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of the
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EARTHQUAKE NOTES

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MANUSCRIPTS

EARTHQUAKE NOTES is a Journal for the Seismology of Eastern North America. Articles pertaining to Eastern North American earthquakes, interplate seismotectonics and earthquake engineering are particularly encouraged. EARTHQUAKE NOTES will also accept short (4 pages or less) informational notes on Eastern North American earthquakes and notices of publications pertaining to Eastern North American earthquakes. Page charges are not assessed. Referee's opinions are sought on all papers exceeding 4 published pages.

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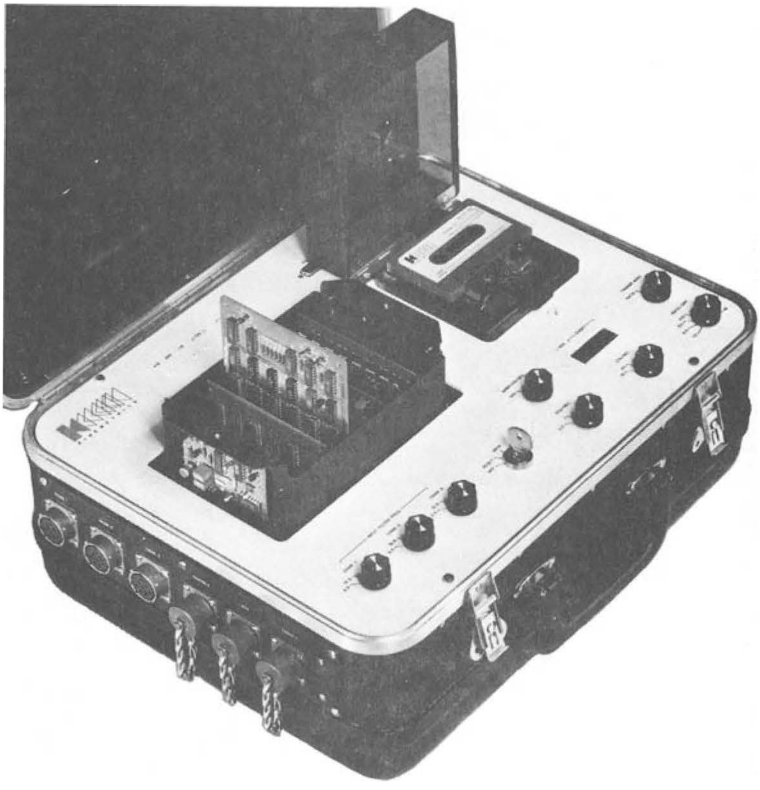

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INTRAPLATE REGIONS: EARTHQUAKE RISK, ENGINEERING SEISMOLOGY, AND STRUCTURAL RESPONSE I

STRESS DROPS OF THE AFTERSHOCKS OF THE 1982 NEW BRUNSWICK EARTHQUAKE

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One week after the New Brunswick earthquake of January 9, 1982, the U.S.G.S. deployed 6 three-component digital seismographs in the epicentral area. Forty aftershocks ($M_L \leq 3.5$) were recorded in the following week; their moments ranged from 10^{18} to 10^{21} dyne-cm and the hypocentral depths ranged from 0.5 to 7.5 km (Mueller and Cranswick, 1982). The recordings are remarkable for the high-frequency content (30-50 Hz) of the body waves. The stress drops of the aftershocks have been computed from measurements of the high-frequency acceleration spectral levels, $\ddot{u}_c(\omega)|$, and the relation,

$$\Delta\sigma = \frac{\mu R}{R^c} \frac{\ddot{u}_c(\omega)|}{\Delta v A^{\frac{1}{2}}}$$

where μ is the rigidity, R is the geometrical spreading factor, R^c is the high-frequency radiation pattern, $\Delta v = 0.8\beta$ is the peak rupture velocity and A is the rupture area (Boatwright, 1982). Frequency-dependent site corrections are used to obtain unbiased estimates of the spectral levels. The computed stress drops range from 40 to 200 bars and have uncertainties of $\simeq 15$ percent. By comparison, the main shock had a moment of 10^{24} dyne-cm and a stress drop of $\simeq 60$ bars (Choy et al., 1983). The stress drops of the aftershocks suggest that the apparent decrease of stress drop with decreasing source size for small mid-plate earthquakes may be determined by site effects rather than actual source characteristics.

WAS MIRAMICHI - 1982 A TYPICAL EASTERN CANADIAN EARTHQUAKE?

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Strong Motion records from the Miramichi 1982 earthquake aftershock series were the first significant set of records obtained in eastern Canada. Peak accelerations from an M4.8 event were several meters per square-second, at frequencies of 15 to 45 Hz. Although some of the high values may be explained by instrument foundation and subsoil amplification, the general high level of acceleration is believed to be real, but is not consistent with reported intensities. The high frequency accelerations are said to be very significant for special engineering systems, but for the purpose of the building code for ordinary buildings, the frequency range of concern is below 10 Hz. Fourier amplitudes (and also response spectra) in this frequency range are factors of 3 to 10 below the maximum and thus agree much better with intensities.

The main event of M5.8 was felt to several hundred kilometers distance which appears typical for eastern Canadian and U.S. earthquakes, and the little available information on epicentral intensities is consistent with other eastern intensities from similar earthquakes. It may, therefore, be justified to extrapolate the Miramichi experience to about magnitude 6 in similar environments such as Western Quebec, including Temiskaming and Cornwall, and perhaps to Charlevoix.

THE EARTHQUAKES OF JANUARY 5, 1843, AND OCTOBER 31, 1895, IN THE CENTRAL MISSISSIPPI VALLEY

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The central Mississippi Valley earthquakes of 1843 and 1895: 1) are the largest historical earthquakes in the region excluding the series of great shocks in 1811-12, 2) have much more data available than the 1811-12 shocks, 3) were located near the south and north ends of the New Madrid seismic zone, respectively, and 4) were strong enough to cause damage at both Memphis and St. Louis. This report is concerned with the results of the reevaluation of intensity data for these two earthquakes.

The 1843 earthquake had a maximum intensity of VIII M.M., an epicenter in northeast Arkansas 32 km west of Memphis, Tenn., and a total felt area of approximately 1,500,000 km^2. Intensity VIII was assigned only to Memphis, Tenn., where chimneys were thrown down and many brick walls were seriously cracked. Intensity VII was assigned to five places within 200 km of the epicenter and also to St. Louis (400 km).

The 1895 earthquake was slightly larger than the 1843 earthquake, and had a maximum intensity of at least VIII and probably IX M.M., an epicenter near Charleston, Mo., and a total felt area of 2,500,000 km^2. Intensity VIII was assigned to four places near the epicenter, and also to three others within 400 km of the epicenter. Details of the isoseismals are very well defined and show markedly different rates of attenuation of intensity in different directions from the meizoseismal area.

In general, the intensity attenuation is highest to the southwest, and lowest to the northwest, northeast, and southeast of the New Madrid seismic zone. Areas of low attenuation to the northeast correlate well with areas of low attenuation noticed in a 1977 study by G.A. Bollinger for the 1886 Charleston, S.C., earthquake. Liquefaction effects were noted for both earthquakes, but were not used for intensity assignment.

SOURCE CHARACTERIZATION FOR SEISMIC HAZARDS ANALYSES WITHIN INTRAPLATE TECTONIC ENVIRONMENTS

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Because of the relatively low rates of seismic activity within intraplate regions, the characterization of seismic sources in terms of source geometry, maximum earthquake magnitude, and earthquake recurrence is usually difficult. These difficulties stem primarily from uncertainties regarding the tectonic mechanisms for intraplate earthquakes and the association of present and future seismicity with mapped geologic structure. An appropriate approach to deal with these uncertainties is to treat the source characterization parameters probabilistically. Logic trees can be used to include the various possible interpretations of the geological and seismological data including parameters such as fault rupture length, fault width, and minimum depth to fault rupture. Appropriate weights are assigned based on expert judgement as to the relative likelihood of the various interpretations.

Reactivation of portions of older pre-existing fault zones appears to be a common cause for present-day seismicity within intraplate regions. A seismic exposure analysis was conducted within such a region using the above approach. The major incertainties treated in the exposure model are: (1) the association of seismicity with the mapped faults in the region and (2) the use of fault-specific geologic

data versus regional seismicity data to define the recurrence of individual sources. The results of this study indicate that despite the uncertainties inherent to intraplate environments, probabilistic methods can be developed to characterize seismic sources for seismic hazards assessments.

EARTHQUAKE HAZARD ZONING IN THE CENTRAL AND EASTERN UNITED STATES: IMPROVEMENTS BASED ON NEW GEOLOGIC FOUNDATIONS

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Three recent developments make it seem likely that future revisions of seismic source zones for regions east of Denver can be based on known geologic structure to a degree not hitherto possible. (1) Recent unpublished map compilations of rifts, including graben and rifted terranes, for the southeast and south-central United States show that seven out of eight locales of damaging or frequent earthquakes coincide with known or probable rifted areas. However, the association is not perfect, and the rifts are of three ages and have diverse histories and varied geologic, geophysical, and perhaps seismogenic characteristics. (2) Some suspect (accreted) terranes have been identified in and east of the eastern Appalachians. Such terranes vary in composition, structure, and history; Bollinger (this meeting) notes that some appear to vary in associations with historical and instrumental seismicity too. For example, Charleston, central Virginia, and southwestern Virginia are in differ terranes and so should be in different source zones, though zone boundaries are not yet clearly identified. (3) In 1981, Jones-Cecil showed that a form of pattern recognition can objectively identify previously unrecognized groups of geologic, geophysical, and topographic factors that are associated with sites of damaging shocks, or with sites of apparent quiescence.

AN ENGINEER'S PERSPECTIVE ON THE CAPE ANN, MASSACHUSETTS EARTHQUAKE OF 1755

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In order to interpret contemporary reports of damage, types of construction existing in Boston and Eastern Massachusetts at the time of the earthquake are identified and studied. Particular attention is given to the number of brick buildings (especially those with gable ends) and chimneys, since damage occurred primarily in such construction. Analytical studies are reported for three situations: a specific multi-story brick building apparently undamaged by the earthquake, interaction between a typical wood-framed house and its chimney, and damage to chimneys as a function of ground shaking and geometry. It is concluded that the peak accelerations in this earthquake, referenced to a ground shaking of standardized duration and frequency content, were unlikely to have exceeded 0.12 g.

INTENSITY SCALES AND EARTHQUAKE RISK

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Intensity scales are still used extensively in estimating earthquake risk, in particular if historical data is analysed. Numerous investigations of this kind told us that some scales are useless or misleading particularly for the epicentral region. Even the better ones are of limited use to describe damage to well designed buildings. As an example we are presenting a correlation between mean damage ratio (MDR) observed in some South Italian towns after the Campania-Basilicata earthquake of November 23, 1980 and various intensity scales. At Balvano MDR for rubble masonry, brick, and rc-frame was 85%, 2-5%, and <2% respectively. The intensity rating as per text of scales was MSK VII-(VIII), MM(31)VII, MM(56)VII-VIII, MCS X, and RF IX-X. However, MM(31)VI-VII would have been more correct. At Calabritto MDR was 70% for rubble masonry, 2-5% for brick with rc-frame, <2% for rc-frame. We assessed MM(31)VII, MM(56)VIII, MSK VII-(VIII), MCS X, and RF IX-X. MDR at San Angelo and Lioni was >90% for rubble masonry, 50% for rc-frame of 2%g, 20% for rc-frame of 3%g, and 1-2% for rc-frame of 5%g. Intensities estimated were MM(31)VIII-IX, IX for MM(56) and MSK, MCS X-XI and RF IX-X. Overall fit was not satisfactory for MSK and MM, in particular the better building qualities presented problems. MCS and RF intensities are of no value to estimate damage to buildings better than adobe, rubble masonry, or ordinary brick. Also MSK and MM provide little guidance when estimating MDR for buildings better than about 4%g. Finally, fit of intensity descriptions and damage to buildings of various quality is generally not satisfactory, sometimes even poor. An error of half to one full intensity degree for MSK and MM is likely even if there is no personal or national bias.

USE OF PATTERN RECOGNITION IN SEISMIC INTENSITY AND DAMAGE ASSESSMENT

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Damage estimation and/or forecasting methods for an ensemble of structures are mainly empirical. These procedures correlate earthquake intensity with a damage severity index, based on statistical observations of past events. However, intensity scales are vague about the damage distributions of modern structures and informations on damage are collected by many sources with a weak emphasis on undamaged structures. Systematic surveys on structures after large earthquakes as those performed recently (China, 1976; Italy and Algeria, 1980) can help to define an earthquake damage intensity scale and can also help in developing more consistent relationships between damage and intensity.

This paper presents a method of identifying earthquake intensity by the theory of "Pattern Recognition". A discriminative function is developed based on Bayes's criterion. All statistics needed for the identification are obtained from the past investigations. This method can be used for intensity identification after an earthquake and also for checking the past classifications. Damage severity versus intensity relations consistent with the actual damage and intensity classification, are derived.

RESPONSE SPECTRAL SCALING STUDIES FOR THE EASTERN U.S.

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The paucity of strong ground motion data in the Eastern U.S. (EUS), combined with well recognized differences between Eastern and Western U.S. attenuation, suggest that simulation studies will play a key role in assessing earthquake hazard in the EUS. Using a hybrid methodology (wave propagation is modeled with an efficient frequency-wavenumber integration algorithm; the source time function for each grid element is empirical, simply scaled from near-field accelerograms), we have simulated over 5000 components of motion representing a parameter study for magnitude, distance, source orientation, source depth and near-surface site conditions for a generic EUS crustal model. We find that the far-field attenuation of peak ground acceleration scales as $R^{-1.75}$ for near surface sources, decreasing to $R^{-1.0}$ for a source depth of 14 km. The shape of the response spectrum is dependent upon all parameters studied; the combined effect of all parameters predicts a dispersion of response spectral values that is consistent with observations. Characterizations that focus on only one parameter, eg. soil versus rock, may be overly simplistic and should be used with caution.

ESTIMATING THE CHARACTERISTICS OF EARTHQUAKE GROUND SHAKING IN URBAN AREAS OF UTAH

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On the basis of the best-available scientific data, estimates of the characteristics of earthquake ground shaking have been made for the following areas of Utah: Salt Lake City-Ogden-Provo urban corridor, Cedar City, and Logan. These estimates are based on: 1) nuclear-explosion ground-motion data recorded simultaneously at selected sites underlain by various types of rock and soil in each urban area, and 2) site transfer functions derived from the ground-motion data. These data, used in conjunction with probabilistic ground-shaking hazard maps constructed by Algermissen and others in 1982, provide a basis for making decisions about land use and earthquake-resistant design. The estimates are in terms of maximum values of ground response expected to occur during various exposure times such as 10 and 50 years which correspond to the functional lifetime of many structures in Utah. The reasonableness of the estimates will be determined when the next magnitude 6 earthquake occurs in the vicinity of the urban areas.

GROUND MOTION ATTENUATION MODELS FOR NEW ENGLAND

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Data from six northeastern United States earthquakes have been used to develop an intensity attenuation model for this area. The magnitudes of these events range from 3.0 to 5.7 (m_b), and the multiple regression has been performed on individual (I, R, m_b) data points. The model we have obtained is

$I(R,m_b) = -1.43+1.79(m_b)-0.0018(R)-1.83\mathrm{Log}(R)$
where R is in km. This model may be combined with a velocity-site intensity correlation for medium foundation conditions to obtain the following velocity attenuation model:

$\mathrm{Log}\,[v(R,m_b)] = -2.34+0.74(m_b)-0.0007(R)-0.756\mathrm{Log}(R)$
where V is in cm/sec. This model compares favorably with theoretical models of Lg-wave attenuation assuming Airy phase propagation and using frequency dependent Q measurements for this area. Measurements of bandpass filtered coda waves have shown that at 1.5 Hz, Q is in the 800-900 range, whereas at 10 Hz, Q is approximately 1500. The model also compares favorably with the integrated velocity measurements from strong motion records of the January 19, 1982 New Hampshire earthquake. Records for this event are available for distances of 7 to 104 km.

These models are used to show intensity, velocity, and likely areas of damage for a number of hypothetical New England earthquakes.

REGIONAL SEISMIC NETWORKS: INNOVATIONS, DIGITAL APPLICATIONS, AND OBSERVATIONS I

SEISMOGRAPHIC NETWORKS: NRC REVIEW

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During 1982 the Committee on Seismology at the National Research Council (NRC) conducted a review of the status of U.S. regional and national seismographic networks, and of the global WWSSN and GDSN networks financed primarily by the U.S. The study, which included a two-day workshop, was prompted by requests to the Committee from its liaison members representing agencies with major funding roles for the networks, and who were faced, in early FY82, with the prospects of major reductions in their support budgets. The Committee report, published by NRC early in 1983, considers regional, national and global networks collectively as an integrated data acquisition system, and individually as entities with special problems and differing purposes. Recommendations for global networks include actions to stabilize funding while avoiding obsolescence, and to promulgate the usage of the growing digital data base. The report supports the concept of a national network and recommends its implementation through coordinated integration of elements from existing U.S. networks. Regional networks are seen in need of greater coordination of operations and data archival procedures and standards. As recommended in the report, a Working Group on Seismic Networks has been established by the Committee to provide an overview, with some continuity and uniformity, of matters arising in network seismology.

CANADIAN DIGITAL TELEMETERED NETWORKS: PURPOSE AND FUTURE RESEARCH DIRECTIONS

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Since the commissioning of the two (eastern and western) Canadian digital telemetered networks in the mid-70's, periodic changes have been made to the network configuration and the operational characteristics to enhance overall performance. Telemetered data transmission introduces a common time base, which speeds up the determination of both epicenter and earthquake magnitude; the digital nature of the recordings improves the accuracy of the results. Moreover the digital feature facilitates the task of deriving source properties and travel-path characteristics of eastern Canada earthquakes, an undertaking that is difficult, if not intractable, when only analogue records are available because of the high-frequency content in the seismograms. Much of the data analyses to date has been confined to a rapid, accurate determination of the epicenter and magnitude of local earthquakes. Recently, with increasing data base, source properties (seismic moment and corner frequency) have been derived from an analyses of Lg-wave amplitude spectra. As the data base increases further, the following can be included in the research program: attenuation, spectral magnitude, conventional (time-domain) magnitudes, spectral scaling laws, and time syntheses. The wide dynamic range provides a link between strong motion and regional (analogue) recordings. Future considerations are broad-band seismographs (to improve magnitude estimates) and outstations with the capability to select and transmit only events of interest (to reduce transmission costs). Modifications to the networks are undertaken not only to increase seismic coverage but also to contribute to the estimate of seismic risk for both general and important special projects.

APPLICATIONS OF DIGITAL PROCESSING TECHNOLOGY TO THE STUDY OF LOCAL EARTHQUAKES IN CALIFORNIA

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The routine use of digital computers for the acquisition and processing of data from telemetered seismic networks in California has greatly expanded their research applications. New opportunities can be found in seismicity studies, crustal studies earthquake source studies and operational earthquake monitoring applications. Common time-base digitization and analysis of events by real-time or off-line pickers has improved the precision of phase arrival time data to 20 msec., or three times more precise than earlier analog-based analysis. Seismicity studies based on such data show that faults retain their geometric complexity on scales of 100 m or less. Structure studies using precisely locatable events and 3-D inversion methods appear to be capable of resolving structure on a scale of 1 km or smaller throughout the upper crust. Waveform studies of nearby earthquake pairs, or doublets, can be used to further refine timing precision (standard error 1 msec) and knowledge of the moment tensor. Differential traveltime studies based on doublets have a precision of 10^{-4} for coda waves. Preliminary results from a study of one doublet that brackets in time the August 6, 1979 Coyote Lake, Calif. earthquake

(M_L 5.9) show a coda wave velocity increase of 0.1% in a spatially limited region about the epicenter.
Real-time analysis of seismicity has already proven invaluable in the monitoring of seismic activity at Mammoth Lakes, Calif. Improvements in the dynamic range of local network data holds considerable promise for providing highly reliable and accurate assessments of earthquakes as they are occurring, thus providing the basis for a strong-motion early warning system.

CUSP - AUTOMATED PROCESSING AND MANAGEMENT FOR LARGE, REGIONAL SEISMIC NETWORKS

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The CUSP (Caltech-USGS Seismic Processing) system was developed at the USGS field office in Pasadena, California to process and manage data from a network of 250 short-period seismometers in southern California. The principal operational problems addressed in the design of this system are derived from the need to process large volumes of digital seismic data (about 1000000 records from 20000 events each year) with limited staffing (4 full-time, highly motivated analysts) with an efficiency adequate to monitor topical variations in local seismicity. In addition, it was required that 1) the products of the analytical effort shall be organized to permit simple and rapid access to derived data both for research purposes and for field maintenance operations, 2) data from diverse sources, digitized at various rates, shall be easily combined and analyzed in concert, and 3) applications resulting from the rapidly evolving requirements of the research and monitoring efforts shall be easily integrated into routine processing procedures. The CUSP system is based on a tailored relational data base package layered on the standard, vendor-supplied file system. The data base is utilized by the applications programs primarily as a content-addressable file system with features including: multiple indexing paths using B+ trees, external data definition language, variable length tuples with no space required for undefined attributes, and efficient access (in excess of 200 tuple operations per second). All data base and applications programs are written in FORTRAN 77. Manual effort in managing data flow is greatly minimized using a data driven, state-transition method for controlling processing from initial acquisition through archiving.

