyo University. Jim Pechmann provided information from the University of Utah seismographic network for the St. George event, and a helpful review of the manuscript. This research was supported by National Science Foundation grant EAR-9017767. Patton acknowledges the support of the U.S. Department of Energy at the Lawrence Livermore National Laboratory under contract W-7405-Eng-48. Contribution number 203 of the Institute of Tectonics and C. F. Richter Seismological Laboratory.

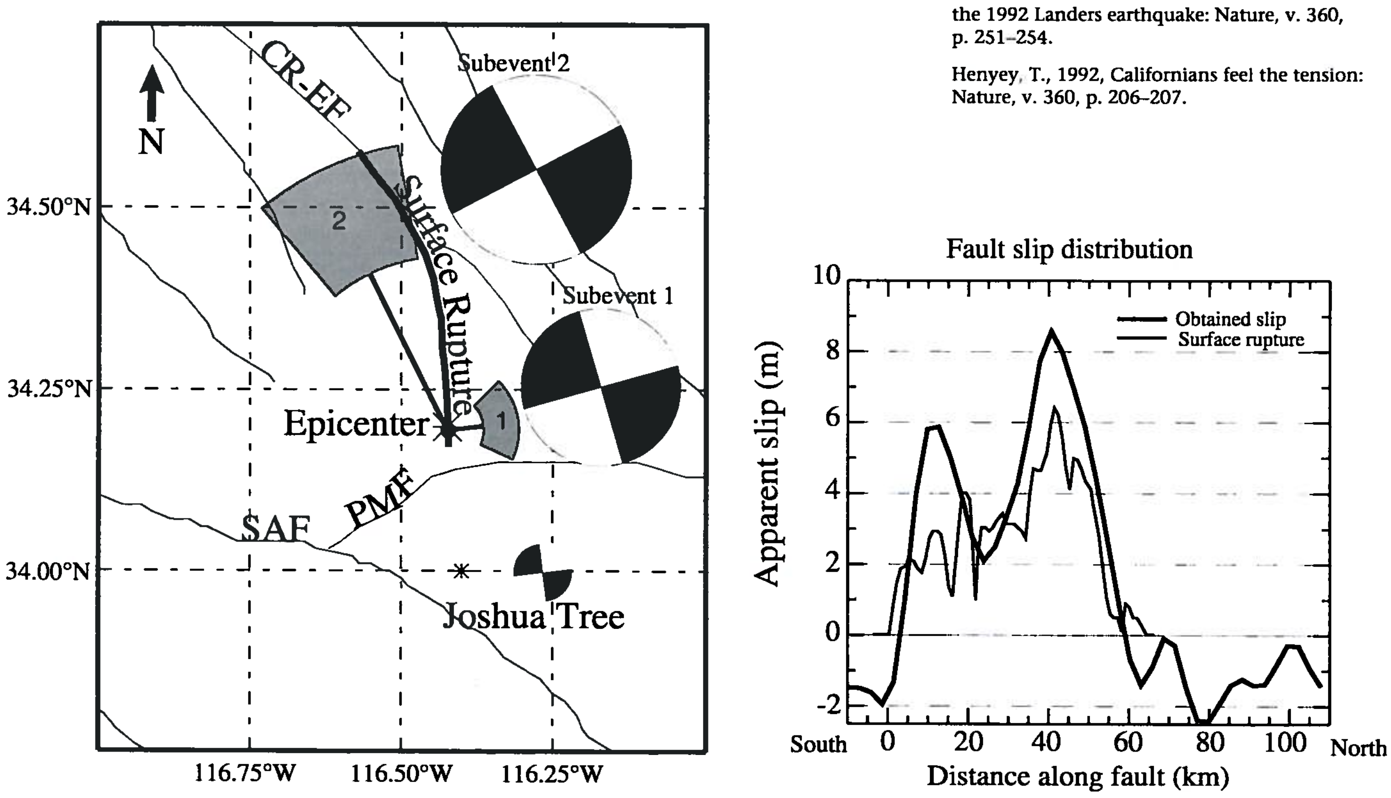


Figure 4. Near–real-time finite source model obtained for the June 28, 1992, Landers earthquake, involving two subevents with slightly different right-lateral strike-slip mechanisms, along a north-northwestward trend with northward rupture propagation (left). The shaded areas indicate the relative positions of the center of energy release in the two subevents relative to the Joshua Tree event to the south (asterisk). The distribution of slip along the fault found for this model (right) is compared to the observed pattern of surface rupture. CR-EF is Camp Rock–Emerson faults; SAF is San Andreas fault; PMF is Pinto Mountain fault.