BEYOND THE "DIGITAL DEVELOCORDER"--THE QUEST FOR QUALITY WAVEFORMS USING THE UNIVERSITY OF UTAH'S SEISMIC NETWORK

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On January 1, 1981, central recording of the University of Utah's 60-station seismic telemetry network was converted to digital event detection and recording on a USGS-supplied PDP-11/34 computer. More than 2,000 local earthquake locations have since been efficiently processed on a timely basis. The computer system was rapidly implemented and effectively functioned as a sophisticated digital replacement for a develocorder--providing accurate arrival times and polarities for hypocentral locations and focal mechanisms. In order to achieve accurate waveform information and use the digital data effectively, we next developed techniques for complete system calibration of each telemetered seismic station (both amplitude and phase response to ground motion).

"System" here means everything from seismometer to the out-put of the 11/34's A/D converter. Our techniques and associated field equipment (e.g., a remotely-activated event-detection trigger) are allowing us routinely to make seismometer-to-digital-data calibrations for stations in our network as part of routine station maintainence. Our procedure, although not as elegant as some proposed schemes, is proving to be robust and efficient. The University of Utah's seismic network spans a seismically active area comparable in dimension to that along the San Andreas fault from the northern Gulf of Mexico to San Francisco. Our short term strategy for advancing observational capabilities in this area--in the face of "no-growth" funding--is to supplement network recording with portable digital event recorders. Calibrated digital data from both the portable and fixed network systems allow our first real step beyond the digital Develocorder.

A MICROPROCESSOR BASED LOW-POWER DATA AQUISITION SYSTEM

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The U.S. Geological Survey has developed a data-acquisition system for use in geophysical data-logging applications where size and low power consumption are primary considerations. The system is modeled on an S-100 bus and incorporates a CMOS microprocessor for system control. Pertinent specifications are: software selectable sample rates from 128 Hz to 2048 Hz; one to twelve simultaneously sampled data channels; 132 dB useful dynamic range per channel from a 12-bit main A-D converter and 10-bit floating point amplifier; 32 kilobytes of event buffer allowing 32 seconds of 4-channel data storage at a 128-Hz sample rate; and power consumption of 250 milliwatts exclusive of the tape recorder. The digitized sample data, along with the time and gain information, are written to either a cartridge recorder that has a storage capacity of 14.5 megabytes or to an in-house designed reel-to-reel recorder that has a storage capacity of 75 megabytes. The system may be housed in hermetically sealed cases for land based applications or in aluminum spheres having depth ratings of up to 5.5 km for ocean-bottom seismograph applications. Major emphasis was placed on developing a system that minimized dependence on technical support. The system is entirely set up in an interactive querying session from a video display terminal. This paper describes both the instrument and the philosophy behind its development.

REALTIME MONITORING OF THE MAMMOTH LAKES, CALIFORNIA EARTHQUAKE SWARM WITH AUTOMATIC PROCESSING EQUIPMENT

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The Mammoth Lakes California earthquake swarm beginning January 7, 1983 (G.m.t.) was recorded on a net of 11 local seismographs telemetered to the USGS offices in Menlo Park, California, and processed by the Real-Time Processor (RTP) which routinely monitors the Calnet stations. The RTP produced 14298 phase cards comprising 2369 earthquakes during the first 3 days of the swarm. An estimated 10-20% of these earthquakes were not properly timed as a result of mistakes by the picker or the associator algorithms due to the very large number of events. In addition, some well-recorded and distinct events were missed by the RTP for reasons not completely understood. The remaining well-picked events, however, enabled observers to monitor in real time the progress of the swarm and migration of activity. During the first 12 hours, when activity was in excess of 200 earthquakes/hr, the RTP picked several hundred events as well as or better than could have been picked by experienced people. The use of such automatic processing equipment can be extremely valuable in situations requiring continuously updated information about intensity and location of seismic activity, but proper use of the equipment requires sufficient experience with it to be able to distinguish unreliable reports. Results from the Mammoth Lakes operation are being used to alter the picker and associator algorithms so as to improve performance of the RTP during future swarms of this type.

ON THE SEISMIC TELEMETRY SYSTEM

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With the present instrumental design of seismic data telemetry which involves a pair of VCO and discriminator, the effective dynamic range of each data transmission channel has seldom reached above 45 dB and frequently much below. Despite the much larger dynamic ranges of sensor and digital computer as a recorder, the small dynamic range of the seismic telemetry link imposes a choke point on the signal flow. For regional seismic networks tuned to high sensitivity, we are often frustrated by the limited usefulness of clipped seismograms for any event larger than M4. Developmental work at the USC Geophysical Laboratory has provided an economical and practical solution to this problem by introducing an optimum telemetry system permitting an effective dynamic range of up to 120 dB yet still conforming with the common specifications of frequency division multiplying as it applied to network seismology. Moreover, a front-end device at the sensor site will detect the event and direct the signal traffic so that signals from a three-component field station can generally all pass through a single telemetry data channel.

NEVADA DIGITAL SEISMIC NETWORK

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The University of Nevada has developed and tested a digital seismographic system for remote operation. The digital station is a data acquisition system designed to digitize from one to three channels of low-level, wideband seismological data. The system features 12-bit resolution with one bit of gain range, yielding 72 dB resolution and 96 dB dynamic range. Sample rates are selectable from 18.75 to 600 samples/second and amplifier gains are selectable from 600 to 16,000. Data are phase encoded and currently input to a 1200 baud modem for telephone line or VHF radio transmission. The design uses CMOS devices to facilitate battery operation.

The recording facility consists of a computer input assembly which accepts phase modulated data from the field stations and formats it for input to an LSI-11/03 computer. The data are recorded on digital tape.

Three 3-component digital stations were operated as a tripartite array for several months at a remote site in Hot Creek Valley, central Nevada. The stations are now being deployed at widely-spaced sites (Mina, Battle Mountain, Current) in the western Great Basin, in an experiment to assess the contribution that a few high-quality stations might make to a regional seismic network. A fourth station is being assembled and will be added to the network in the near future. Examples of data will be presented.

REGIONAL STRAIN

DEFORMATION ACROSS THE SAN ANDREAS FAULT NEAR SAN FRANCISCO, CALIFORNIA, 1978-1982

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Preliminary results from three trilateration lines from the Farallon Islands to the coast near San Francisco, California, in the vicinity of the 1906 epicenter, are inconsistent with models of strike-slip motion. The Farallon Islands lie about 45 km west of San Francisco and provide an unusual opportunity to measure deformation to the west of the San Andreas fault in northern California, where the fault is a coastline or offshore feature. Two lines have been measured three times since late 1978, and the other twice since that time. One line at right angles to the San Andreas fault is changing at a rate of 5.6 $\pm$ 3.2 mm/a, although it should be totally insensitive to strike-slip motion at any rate or depth. The end points of a second line are located such that, if the fault were slipping at 12 mm/a below 6 km, this line should have lengthened by about 12 mm since the measurements began. However, the observed rate of change does not differ significantly from zero. The rates for both these lines are based on three observations, but in each case the points lie very close to the regression line. The third line is consistent with the previously mentioned model, lengthening at a rate of 6.7 mm/a. However, this rate is based on just two observations. Since these lines are long and have a large estimated standard deviation, it is possible that these trends are the result of measurement error and may change as more observations are made.

GEODETIC MEASUREMENTS OF HORIZONTAL DEFORMATION IN THE NORTHERN SAN FRANCISCO BAY REGION, CALIFORNIA

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Analysis of Geodolite measurements spanning the past 10 years indicates that relative motion north of San Francisco Bay is distributed over a band parallel to the San Andreas Fault that is at least 70 km wide. The measured lines cover an area from just southwest of the San Andreas Fault at Pt. Reyes to just short of the Green Valley Fault 65 km northeast. Shear strain accumulation rates are highest on the San Andreas Fault, 0.63 $\pm$ 0.07 μrad/yr. Near the Rodgers Creek Fault the shear strain is 0.31 $\pm$ 0.02 μrad/yr, and near the West Napa Fault 0.18 $\pm$ 0.06 μrad/yr. The right lateral displacement rate parallel to the plate boundary is 15$\pm$1 mm/yr. It is probable that additional displacement is occurring southwest, and possibly northeast, of the region spanned by the observations. The deformation appears to have occurred at a uniform rate during the 1972-1982 time period. The dilatation record at Pt. Reyes indicates some irregularity, but the change is probably not real.

HORIZONTAL DEFORMATION ASSOCIATED WITH THE OCTOBER 15, 1979 IMPERIAL VALLEY EARTHQUAKE, AND IN THE THREE YEARS FOLLOWING

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A substantial part of the dense geodetic network spanning the Imperial fault near El Centro was remeasured during 1982. This is the third remeasurement since the earthquake. It is the most complete, and extends detailed knowledge of the unusual horizontal ground deformation associated with the earthquake to a distance of 8 km from the fault.

The most surprising feature of the deformation is the large amount of strain normal to the fault. Thus on its NE side there is a 4 km wide zone of compressional strain normal to the fault, averaging 200 ppm, followed by a zone of up to 100 ppm extension. On the opposite side the reverse occurs, a 4 km wide zone of extension, averaging 150 ppm, being followed by a zone of up to 100 ppm compression. The net result is that points 4 km from the fault on its NE side have moved by as much as 80 cm towards it, while points a similar distance away on the SW side have moved by as much as 60 cm away from it. At distances beyond 10 km from the fault these strains fall away to less than 30 ppm.

The measured coseismic slip on the fault decreases generally from south to north, from about 60 cm at the southern end of the surface rupture to less than 40 cm at the northern end of the network, 15 km away, and dies away rapidly thereafter. However, in this northern part of the network the creep displacement is complemented on both sides by right-lateral shear parallel to the fault, the total right-lateral displacement between points on opposite sides 4 km apart being about 90 cm.

Since the earthquake, the fault has continued to creep, at a rate decreasing approximately exponentially with time. As of mid-1982 the total post-earthquake creep ranged between 20 and 30 cm, being a maximum at Waterman's corner, 10 km from the southern end of the rupture.

AN EXPLANATION FOR CONTRADICTORY GEODETIC STRAIN AND FAULT PLANE SOLUTION DATA IN WESTERN NORTH AMERICA.

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Geodetic strain averaged over spans of 4-7 years at Seattle, WA., Ogden, UT., Socorro, NM., differs significantly in principal strain azimuth and type of deformation with that inferred from fault plane solutions of earthquakes (FPS). The minimum principal geodetic strain axis (most compressional) trends ENE at Seattle and Ogden, while the equivalent strain axis from FPS trends N-S. The areal strain (dilatation) at Ogden and Socorro is compressional in contradiction to evidence for regional extension from FPS and geology.

Computation of shear strain relieved by earthquakes yields values in the range of 40 to 100 microradians essentially independent of Mo, which is about 100 times larger than total shear strain recorded by the above geodetic arrays. It is proposed that the above geodetic results may reflect a local deviation from the long-term strain accumulation and that FPS may provide a more reliable measure of the orientation and style of long-term principal strain.

One explanation for the ENE geodetic compression at Seattle may be coupling of the Juan de Fuca and North American plates (Savage et al., 1981). This, however, would have to be temporary coupling that yields aseismically and at low stress levels, since no interplate thrust earthquakes have been observed in this region.

GENERAL SEISMOTECTONICS

THE FLORES EARTHQUAKE OF DECEMBER 23, 1978: EVIDENCE FOR ACTIVE BACK-ARK THRUSTING BEHIND THE BANDA ARC

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The Flores earthquake of December 23, 1978 occured in the region behind the Banda Island Arc where back-arc thrusting has been suggested on the basis of seismic refraction and reflection data. The back-arc thrusting appears to be a reaction to the collision of the Australian continent with the Banda Arc. We investigate the source mechanism and depth of the Flores earthquake by inversion of long period P waveforms and relocate the earthquake's epicenter incorporating arrival time data from local stations. We find that this event occured about 30 km south of the thrust zone north of Flores at a depth of 11 km. The best fit fault plane solution is consistent with active southward thrusting of the floor of the Flores Basin beneath the volcanic arc along a shallow dipping fault plane. Gravity data from the Flores Sea require that the crust of the Flores Basin dips below the small accreted wedge at an angle of 2 - 4°. We speculate that the Flores Thrust stands a good chance of becoming a self sustaining subduction system resulting in the reversal of arc polarity.

SEISMICITY OF THE NORTHERN TIEN SHAN REGION

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We have been investigating the seismicity and tectonics of the Northern Tien Shan region of the Soviet Union (40°-46°N, 74°-82°E). In the historical record this area has been the location of some of the strongest earthquakes in the active seismic zone extending along the southern Russian border. We have used data from the yearly Russian earthquake catalogs for the years 1962 through 1977 to analyze the spatial distribution of earthquakes and seismicity rate for the region. Within the area investigated earthquakes are concentrated along east-west and east-northeast trending folds and related Cenozoic faults. During the period studied the areas of heaviest seismic activity were located just south of the border in China and east and north of Lake Issyk-Kul. The cumulative rate of seismicity for Northern Tien Shan is described by the relation $\log N = 6.25 - 0.45K$ where N is cumulative frequency and K is energy class. The slope of the recurrence relation for the area is the lowest in the four areas of the southern Soviet border seismic zone which we have studied to date (viz. Northern Tien Shan, Pamir-Hindu Kush, Fergana Basin and Lake Baikal). This result is indicative of a higher proportion of large energy class events in the Northern Tien Shan region which may be interpreted in terms of tectonic differences. In addition, we have compiled published fault plane solutions for earthquakes in the region and used these to develop a dominant focal mechanism. This mechanism corresponds to reverse motion on an east-northeast trending fault.

SURFACE EFFECTS AND TECTONICS OF THE 13 DECEMBER 1982 YEMEN EARTHQUAKE

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The destructive Yemen earthquake (M_s=6.0) resulted in at least 1700 deaths and left tens of thousands homeless in a region centered 70 km south of the capital city, Sana. The extensive destruction and heavy loss of life resulted primarily from widespread collapse of unreinforced masonry and adobe structures. Except for numerous rockfalls, geologic effects attributable to shaking were minimal. Maximum estimated MMI was probably only VII-VIII. The main surface geologic effect that is ascribed to tectonic activity is the occurrence of north- to northwest-trending earthquake-related extensional ground cracks in the epicentral region. The known cracks occur in four relatively continuous linear zones with average north-northwest trends that are from a few hundred meters to 15 km in length. Data from strain quadrilaterals across the cracks indicate that dilation was continuing at a high rate almost 1 month after the main shock.

Available data indicate that the earthquake sequence is caused primarily by dilatant cracking. It is inferred that extension in the source region reflects local uplift at the surface over an area up to 15 km long and 10 km wide, most probably related to upward movement of magma at depth. This interpretation is based on: 1) the occurrence of purely extensional surface cracking in the epicentral region, 2) a high level of aftershock activity as is common for many earthquake sequences related to volcanism, and 3) a geologic setting in a region of young volcanic activity where there has been at least one historic eruption.

AFTERSHOCKS OF THE YEMEN EARTHQUAKE OF DECEMBER 13, 1982:
A DETAILED STUDY FROM LOCALLY RECORDED DATA

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The magnitude 6.0 (m_b and M_s, NEIS) Yemen earthquake of December 13, 1982, occurred at 0912^h 49.3^s (UTC) in a densely populated area of the southwestern Arabian Peninsula, about 70 km south of Sana'a, capital city of the Yemen Arab Republic. Estimated hypocentral location (NEIS) was: lat. = 14.779°N, long. = 44.344°E, depth (fixed) = 10.0 km. Because of the widespread destruction, accounts of thousands dead, injured, and homeless, and various reports of ground fissuring and possible volcanic activity, the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, organized a post-earthquake investigations team to study the earthquake and its effects. As members of this team, the authors were responsible for the installation and operation of 11 portable seismographs to monitor and locate the aftershocks and compute their source parameters. During the period between 29 December 1982 and 11 January 1983, 14 sites that surrounded the epicentral region were occupied and several thousand aftershocks were recorded at all stations. The high degree of seismic activity, that included a magnitude 5.3 aftershock on 30 December, was unexpected considering that more than two weeks had elapsed following the main shock. The greatest amount of seismicity appeared to occur along a 10-15 km long north-northwest trend, on line with but south of the given epicenter.

SEISMICITY OF GAPS ADJACENT TO THE AFTERSHOCK ZONES OF MAJOR EARTHQUAKES

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The concept that maximum lateral rupture widths are associated with major subduction-related earthquakes constituted a great advance for forecasting the maximum size of associated major earthquakes. This observation, based on the historical record of major earthquakes and aftershock zones, was difficult to make because the earthquake locations are uncertain and the data are scattered throughout the world's observatories. In this paper, we report evidence suggesting that gap boundaries and widths are also observable in the lineations of epicenters along seismic gaps adjacent to a recently-ruptured gap.

During Project ROSE, we devoted most of our seismographs to monitoring closely the aftershock area of the Petatlan earthquake (M_S 7.6), but moved others parallel to the coast through the adjacent Guerrero gap. Small earthquakes were located in the Guerrero gap; offshore, they were almost all along two linear zones perpendicular to the coast. The smaller number were aligned on the southeast boundary of the Guerrero gap that had been inferred from the historic record. However, another lineation appears about midway in the previously-defined Guerrero gap. Further, the seismograms exhibit reversed polarity on either side of the extensions of these trends to shore. We infer that these are two linear zones of weakness, and that both are gap boundaries. The probable maximum earthquake forecast is thus cut in two. If gap boundaries can be located in this way, then aftershock studies of major earthquakes must be extended to include monitors on the adjacent gaps, which are strained by movement associated with nearby major events.

INDUCED SEISMICITY OBSERVED IN THE VICINITY OF TAVERA RESERVOIR, DOMINICAN REPUBLIC

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In June and August of 1980, two separate swarms of microearthquakes occurred in the proximity of the Tavera Reservoir, Dominican Republic. The earthquakes were located along the Tavera Fault that runs through Tavera Reservoir. These swarms were observed after abrupt changes of water level occurred. However, gradual increase of water level during the period of September through November did not produce induced earthquakes except spoladic events despite the fact that the highest water level surpassed the peak elevations of two abrupt changes. It was inferred from these observations that the induced seismicity was sensitive to the abrupt changes of water level rather than or in addition to the water level itself. The foci of the second swarm in August was distributed adjacent to the area occupied by the first swarm in June, implying that the rock fracture propagated from one zone to another during these two active swarm sequences.

TSUNAMI PERIODS, SEISMIC MOMENT, AND GREAT HISTORIC TSUNAMIGENIC EARTHQUAKES

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Using about 1000 tsunami period readings from tide gauges in Japan, we study the relations between tsunami period T, moment magnitude M_W, and tsunami magnitude M_t (an estimate of M_W based on tsunami amplitude). For a set of calibration events with moments known from seismic waves, there is considerable scatter in the M_W vs. log T relation, but a trend of longer periods with increasing M_W is clear. Thus tsunami periods can be used to infer, roughly, moment or to supplement other data, such as tsunami amplitudes, in doing so. We therefore compare M_t to log T for a larger set of events, which mainly confirms, through the M_W vs. log T relation, the estimates of moment implied by M_t. However, some anomalies stand out, including the 1896 Sanriku, 1923 Kamchatka, 1946 Aleutian, and 1952 Kamchatka events. Each of these has appeared anomalous through previous observations and their tsunami periods may help determine whether unusual generation mechanisms are involved.

FOCAL MECHANISM SOLUTIONS AND P-WAVE SIGNAL COMPLEXITY OF HINDUKUSH EARTHQUAKES

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Focal mechanism solutions of a number of earthquakes from the Hindukush region show thrust type of faulting along the nodal planes trending in NE and SE directions. Some of the solutions show small components of strike slip motions. The dip of the compressional axes rarely exceeds 25°. Orientation of tensional axes in all the cases was found to be almost vertical. It may be interpreted that these earthquakes were caused by down dip extension within a sinking slab.

Visual search of the recordings of earthquakes from Gauribidanur array in southern India, revealed that most of the events occurring at shallower depths had complex signatures as compared to the deeper events. A positive correlation of complexity with magnitude is found. Spectral ratio measurements have shown that complex signals are richer in low frequency energy contents. Several theoretical seismograms for short period P-waves were computed and their analysis reveals that complexity increases with focal area but decreases with the increase in focal depth within certain constraints. The source structure, complicated source functions and probably the scattering confined to the crust-upper mantle near source are mainly responsible for the complex signatures of the earthquakes as the transmission zone of the ray tubes from turning point to the array is practically the same.

INTRAPLATE REGIONS: EARTHQUAKE RISK, ENGINEERING SEISMOLOGY, AND STRUCTURAL RESPONSE II

INCORPORATION OF UNCERTAINTIES IN PROBABILISTIC SEISMIC EXPOSURE ANALYSES: EFFECTS ON COMPUTED SEISMIC EXPOSURE

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Computation of the seismic exposure at a site requires: (1) identification of the seismic sources, (2) assessment of earthquake recurrence on these sources, and (3) development of relationships describing the attenuation of ground motion parameters with distance due to potential earthquakes in these sources. This paper examines the effects on the computed seismic exposure (at a site located in the near-source region of active seismic sources) of: (1) the uncertainty in the maximum magnitude earthquake assigned to the potential seismic sources, and (2) the uncertainty in the ground motion attenuation. The findings of particular engineering significance are:

Uncertainty Parameter	Sensitivity of Computed Values
o Maximum magnitude earthquake assigned to seismic sources	somewhat sensitive at high but very sensitive at low probability levels
o Constant dispersion vs. magnitude-dependent dispersion	very sensitive at essentially all probability levels.
o Truncation of ground motion distribution	somewhat sensitive at high but very sensitive at low probability levels

Note: the high or low probability level is used herein in a relative manner, i.e. relative to the degree of activity of the dominant seismic sources. For example, in Intraplate Regions where the seixmic sources may be characterized by a low-to-medium degree of activity (in contrast to a high-to-very high degree of activity in Interplate Regions) annual probability levels $\geq 10^{-3}$ may be considered high on a relative basis, whereas levels $< 10^{-5}$ may be considered low.