REFERENCES CITED

Aki, K., and Richards, P. G., 1980, Quantitative seismology, Volumes I and II: San Francisco, W. H. Freeman and Co., 932 p.

Ammon, C. J., Velasco, A. A., and Lay, T., 1993, Rapid estimation of rupture directivity: Application to the 1992 Landers (Ms = 7.4) and Cape Mendocino (Ms = 7.2), California earthquakes: Geophysical Research Letters, v. 20, p. 97–100.

Boschi, E., Giardini, D., and Morelli, A., 1991, Mednet: Il Cigno Galileo Galilei, 514 p.

Dreger, D. S., and Helmberger, D. V., 1990, Broadband modeling of local earthquakes: Seismological Society of America Bulletin, v. 80, p. 1162–1179.

Dreger, D. S., and Helmberger, D. V., 1991, Source parameters of the Sierra Madre earthquake from regional and local body waves: Geophysical Research Letters, v. 18, p. 2015–2018.

Ekström, G. A., 1993, Rapid earthquake analysis at Harvard: IRIS Newsletter, XII, p. 4–6.

Ekström, G. A., Dziewonski, A. M., and Steim, J. M., 1986, Quasi-real time CMT solutions for July 1986 Californian earthquakes: Eos (Transactions, American Geophysical Union), v. 67, p. 1090.

Fan, G., and Wallace, T. C., 1991, The determination of source parameters for small earthquakes from a single, very broadband seismic station: Geophysical Research Letters, v. 18, p. 1385–1388.

Fukushima, T., Suetsugu, D., Nakanishi, I., and Yamada, I., 1989, Moment tensor inversion for near earthquakes using long-period digital seismograms: Journal of Physics of the Earth, v. 37, p. 1–29.

Giardini, D., Boschi, E., and Palombo, B., 1993, Moment tensor inversion from Mednet data, 2: Regional earthquakes of the Mediterranean: Geophysical Research Letters, v. 20, p. 273–276.

Harris, R. A., and Simpson, R. W., 1992, Changes in static stress on southern California faults after the 1992 Landers earthquake: Nature, v. 360, p. 251–254.

Henyey, T., 1992, Californians feel the tension: Nature, v. 360, p. 206–207.

Ho-Liu, P., and Helmberger, D. V., 1989, Modeling regional Love waves: Imperial Valley to Pasadena: Seismological Society of America Bulletin, v. 79, p. 1194–1209.

Incorporated Research Institutions for Seismology, 1992, IRIS annual report: Arlington, Virginia, IRIS, 24 p.

Kanamori, H., Mori, J., and Heaton, T. H., 1990, The 3 December 1988, Pasadena earthquake ($M_L = 4.9$) recorded with the very broadband system in Pasadena: Seismological Society of America Bulletin, v. 80, p. 483–487.

Kanamori, H., Thio, H.-K., Dreger, D., Hauksson, E., and Heaton, T., 1992, Initial investigation of the Landers, California earthquake of 28 June 1992 using TERRAscope: Geophysical Research Letters, v. 19, p. 2267–2270.

Lee, W. H. K., and Stewart, S. W., 1981, Principles and applications of microearthquake networks: Advances in Geophysics, suppl. 2, 293 p.

Nakanishi, I., 1991, Source process of the 1989 Sanriku-Oki earthquake, Japan: Source function determined using empirical Green function: Journal of Physics of the Earth, v. 39, p. 661–667.

Pasayanos, M., and Romanowicz, B., 1992, Inversion of regional surface waves for source parameters and structure in California: Eos (Transactions, American Geophysical Union), v. 73, p. 372.

Patton, H. J., and Zandt, G., 1991, Seismic moment tensors of western U.S. earthquakes and implications for the tectonic stress field: Journal of Geophysical Research, v. 96, p. 18,245–18,259.

Pearthree, P. A., and Wallace, T. C., 1992, The St. George earthquake of September 2, 1992: Arizona Geology, v. 22, p. 7–8.

Pechmann, J. C., Arabasz, W. J., and Nava, S. J., 1992, The St. George, Utah, earthquake of September 2, 1992: A normal-faulting earthquake with very weak aftershock activity: Eos (Transactions, American Geophysical Union), v. 73, p. 399.

Ritsema, J., and Lay, T., 1994, Rapid source mechanism determination of large ($M_w \geq 5$) earthquakes in the western United States: Geophysical Research Letters (in press).

Romanowicz, B., and 12 others, 1991, The GEOSCOPE program: Present status and perspectives: Seismological Society of America Bulletin, v. 81, p. 243–264.

Sieh, K., and 19 others, 1994, Near-field investigations of the Landers earthquake sequence, April to July, 1992: Science (in press).

Stein, R. S., King, G. C. P., and Lin, J., 1992, Change in failure stress on the southern San Andreas fault system caused by the 1992 magnitude 7.4 Landers earthquake: Science, v. 258, p. 1328–1332.

Thio, H.-K., and Kanamori, H., 1992, Moment tensor inversions in Southern California using surface waves recorded by TERRAscope: Eos (Transactions, American Geophysical Union), v. 73, p. 376.

Uhrhammer, R. A., 1992, Broadband near-field moment tensor inversion: Eos (Transactions, American Geophysical Union), v. 73, p. 375.

Velasco, A. A., Lay, T., and Zhang, J., 1992, Improved resolution of earthquake source parameters from long-period surface wave inversions: Physics of the Earth and Planetary Interiors, v. 74, p. 101–107.

Wallace, T. C., and Helmberger, D. V., 1982, Determining source parameters of moderate-size earthquakes from regional waveforms: Physics of the Earth and Planetary Interiors, v. 30, p. 185–196.

Manuscript received, May 3, 1993; revision received August 19, 1993; accepted October 18, 1994 ■

GSA Section Officers—1994–1995

GSA has six regional North American sections, generally including GSA members who live within the geographical limits of each section. (Members who live in one section but have professional interest in another section can declare membership in the section of interest rather than their geographical section.) Each section holds annual technical and business meetings. The number of voting members shown for each section is as of December 31, 1993.

CORDILLERAN Voting members: 3716

Geographic area: Alaska, Arizona south of lat 35°N, California, Hawaii, Nevada, Oregon, Washington, British Columbia, Yukon, Northwest Territories.

Officers: Eldridge M. Moores, chair; Catherine J. Hickson, vice-chair; Bruce A. Blackerby, secretary; Darrel S. Cowan, past chair.

ROCKY MOUNTAIN Voting members: 1813

Geographic area: Arizona north of lat 35°N, Colorado, Idaho, Montana, New Mexico, North Dakota, South Dakota, Utah, Wyoming, Alberta, Saskatchewan.

Officers: Stephan G. Custer, chair; David R. Lageson, vice-chair; James Schmitt, vice-chair; Kenneth E. Kolm, secretary; Douglas C. Brew, past chair; Robert W. Blair, Jr., past vice-chair.

NORTH-CENTRAL Voting members: 1307

Geographic area: Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Nebraska, Ohio, Wisconsin, Manitoba, Ontario west of 89th meridian.

Officers: Robert F. Diffendal, Jr., chair; James B. Swinehart, vice-chair; George R. Hallberg, secretary; Alan E. Kehew, past chair; Ronald B. Chase, past vice-chair.

SOUTH-CENTRAL Voting members: 1288

Geographic area: Arkansas, Kansas, Oklahoma, Texas.

Officers: Philip L. Kehler, chair; Page C. Twiss, vice-chair; Rena M. Bonem, secretary-treasurer; John A. Breyer, past chair.

NORTHEASTERN Voting members: 2178

Geographic area: Connecticut, Delaware, District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, New Brunswick, Newfoundland, Nova Scotia, Prince Edward Island, Quebec, Ontario east of the 89th meridian.

Officers: Stephen G. Pollock, chair; Barry Doolan, vice-chair; Kenneth N. Weaver, secretary-treasurer; Sandra M. Barr, past chair.

SOUTHEASTERN Voting members: 1568

Geographic area: Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, West Virginia.

Officers: Donald C. Haney, chair; Harry Y. McSween, vice-chair; Michael J. Neilson, secretary-treasurer; Molly Fritz Miller, past chair; Lynn Glover, III, past vice-chair. ■