A COMPARATIVE STUDY OF EARTHQUAKE HAZARD IN SWITZERLAND AND SOUTHERN SPAIN

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The assessment of seismic hazard is of growing importance in Europe for evaluating critical structures, lifelines and building codes. For many countries hazard maps already exist, but several of them were developed using different methods. The results are therefore not necessarily comparable. We have calculated probabilistic models for two different areas of active seismicity in Europe using the same methodology and input parameters. The results show that the areas of Mourcia-Alicante, Spain and the Valais region in Switzerland have higher seismic hazard with expected MSK-intensities of IX-X and VIII-IX, respectively at a probability level of .001 P.A.

UNCERTAINTIES IN SEISMIC HAZARD ANALYSES FOR INTRAPLATE REGIONS

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The uncertainties taken into account in seismic hazard analyses (SHA) for intraplate regions can be divided into two categories. The first involves probabilistic variability that constitutes the SHA. This includes the location and times of occurrence of future earthquakes, the source characteristics of those events, and the generated ground motion. The second category involves statistical and "professional" uncertainties which can be reduced with additional data. This includes the identification of active tectonic structures, the parameters of earthquake source distributions, and the estimated mean and truncated level of ground motion. Uncertainties of the second kind are best treated by performing multiple SHA and expressing the uncertainty in SHA results as a function of these statistical and professional uncertainties.

These uncertainties (statistical and professional) vary with ground motion level. At low ground accelerations, uncertainties imply a factory of ten range in probability. At high levels, the 90% confidence bound range in probabilities is larger and may be infinite; it is governed by uncertainties in maximum earthquake size, Richter b-value, mean ground motion, and ground motion truncation. These uncertainties do not reflect an inadequacy of the SHA but rather reflect our lack of knowledge and point to areas of investigation most likely to reduce the uncertainty. This will lead to better seismic hazard mitigation in intraplate regions.

PROBABILISTIC ESTIMATES OF SEISMIC HAZARD AND NUCLEAR POWER PLANTS

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The use of probabilistic estimates is playing an increased role in the review of seismic hazard at nuclear power plants. The NRC Geosciences Branch emphasis has been on using these estimates in a relative rather than absolute manner and to gain insight on other approaches. Examples of this use include estimates to determine differential hazard at the same site for different design levels, to determine equivalent hazard at different sites, to help define more rational seismotectonic provinces, to place deterministic estimates of fault offset in perspective and to assess implied levels of acceptable risk using deterministic methods. Increased use of probabilistic estimates is expected because of the rapidly changing nature of seismological knowledge in the eastern U. S., the need to reexamine older plants and the appeal of quantitative methods to decision makers. Comprehensive Probabilistic Risk Assessments (PRA's) have been and are presently being done for many nuclear power plants. Probabilistic estimates of seismic hazard have a potential for misuse however and their successful integration into the decision making process requires they not be divorced from physical insight and intuition.

PROBLEMS ASSOCIATED WITH THE EXTENSION OF PROPOSED CANADIAN SEISMIC CODE GROUND MOTIONS TO LOW PROBABILITIES

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The proposed seismic provisions for the National Building Code of Canada are based on assumptions that seismic source zones can be defined within which earthquakes are distributed uniformly according to a magnitude/frequency of occurrence relation, and that a set of attenuation relationships hold for the magnitude and distances which dominate the selected risk level of ten percent possibility of exceedance in fifty years. It is shown that these are reasonable assumptions at these levels for the average structures included in the Code. However, attempts which are made to extend the calculations to significantly lower levels for special structures may invalidate the original assumptions. With decreasing probability, the dominant contribution ranges of magnitudes and distances are outside of the intended scope of the ground motion relations. Moreover, the basic assumption that earthquakes may be uniformly distributed over large source zones is seriously compromised. The addition of a stochastic term in the calculation compounds these problems.

GENERAL EARTHQUAKE RISK

SENSITIVITY OF PROBABILISTIC ESTIMATES OF NEAR-FAULT GROUND MOTION TO PARAMETERS OF THE FREQUENCY-MAGNITUDE RELATIONSHIP

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The use of moment magnitude and a frequency-magnitude relationship constrained by slip rate on a fault gives probabilistic estimates of near-fault ground motion that are insensitive to other parameters of the relationship. Common practice has been to make such estimates using a Gutenberg-Richter relationship, truncated at a maximum magnitude M_{max}. There are possible difficulties with this approach. In making estimates for a specific fault zone, M_{max} is commonly taken as the magnitude corresponding to the rupture of the entire length of the fault zone. For long fault zones, however, there may be no assurance that the entire length ever ruptures in one event. There may also be uncertainty concerning the appropriate value for the magnitude coefficient b in the Gutenberg-Richter relationship. Although values near one are commonly used, a number of workers (in particular those espousing the "characteristic earthquake" model) believe that much smaller values are appropriate for individual faults (as opposed to broad regions). Fortunately, our calculations show that the value of ground motion (peak horizontal acceleration, velocity, or response spectral value) that will be exceeded at a specified average return period is insensitive to variations in b or M_{max} over the range of those parameters that is appropriate for use in estimating ground motion, provided that the site is near the fault and that the frequency-magnitude relationship is expressed in terms of moment magnitude and is constrained by the slip rate on the fault.

SEISMIC HAZARD ESTIMATION USING A FINITE FAULT RUPTURE MODEL
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Earthquakes along a fault should be modeled as linear ruptures rather than as points; for the same attenuation function, calculated exceedances of ground motion levels at sites near the center of the fault may be 3 to 5 times as high for linear ruptures as for point sources. The difference is less for sites beyond the end of the fault, but may be significant at those sites also if rupture length is a substantial fraction of fault length at some magnitudes. In the fault-rupture model analyzed here, ruptures must be wholly contained within the fault, in contrast with the model of Der Kiureghian and Ang, which permits a rupture to extend beyond the fault by one half the rupture length. For sites near the center of the fault, both finite-rupture models give very similar exceedance values, but for sites near or beyond the end of the fault, the Der Kiureghian and Ang model gives exceedances of some levels of ground motion that are several times higher than those obtained using the model presented here.

Requiring ruptures to lie wholly within the fault may mean that a smaller fraction of the possible ruptures will produce a specified ground motion level at a site if fault length increases; thus fewer exceedances of the motion level may be calculated for a longer fault than for a shorter one, given a constant earthquake rate per unit length of fault. Calculated motions are also affected by magnitude range, and ground motion exceedance curves at a site may flatten at lower and steepen at higher levels because of magnitude cutoffs.

Exceedances of a motion level tend to remain fairly constant as the site location is moved parallel to the fault from near the center toward an end of the fault, then decrease by a factor of 1.5 or 2.0 within the last 10 or 20 km of the end. Continuing 10 km past the end may yield another factor 2 or 3 decrease. This result suggests that fault-end location, if not known exactly, should be treated probabilistically.

HISTORICAL SEISMIC HAZARD ANALYSIS
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Now-standard methods of seismic hazard analysis depend upon specification of seismic source zones and magnitude-frequency relationships, both of which may be difficult to estimate in regions such as the eastern U.S. More empirical procedures, called historical methods, estimate mean recurrence rates of local site intensities (M.M.I., peak ground acceleration, etc.) directly from a regional catalogue of earthquake times, locations, and sizes together with a ground motion prediction model.

This paper will first review several (best-estimate-only) historical methods introduced by others. The best of these methods allows for attenuation law dispersion and catalogue incompleteness. These methods are non-parametric in the statistical sense. Second, the paper will present a new (parametric) method that permits the development of confidence bands on the estimated mean recurrence rates, especially in the lower probabilities (higher mean return periods) of engineering interest. The method utilizes formal Bayesian statistical parameter estimation procedures.

The historical method can be used to supplement and confirm the conventional method of seismic hazard analysis, which is based on more professional information and hence usually preferred for estimation of very long mean return periods (e.g., > 1000 years). The two methods should agree at levels (ten to a few hundred years) well within the range of empirical (historical) estimation.

EARTHQUAKE RISK IN IRAN

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Analysis of the seismic risk of Iran is made assuming seismotectonic provinces of Iran. The earthquake data of various seismotectonic provinces are compiled and treated statistically. The coefficients of a log-linear and a log-quadratic frequency magnitude relationships are calculated and return periods for several earthquake magnitudes are found. From log-linear coefficients the probalistic seismic risk, intensities, and ground acceleration for a set of return periods and epicentral distances are estimated and the probalistic seismic risks for various ground accelerations are discussed. Substantial variations in return periods for a given magnitude are noted. The provinces which are located southwest of the Zagros thrust are the most active in producing earthquakes with magnitude of about 6 in less than a decade, whereas the northern and northeastern provinces are capable of producing a magnitude 7.5 earthquake about each century. The probalistic seismic risk is lowest for the Esfahan-Sirjan, Central Iran, and the Arvand-Shatt-al-Arab provinces, and the highest seismic risk is for the Elburz, Kopet-Dagh, and the Fars provinces. The expected peak ground acceleration is highest, for a time exposure of 30 years, for Fars, Ferdows and Tabas provinces, and least for Esfahan-Sirjan; although for a time exposure of 200 years, the expected peak ground acceleration is highest for Elburz, Kopet-Dagh and Ferdows provinces.

MAXIMUM SINGLE-EVENT DISPLACEMENT, ARROYO FAULT, LNG TERMINAL SITE, POINT CONCEPTION, CALIFORNIA

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The interpretation of the maximum single-event displacement on any one of the many late Quarternary/Holocene faults at the Point Conception LNG site has been a major issue in the development of criteria for the design of structures proposed for this critical facility. Stratigraphic and structural relationships exposed in the upper third of the Quaternary terrace sequence at Arroyo Central establish the occurrence of a single fault event with a vertical component of displacement of approximately 74 cm (2.4 ft). This event is expressed as rupture in the lower terrace units and as a monoclinal flexure in the shallow section. A later event, or events, resulted in rupture of the shallow section along three fault strands with a total minimum displacement (apparent dip separation) of 30 cm (1.0 ft) and total vertical component of 21 cm (0.7 ft). A similar sequence of events can be interpreted from exposures in the east wall of Trench SD located approximately 1000 feet to the east of Arroyo Central. The later rupture event(s) exhibits a displacement (apparent dip separation) of 30 cm, and the prior event is expressed in the shallow terrace units as a monoclinal fold with an amplitude of approximately 75 cm. If the displacement of the later event(s) is subtracted from the total apparent dip separation at the base of the terrace sequence of 120 cm, the minimum displacement for the prior event at this location is 90 cm (3.0 ft). The maximum known displacement of the Arroyo fault is exposed in the west wall of Trench SD, but the shallow terrace section has been eroded at this exposure. However, if the same second-event displacement is assumed at this location, the maximum known single-event displacement for the Arroyo fault is 145 cm (4.8 ft).

REGIONAL SEISMIC NETWORKS: INNOVATIONS, DIGITAL APPLICATIONS, AND OBSERVATIONS II

COMPOSITE MOMENT TENSOR INVERSION FROM FIRST MOTION DATA

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Inversion of first motion data for small earthquakes in a local network yields an estimate of a normalized moment tensor. Averaging such moments gives estimates of the direction of principal stresses over the region. Individual normalized moments can be weighted by the scalar moment which is estimated from magnitude, or they may be given equal weight. Arguments can be made to defend either procedure. Alternatively, a joint inversion of a number of earthquakes can be made. The process, which simply uses plus or minus 1 for the amplitudes corresponding to compressions and dilations, and take-off angles from the appropriate location program, works remarkably well. Comparisons with other automatic processes for fitting focal mechanisms are favorable. It seems to be a more physically plausible way to characterize average tectonic stresses in a region than is either a composite focal mechanism, or a vector average of individual mechanisms.

PMEL OF EARTHQUAKES IN THE COSO SEISMIC NETWORK

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We have applied our recently developed progressive multiple event location (PMEL) procedure to a set of 648 earthquakes and 4 explosions (8049 arrival times) recorded by the USGS seismic network at the Coso geothermal area. The program used only 142 kBytes of computer memory for this calculation and converged after 4 adjustments to the station corrections. The final station correction estimates correlate strongly with surface geology and produce an exceptionally good fit to the data (rms residual = 58 msec). This suggests that lateral velocity variations in the top 10 km of the crust at Coso are negligible except in the very near surface layers. To further substantiate this conclusion, we are investigating variations in the station corrections calculated by PMEL from a number of earthquake clusters. Station corrections from such clusters can be interpreted in terms of a path anomaly for the ray path joining the hypocentroid of the cluster and a given receiver (Jordan and Sverdrup, 1981). We show, however, that these anomalies cannot be compared directly. Instead, we can only compare their projections onto the subspace $N(A_1^{\dagger}) \cap N(A_2^{\dagger})$, where $A_1^{\dagger}$ and $A_2^{\dagger}$ are the pseudoinverses calculated from the equations of condition for the hypocentroids of the two clusters that we wish to compare and the symbol N () symbolizes the null space of the operator within the parenthesis.

A METHOD FOR DETERMINING IN-SITU VELOCITY AND RELATIVE HYPOCENTER RELOCATIONS USING REFRACTED WAVES

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An arrival time difference (ATD) method (Fitch, 1975) utilizing refracted arrivals from a homogeneous, layered earth model is developed for the simultaneous determination of in-situ velocity and relative relocations of earthquakes. The method is particularly applicable when analyzing data from arrays in which most of the

recording stations are far (e.g. several focal depths) from a group of events. The travel times along refracted segments of P_n waves from a cluster of events to a distant station are nearly the same. Thus, the residuals from calculating the ATD are the result of near source velocity anomalies or mislocation of events. In minimizing these residuals, this iterative scheme first relocates earthquakes relative to a master event using a generalized inverse - least squares estimation procedure. Then an in-situ velocity inversion is performed using the Pavlis and Booker (1980) method of parameter separation and a damped least squares estimation of a solution. Results of tests on hypothetical data sets are given.

A HYBRID METHOD FOR DETERMINING RELATIVE RELOCATIONS AND IN SITU ELASTIC WAVE VELOCITIES IN SUBDUCTED SLABS

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Accurate estimates of the elastic wave velocity structure of and the locations of earthquakes within a subducted slab provide vital clues to its role in tectonics. In this study a method, which is a hybrid of the arrival time difference (ATD) technique of Fitch (1975) and the constrained media method of Spencer and Gubbins (1980), is presented for determining the in situ velocities of slabs simultaneously with the relative relocations of earthquakes. Several assumptions are made about the characteristics of raypaths in and around the slab in order to take advantage of the realism of the constrained media method without completely sacrificing the simplicity inherent in the ATD technique. The errors introduced by these approximate rays are estimated by comparing them with more exact rays calculated with a three-dimensional ray tracing routine. In general, the comparisons suggest that these errors are usually much less than 0.1 second. The inverse method is tested on the same set of hypothetical data. The results of these tests show that the parameters most sensitive to arrival time differences are the amplitude of the slowness anomaly in the slab and the azimuth and take off angle for rays leaving the master event. The arrival time differences are relatively insensitive to other parameters describing the slab (strike, dip, half width, and position of the master event), which implies that the hybrid scheme is fairly insensitive to the particular choise of analytic function to describe the slowness variation within the slab. Convergence of the inverse routine is rapid in the tests; usually less than five iterations are required before a stable solution is reached. Further, it appears that coupling between solutions for slab and ray parameters is insignificant.

AN OPTIMAL DESIGN OF A SEISMOLOGICAL NETWORK FOR THE ARAB COUNTRIES.

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The Arab countries cover a large portion of the African and Arabian plates. The region is characterized by seismic activity along complex continental collision zones, active sea-floor spreading, rifting, as well as intraplate earthquakes. Therefore, establishing standardized regional seismic networks in these countries is of great importance. Considerable efforts by some Arab countries and UNESCO under

project PAMERAR is underway to achieve this goal. A design for the spatial distribution of a regional seismic network in the area is proposed, based on a D-optimal planning criterion (Kijko, 1978). The method involves optimizing the geographical locations of stations, based on the probability of earthquake occurrence at a given point in the seismic region, travel times of seismic waves, and minimization of the ellipsoid volume of earthquake location errors.

SYNTHESIZED CALIBRATION OF ONE SECOND PERIOD SEISMOMETERS AT ST. LOUIS UNIVERSITY.

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Computer simulation of currently operating 1 second period seismometers at St. Louis University is used to study the feasibility of calibrating these instruments with random binary signals. The signals are constructed as time series with a .01 second sampling rate. The system response (instrument and anti-aliasing filters) is synthesized on the computer from the input RB signal, with Gaussian noise added. Spectral analysis of the input and synthesized output is performed to determine effects of noise levels on the computed transfer function of the system. Smoothed cross spectral estimates of the synthesized signals are computed to determine the system transfer function, with phase alignment of the signals to reduce bias. Simulated results indicate that a minimum of 60 seconds of data (6000 samples) is needed to compute satisfactory transfer functions (coherency spectrum greater than .9) in the presence of high ambient noise levels.

A JOINT HYPOCENTER RELOCATION STUDY IN THE NEW MADRID SEISMIC ZONE

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Since 1974, a regional microearthquake network operated by St. Louis University has recorded over 2500 events in the New Madrid seismic zone. Several distinct trends of seismicity are apparent as reported by Stauder et al (1976), Herrmann and Canas (1979) and others. A joint hypocenter relocation technique proposed by Herrmann (1981), is used to study spatial interrelationships of earthquakes comprising the trends mentioned above. A series of U.S.G.S. refraction blasts, Mooney et al (1982), are used as master events to constrain the solutions in many of the relocations. The earthquake relocations also use the velocity models suggested by Mooney et al (1982) for the Mississippi Embayment and the surrounding upland areas. The results of using the new models indicate that almost all of the earthquakes are relocated in the basement, 4 km in depth or more beneath the surface. Given the improved depth estimates, composite focal mechanisms for the main seismicity trends will be presented in relation to the spatial distribution of hypocenters.

AIRBLAST RECOGNITION AND LOCATION WITH REGIONAL SEISMIC NETWORKS

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Regional seismic networks are occasionally useful for purposes other than earthquake studies. Three such applications are described here: (1) The detection and location of a missile silo explosion in Arkansas;

(2) Determining the time of an airplane crash for the National Transportation Safety Board; (3) Locating the point of origin of an aircraft sonic boom for the Federal Aviation Administration.
In the above cases the seismic instruments respond to the air-coupled Rayleigh wave generated in the wake of the atmospheric shock front advancing with the speed of sound in air. Thus the disturbance's point and time of origin can be determined using a standard iterative hypocenter program with a "crustal" velocity model appropriate to the prevailing atmospheric temperature and pressure conditions.
Theoretical considerations predict that air-coupled surface waves are significant only when the speed of sound in air is greater than .92 times the shear wave velocity of the surface crustal layer. This is normally the case only when a deep surface layer of unconsolidated sediments is present. Our observations with the Memphis Area Seismic Network confirm this prediction: bedrock-sited instruments exhibited little or no response to the air shock waves, while Mississippi Embayment instruments yielded large and clear recordings.

SEISMIC MONITORING OF A HEATED UNDERGROUND REPOSITORY

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Acoustic emission activity (AE) and wave propagation characteristics (velocity and amplitude) have been monitored for a three-year period during the spent fuel project at the Climax Stock at the Nevada Test Site. The aim of the project was to assess the utility of modern seismological methods for monitoring the integrity of the repository during storage of high levels of nuclear waste. The experiment consists of a fifteen station, three-dimensional array (50m x 20m x 10m) of accelerometers surrounding eleven canisters of spent nuclear fuel and six electrical heaters. The canisters are arranged in a linear array at a depth of 420 m in the quartz manzanite. The 1-10 kHz data are digitized at 100,000 samples/sec and converted to low-frequency data (10-100 Hz) with a transient waveform analyzer and processed in-field with the ASP (Automated Seismic Processor). Velocity and attenuation control are provided by a piezoelectric source located within the array. Results indicate ongoing failure (AE activity) due to stress relaxation around the mined openings and, principally, due to the stress field from the heating and cooling of the rock. This AE activity shows a definite correlation with temperature in both the heating and cooling stages of the experiment. P- and S-wave characteristics indicate a significant and very systematic change in S/P wave amplitudes during the heating and cooling of the repository. Little change was seen in P- or S-wave velocities at the resolution of 10μsec in travel-time. The Climax experiment demonstrates that seismic source and wave propagation methods commonly used in earthquake studies can be scaled successfully for application in the AE range of meters and milliseconds, providing a powerful technique for repository monitoring.

EARTHQUAKE WAVES AND SOURCES

INVESTIGATION OF HIGH-FREQUENCY SPECTRAL SLOPE VERSUS DEPTH

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The objective of our study of reservoir induced earthquakes was to evaluate the influence of depth-of-focus on spectral slope above the corner frequency. The data set consists of 51 events recorded at close range on digital event recorders at Monticello Reservoir, South Carolina. Particle motions were used to determine the angle of incidence and spectra were computed from trace displacement in the direction of propagation. Depth of focus was estimated either by standard location procedures or by using S-P time to project distance along the ray path. The events studied to date show no depth variation in the slope of the high-frequency spectra, although they do cluster in a narrow depth range. The evaluation of particle motion indicates that the arrivals following the first cycle of P-wave motion are highly scattered and the window for spectral estimation must be chosen carefully to be sensitive to focal mechanism.

ANALYSIS OF DIGITAL DATA FROM LOCAL CHARLESTON, S.C., EARTHQUAKES

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Preliminary analysis of digital data derived from analog tape recordings of local South Carolina earthquakes produced estimates of Q, earthquake source radii and stress drops. Data from 10 vertical component stations, within 100 km of the earthquake zone for 12 earthquakes with coda duration magnitudes 1.8-2.9, were examined. Q was determined by the coda decay method developed in a 1969 study by Aki, and modified in a 1980 study by Hermann. Data were bandpass filtered, and Q was determined at 2, 3, 5, and 10 Hz. Exponentially increasing Q with frequency is observed from 350 at 2 Hz, to 500 at 3 Hz, to 750 at 5 Hz, to 1900 at 10 Hz.

Spectral high-level asymptote and corner frequency were determined from logarithmic least square fit of the data to an equation with flat, low-frequency response and w-squared high-frequency fall-off. Corner frequencies occur in the 5-10 Hz range. Assuming $v=0.9B$, where v is rupture velocity and B is shear-wave velocity, the source radii, for a circular crack model, are on the order of 100 m for the earthquakes studied. Their seismic moments are on the order of 10^{19} dyne-cm, and their stress drops are less than 10 bars.

STABILITY OF EARTHQUAKE CENTROIDAL PARAMETERS FOR FINITE COMPLEX SOURCES FROM INVERSION OF TELESEISMIC BODY WAVES

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Average centroidal parameters are the basic parameters describing the earthquake source. In practice the data is band limited and the apparent point source parameters determined from this data may not give the proper centroidal values. In this paper I will present simple examples designed to test the stability and biases of the point source parameters obtained from inversion of body waveforms. Finite sources were simulated by numerical integration of point sources. The source geometries and

complexities chosen are representative of those commonly occurring in nature. The inversions were carried out in three frequency bands corresponding to the long-period SRO, WWSSN and short-period WWSSN instruments, with station distributions typically found in teleseismic studies.

Some of the conclusions follow. 1) Inversion generally gives the correct centroidal values when the corner frequencies of source finiteness and other complexities are higher than the frequency of peak magnification of the recording instrument; other large relative minima, however, may exist. 2) When the corner frequencies are lower than the recorder's peak frequency, the inversion is unstable and does not converge to the centroidal values. 3) Directivity due to the vertical component of rupture propagation strongly distorts the observed signal but the effect is averaged out by the presence of both the direct and reflected phases. 4) Parameterizations which ignore the source time function tend to overestimate the centroidal depth. 5) Poor azimuthal coverage may cause a large bias in the parameter estimates. 6) The matches between the data and the average centroidal synthetics may appear poor to the naked eye which tends to focus on the high frequency portion of the signal; trial-and-error matching may therefore result in biased centroidal values.

INVERSION OF RAYLEIGH-WAVE GROUP VELOCITIES FROM SMALL YIELD HIGH-EXPLOSIVE TESTS

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Rayleigh-wave group velocities have been determined from high-explosive tests conducted in alluvium at the McCormick Ranch Test Site near Albuquerque. The frequency-time analysis method was used to determine the group velocities. The general results involved fundamental-mode group velocities (225-264 m/sec) for the period range 50-104 msec and distance range 73-229 m. In addition, higher mode group-velocities (260-300 m/sec) for periods of 25-60 msec were observed. Inversion of the group velocities yielded a shear-wave velocity distribution of V_s = 250-400 m/sec for the depth range of 0-22 m. These results were also modeled with respect to the Air Force seismic refraction data at the test site.

EVENT J OF THE 1975 OROVILLE AFTERSHOCK SEQUENCE: AN EXAMPLE OF THE BREAKING OF A SINGLE ASPERITY?

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The ground displacements due to the rupture of a single circular asperity on an ∞ fault plane (Das and Kostrov, 1983) are differentiated twice to obtain theoretical accelerograms. Instead of directly studying the acceleration $\ddot{u}(t)$, say, we study the acceleration envelopes $e(t)$ obtained by the formula

$$e(t) = \sqrt{\frac{\ddot{u}^2(t)+H^2((\ddot{u}(t)),}{2}}$$

where H is the Hilbert transform. This is equivalent to neglecting the angle information contained in the accelerograms and only retaining the amplitude information. The theoretical acceleration envelopes are

filtered to eliminate frequencies higher than those contained in the observed data. The filtered acceleration envelopes are then compared with the acceleration envelopes obtained at several stations due to the J event of the 1975 Oroville aftershock sequence. From this comparison we conclude that the J event was mainly due to the breaking of a single asperity.

GROUND MOTION NEAR AN EXPANDING PREEXISTING CRACK

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We present a study of the motion of the ground in the near field of a preexisting vertical crack driven by excess tensile stress. Using the discrete wave number method, we make a complete representation of the three components of ground displacement resulting from a small incremental extension of the bottom tip of the crack and analyze the effects of the medium structure on the ground response. The results show the strong impulsive character of the dynamic motion near the source and demonstrate that the first motion is directed everywhere outward. Marked oscillations are observed in the ground response associated with the ringing of the crack faces triggered by the rupture. The displacement is dominantly vertical near the epicenter but becomes predominantly horizontal beyond the immediate source region. The presence of layers has a strong effect on the complexity and duration of the ground response. The static vertical and longitudinal displacements are respectively downward and inward in the epicentral area.

SCATTERING OF ELASTIC WAVES BY A FINITE VOLUME OF RANDOM MEDIUM

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In the study of scattering and attenuation of seismic waves in three-dimensional heterogeneous media, Chernov's theory on scalar wave scattering in random media has often been used. In this paper we derived the scattered fields and the total scattered power for elastic waves by a finite volume of random medium (characterized by fluctuations of elastic constants and density) using the body-force equivalent theorem and the Born approximation. We found that, in both the spatial scattering pattern and the frequency dependence of the total scattered power, there are some significant differences between the scalar wave scattering and the elastic wave scattering when the wavelength is comparable to the size of inhomogeneities, which is often encountered in the study of short-period seismic body waves. For example, the average backscattering coefficient of the random medium can be much greater in elastic wave scattering than that in scattering due to velocity perturbations. Thus, in addition to the multiple scattering, the elastic wave scattering can contribute to solving the puzzle of the coda excitation problem that the random media with parameters estimated from observed attenuation of primary waves seemingly cannot account for the amplitude of coda waves considered as backscattered waves (e.g. Sato, JGR, 87, B9, 1982).

A MODEL OF THE THERMOELASTIC STRESS FIELD GENERATED BY A PLUTONIC INTRUSION

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A computational study of the thermoelastic stresses due to a cylindrical source embedded within a homogeneous and isotropic half-space reveals a complex system of stresses which change with time as well as with distance from the source region. At certain times during the cooling history and within a particular range of depths of observation the stress distribution versus distance from the source axis may change from one favoring normal faulting along the axis, to one favoring reverse faulting and finally to one favoring strike-slip faulting at larger off-axis distances. The principal stress axes along the same line may change from a predominantly vertical to a horizontal orientation, and the attitude of the horizontal axes may change from a tangential (relative to the cylindrical source) orientation to a radial orientation. The Northern Mississippi Embayment is examined as a possible example of such a stress system.

POLARIZATION ANALYSIS AND THE EFFECT OF LITHOLOGY ON THE CODA OF TWO EARTHQUAKES IN THE SAN ANDREAS FAULT ZONE, CENTRAL CALIFORNIA

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Particle motion from three-component velocity data contains important information which may prove useful in decomposing seismograms and in determining the nature of late arrivals. Through the method described by Montalbetti and Kanasewich(1970) parameters describing the the azimuth, emergence angle and rectilinearity can be derived from a single three-component station. Such parameters provide characterizations of various coda components and allow filtering of off-azimuth, off-emergence angle and incoherent energy.

In order to explore the effect of lithology on coda formation, an experiment was conducted in central California 25 km south of the city of Hollister. Two arrays of digital event recorders were placed equidistant from the San Andreas fault zone. The arrays were located on opposite sides of the fault zone. However, they were not operated concurrently. The configurations overlay contrasting lithologies: to the west Gabilan granite and to the east Franciscan greywacke, mudstone and blueschist. Small and large instrument spacings of tens and hundreds of meters, respectively, were used. The polarization parameters were estimated for two events occuring within the fault zone. The effect of time window lengths appears to have a large effect upon parameter estimates. Finally, stations in the array were rotated, filtered and stacked upon the azimuths estimated in the polarization analysis.

Montalbetti, J.F. and Kanasewich, E.R. (1970) Geophysical Journal of the Royal Astronomical Society 21, 119-129

THE EFFECT OF INSTRUMENT RESPONSE ON THE DETERMINATION OF m_{bLG}

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Nuttli (1973) proposed the use of the short period Lg phases as an estimator of m_b, which was defined at m_{bLg}. The formula is of the form

$$m_{bLg} = G(R) + \log_{10}(A/T)$$

where G(R) is the correction for geometrical spreading and anelastic attenuation, A is the sustained peak ground amplitude of the Lg phase at a period T. This relation was defined using data from the short period WWSS vertical instrument using periods $0.5 \leq T \leq 1.5$ seconds. For lack of any other formula, this relation has been used in eastern North America with different short period instruments and periods less than 0.5 seconds.

To understand the effect of instrument response, earthquake source spectrum and anelastic attenuation on the magnitude estimate, synthetic Lg seismograms were generated by using a) shaped random number sequences and b) normal mode theory. Three different magnitude measures were considered: A) peak trace amplitude, B) peak trace amplitude corrected for instrument magnification, and C) the peak ground motion value of (A/T). The experiment proposed placed four instruments, the WWSS SP, the CSSN SP, the USGS microearthquake and the Wood-Anderson on the same pier with the same ground motion input to each. Measure B provided the most consistent results among the four instruments for source corner frequencies between a minimum of 0.3 Hz and a maximum of 10.0 Hz, considered. Measure C worked better than measure B when anelastic attenuation and corner frequency were such to limit the high frequency content on the recorded seismogram. Measure B is recommended. The relationship of the time domain amplitude measure to source spectrum excitation is also considered.

AN ANALYSIS OF TECTONIC RELEASE EFFECTS ON THE OBSERVED TELESEISMIC P WAVES FROM THE RULISON EXPLOSION

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The observed teleseismic m_b value for Rulison is biased significantly low relative to that expected on the basis of Gasbuggy experience. Analyses of near-regional, broadband seismic data suggest that this anomaly cannot be attributed to differences in explosive source coupling. Moreover, our analyses of the P wave spectra recorded from the two explosions at common teleseismic stations indicate that the upper mantle attenuation beneath the two sites must be nearly identical, in agreement with previously reported results based on reciprocal experiments. These findings have led us to re-examine the variety of seismic data recorded from the Rulison explosion. This examination revealed evidence of long-period Love waves as well as an unusually strong SH pulse in the near-regional recordings, both of which are suggestive of tectonic release. Simple theory suggests that if this release is consistent with normal faulting on a plane dipping at about 45°, then the teleseismic P waves could be expected to be suppressed at all azimuths. Effects of tectonic release on m_b have generally been dismissed in the past on the basis of the argument that the stress drops required to produce a significant effect are unreasonably large. However, these arguments are largely based on the assumption of strike-slip motion on a vertical plane, and it can be shown that dip-slip motion on a plane dipping at 45° is about 3 times more efficient in the generation of short-period teleseismic P waves. We are currently modeling the observed Rulison SH pulse in an attempt to quantitatively determine whether the stress drop required to match these observations is consistent with the hypothesis that tectonic release is having a significant effect on the observed Rulison m_b value.

CHARACTERISTICS OF LG BASED ON SPECTRAL RATIOS BETWEEN ORTHOGONAL COMPONENTS OF GROUND MOTION

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Short-period, three-component records of several earthquakes and the underground nuclear explosions, SALMON, all located in the eastern United States, are rotated to obtain the radial (R) and transverse (T) components, in addition to the vertical (Z) component, of the Lg phase. Fourier spectra of the three components of Lg are obtained for sites at epicentral distances of a few hundred kilometers. Spectral ratios between the three components (i.e. R/Z, Z/T and R/T) for the frequency band of about 0.5 to 5 Hz appear to be significantly different for rock and alluvial sites. An explanation for the observed results is offered in terms of the scattering mechanism proposed earlier (Gupta and Blandford, 1983) according to which the dominant motion in Lg may be considered to be due to the upward propagation of S waves with almost no preferred direction of polarization. Theoretical component spectral ratios are computed for typical rock and alluvial sites, assuming propagation of S waves with equal SV and SH components through plane stratified media. Satisfactory agreement between theory and observations is found for both rock and alluvial sites. It seems therefore that Lg observed at epicentral distances of a few hundred kilometers and in the frequency band of about 0.5 to 5 Hz is primarily composed of nearly isotropically polarized S waves approaching the site from below and being modified by the local structure of the recording site.

SEISMOTECTONICS: CALIFORNIA-PACIFIC NORTHWEST

SEISMICITY OF THE ROCKLIN/PENRYN PLUTON

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There has been an increased interest in the seismicity of the western Sierra Nevada Foothills fault system since the occurrence of the M_L 5.7 Oroville earthquake on August 1, 1975. Of particular interest is the observed seismicity within the 130 My old Rocklin/Penryn Pluton and vicinity. A network of 14 local seismographic stations (telemetered to Menlo Park) was installed in the Auburn region (within 50 km of the pluton) by the U.S. Geological Survey starting in July 1976. Sixty-three earthquakes ($0.1 \leq M_L \leq 1.8$), centered in the Rocklin/Penryn Pluton and vicinity, were recorded by the Auburn network between November 1976 and September 1980. The onset time and first motion data for 23 of the best recorded earthquakes were used in the present analysis. A group location procedure which simultaneously estimates the hypocentral locations and the average station adjustments showed that the hypocenters in the pluton and vicinity broke into 3 distinct groups. A plane fit by least-squares through the southern group had a northerly strike and dipped 70° ±7° to the west. A group focal mechanism was computed using first motion data from 10 of the best recorded earthquakes (including the earthquakes from each of the 3 groups) and the resulting mechanism showed east-west tension which is compatible with the regional tectonics. The cumulative rate of seismicity for the western Sierra Nevada Foothills fault system is given by $\log N = 4.38 - 1.00\ M_L$ where N is the expected cumulative number of earthquakes of magnitude M_L or larger per century per 100 km length of fault. For comparison, the rate of seismicity of the western Sierra Nevada Foothills is approximately one-thirtieth of the rate of seismicity of the central coast region of California.

AN UNUSUAL SEQUENCE OF SWARMS IN INDIAN WELLS VALLEY, SOUTHERN CALIFORNIA

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In April of 1981 an unusual series of earthquake swarms began in Indian Wells Valley near Ridgecrest, California. This sequence has been sporadically increasing in intensity and areal extent since it began. By 14 January, 1983 there had been 14 events of magnitude 4.0 or greater. The largest event (M_L = 5.2) occured on 1 October, 1982. There is no evidence that such intense activity has occured in the area in the past 50 years. Individual swarms generally consist of multiple bursts of activity. The bursts begin as tight clusters of moderate sized events in a limited magnitude range (magnitude modality). These early stage events usually occur near the base of the seismogenic zone (7-8km). Later stage events have a more usual magnitude distribution and occur throughout the seismogenic zone (3-9km). Individual swarms are separated by periods of low seismicity lasting from several weeks to several months. Physical models proposed to explain similar swarm sequences frequently involve fluid migration. The attending increase in pore pressure causes local reduction in strength resulting in release of stored tectonic stress. Attributing variations in seismic activity to fluctuations in stress rates do not appear to be permitted by recent geodetic measurements (leveling and trilateration) which show little if any change over the past decade.

MIGRATION OF MODERATE EARTHQUAKES IN CENTRAL CALIFORNIA.

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Moderate earthquakes migrate repeatedly along the Central California section of the San Andreas fault zone system, at rates of 2.25km/yr and at regular intervals of 6.0yr.

The data consist of earthquakes greater than magnitude 5 occurring between 1934 and 1982. The October 25, 1982 earthquake is not included in the list and is used as a test to verify the results. The area covered is the currently active portion of the San Andreas fault zone system between latitudes 35.5°N and 38.5°N, and longitudes 120.0°W and 123.0°W.

Our basic tool is the space-time diagram transformed by two-dimensional spectral analysis and stacking. Earthquake locations are projected on a space-axis whose orientation produces the largest signal-to-noise ratio in the two-dimensional spectrum. The best orientation is parallel to the San Andreas fault. The largest peak occurs at periods of 6.0yr and 13.5km. This indicates that the space-time diagram may be divided into alternating bands of high and low seismicity. Most earthquakes (~75%) fall within the high seismicity bands; these bands would have included the October 25, 1982 earthquake which was excluded from the analysis.

The probability of where and when an earthquake ($M \geq 5$) occurs in Central California can vary by a factor of 3 depending on the current location of the migrating bands.

SEISMICITY OF THE MOUNT SHASTA AND LASSEN PEAK AREAS, CALIFORNIA

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In February 1981, seismograph networks were upgraded to 9 and 11 stations, respectively, to monitor earthquakes in the vicinity of Mount Shasta and Lassen Peak. Since February 1981, the Lassen Peak network has recorded nearly 500 locatable earthquakes, in comparison with the 150 earthquakes recorded by the Mount Shasta network. Earthquakes in the Lassen Peak area, which are generally of $M < 3$, clearly delineate the previously reported northwest-trending seismic zone running through the geothermal area of Lassen Volcanic National Park. Earthquake swarms are common in the geothermal area, where they coincide with areas of hot springs. This seismic zone is well delineated to the southeast of the geothermal area but appears to terminate about 25 km northwest of Lassen Peak. Around Mount Shasta, locations of earthquakes to both the southeast and northwest of the Mount Shasta volcano suggest that the northwest-trending seismic zone also extends into this area. Bisecting the seismic zone between Mount Shasta and Lassen Peak areas is a wedge of the Klamath Mountains terrane that is nearly aseismic. Additional swarms of earthquakes that occur between Mount Shasta and the Medicine Lake Highlands appear to coincide with the axis of the Cascade Mountains in northern California.

CRUSTAL STRUCTURE OF THE COLUMBIA PLATEAU REGION, WASHINGTON

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Refraction data from blasts recorded in eastern Washington between 1980 and 1983 are used to determine the upper crustal structure of the Columbia Plateau. Fourteen blast sites with over 25 individual shots were recorded on the University of Washington regional seismic network made up of 36 short-period seismograph stations recorded digitally at 100 samples/sec. Additional data were obtained from a 12-station dense digital network in the central plateau operated by the Basalt Waste Isolation Project.

Major crustal refractors of 5.1 and 6.05 km/sec are observed at distances of 15 to 50 km and 50 to 120 km respectively. A time term method is used to model layer thicknesses below the stations for each major refractor. A statistical source-receiver separation operation is used to handle the inherent nonindependence of the data. Constraints are used to fix the mean values of the time terms. Ray tracing through two-dimensional velocity structures is used to augment the interpretation of the time term solutions for areas where the lateral velocity changes are large.

Station delays for the 5.1-km/sec layer show a good correlation with elevation and surficial geology. The areal extent of the 5.1-km/sec layer roughly coincides with the Columbia River Basalts. Time terms from the 6.05-km/sec layer indicate a nearly uniform depth of 1 to 2 km in the northern plateau. Time terms in the central plateau indicate a depth to the 6.05-km/sec layer of over 8 km, and a systematic thinning away from its center. Magneto-telluric studies indicate that the basalts are probably no thicker than 5 km in the central Columbia Plateau region.

SEISMICITY AND SEISMOTECTONIC BOUNDARIES IN WASHINGTON

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The contemporary seismicity distribution (1969-82) in Washington state is overprinted by three seismotectonic boundaries. The first boundary strikes north-northeast from the Pacific Coast near the mouth of the Quinault River to southern Vancouver Island (QRVI); the second boundary strikes northeast from near the mouth of the Columbia River to Mount Rainier (CRMR), and the third boundary strikes north-northeast from the Oregon coast to Lake Chelan (OCLC). The QRVI and the CRMR bracket both the change in strike of the subduction zone at the coast (from north-southward to northwestward) and, inland, the limits of the North Cascade Range (NCR). The OCLC bounds the extensive late Cenozoic volcanism east of the Cascade Range and separates the isolated Quaternary volcanic centers at Mount Rainier and Mount St. Helens from the extensive basalt fields of the southern Washington Cascade Range.

Within this framework, earthquakes in Washington occur subcrustally in the subducting Juan de Fuca plate (JFP) and in the crust of the overlying North American plate. These subcrustal events all occur in the limited spatial area bounded by the coast, the QRVI, the CRMR, and the western edge of the NCR. The CRMR divides the crustal earthquakes into events in Puget Sound and events to the southeast. Crustal earthquakes in the Puget Sound area are generally confined to a 100-km-wide zone between the position of the change in the dip of the JFP and the NCR. The interior of the NCR is aseismic. Southeast of the CRMR, crustal earthquakes are distributed over a 300-km-wide area. These earthquakes end near the OCLC, and so the areas of extensive volcanism in the southern Cascade Range are nearly aseismic.

This relation between the subcrustal events and the two crustal groups suggests that the CRMR is fundamental to the seismotectonics of Washington and that the position of the CRMR is controlled by the interaction of the NCR with the JFP.

POSSIBLE BLOCK TECTONICS IN NORTHWESTERN WASHINGTON

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The spatial distribution of earthquakes in NW Washington may define a complex crustal block system. A 2500–3000 km^2 aseismic area at the north end of Puget Sound is clearly delineated. The north quiescent zone (NQZ) has been aseismic at the $M \geq 2.0$ level since 1974. Earlier and lower quality data suggest that the NQZ has been very quiet at the $M \geq 3.5$ level since 1955. The NQZ has a $\approx$3000 km^2 counterpart immediately SE of Puget Sound which was first reported by Weaver and Smith.

Relatively intense seismicity defines the Kitsap seismic zone (KSZ), a narrow NNW-striking 35 km long zone in the southern Puget basin. In 1978, the largest crustal earthquake in the Puget basin since 1971 occurred in the KSZ. Differences in composite focal mechanisms from different parts of the zone suggest that the KSZ may itself contain complex structure. However, if the KSZ were to sustain simultaneous slip along its entire length, an $M_L \approx 5.5$ earthquake would result.

The central Puget basin is crossed by several approximately E-W trending gravity and magnetic features. The imperfect alignment of epicenters along these features suggests that they do not represent through-going faults along which a larger (M>5) earthquake could occur. These epicentral alignments help define three or four 300–350 km^2 crustal blocks within which the observed rate of seismic energy release is less than the rate along the blocks' boundaries.

The crust of NW Washington is structurally complex. From the distribution of epicenters, at least five or six blocks are inferred to exist. Because much of this structure may predate the modern stress field, modern crustal seismicity in the region may occur, at least in part, along tne older structure in response to the modern stress field.

SEISMICITY OF THE OLYMPIC PENINSULA, WASHINGTON

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Two and a half years of data from an expanded, telemetered seismic network on the Olympic Peninsula reinforce the conclusion that the Juan de Fuca plate is still subducting beneath Washington. However the rate of seismicity is much lower than most other convergent margins.

The earthquakes can be divided into two groups on the basis of depth. At the coast, the shallow zone extends to a depth of approximately 20 km while the deep zone begins at 25 km. On the eastern edge of the Peninsula the shallow zone has thickened to 30 km and the top of the deep zone has dropped to 45 km. The deep zone is 5-10 km thick and dips to the east at an angle of about 10 degrees. The separation between the two zones is not clearly defined near the coast. The rate of crustal seismicity is much lower on the Peninsula than in the adjacent Puget Sound region, with the change occuring abruptly at the eastern boundary of the Crescent formation. The concentration of deep events is greatest in the northeast quadrant of the Peninsula, where the distribution of events and their focal mechanisms suggest a bending of the plate. The deep events appear to be occurring in the upper part of the subducting oceanic lithosphere.

Focal mechanisms were constructed for 16 events in the suite of deep events with magnitudes ranging from 1.6 to 4.3. The solutions show primarily normal faulting with the P axes normal to the slab and the T axes displaying a range of angles within the slab with the average T axis in the downdip direction. Small downdip tension events in the downgoing slab are consistent with the slab sinking under its own weight. Several strike-slip events may be caused by a shearing within the slab.

DEEP EARTHQUAKES UNDER THE PUGET SOUND BASIN

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Modern seismicity patterns indicate the Juan de Fuca plate is actively subducting beneath North America. The slab is deforming internally, and may be controlling the seismicity patterns in the lower crust of the overriding plate. During the past 10 years, the quality of the data has improved greatly and earthquakes down to magnitudes $M < 1$ are now routinely located. Sub-crustal earthquakes under western Washington and southwest British Columbia are distributed in a thin Benioff zone dipping shallowly (approximately 10°) to the east. At 122.5°W, beneath central Puget Sound, the Benioff zone steepens. The deepest events occur at 95-100 km, beneath the western Cascade Range.

Lower crustal seismicity (depths < 35 km) is concentrated in central Puget Sound and ceases abruptly at the Cascades, directly above the steepest portion of the Benioff zone. Events in the lower crust exhibit a variety of focal mechanisms, and generally have a large strike-slip component with N-S horizontal compression. Alignment of the deep hypocenters indicate at least 2 or 3 N-S striking fault-like features in the lower continental crust and one within the subducted oceanic plate.

Subcrustal earthquakes (depths > 35 km) have predominantly normal focal mechanisms with sub-horizontal, E-W T-axes. Small variations in the plunge of the compressional axes are consistent with an eastward steepening of the subducting Juan de Fuca plate. A significant number of sub-crustal earthquakes beneath central Puget Sound have thrust mechanisms with near horizontal E-W compressional axes, in the approximate direction of maximum plate convergence. These events suggest that seismicity in the subducting plate is not simply due to body forces acting on the slab, but has more complicated origins.

THE SEISMICITY OF GEORGIA STRAIT, BRITISH COLUMBIA

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Georgia Strait is located between Vancouver Island and North America and is the northern continuation of the Puget Sound depression. The seismicity of Georgia Strait has been monitored by a local network of seismograph stations since 1951. The addition of new telemetered stations in 1981 and 1982 has increased the location capability and provided good depth control. Reprocessing of earlier solutions with a local crustal model derived from refraction studies has allowed more precise epicentres to be calculated and depth information to be extracted in some cases. As in Puget Sound, there is a shallow suite (less than 30 km) and a deeper suite (40 km - 70 km) of hypocentres. However, the areal distribution is not simply a northern continuation of the Puget Sound seismicity as there is a paucity of both shallow and deep events in southern Georgia Strait immediately north of Puget Sound.

TEMPORAL VARIATION OF THE MAGNITUDE-FREQUENCY RELATION AT ELK LAKE, WASHINGTON

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From May 19, 1980 to December 31, 1982, 1,153 earthquakes have been located in the Elk Lake area of southwestern Washington in the immediate vicinity of the February 14, 1981 shallow crustal earthquake (M_L=5.5). Of these events, 148 occurred in the 9 month period preceding the main shock.

We have used least-squares and maximum-likelihood techniques to compute b-values on a sliding basis that establishes constant sample size and variable time windows. Both methods yield similar results, and b ranges from 0.5 to 1.1 over time. Using the results obtained from the maximum likelihood method, we observed that the b-value increased immediately after the main shock from approximately 0.5±0.1 to approximately 1.0±0.1 two weeks later, and then decreased to 0.7±0.1 before the occurrence of a M_L=4.0 aftershock on May 13, 1981. The b-value increased from May to October 1981 to 0.9±0.1 and then decreased before the largest (M_L=4.1) aftershock of the sequence on March 1, 1982. From March through December 1982, the b-value appears to have stabilized at about 0.6±0.1, which establishes a baseline for the comparison of future activity in the Elk Lake area. The b-value for the entire aftershock sequence excluding the main shock is 0.63±0.02 using the maximum-likelihood method and 0.69±0.01 using the least-squares technique, with a minimum magnitude cutoff of M_L=0.5.

AN INTENSITY MAP OF THE ELK LAKE, WASHINGTON, EARTHQUAKE

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On 14 February 1981, at 0609 UTC, a magnitude 5.5 shallow crustal earthquake occurred in the Elk Lake area (46 21.01N, 122 14.66 W) of southwest Washington, about 15 km NW of Mount St. Helens. The earthquake was felt over an area of approximately 102,000 sq km, from Vancouver, B.C. (Canada) to Eugene, Oregon. Data from nearly 4000 questionnaires and letters were used to prepare the intensity map. This is the most extensive data set yet collected for an intensity study of an earthquake in Washington State. The maximum intensity reported in the epicentral area was VI (Modified Mercalli Scale, 1931). Only 73 responses (primarily from north and west of the epicenter) were from within the sparsely populated area enclosed by the intensity V-VI contour, which is an area of roughly 10,000 sq km around the epicenter. The nearest data point was 15-20 km northwest of the epicenter. The maximum intensity could, therefore, be somewhat higher than reported here.

Damage reported included displaced support beams in a pole barn, several chimneys with cracks or brick loss, numerous minor cement, wood frame and plaster cracks, several cracked windows and some breakage of small objects which fell or overturned. Higher intensity areas outside of the epicentral region were usually associated with specific site conditions: filled-in river meanders and old drainages, steep slopes with a previous history of slides, and other soft sediment sites.

IMPLICATIONS OF HEAT DRIVEN EXTENSION FOR SOME CENOZOIC STRUCTURES IN OREGON

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Long term strain produced by a right-lateral Brothers Fault Zone (BFZ) can account for the pattern of folds, normal faults, and tear faults (e.g. Indian Cr.) in east-central Oregon. Fold axes ranging in age from 40?-0 Ma are coincident, implying that the BFZ is an old structure which is continually reburied and displays only Riedel shears in young surface rocks. South of the BFZ heat driven extension and consequent listric normal faulting, active for a minimum of 25 my, and localized under the Alvord Desert, Summer and Goose Lakes, and Warner Valley, would best explain the increasing dips with age seen in Steens, Winter, and Abert scarps. Ignimbrites and domes throughout central and southern Oregon with 36-15 my ages testify to strong mid-Cenozoic crustal heating. The BFZ appears to end westward at Newberry volcano. More rapid extension south of the BFZ would produce both extensional Fe-Ti rich arc lavas from, and a graben along, the north-central portion of the Cascade arc. Fe-Ti rich Scorpion Mtn. (25-18 Ma) and Deschutes Fm. (8?-3 Ma) lavas appear to mark two episodes of such extension—the first due to profound heating culminating some 20-25 Ma followed by slow cooling, and the second due to reheating beginning some 10 Ma (the age progression of domes 10-4 Ma). We suggest that the Sardine Fm. fills a graben which has been rotated CW away from the site of its formation. CW rotation of western Oregon rocks is a consequence of extension increasing southward from Montana to Nevada. A monotonic increase in such extension would lead to constant rotation of western Oregon and no rotation of the Klamath Mtns. The step-like increase in extension across the BFZ appears to require decreasing rotation southward in the Western Cascade and Coast Ranges.

INTRAPLATE REGIONS: SEISMICITY, LITHOSPHERIC STRUCTURE, AND CONTEMPORARY TECTONICS

STRUCTURE OF THE LITHOSPHERE IN INTRAPLATE NORTH AMERICA

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Seismic velocity structure of the crust and uppermost mantle of North America has been extensively studied utilizing seismic refraction, surface wave dispersion and deep seismic reflection profiling. A compilation of seismic refraction and surface wave dispersion velocity models has been used to compute average values of crustal thickness (H_c), upper mantle seismic velocity (P_n) and average velocity of the crystalline crust ($\bar{V}_p$). Poisson's ratios determined from these data are 0.25 ± 0.04 and 0.27 ± 0.02 for the crust and uppermost mantle, respectively. Contour maps of H_c, P_n and $\bar{V}_p$ display regional variations correlative with major tectonic elements and earthquake zones of North America as well as the prominent differences in lithospheric structure between the craton and the western North American orogenic belt. The principal structural features of the continental crust (Mohorovicic discontinuity, upper and lower crustal velocities) are generally laterally continuous with gradual variations in properties. In some areas, lateral variations are abrupt and fine structure of the crust can be shown to vary laterally on a scale of a few kilometers to tens of kilometers. Deep reflection profiles in conjunction with more regional refraction and deep seismic sounding techniques are particularly useful for study of these areas. As more detailed information on continental lithospheric structure becomes available, we expect additional meaningful correlations with ancient and contemporary tectonic features and earthquake zones to be recognized.

IN-SITU STRESS, CRUSTAL DEFORMATION, AND INTRAPLATE SEISMICITY

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The occurrence of intraplate seismicity seems to be controlled by interaction of the in-situ stress field and favorably oriented faults. An important unresolved problem, however, is whether potentially damaging earthquakes are restricted to certain types of intraplate structures such as ancient rift zones, or whether they could occur on appropriately oriented faults located anywhere. To address this question, earthquakes in the central and eastern United States are considered in light of updated data on the intraplate stress field and physical mechanisms possibly responsible for concentrating seismicity along particular structures.

Data on the state of stress in the conterminous U.S. have been updated with recently available stress measurements, focal mechanisms, fault-slip data, and data on stress induced wellbore breakouts. The new data confirm that deformation within intraplate seismic areas is consistent with that in surrounding regions and suggest that the earthquakes are occurring within a relatively uniform stress field caused by large-scale tectonic forces. This uniformity of the stress field apparently rules out small-scale stress amplification mechanisms for localizing seimicity. Furthermore, localized crustal weaking can probably be ruled out as avail-

able stress measurements at depth near active faults suggest that stress in the crust is limited by the frictional strength of the faults with coefficients of friction ranging between 0.6 and 1.0. Thus, most faults in the brittle part of the crust do not seem to be anomalously weak. The presence of pre-existing ductile shear zones within the lower crust in intraplate regions may play a key role in the localization of seismicity on associated faults in the brittle crust. We examine field and laboratory evidence suggesting that such zones in the lower crust may act to concentrate crustal deformation.

ELASTIC STRAIN RELEASE IN THE BASIN-RANGE AND SOUTHERN CALIFORNIA: INFERENCES FROM SEISMICITY AND GEOLOGICALLY DERIVED MOMENT RATES

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Using a new compilation of historic seismicity for the southwestern U.S. (mostly from regional networks), ~14,000 epicenters of M>3, and 320 slip-rate determinations on Late Cenozoic faults, we have calculated contemporary moment rates from the seismicity, and Quaternary moment rates from the slip data. These data provide estimates of the direction and magnitude of the strain field due to elastic moment release. Contemporary E-W extensional strain across the eastern Basin-Range occurs non-uniformly at rates up to 10^{-14} s^{-1} (corresponding to maximum extension of ~3.9 mm/yr) with the principal deformation occurring in the central Nevada seismic zone and the southern Intermountain seismic belt. Strain across the transition zone from southern California into the Basin Range is comparable to that in the Great Basin but shows oblique extension. Contemporary N-S compression at rates up to ~10^{-12} s^{-1} characterizes southern California including the San Andreas fault. Quaternary deformation rates were remarkedly similar to those determined from the contemporary seismicity and suggest the continuity of the Late Cenozoic lithosphere deformation mechanism. Where accurate focal depths are available in the eastern Great Basin, 80% occur below 7-8 km; a depth that correlates with the top of an upper-crustal low velocity layer. Quasi-plastic, strain-rate dependent deformation modeled for appropriate geotherms and a quartz rheology begins at the same depth and suggests a thermally controlled mechanism for limiting the depth of brittle deformation in the intraplate lithosphere. These data are consistent with a model for contemporary extension above an extending and plastically deforming lower crust in the Basin-Range.

RIFT STRUCTURE FROM COCORP SURVEYS IN THE MIDCONTINENT

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COCORP profiling across the Midcontinent Geophysical Anomaly in northeastern Kansas and central Michigan reveal structural basins of the Precambrian Keweenawan rift buried beneath the Paleozoic cover. The Kansas results are especially informative, showing the southern rift basin to be approximately 8 km deep and 40 km wide and highly asymmetric. The Kansas rift is characterized by a lower layered sequence of strong, continuous west-dipping reflectors which may correspond to the Middle Keweenawan interbedded volcanic and clastic rocks exposed along the MGA in the Lake Superior region. Overlying this layered sequence is a zone of weaker, discontinuous reflectors interpreted as predominently

clastic rocks such as are characteristic of the late Middle and Upper Keweenawan rocks. Normal faults associated with the rift basin appear to dip at moderate angles to the east. Palinspastic reconstruction indicates that the rift basin formed by the rotation of fault bounded crustal blocks during extension. Mafic intrusions are inferred to be emplaced beneath the rift basin on the basis of seismic character, seismic velocity distribution, and gravity modeling. The Michigan data exhibit a similar layered seismic character but structural details are less distinct. Asymmetric, well-layered reflector sequences are also evident in COCORP data from the Tertiary Rio Grande rift in New Mexico and from a Triassic graben in southeast Georgia, suggesting that such distinctive sequences are characteristic, and perhaps diagnostic, of rifts in general.

SEISMICITY ALONG THE PACIFIC-NORTH AMERICAN PLATE BOUNDARY IN CALIFORNIA AND WESTERN NEVADA, 1980-81

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Beginning in 1980, the number and distribution of telemetered, high-gain seismic stations operated in California and western Nevada provided the capability for locating earthquakes of $M \geq 2.0$ occurring throughout the broadly-deforming Pacific-North American plate boundary from the Salton Trough to the Mendocino triple junction and as far inland as the western Great Basin. Four networks combine to provide this capability: (1) the 300-station Central California Network operated by the U.S. Geological Survey from Menlo Park, CA; (2) the 200-station Southern California Network operated jointly by the California Institute of Technology (CIT) and the U.S. Geological Survey from Pasadena, CA; (3) the 40-station Western Nevada-Eastern California Network operated by the University of Nevada from Reno, NV; and (4) the 55-station Southern Nevada Network operated by the U.S. Geological Survey from Golden, CO. The distribution of earthquake hypocenters located by this combination of networks for 1980 and 1981 brings into focus detailed seismicity patterns within the broad bands of earthquake activity that have persisted for 50 years or more based on locations of $M \geq 3$ earthquakes from the regional networks operated by CIT and the University of California, Berkeley, since the early 1930's. The precise focal parameters of $M \geq 2.0$ earthquakes afforded by these four telemetered networks provide critical constraints on the kinematics of seismogenic deformation of the western margin of the North American plate adjacent to the San Andreas transform-fault system.

POTENTIAL FOR LARGE EARTHQUAKES IN THE CENTRAL NEVADA-EASTERN CALIFORNIA SEISMIC BELT

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Earthquakes in the range $M=6.8$-8 occurred in 1872, 1915, 1932, and 1954 in eastern California and western Nevada. These earthquakes were accompanied by large-scale surface faulting that broke successively along different segments of a beltlike zone which extends for more than 400 km from the southern Owens Valley to north-central Nevada. Three major gaps in the continuity of historical surface faulting, however, remain unbroken, from north to south: the Stillwater gap, 40 km long; the White Mountain-Mono Lake gap, 90 km long; and the southern Owens Valley gap, 60 km long.

If the belt-filling pattern of large-scale faulting continues, any one of these 3 gaps must be considered as a likely site for a future M=7-8 earthquake. The few-decades interval between previous large historical events, in combination with the 29-year elapsed time since the last large events in 1954, suggests that the next of these large events may occur within a few years.

Evidence that the White Mountain-Mono Lake gap is the most likely site for the next large event includes: (1) the demonstrated capability of the state of stress in the region to generate earthquakes of M=6; (2) the large volume of crust prepared to generate earthquakes, as indicated by the 70-km-wide ring of seismicity surrounding much of the gap area; (3) regional stress changes indicated by reactivation of the resurgent dome in Long Valley caldera; and (4) a general increase of seismicity in the region. Seismicity has also increased recently in the southern Owens Valley gap, but the Stillwater gap is still seismically quiet. All 3 gaps contain faults large enough to generate earthquakes of M>7.

FOCAL MECHANISMS AND STRESS PATTERNS IN THE WESTERN GREAT BASIN

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A comparison of more than 130 focal mechanisms for earthquakes in the western Great Basin and eastern Sierra Nevada shows some similarities and some differences. The mechanisms show a consistent pattern of primarily strike-slip motion for shallow events and oblique or normal slip for deeper events. However, orientation of the axis of least principal stress (T-axis) is different for different areas: NW-SE for western Nevada and the Mono Lake region, and NE-SW for the Mammoth Lakes area. Along the remainder of the Sierra Nevada frontal fault zone, T-axes show both orientations.

The Mono-Excelsior zone is exceptional, in that none of the earthquakes studied had normal slip, even for focal depths greater than 10 km. Also, while T-axes for the rest of the region are almost horizontal, those for events in the Mono-Excelsior zone have plunge of up to 40 degrees.

In general the change in mechanism with depth is interpreted as the result of increasing overburden pressure, resulting in rotation of the maximum compressive stress (P-axis) from horizontal at shallow (less than about 6 km) depth to vertical at larger (greater than 9 km) depth. The absence of normal-slip events in the Mono-Excelsior region may be explained by a larger horizontal compressive stress, compared with areas characterized by normal faulting at larger depth.

GEOMETRY OF ACTIVE FAULTS AND SEISMIC DEFORMATION WITHIN THE BASIN AND RANGE-COLORADO PLATEAU TRANSITION, CENTRAL AND SW UTAH

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Detailed earthquake studies (1979-82) carried out by the University of Utah in the transition zone between the Basin and Range (BR) and Colorado Plateau (CP) provinces in central and SW Utah provide detailed data pertinent to current considerations of the subsurface geometry of active faults, upper-crustal deformation, and stress orientation in that area. Important findings include: (1) the predominance of seismic slip on fault segments with moderate (>30°) to high-angle dip--with no suggestion of seismic slip on listric (downward-flattening) faults [Note, however, that total extension within the BR-CP transition is probably much less than within the BR province to the west]; (2) the predominance of diffuse seismicity, with clustering chiefly on secondary, rather than on first-order, mapped faults; (3) the observation of spatially discontinuous seismicity with depth (e.g., at 5-7 km beneath the Sevier Valley) that may reflect local structural discontinuity, rather than a brittle-ductile transition; and (4) the observation of intermediate stress states within the eastern BR-CP transition in relation to ~E-W minimum compressive stress within the BR province to the west and ~E-W maximum compressive stress within the interior of the CP to the east. Abundant new focal mechanism information indicates that within the upper crust of the eastern BR-CP transition: $\sigma_{NNE}>\sigma_v>\sigma_{WNW}$ (strike-slip faulting) between 38° and 39°N, and $\sigma_{NNE}>\sigma_{WNW}>\sigma_v$ (reverse faulting) between 39° and 40°N. Maximum horizontal compressive stress parallel to the BR-CP province boundary (NNE) agrees with model predictions of McGarr (1982: JGR 87, 9279) for the eastern part of the transition zone due to basal tractions from thermally-induced mass transport below the elastic-brittle layer.

INSTRUMENTAL SEISMICITY OF THE NORTHERN ROCKY MOUNTAINS OF THE UNITED STATES

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More than 500 regionally or teleseismically recorded earthquakes that occurred in Montana, northern Wyoming, and northern Idaho in the period 1925 through 1980 have been relocated by the method of joint epicenter determination. The epicenters computed for the period 1925-1971 in this study are presented as improvements over those relocated in a 1972 study by J. W. Dewey and others because: (1) the new epicenters are computed with respect to independently known calibration events, and (2) the new epicenters are computed using Pg, S, and Lg arrival times in addition to the P-wave first-arrival times used in the earlier study. The revised epicenters from the Hebgen Lake, Montana, region support the suggestion made in a 1975 study by A. B. Trimble and R. B. Smith that the epicenters cited by Dewey and others were biased by about 10 km east-northeast because of bias in the calibration event. The revised epicenter of the Hebgen Lake mainshock is about 8 km south of the surface fault scarps associated with the shock and is estimated to be accurate to within 8 km at a 90 percent level of confidence. The revised epicenters of the 1935 Helena, Montana, earthquakes support the conclusion of Dewey and others that the shock of October 19 occurred significantly north of the shock of October 31. The revised epicenter of the Montana earthquake of June 28, 1925, is consistent with the shock occurring within or near a zone of recent small earthquake activity identified in the Clarkston Valley in a 1979 study by A. Qamar and B. Hawley.

EARTH STRUCTURE I

BUMPS ON THE CORE-MANTLE BOUNDARY?

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We are testing the hypothesis that the variation of long period SHcSH/SH amplitude ratios in the range 65°-70° is caused by localised topography on the core-mantle boundary. These amplitude ratio variations are observed at European stations for deep Sea of Okhotsk events and at U.S. stations for deep Argentine events. We generate long and short period SHcSH synthetics by numerically evaluating the Kirchhoff-Helmholtz integral. The starting model for the cmb is flat and produces the correct amplitude ratio SHcSH/SH for a J-B earth in the range 60°-70°. We then perturb the shape of the boundary with a variety of two and three dimensional topographies. We include both smoothly undulating surfaces and surfaces which have sharp discontinuities. We conclude that a bump which is 8-10 kilometers high and several hundred kilometers wide can defocus SHcSH waves enough to match the observed changes in amplitude ratio. Whether bumps of such magnitude at the cmb are unacceptably large is not known.

Q_β FROM MULTIPLE ScS BENEATH MEXICO AND MIDDLE AMERICA

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The multiple ScS waves from the June 19, 1982 El Salvador earthquake were analyzed to determine whole mantle attenuation beneath Mexico and Middle America. Although the El Salvador event is shallow (depth $\sim$ 60 km) the source mechanism is a steeply dipping normal fault which produced strong excitation of ScS. Stations in the Western U.S. (ultra long-periods at Pasadena and Berkeley and GDSN station ANMO) provide 15 bounce points concentrated within Mexico. GDSN stations BOCO, ZOBO, and BDF provide 13 bounce points in Central and South America. Two methods were used to determine the attenuation operator; the stacking technique of Sipkin and Jordan (1977) and the maximum likelyhood technique of Nakanishi (1979). Both procedures give stable estimates of the attenuation operator amplitude and phase in the frequency interval of 5 mHz to 40 mHz. For the Mexican paths the estimated Q for ScS of 157 is the same for both techniques. For Middle American paths the Q determined by the two methods differs by 25%, which is the result of differences in the averaging algorithms. A comparison of techniques shows that great care must be taken when relatively small data samples are used. The average Q of 146 determined for this path is significantly lower than that previously determined further to the south using deep events. This suggests that the upper mantle Q in Northwestern South America is less than 70.

INVERSION OF TAU DATA FOR AN AVERAGE VELOCITY MODEL

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A model for the average P and S velocities in the Earth has been constructed from ISC travel time data. A uniform statistical method was used to reduce travel time data to estimates of the intercept time tau for the phases P, S, PKP, PKIKP, SKS, and SKKS. Because

secondary branches of the travel time curve for the upper mantle can not be satisfactorily separated in the ISC data, published models were used to fill in the upper mantle portions of the tau curves. Various types of smoothness criteria can be applied to the data by making use of the statistical uncertainties of the tau estimates.

The inversion to velocity models was performed by the method of Bessonova et al. (1976). Both the mean model and its uncertainty, as represented by various types of probability bounds, were estimated. The result is a model for the entire Earth which is based on a single type of data, short period body waves, and where all of the data have been analyzed in a uniform manner. Such an average radial model provides a convenient means of testing the significance of possible lateral variations in the velocity structure.

A NOTE ON LATERAL VARIATION IN UPPER MANTLE SHEAR WAVE VELOCITY ACROSS THE ALPINE FRONT

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We have detected what appears to be strong lateral variations in upper mantle shear wave velocities under Europe and western Eurasia. We present evidence that suggests that the Alpine belt of southern Europe is underlain by a tectonic upper mantle, with a thin lid and thick low velocity layer whereas the eastern Europe - western Russia precambrian platform is underlain by shield-like upper mantle. The transition zone between the two appears to be sharply defined and coincident with the northern boundary of the Alpine belt. Below the 400km discontinuity the lateral differences appear not to be significant. The techniques used in the analysis include the construction of synthetic seismograms for long period S and SS waves in the distance range 30°-60°, where differences in upper mantle structure most strongly affect the differential times (SS-S) and the ratio of SS to S amplitudes as a function of epicentral distance.

BODY WAVE AMPLITUDE AND TRAVEL TIME CORRELATIONS ACROSS NORTH AMERICA

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Correlations between travel time and amplitude station anomalies are examined for short- and long-period SH-waves and short-period P-waves recorded at North American WWSSN and CSN stations. Data for two azimuths of approach to North America are analyzed. To facilitate intercomparison of the data, the S-wave travel times and amplitudes are measured from the same records, and the amplitude data processing is similar for both P- and S-waves. Short-period P- and S-wave amplitudes have similar regional variations, being relatively low in the western tectonic region and enhanced in the shield and mid-continental regions. The east coast has intermediate amplitude anomalies and systematic, large azimuthal travel time variations. There is a general correlation between diminished short-period amplitudes and late S-wave arrival times and enhanced amplitudes and early arrivals. However, this correlation is not obvious within the eastern and western provinces separately, and the data are consisent with a step-like shift in amplitude level across the Rocky Mountain front. The factor of 2.4 variation in

average short-period S-wave amplitude between the two regions can be explained by a Δt^*_β = 0.8 sec. Long-period S-waves show little overall correlation between amplitude and travel time anomalies. Comparison of the S-wave travel time anomalies with azimuthally dependent P-wave travel time anomalies determined by Dziewonski and Anderson (1983) indicates that the relative variation of P and S residuals is significantly greater than found in studies which neglect the azimuthal variations.

ATTENUATION NEAR THE SAN ANDREAS FAULT ZONE FROM REFLECTION DATA

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Marked contrasts in reflectivity between the Franciscan crust of the North American Plate and the granitic crust of the Pacific Plate are revealed in a deep seismic reflection profile crossing the San Andreas fault in Central California. Clear coherent reflections, prominent in the granitic crust degrade and disappear eastward across the fault zone. For the short seismic wavelengths of the 6-24 Hz. VIBROSEIS data considered, the effects of crustal heterogeneities may be significant. Modelling the energy propagation in a strong scattering environment as a diffusion process allows detailed comparison of the Q and diffusivity of the two crusts. Narrow band filtering yields information on the frequency dependence of these parameters.

Q IN THE BASIN AND RANGE FROM LG WAVES*,

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Estimates of the spatial attenuation coefficient, η, of Lg have been made in the frequency range 0.2 to 1.0 Hz from the decay of Lg spectra on paths in the Basin and Range of western United States. Lg waves were extracted from the seismograms of the Massachusetts Mountain earthquake of 5 August 1971, recorded on the Livermore and Sandia networks (168 km $< \Delta <$ 430 km). Values of η vary from 1.3 to 7.2 x 10^{-3} km^{-1} in this frequency range, with a value of 4.5 x $10^{-3} km^{-1}$ at 1 Hz. For purposes of interpretation the observed η's are converted to values of attenuation, 100/Q. Attenuation shows a large increase at low-frequencies (< 0.4 Hz) and a pronounced peak at 0.75 Hz with a value of 1.0 ± 0.2 at the peak and values of 0.3 - 0.5 at the minima.

Using normal-mode synthetics to model these observations and to the extent that the Priestley and Brune model is representative of the average velocity structure, we find an average Q of 250 for the entire crust. Furthermore, we interpret the increase in attenuation at low frequencies as an effect due to Q variation with depth. On the other hand, to date, we have not been able to find a Q-structure independent of frequency that predicts a peak at 0.75 Hz. This suggests possible frequency dependence, although we cannot preclude effects of velocity structure in our modal analysis. It is interesting to note that the Q values derived from coda waves in tectonic regions show a peak at frequencies similar to that found for Lg.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

INVERSION OF RECEIVER TRANSFER FUNCTIONS FOR CRUSTAL STRUCTURE*

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A linearized frequency domain inversion of receiver transfer functions is investigated as a means for determining crustal structure. The forward problem is solved using a Thomson-Haskell method which includes the effects of attenuating layers. The function to be fit consists of the deconvolved radial component (to remove source effects) which is sensitive to variations in shear velocity. Compressional velocity and attenuation are adjusted by assuming a Poisson solid. Complex partial derivatives are computed with respect to the complex shear velocity in each layer using a finite difference approach. Thus, it is possible to simultaneously invert for shear velocity and shear attenuation. Test cases show that for short path lengths, the effects of attenuation are relatively small compared to velocity contrasts at layer interfaces.
Preliminary results utilizing broadband digital data from DOE's Regional Seismic Test Network indicate that although the method appears to be fairly stable, problems are encountered fitting multiple arrivals appearing later in the waveform. Thus, while the technique may be useful for determining first order crustal models, refinements involving transitional layers might require the use of less time-consuming, more stable forward modeling.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48."

CRUSTAL AND UPPER MANTLE VELOCITY STUDIES IN THE COLORADO PLATEAU INTERIOR FROM SEISMIC P-WAVE ARRIVALS AND GRAVITY DATA

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The Colorado Plateau is a thick, coherent, uplifted crustal block that has been tectonically stable for the past 40 million years relative to the adjacent tectonic provinces. Crustal and upper mantle velocity studies were performed in the plateau interior employing data from: (1) a 16- to 24-station microearthquake network that has been operating in the Paradox Basin of southeastern Utah; and (2) local and regional Bouguer gravity data. The network consisted of short-period vertical seismometers spaced 10 to 20 km apart, arranged in a roughly rectangular array approximately 160 km long in a north-south direction and 60 km wide. P-wave arrival times from 70 azimuthally well-distributed teleseisms ($30° < \Delta < 95°$), corrected for station elevations, were used to determine relative travel time residuals for each station based on an average event residual. The analysis indicates relative residuals as much as 0.5 second that could be explained primarily in terms of depth variations to the Precambrian basement. Some residuals were apparently a result of compositional differences in the shallow crust as reflected in the gravity data. The apparent lack of contribution to the travel time residuals from the lower crust and upper mantle beneath the Paradox Basin is consistent with a relatively homogeneous lithosphere beneath the Colorado Plateau.

Arrival times of P_n waves from events at distances of 5° to 10° from the array were also used to determine a P_n velocity based on apparent velocities. The P_n velocity was estimated to be 7.9 ± 0.1 km/sec, in agreement with other published values.

ATTENUATION OF AMPLITUDES WITH DISTANCE FOR CRUSTAL SEISMIC PHASES IN THE YELLOWSTONE-SNAKE RIVER PLAIN REGION

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The rate of decrease of seismic compressional wave amplitudes with distance was examined for upper crustal phases in the distance range of 0-100 km for a number of seismic refraction profiles in the Yellowstone-Snake River Plain region. For each profile, an averaged amplitude-distance relation is found from the slope of a least squares linear fit through a log-log plot of amplitude versus distance. These amplitude-distance relations are then divided into three groups based on velocity structure and geologic setting: 1) Snake River Plain, 2) Yellowstone caldera paths, and 3) Basin and Range or Northern Rocky Mountain Provinces adjacent to Yellowstone and the Snake River Plain. The last group exhibits approximately the same amplitude distance relations as those found within the Snake River Plain where amplitudes decrease with distance (X) approximately as $X^{-1.5}$. Seismic profiles with travel paths through the Yellowstone caldera, however, show an amplitude decrease with distance of from X^{-3} to X^{-5}. Synthetic seismogram studies indicate that velocity structure has the greatest effect on the amplitude-distance relation. However, distinctly different velocity-depth structures, such as between the Snake River Plain and the surrounding provinces, can result in a very similar decrease in amplitude with distance. The Yellowstone caldera shows much more rapid attenuation both due to the velocity structure and the low Q of the thick Quaternary volcanic rocks within the caldera.

COMPRESSIONAL-WAVE-VELOCITY STRUCTURE OF THE YELLOWSTONE-SNAKE RIVER PLAIN SYSTEM TO A DEPTH OF 300 KM: FUNDAMENTAL CONSTRAINTS ON SYSTEM MODELS.

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Traveltime residuals for distant earthquakes recorded at Yellowstone and near Rexburg and Blackfoot, Idaho, on the Snake River Plain constrain models of the northeast-propagating Yellowstone volcanic system. Inversions of these data indicate that the velocity is about 5% lower than normal under the hotspot track between depths of 60 and about 200 km from Yellowstone to at least as far southwest as Blackfoot. Compressional-wave velocity above 60 km varies considerably and is much lower (15% below surroundings) at Yellowstone than under the Snake River Plain (≤5% below surroundings); at Rexburg, almost no velocity anomaly is present above 60 km. Thus, there is a volume of extremely anomalous upper lithosphere under Yellowstone and a deeper less anomalous extension of this body under both the hotspot and its track. The deeper part of the anomaly is consistently northwest of the surface hotspot track; this offset suggests some shallow control of surface features, that is, heat from the mantle body may be following a path of least resistance to the surface, diverting southeast from a simple buoyancy path. The Yellowstone-Snake River Plain system is very deep seated, and any models of it should explain this major underlying structure.

STRONG GROUND MOTION I

FIFTY YEARS OF THE UNITED STATES STRONG-MOTION PROGRAM

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The United States strong-motion program was inaugurated by the Coast and Geodetic Survey in 1932 to provide instrumental data useful to engineers and architects. Some of the more important milestones in the first 50 years include:

1) The first useful records obtained from the 1933 Long Beach earthquake led to a rapid expansion of the network to a total of 51 instruments in the western United States.
2) Introduction of the first "modern" accelerograph in 1963, combined with impetus of the 1964 Alaska earthquake, resulted in rapid deployment of several strong-motion networks.
3) Since 1965 more than 450 buildings in California have been instrumented under Los Angeles and UBC building codes.
4) Modern digitization and computer processing of accelerograms were developed at Caltech during the late 1960's.
5) The 1971 San Fernando earthquake provided the largest complete set of strong-motion records from an important damaging earthquake.
6) In 1972 the California Division of Mines & Geology began installing extensive ground-motion and structural arrays throughout the state.
7) New remote sensor instrumentation introduced in the 1970's has allowed more effective monitoring of structures.
8) Strong-motion efforts in the 1970's have had increasing seismological input raising questions of the long term relative strength of engineering and seismological support of major programs.

A STRONG-MOTION ARRAY IN THE PEOPLE'S REPUBLIC OF CHINA

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As part of a cooperative project between the United States and the People's Republic of China, an array of strong-motion instruments has been installed in the seismically active western outskirts of Beijing. By the end of this year the array will increase to a total of 40 instruments, about evenly split between digital (PDR-1) and analog (SMA-1) recorders. Absolute time is provided by internal clocks calibrated with a master clock. Because the seismic activity in China is so diffuse, it was decided that rapid redeployment of all or part of the instruments, in response to an earthquake prediction or for use in aftershock studies, was an essential part of the array design. The necessity of being near a center of transportation dictated the choice of a site near Beijing. Initially, subgroups of the instruments have been deployed in temporary arrays in other regions. Thirteen of the instruments were installed in an experimental array in the aftershock of the Tangsham earthquake. In the first 5 months of operation more than 180 records were obtained

from about 30 events, with a peak horizontal acceleration of 0.23 g being recorded about 5 km from an earthquake of magnitude $M_s = 5.3$. We will report on our experience in operating this array of instruments at temperature down to $-10^{\circ}C$. A local laboratory array (Iwan, 1978) of strong-motion insruments is being deployed in the coal mining region east of Beijing, where some instruments will be placed in underground mining tunnels. From this array we hope to obtain information on the depth dependence of the strong ground motions. Finally we plan to deploy five SMA-1's in the Xichong region of the Sichuan province, where a large earthquake ($M \approx 7$) is expected.

SYNTHETIC ACCELEROGRAMS FOR TESTING PROCESSING PROCEDURES

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The digitization and processing applied to strong-motion film accelerograms include steps commonly adapted from other fields. The accuracy of some of these processing procedures when applied to a nonstationary earthquake recording may be questionable. The procedures of automatic digitization, long-period removal, integration, and spectral analysis are generally the steps that cause most concern. In this report, we describe the derivation of synthetic accelerograms with which to measure the accuracy of these and other processing steps. The fundamental characteristics of the synthetics are that they have the appearance of recorded accelerograms, their integrals are known and approach zero after some time, and they remain integrable after particular frequency components have been removed. Some preliminary applications of our current processing to particularly chosen synthetics show that the use of these synthetics can play an important role in ensuring the quality of a total processing package.

PRELIMINARY ANALYSIS OF THE NEAR-SOURCE SCALING CHARACTERISTICS OF 5 TO 10 HZ PSEUDO-RELATIVE VELOCITY

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A multiple regression analysis similar to that performed previously for peak acceleration (Campbell, BSSA, Vol. 71, pp. 2039-2070) was used to establish preliminary scaling relationships for horizontal pseudo-relative velocity (S_V) for frequencies of 5 to 10 Hz and damping values of 2, 5 and 10%. In order that the predictions would represent free-field conditions as much as possible, recordings from large structures were excluded. The data base represented 62 recordings from 16 world events of M5.1-7.7, all located within 50 km of the fault rupture surface. Because some records had not as yet been digitized approximately 20% of the records used previously were unavailable for the analysis. Weighted nonlinear regression techniques were used to establish scaling relationships from the expression,

$$\ln S_V = a + bM - d\ \ln[R + c_1\exp(c_2M)]$$

where S_V is the mean of the two horizontal values, M is magnitude, and R is closest distance to the fault rupture surface.

Preliminary results indicate that reverse faults are associated with S_V values approximately 40% higher than those from strike-slip faults and that S_V values are approximately 25% lower when recorded at the base of embedded structures. The 5 to 10 Hz response spectral values were inexplicably found to exhibit substantially more dependence on magnitude in the near field than peak acceleration. Our near-source predictions of S_V are found to exhibit greater attenuation than those offered by Joyner and Boore (1982). Their values are essentially bounded by our ground-level predictions for strike-slip and reverse faults.

RIDGE AND TUNNEL EFFECTS: COMPARISON OF THEORY AND OBSERVATION

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Large, narrow-band differences were observed in seismograms recorded at five sites at different depths in tunnels into basement-rock and at three sites on rock outcrops located on hills. These differences are determined by the depth into the tunnel or the dimension of the hill and are weakly dependent on the input signal's azimuth and incidence angle.

Tunnel sites affected the amplitudes of incident signals by as much as a factor of three at frequencies inversely proportional to the depth of the site into the tunnel. For example, the maximum effect of a site 12 m deep was at 25 Hz while that of a site 85 m deep was at 11 Hz. Most of the observed tunnel effects could be explained in terms of interference between the incident and surface-reflected waves, using a 1-D model with a surface velocity-gradient.

Rock outcrop sites on hills affected the amplitude of incident signals by as much as a factor of eight, at frequencies inversely proportional to the dimension of the hill, and more for horizontally than for vertically polarized signals. The dependence on the hill's dimension and the signal's polarization is predicted by theories that assume smoothly varying topographies and homogeneous media. However, such theories predict significantly smaller, more broad-band effects than those observed. Taking into account the presence of several nearby, parallel ridges and a low-velocity surface layer will explain the observations.

The amplitude of these hard-rock site effects varied by no more than a factor of two for input signals with widely different azimuth and incident angles.

EXPERIMENTAL STUDY OF SOIL-STRUCTURE INTERACTION AT AN ACCELEROGRAPH STATION

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Forced harmonic vibration tests, using eccentric mass shakers, were conducted at an accelerograph station to determine the effects of soil-structure interaction on the motions recorded during four small magnitude earthquakes. The station consisted of a 4'x4'x2' concrete pad that was almost fully embedded in a stiff clayey to medium sandy silt with a shear-wave velocity estimated at 500 fps. A five foot high wooden hut was attached to the pad and provided shelter to the SMA-1 accelerograph,which was bolted directly to the pad. The tests showed that the soil-pad-hut system had two strongly coupled translation and rocking modes of vibration in the frequency range 1-60Hz. The soil-structure interaction model established from test data indicated that the recorded earthquake motions were amplified by an aver-

age of about 25 percent for frequencies greater than 15 Hz. Surprisingly, the hut, although one-tenth the mass of the pad, played a significant role in the soil-structure interaction. This suggests that careful attention must be given to the design of not only the concrete pad but also the instrument shelter if accelerograph stations are to record true ground motions over a wide frequency range.

ARRAY ANALYSIS OF THE GROUND VELOCITIES AND ACCELERATIONS FROM THE 1971 SAN FERNANDO EARTHQUAKE

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Profiles of ground velocity and acceleration, displayed as a function of epicentral distances, are analyzed for recordings of the 1971 San Fernando earthquake. Three long profiles (> 50 km) and three short profiles (< 2 km) are studied. Although there is considerable variation in waveforms and peak amplitudes observed along the long profiles, there are also many examples of coherent phases seen on adjacent stations. Ground velocity profiles show striking differences between stations located on hard rock sites and stations located within the large sedimentary basins of the Los Angeles area. The San Fernando basin, in which the source is located, seems to respond quite differently from the Los Angeles basin which is about 30 km from the earthquake source area. Ground acceleration profiles show that there is relatively little change in the duration of high-frequency shaking along the long profiles. The three short profiles, which are all located within the Los Angles basin, demonstrate that ground velocity waveforms are nearly identical along these profiles. Although great variation of waveforms and amplitudes are seen for ground acceleration along these short profiles, strong phase coherence is still observed.

A COMPARISON OF STRONG GROUND MOTIONS RECORDED IN JAPAN AND THE WESTERN U.S.

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Catalogs of accelerograms from the U.S. (240 records) and Japan (90 records) are studied to compare the relationships between peak values of displacement, velocity, and acceleration with fault distance and earthquake magnitude. The distribution of available Japanese records with respect to magnitude and site distance is markedly different from the distribution of U.S. records. In the U.S. data set, there are many records at relatively small distances from earthquakes ranging between M5.5 and M7. Furthermore, there are few records at any distance from earthquakes of M > 7. In contrast, few Japanese records are available at small distances from any earthquakes larger than M5.5. There are, however, many records available at large distances from large earthquakes (M>7). Consequently, the largest ground motions have generally been recorded in the U.S. and are from sites located close to moderate earthquakes. In Japan, however, the largest motions have been recorded at sites at distances beyond 50 km from large subduction-zone events. Despite these differences, when peak ground motions observed at compar-

able site distances and magnitudes are compared, we find that Japanese and U.S. motions are remarkably similar. Furthermore, peak ground velocities observed in both Japan and the U.S. for earthquakes of $M < 7$ decay with site distance in a manner compatible with Richter's local magnitude distance attenuation law. However, if this attenuation law is applied to earthquakes of $M > 7$, then we obtain peak source region ground velocites of greater than 5 M/sec. Thus we conclude that either very large ground velocities are seen very close to large earthquakes, or else, Richter's distance attentuation law is inappropriate for very large earthquakes at short distances.

BONDS CORNER ACCELEROGRAMS OF THE OCTOBER 15, 1979, IMPERIAL VALLEY EARTHQUAKE

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Most of the recent empirical nearfield attenuation relationships derived for the western U.S. rely on the horizontal PGA observations at Bonds Corner during the 1979 Imperial Valley earthquake. At approximately .8g these observations are among the highest free field accelerations recorded within 4 km of the surface trace of a strike-slip fault associated with a strong earthquake. Recently, however, the integrity of the Bonds Corner accelerograms has been questioned, because of the occurrence of a number of spikes on the time histories (Bycroft, 1981)*. The spikes are suspected to have been produced by the inferred impact of a fallen steel beam. The most conspicuous of these acceleration impulses has around .3g amplitude and occurs about 12 seconds after trigger time, thereby resulting in a relatively long duration (PGA > .1g) in excess of 13 seconds.

Because of the important implications these observations have with regard to problems of earthquake engineering, we have reanalyzed the horizontal time histories, in both time and frequency domains. The unfiltered records exhibit substantial energy at frequencies below 1 Hz. Both 140 and 230 degree components are associated with a 2 Hz corner frequency. The particle motions of the isolated pulses at low frequencies are predominantly in the NNE direction, in general compliance with the coda. However, the high frequency components at f > 10 Hz are predominantly in the WNW direction. Based on this information, various possibilities regarding the nature of these spikes are discussed. The digitization process seems to have introduced an approximately .15 second phase lag in the 230 degree component with respect to the 140 degree component at this station.

*USGS Open-File Report 82-318.

EXTENDED GUYAN REDUCTION METHOD

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The application of the response spectrum for earthquake design of structures as well as for other applications in structural dynamics, requires the determination of natural frequencies and modal shapes. Since a reasonably accurate model of a fairly large or complicated structure may involve a large number of degrees of freedom to generate the stiffness and mass matrices of corresponding dimension, it is often required that a reduction of the number of degrees of freedom. A practical method of accomplishing this reduction is provided by Guyan Method for static condensation. This method, though exact for reduction of massless degrees of freedom, may otherwise result in substantial errors. In an effort to reduce errors inherent in Guyan reduction, several modifications of the method have been proposed. Unfortunately, the application of these modifications, require undesirable calculation matrix inversion and the truncation of a series expansion.

This paper presents a method of reduction which may be considered an extension of the original method of Guyan reduction. The method begins with the application of Guyan reduction and the solution of the reduced eigenproblem. It continues by extending Guyan method in such a way that neither matrix inversion nor series expansion is required. Application of the proposed Extended Guyan Method to multi-story buildings subjected to earthquake excitation, has reduced Guyan's errors in the response by a factor of about ten.

IMPORTANT CONSIDERATIONS IN DEVELOPING ATTENUATION RELATIONSHIPS FOR RESPONSE SPECTRAL ORDINATES

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This paper presents the results of a study using multiple-regression analyses to develop relationships for response spectral ordinates as a function of magnitude, distance, and site conditions. The general procedure used is similar to that commonly used for developing attenuation relationships for PGA. However, with regard to prediction of spectral values for conditions beyond the magnitude and distance range of the majority of the data, multiple regression analysis results could be extremely sensitive to the analysis procedure, regression model, and constraints on regression parameters. Development of regression relationships for response spectral ordinates by means of multiple regression analysis entails additional considerations compared to development of regression relationships for PGA. This is mainly due to: (1) much smaller number of available digitized and processed accelerograms compared to available PGA values; and (2) less experience of the profession with response spectra than with PGA and therefore lack of well-tested and well-constrained regression models for spectral ordinates.Selection of the regression model and development of constraints for regression parameters were based on: (i) examination and analysis of data from individual earthquakes, (ii) analysis of data from limited magnitude and distance bands, and (iii) consideration of theoretical and physical concepts regarding generation of seismic waves and their transmission through earth materials. Dispersion relationships for spectral ordinates were developed as a function of magnitude and period by conduction multiple regression analyses of several subsets of the data separated by magnitude bands.

COMPARISON OF DECREASE OF RESPONSE PEAKS AND THE DEGRADATION OF "DUCTILE" DETAILING STRENGTH DURING EARTHQUAKE INDUCED EXCITATION

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One limitation of response spectra investigations is that only the maximum response is used while other non-maximum peaks are ignored. A technique developed to measure other non-maximum peaks is used to study the decrease of the response peaks throughout the duration of an earthquake. These studies indicate that the ratio of the amplitude of response for a given number of cycles to the maximum response is fairly independent of period. The decrease of response peaks for a given number of cycles is compared to the degradation of strength for varying number of cycles of excitation for typical systems using "ductile" and with "non-ductile" detailing. If the degradation of strength with increasing number of cycles is less than the decrease of the amplitude of the corresponding response peaks, then the system can withstand the multiple cycles induced during strong earthquake ground motion.

EARTHQUAKES AND FAULTING: GEOMETRY MECHANICS, AND TIMING

FAULT ZONE SEGMENTATION BASED ON GEOMETRY AND RECURRENCE - THE WASATCH FAULT ZONE, UTAH

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The Wasatch fault zone is a 370-km long normal fault. During a surface faulting earthquake, the fault will only rupture along part of its total length. Six rupture segments of varying lengths are proposed for the Wasatch fault. Segment identification is based on fault geometry combined with data on recurrence and timing of the most recent event (MRE). From north to south the segments are: 1) Collinston - Brigham City ($\geq$ 30 km, N20W, no events post 13,500 yr B.P.); 2) Brigham City - Bountiful (70 km, N10W, two events post 1580 ^{14}C yr B.P., MRE < 500 yr); 3) North Salt Lake City - Corner Canyon (35 km, convex east N30E to N30W, average recurrence 2500 yr, MRE uncertain); 4) Alpine - Spanish Fork (55 km, N25W, average recurrence 1700-2700 yrs, MRE $\sim$ 1000); 5) Payson - Nephi (35 km, N10E, two events between 4580 and 3640 ^{14}C yr B.P., MRE 300-500 yr); 6) Levan - Fayette (40 km, only 1 event post 7300 ^{14}C yr B.P., MRE < 1750 ^{14}C yr B.P.).

Proposed segment boundaries may represent structurally complex transition zones several kilometers wide. They are generally expressed as salients in the range front that are coincident with the intersections of major structural trends. While the possibility that some ruptures have crossed boundaries cannot be excluded, the segments along the Wasatch fault zone appear to have behaved as discrete units through time. The integration of structural and recurrence data suggests that the segments defined at the surface have expression at seismogenic depths and segment boundaries may act as barriers to rupture propagation.

SEISMOLOGICAL EVIDENCE IN SUPPORT OF THE EXISTENCE OF "CHARACTERISTIC EARTHQUAKES"

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It is well known that large and small earthquakes are dynamically self-similar if we consider the whole range of magnitude from ultra-micro-earthquakes to giant earthquakes. There is, however, accumulating evidence supporting the existence of certain unique scale lengths governing earthquake phenomena if we restrict our attention to earthquakes of a certain range of magnitude occurring in a specific area.

The evidence includes (1) geological and paleoseismological data on repeated earthquakes characteristic of a given fault (Coppersmith and Schwartz [1982] and Wesnousky and Scholz [1982]), (2) a unique relation between the maximum slip and the barrier interval obtained from strong motion acceleration data (Papageorgiou and Aki [1983]) and its agreement with the similar relation observed by geologists, (3) the departure of the global scaling law of seismic spectrum from the self-similar case (Gusev [1981]), (4) the departure of the corner-frequency vs. moment relations from the self-similar case, and (5) the existence of earthquake families, as demonstrated spectacularly for earthquakes at the volcano Usu by Okada et al. (1981) and Takeo (1982).

The above evidence supports the existence of more or less permanent asperities and barriers over many repeated earthquakes on a given fault and suggests a significant departure from the idea that there is no unique physical length governing earthquake phenomena.

THE CHARACTERISTIC EARTHQUAKE MODEL: IMPLICATIONS TO RECURRENCE ON THE SAN ANDREAS FAULT

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Recent geologic investigations have provided data on the size and timing of paleo-earthquakes that suggest faults generate characteristic earthquakes having a relatively narrow range of magnitudes and that linear (constant b-value) recurrence models may not be appropriate for individual faults or fault segments. A check of this hypothesis can be made by comparing geologic recurrence data with calculated repeat times of earthquakes based on a linear recurrence model and a characteristic earthquake model.

Geologic investigations along the 1857 rupture segment of the San Andreas at Pallett Creek and Wallace Creek by Sieh, and in the Big Bend area by Rust, have shown that prehistoric displacements were comparable to those of the 1857 event. This suggests that the 1857 segment generates a characteristic earthquake having a magnitude comparable to that of the 1857 event ($M \sim 8$).

Using the fault slip rate (20 to 45 mm/yr) and a moment rate calculation, the repeat time for a M8 earthquake based on a linear recurrence model ranges from 500 to 1200 years, which is not in agreement with Sieh's 145-year average recurrence interval arrived at from the geologic data. The repeat time for a moderate (M6-1/2) earthquake based on the linear model is only 20 years; however, no events of this magnitude or larger have occurred on this segment since 1857. Assuming a characteristic earthquake model, the repeat time for a M8 event is about 150 to 400 years, which is in better agreement with the geologic data. The repeat times for moderate events based on this model are longer than are expected by a linear relationship and may explain the lack of these events during the past 125 years.

SEISMICITY PATTERNS NEAR PARKFIELD, CALIFORNIA

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Recent work on the recurrence of M 5 3/4 earthquakes on the San Andreas fault near Parkfield, Calif., suggests that the next event can be expected in 1987-1988, although estimates of the credible time window range from 2 to 10 years. We have undertaken a detailed examination

of the seismicity near the 1966 epicenter in hopes of (1) understanding the physical process leading up to a larger event, and (2) predicting the next M 5 3/4 or larger event. Master-event relocation of the 1966 event shows that it occurred at Lat. 35° 57' N; Long. 120° 30' W at a depth of 9 (±1) km. The M 5 foreshock that preceded it by 17 minutes was located 1 km to the northwest at about the same depth. Relocation of 15 years of subsequent seismicity within a 10 km radius reveals several spatial and temporal patterns. Although M 3 events were rare to the northwest of the 1966 hypocenter before 1975, M 3-4 events have been frequent in the same area in recent years. These events occur in distinct clusters below and to the northwest of the 1966 hypocenter, in sequences that migrate upward from depths of 13 to 8 km over 3-4 year periods. The immediate hypocentral area of the 1966 foreshock and main event, including a zone 1-2 km in diameter, remains seismically quiet. We anticipate that the next M 5 3/4 Parkfield event will nucleate within this zone. Stress drops of $2 < M < 4$ events, estimated from P-wave zero-crossing times, are uniform over the fault plane except for three events with stress drops about 3 times greater located 2-3 km below the 1966 hypocenter. On-scale seismograms from an array of digital event recorders deployed in this area will be used to relate stress drops derived from corner-frequency measurements to these estimates, and also to establish any spatial and temporal patterns in other source parameters.

AN IN DEPTH LOOK AT THE 1979 IMPERIAL VALLEY EARTHQUAKE

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Using trial and error modelling, a faulting model for the 1979 Imperial Valley earthquake has been found. The model accurately predicts the phase and amplitude of the three components of particle velocity time histories recorded at 15 sites in the United States in the frequency range 0.0-1.0 Hz.

The elements of the faulting model are as follows: (1) Slip on the Imperial fault extends unilaterally 35 km NW from the epicenter and extends to a depth of 13 km on a plane dipping 80° NE. Right-lateral strike-slip below depths of 5 km dominates faulting on the Imperial fault with a small amount of normal faulting at the northwest end. Two areas, one 20 km and the other about 27 km from the epicenter, show a maximum slip-rate of about 100 cm/s. The maximum slip of 178 cm occurs at about 20 km north of the epicenter and at a depth of 10 km. (2) The Brawley fault was activated by rupture on the Imperial fault. The Brawley fault is a vertical fault 10 km long beginning at its intersection with the Imperial fault. It ruptured between 0 and 8 km depth. The Brawley fault is a mixture of strike-slip and dip-slip, east side up with a maximum strike-slip rate of about 44 cm/s and dip-slip rate of 14 cm/s. Faulting on the Brawley fault significantly affects ground motion at nearby stations. (3) Total seismic moment of the two faults is 6.6×10^{25} dyne-cm with the Imperial fault contributing 96 percent. (4) The rupture velocity on the Imperial fault is highly variable. At the hypocentral depth of 8 km where the S-wave speed is 3.3 km/s the rupture velocity is initially slow, about 1.7 km/s, but accelerates, reaching a velocity about 6.7 km/s 20 km from the hypocenter after which the rupture velocity decelerates to a value about 2.5 km/s.

FRICTION, FAULTING, AND IN-SITU STRESS

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Available in-situ stress data from regions of active faulting are analysed to estimate the frictional strength of crustal faults. Data from areas of active normal faulting in Nevada, Utah, and Colorado all indicate that the in-situ coefficient of friction appears to be in the range 0.6 to 1.0. Data from an area of shallow reverse faulting in South Carolina yield similar results as do data from the Rangely oil field where fluid injection triggered strike-slip faulting. These estimates of the coefficient of friction are consistent with laboratory measurements for a wide variety of rock types.
In-situ stress measurements made adjacent to the actively creeping section of the San Andreas fault, however, imply a coefficient of friction of only 0.35. Although this is considerably lower than the frictional strength of most rocks, it is similar to the frictional strength of clay-rich gouge samples exhumed from the fault nearby. These results suggest that in priniciple, the proximity of a given fault to failure can be determined through in-situ and laboratory experimentation.

CONTROLS ON THE DEPTH AND STYLE OF SEISMIC ACTIVITY IN CONTINENTAL CRUST

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Studies of deformation processes in ancient fault zones have shown that in quartz-bearing crust, a significant change from friction-dominated faulting to quasi-plastic shearing is associated with the onset of greenschist facies metamorphic conditions at about 300-350°C. This transition in behavior is correlated with the cut-out of microseismic activity at mid-crustal depths. Composite shear resistance profiles modeling the transition have been constructed from laboratory studies of the frictional and rheological properties of quartzo-feldspathic rocks. Shear resistance increases with depth through the frictional regime to peak at the frictional/quasi-plastic transition, beneath which it falls off exponentially with increasing temperature. Larger earthquakes (M >5.5) generally appear to nucleate around this transition region at the base of the seismogenic zone where the highest strain energy concentrations may accumulate. Varying depth and amplitude of the peak shear resistance along strike must induce strain energy fluctuations along the base of the seismogenic zone, affecting the nucleation and propagation of large ruptures. Crustal composition (especially the quartz/feldspar ratio), fault geometry, fluid content in the quasi-plastic regime, fluid pressure in the frictional regime, quasi-plastic strain rate, and geothermal gradient may all affect the depth of the frictional/quasi-plastic transition. Because several of these factors are interdependent, evaluation of their relative importance is complicated. However, regional variations in heat flow look to be particularly effective in creating long-wavelength heterogeneities in strain energy concentration affecting faulting style.

PROCESSES OF LOW-ANGLE NORMAL FAULTING: MINERAL MOUNTAINS, UTAH

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Tertiary granite in the Mineral Mountains of southern Utah is cut by low-angle normal faults that constitute part of a regional fault system related to extension in the eastern Great Basin. We have studied the structure and geochemistry of one of the faults to document the mechanical and chemical processes of faulting. Cataclasis was accompanied by hydrothermal alteration of the granite. Fluid inclusions in the fault zone and in veins in the wall rock have $NaCl > 26$ wt.%. Temperatures during faulting are estimated at 180-400 C. Alteration minerals include chlorite, epidote, sericite, biotite, fe-oxides, calcite, quartz, k-feldspar, albite and apatite. The cataclasite is enriched in Fe, Mg, Ti, P and volatiles, and depleted in Si relative to undeformed granite.

The static coefficient of friction (μs) was < 0.5 and fluid pressures were probably near hydrostatic due to permeability induced by penetrative microfaulting and jointing in the fault zone and adjacent wallrock. The low μs was presumably caused by hydrothermal alteration - perhaps by stress corrosion and pressure solution at asperities. Clay minerals (smectite) with low friction coefficients formed only a minor part of the alteration assemblage.

PHYSICAL PROCESSES RESPONSIBLE FOR SUCCESSIVE EARTHQUAKES

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Successive earthquakes in a limited region represent crustal response to an interplay of tectonic loading, stress changes resulting from previous earthquakes, and anelastic processes leading to weakening or redistribution of stress. Model calculations are compared with observations of spatially related earthquakes to infer the physical processes most likely to be responsible for the lags between successive earthquakes. Fluid diffusion leading directly to weakening the fault zone (or indirectly to reloading) appears dominant in such earthquake sequences as the Lake Monticello, South Carolina reservoir-induced earthquakes, and perhaps some aftershock sequences in central California. Stress readjustment due to quasi-plastic flow in the lower crust seems more applicable to larger scale earthquake sequences such as moderate earthquake sequences in Bear Valley and Parkfield, California and large earthquake sequences in Turkey and Iran.

GEOPHYSICAL AND GEOCHEMICAL OBSERVATIONS PERTINENT TO FAULT ZONE EVOLUTION AND THE EARTHQUAKE CYCLE

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Geophysical measurements near the San Andreas, Garlock and San Jacinto faults of California show that rocks adjacent to these faults are fractured and altered chemically to seismogenic depths. In granitic rocks, the first stage of alteration is characterized by the reaction mica + water → montmorillonite (MO). Alteration in geothermal fields exhibits formation of MO to 150°C, with layered clays (illite and MO) stable to 230°C. Thus, the MO and related clays found in fault gouge are probably present throughout the seismogenic zone.

This conclusion yields important clues to the earthquake process. Faults are relatively impermeable to water flow, yet the fractured wall rocks can be highly permeable. Fractures carry the fluids that form hydrous minerals into the seismogenic zone. Alteration tends to fill these fractures with clay. Fluids in such fractures can attain pressures exceeding hydrostatic. High pressures are restricted to the fractured wall rock, as the gouge itself is rather impermeable. Slip occurs along the boundary separating the gouge from the country rock. As a result of an earthquake many fractures reopen. Newly exposed mineral faces react, forming more clays. As the cycle repeats, gouge zones expand.

At least three important implications follow from this model. 1: The physical conditions of the seismogenic zone vary in time, and mineral deposition in fractures decreases (rather than "heals" or increases) fault strength. 2: Because of the electrical properties of MO, changes in saturation of rock containing these clays can remain undetectable. 3: Since the weak surface occurs between the gouge and the wall rock, targets for drilling near faults should focus on wall rocks rather than the heart of a gouge zone no longer involved in the earthquake cycle.

EARTH STRUCTURE II

TELESEISMIC P-DELAYS IN THE VICINITY OF THE LUNAR CRATERS VOLCANIC FIELD, CENTRAL NEVADA.

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Teleseismic P-wave travel-time residuals have been determined relative to the Herrin travel-time tables, for seven stations in the vicinity of the Lunar Craters volcanic field (Quaternary Age) in central Nevada. The average travel-time delay across the seven stations is greater than 2 seconds, typical for the Great Basin. The pattern of individual station residents relative to this average roughly correlates with the pattern of recent volcanic activity. However the site located within the Hot Creek Valley Cauldron complex (Tertiary Age) shows a 1 second advance in travel time relative to the region as a whole. The Faultless Nuclear explosion, also located within the Hot Creek Valley Cauldron complex, shows similar small Herrin travel-time residuals. The 1 second relative advance for both event

and receiver within the cauldron suggest the existence of high velocity, shallow mantle material beneath the Tertiary volcanic center. Spence (1974) has reported a similar observation associated with the Silent Canyon Caldera at the Nevada Test Site. The required velocity difference beneath the Cauldron compared to more "typical" Great Basin mantle material, is within the range predicted by Jordan (1979), which would result from compositional variation in the upper mantle associated with basaltic differentiation.

CRUSTAL STRUCTURE UNDER PASADENA, CALIFORNIA INFERRED FROM TELESEISMIC P WAVE DATA

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Teleseismic P wave data are collected from the Benioff 1-90 station at Pasadena (PAS) to infer the crustal structure under the station. By using a 3-D ray method and a waveform matching technique through the trial and error approach, major structural characteristics, including three dimensional nonplanar interfaces, are deduced. The proposed model includes four crustal layers over a half space. Waveform modeling shows that a curved top interface and a nonplanar Moho are significant to give a reasonable match to the observed data. Compared to a planar dipping layered model, the curved interfaces used are found to substantially enhance the computed amplitudes due to the geometric focusing effects and yield a better explanation of the large recorded off-azimuth tangential effects. The Moho is inferred to lie at a depth of approximately 32 km and generally trend WNW dipping toward the NNE. This orientation is generally consistent with the east-west trending Transverse Ranges and implies that the Transverse Ranges are a dominant factor in controlling the deep structure under the station.

A TOMOGRAPHIC INVERSION OF TELESEISMIC P DELAYS BELOW THE TRANSVERSE RANGES

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An investigation of teleseismic P arrivals to the Southern California Seismic Array has resulted in a determination of the variations in seismic P velocity below Southern California to a depth of 500 km. A tomographic method of inversion was used on relative P delays for about 8000 rays well distributed in azimuth and ranging in slowness from 0 to 10 sec/deg. The tomographic method allows for a fairly detailed inverse; in this case the inversion was done with nearly 2500 bins, each approximately cubic and about 50 km on a side. Teleseismic rays cannot resolve absolute velocity or changes which may occur at a given depth across the entire study region, but given a reference "background" velocity model can resolve local perturbations to the reference model. The deviations in bin velocity range from plus or minus 2.5% of the average reference model velocity to account for a net delay of plus or minus 1 second of travel time. The most pronounced feature is a high velocity region roughly below the Transverse Ranges apparently extending in depth to at least 500 km, with the maximum of the anomaly at about 150 km depth. The shallow features of this anomaly appear to align with the strike of the Transverse Ranges while the deeper parts follow a more north-south strike.

FAULT ZONE STRUCTURE FROM REFLECTION DATA

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A seismic reflection profile was fun in 1978, crossing the San Andreas fault zone in central California. Results are complicated by the extreme lateral heterogeneity and low velocities in the fault zone. Other evidence for severe lateral velocity change across the fault zone lies in hypocenter bias and nodal plane distortion for earthquakes on the fault. Conventional interpretation and processing methods are hard-pressed in this situation. Using the inverse ray method of May and Covey (1981), with an initial model derived from a variety of data and the impedance contrasts indicated by the true-amplitude stacked section, an iterative process yields a velocity model consistent with the various lines of evidence.

A TIME-TERM STUDY OF THE IMPERIAL VALLEY, CALIFORNIA

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We have constructed traveltime and time-term contour maps using data from the U.S. Geological Survey's 1979 seismic-refraction experiment in the Imperial Valley region, Calif. Traveltime-contour maps are approximately equivalent to sediment-isopach maps when traveltimes are reduced by 5.8 km/s, the average basement velocity in the region as determined from modeling of reversed profiles. From these maps and the profile models, we determined which arrivals are from basement, eliminating arrivals from the sedimentary layer (V_p=1.8-5.6 km/s) and from a subbasement layer (V_p=7.2 km/s). The set of all basement arrivals was then used to construct a time-term map with the following features: (1) A region of high time-terms (max. 1.5 s) along the axis of the Salton Trough, where the highest time-terms are within a region 16 km in radius with a closure of 0.25 s, centered about 7 km southeast of Brawley; and (2) a region of low time-terms (min. 0.25 s) on West Mesa, west of the Imperial Valley, that is separated from the high time-term region by a scarp with an irregular but generally northwestward trend and numerous terraces; and (3) a low time-term region in the Chocolate Mountains delineated by a steep northwest-trending scarp. Known geothermal-resource areas in the Imperial Valley correlate well with time-term lows and terraces superimposed on the central time-term high.

VELOCITY STRUCTURE OF SOUTHERN CALIFORNIA CONTINENTAL BORDERLAND AS SEEN FROM CATALINA ISLAND

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On Nov 20, 1981, a 180,000-lb quarry blast was detonated on the southeast end of Catalina Island and was well recorded throughout southern California. Travel time plots using all the data give considerable scatter, probably due to the complex crustal structure of southern California. However, if we consider only continental borderland travel paths, by restricting the data to near-shore and island stations, we get a more coherent picture. These data are best fit by a 4-layer structure as follows: a 300-m-thick, 2.5-km/sec surface layer, underlain by 5.5-km/sec crust; a transition to 6.2-km/sec crust at 2.5-km depth, and a Moho of 7.8 km/sec at 22-km depth. Initially, several stations in the 150- to 200-km range appeared to exhibit very late P_g arrivals. However, analysis of synthetic seismograms for these stations reveals that these arrivals are probably really Moho reflections, P_mP. San Nicolas Island, the station farthest offshore, has systematically early arrivals. This might be interpreted either as faster crust or as a shallowing Moho as one goes seaward. This velocity model has been used to relocate the Sept. 4, 1981, Santa Barbara Island earthquake and its aftershocks. These new locations indicate that this seismic activity was about 4 km farther east than previously believed.

STRONG GROUND MOTION II

DEVELOPING DESIGN GROUND MOTIONS FOR EARTHQUAKES OCCURRING IN SUBDUCTION ZONES

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Based on a study of 177 components of strong ground motion data obtained primarily from earthquakes along subduction zones near Japan, and compiled by Exxon in 1981, the paper discusses the elements that define the ground motions for earthquakes occurring in subduction zones.

The study shows that 1) source and travel path characteristics for subduction zones are quite different from those for shallow transform faults; 2) at shallow to intermediate depths, fault motions can vary anywhere from strike-slip to normal, and at intermediate depths can vary to predominantly underthrust; and 3) for earthquakes of nearly the same size that are triggered at comparable depths, the rupture surface may or may not propagate to the ground surface. Considering the above factors, it was concluded that acceleration attenuation relationships, ground motion spectral content, and local soil condition effects in subduction zone earthquakes are quite different from those of earthquakes occurring in shallow transform faults. The results of this study have been used to develop parameters for design ground motions that are representative of subduction zone effects.

PEAK VELOCITY AND SEISMIC MOMENT

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Peak ground velocity $\underline{v}$, as recorded at small hypocentral distances, is a well-defined function of seismic moment, M_o. A large set of earthquake and mine tremor data is in remarkably close agreement with the regression line

$$\log M_o = 9.3 + 2.1 \log R \underline{v} \qquad (1)$$

where R is hypocentral distance, typically 10 km for earthquakes and 0.1 to 1 km for mine tremors; the units in (1) are C.G.S. Because this relationship provides quite an effective means of estimating M_0 from measurements of peak velocity, especially at multiple sites, $R\bar{v}$ can serve as the basis of a magnitude scale using the moment-magnitude scale of Hanks and Kanamori as an intermediary. Thus M (moment magnitude) = $- 4.5 + 1.4 \log R\bar{v}$ is a means of estimating magnitude that is useful because of its close association both to the earthquake source and to damage potential. Furthermore, there is little likelihood of magnitude saturation with this scale. Unexpectedly, equation (1) suggests that $R\bar{v}$ scales as the square root, rather than the cube root, of M_0, in contradiction to generally accepted scaling principles.

GENERATION OF PROBABILISTIC SPECTRA SUBJECTED TO NON-STATIONARY INPUT MOTIONS

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In computing response spectra of a system subjected to earthquake ground motions, it is of practical importance to consider the uncertainties involved in specifying these motions. This can be accomplished through the use of probabilistic techniques for constructing the spectra. The currently available methodologies for addressing this problem are most typically based on the use of Poison processes. This Poison assumption has the drawback of providing results with varying degrees of accuracy from frequency to frequency. Although a more accurate technique, the so-called first passage probability, is also available, only limited applications of such techniques, using stationary input motions, have been carried out. Furthermore, it is extremely time consuming and thus impractical to use such techniques when the input motions are non-stationary.

The purpose of this paper is to present an improved and practical procedure for generating probability response spectra considering non-stationary input motions and first passage probability concepts. The procedure involves the step-by-step evaluation of the probability of exceeding a specified barrier level. Each step is assumed to be piecewise stationary so that the existing results of the first passage probabilities using stationary input motions can be employed. Results using this approach have been compared favorably with those computed from the more accurate but extremely time consuming methods. The advantages of the present procedure are a) The input motions are not restricted to stationary processes, so that any arbitrary time-varying intensity functions can be used, b) The Methodology used results in a consistent degree of accuracy for different systems (i.e. different frequency and damping ratio), and c) The procedure provides an efficient and cost effective computation of the response spectra.

ESTIMATING THE FOURIER SPECTRA USING DATA WITH POOR RESOLUTION

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Strong motion seismometers are usually deployed with the intent of recording large earthquakes. The gains of digital instruments are often kept low to avoid clipping on large motions. However, many of the events which trigger the instruments have relatively small signals and produce records with poor resolution, which appear choppy.

The effect of poor resolution on estimating the spectrum is studied using synthetic data for continuous and discrete cases. Analysis indicates that, for the continuous case, the Fourier amplitude spectrum has significant levels of high frequency noise for 2-4 bits of resolution and yet can be sufficiently described with > 5 bits of resolution. The discrete case shows less noise in the high frequencies and more noise at the lower frequencies than the continuous case. A filtering technique is applied to the discrete case which reduces the noise in the lower frequencies.

STOCHASTIC SIMULATION OF HIGH FREQUENCY GROUND MOTIONS BASED ON SEISMOLOGICAL MODELS OF THE RADIATED SPECTRA

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Predictions of seismic motions as a function of source strength are often made from frequency-domain scaling models. The observations, however, are usually in the time domain (eg., various peak motions, including magnitude). A simple method relating the two domains is to filter stochastic time series so that the amplitude spectra are equal, on the average, to the specified spectra. Using this method, I find that an ω-squared spectrum with a high-frequency cutoff and a constant stress drop of 100 bars gives a good fit to a number of ground motion indices based on the analysis of hundreds of recordings from earthquakes in western North America. The measures of ground motion include peak acceleration, peak velocity, Wood-Anderson instrument response, and response spectra. The remarkable thing about the model is its simplicity; the scaling with source size depends on only one parameter: seismic moment or, equivalently, moment magnitude. Although the simulation method is useful for applications requiring one or more time series, I find that with the possible exception of small earthquakes, the peak motions are well predicted by various formulae from random vibration theory. This is an extension, and in a sense a justification, for a similar application by Hanks and McGuire (1981) of random vibration theory to the prediction of peak acceleration. The formulae I use depend on the moments (in the statistical sense) of the squared amplitude spectra, and therefore, can be applied to any time series having a stochastic character, including ground acceleration, velocity, and the oscillator output on which response spectra and magnitude are based.

THE JUNE 9, 1980 MEXICALI VALLEY, BAJA CALIFORNIA NORTE, MEXICO EARTHQUAKE: PRELIMINARY RESULTS FROM INTERPRETATION OF STRONG MOTION DATA.

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This study uses six accelerograms from sites south of the international border to study the June 9, 1980 Mexicali Valley earthquakes (M_L = 6.1). Fault rupture is inferred to extend for 25 to 30 km, past the Victoria station about 2 km from the fault, and toward the other five sites, which are from 7 km to 35 km from the northerly end of the rupture. Excluding the Victoria record, the moment is estimated to be 10^{25} dyne-cm from the spectra of the accelerograms. Stress drop has been estimated by three methods: Brune (1970), 450 bars; RMS acceleration, 300 bars; the barrier model of Papageorgion and Aki (1982), 550 bars. No correction has been applied to the spectra for unusual sediment amplification at the sites on sediments; stress drop estimates obtained

from the site on the basalt of the Cerro Prieto volcano are consistent with the others.

In determining the stress drop from RMS acceleration, Q was chosen for each station to reconcile the observed S-wave spectral shape with an assumed f^{-2} falloff in the source displacement spectrum above the corner frequency. Values of Q which are independent of frequency appear adequate to match observed spectral shapes on the f^{-2} falloff assumption. The estimate for Q increases with distance, but corresponds to values of t* which at most increase very slowly with distance from an intercept of t* $\tilde{\sim}$ 0.04 sec to 0.05 sec. Estimates of t* from the Cerro Prieto volcano site are again consistent with other sites.

Interpretation of the accelerogram from Victoria is complicated because the digital record was not easily played back from the magnetic tape cassette. Our best reconstructions of the three components contain between 25 and 33 short gaps, with the median gap length of 0.035 sec, and a cumulative loss of 5.7 to 7.3 percent during the strongest shaking. What is recovered shows peak horizontal accelerations of 960 cm/sec^2 and 860 cm/sec^2, and peak vertical acceleration of 980 cm/sec^2.

EFFECT OF STRUCTURE GEOMETRY ON STRONG GROUND MOTIONS: THE DUWAMISH RIVER VALLEY, SEATTLE, WASHINGTON

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A three-dimensional ray tracing algorithm is used to compute the high frequency response of an SH plane wave incident under several models of the sediment filled Duwamish River Valley of central Seattle. Models are based on valley geometry previously determined using borehole logs. The SH wave response is considered in an effort to simulate the S wave radiation from the 1965 magnitude 6.5 Puget Sound earthquake. Although the structure models considered are two dimensional, three dimensional ray tracing is needed to treat incident SH waves of various incidence angles and azimuths of approach appropriate for the USCGS and ISC hypocenters of the 1965 event. Generally, amplification of the direct SH wave due to the curved basin geometry is comparable to an equivalent elastic layer over a halfspace model. However, for points near the center of the valley multiple S rays become focused after undergoing several reflections from the curved lower boundary of the valley fill. This produces an order of magnitude increase in effective amplification. A detailed study of these rays shows that significant amplitudes occur over narrow distance ranges (~200m) at the surface and that they are sensitive to moderate changes in incident wave direction. Focusing effects of this type were probably an important factor in damage caused by the 1965 earthquake, especially over the thicker portions of the Duwamish River Valley. Effects of "randomly" focused rays also give an explanation for the apparantly capricious nature of strong ground shaking in the Puget Sound area.

GEOGRAPHIC VARIATION IN GROUND SHAKING AS A FUNCTION OF CHANGES IN NEAR-SURFACE PROPERTIES AND GEOLOGIC STRUCTURE NEAR LOS ANGELES, CALIFORNIA

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A total of 19 Nevada Test Site nuclear tests were used to obtain a three-component data set at 97 sites throughout the Los Angeles basin and vicinity. Our study of these data addressed three main points: (1) to test the hypothesis that the site effects generated by strong earthquake ground motions can be predicted from low-strain nuclear tests, (2) to test the ability of a theoretical model to predict site response, and (3) to develop empirical models to predict site response on the basis of the available geotechnical data. Only point (3) is emphasized here.

Detailed studies of these data suggest effective empirical methods of predicting site response by clustering stations on the basis of their surface properties as well as on underlying structure; the mean response can then be computed for each generic site type. We found that 8 to 12 generic site types provide a useful description of the site response, yet preserve the important physical aspects of the problem. The mean site response for each cluster ranges between factors of 1 and 6.5, and we found that the true response can be predicted to better than one Modified Mercalli intensity unit increment 90 percent of the time. From these detailed studies, prediction of site response in 3 ground motion period bands for limited areas in Los Angeles has been completed.

LONG VALLEY CALDERA: RECENT ACTIVITY I

GEOLOGIC AND PETROLOGIC DATA BEARING ON POTENTIAL VOLCANIC HAZARDS IN LONG VALLEY CALDERA, EASTERN CALIFORNIA

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Since June 1980, repeated seismic swarms in the south moat of Long Valley Caldera and apparent coseismic uplift of the central resurgent dome suggest that the subjacent magma chamber has recently become mobilized, thereby increasing the potential for volcanic eruptions within the caldera. Intracaldera volcanism since eruption of the Bishop Tuff 700,000 years ago has included 1) three episodes of rhyolite eruptions about 500,000, 300,000, and 100,000 years ago; 2) numerous quartz latite dome-building eruptions 220,000 to 50,000 years ago; 3) several basalt eruptions 200,000 to 62,000 years ago; and 4) a few phreatic eruptions about 500 years ago. Although recurrence of any one of these four types of activity is possible, 1) the site of the current seismic activity in the caldera moat where rhyolite eruptions have occurred frequently in the past, 2) the prolonged, 2-year duration of the seismicity, and 3) the occurrence of spasmodic tremor suggest that viscous rhyolitic, rather than more fluid basaltic magma is likely to be involved. Major, minor, and trace element analyses of the postcaldera rhyolites, indicate that during the past 300,000 years the residual magma has evolved chemically toward a composition similar to that of the Bishop Tuff, being enriched in U, Th, Nb, Cs, and other imcompatible elements. The chemical fractionation pattern of the most recent eruptive products suggests that the chamber contain a volatile-enriched rhyolite magma capable of producing plinian and/or ash-flow eruptions.

Historical activity at calderas of the world as a framework for interpreting recent activity at Long Valley caldera, California

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Periods of increased seismicity, uplift, and other anomalous geophysical or geochemical activity at calderas might be explained by at least four interacting processes: (1) Regional tectonic strain (e.g., Taupo, 1922; Aso, 1964-present), (2) magmatic intrusion into country rock or into an existing body of magma (e.g., Phlegraean Fields, 1538; Rabaul, 1937), (3) in situ expansion of a large magma body (e.g., ?), and (4) heating of ground water as a result of either tectonic activity or magmatic intrusion (e.g., Phlegraean Fields, several episodes; Yellowstone(?), 1959?-present. Each process or combination of processes has different implications for volcanic-hazards assessments. Processes 1 and 3 do not normally cause eruptions by themselves but can trigger process 2 or 4, and thus indirectly trigger an eruption; process 2 generally but not always leads to an eruption, the style of which will depend in large part on the composition of the magma erupted; and process 4 may lead to a phreatic eruption and, on occasion, culminate in a magmatic eruption. On the basis of a comparison of recent activity at Long Valley with observations at other large silicic collapse calderas, only process 1 by itself, i.e., regional tectonic strain alone, may be eliminated as an explanation of the current activity at Long Valley.

LONG VALLEY CALDERA EARTHQUAKE SWARM: JANUARY 7, 1983

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The earthquake swarm that began on January 7, 1983, 4 km ESE of the town of Mammoth Lakes, California, was the ninth major episode of activity following a M6 earthquake in Long Valley Caldera (LVC) on May 25, 1980. During the summer of 1982, the USGS began locating all timeable earthquakes in LVC using a combination of real-time computer processing (RTP) and conventional manual timing methods. This procedure allowed the progress of the January 7, 1983 swarm to be monitored in real time and in greater detail than previous swarms. The swarm began at 0020 (UTC). The number and magnitude of events increased rapidly, with a M 5.3 event at 0138 and a M 5.6 at 0324 (UTC). 120 events $\geq$ M 3 occurred on January 7. From 0100 to 0400 (UTC) activity was estimated to be over 400 events > M 1.5 per hour. During this period, the RTP picked over 130 events, 50 of sufficient quality to be accepted without question. The initial activity and the largest events were located in the SW moat of LVC. A second area of activity 6 km ESE of the first area became active after the first M5+ event. Focal depths ranged from 2 to 10 km in both areas with possibly more shallow events (< 2km) in the first area. Focal mechanisms for events in both zones are predominately strike-slip with one nodal plane indicating right-lateral strike-slip on a WNW-ESE trend, similar to that defined by the earthquakes in this swarm. The T-axes for all focal plane solutions indicate NE-SW extension.

STUDY OF JANUARY 1983 MAMMOTH LAKES, CALIFORNIA, EARTHQUAKE SEQUENCE

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Starting at 0027Z on 7 January 1983, an earthquake sequence occurred near Mammoth Lakes, California, where a major earthquake swarm has been in progress since October 1978. The sequence was well recorded by stations of the University of Nevada seismic telemetry network, and the latter was supplemented by an array of portable stations operated for two weeks by Woodward-Clyde Consultants, Sandia National Laboratories and the University of California, Santa Cruz. The portable instruments included Sprengnether MEQ-800's and DR-100's as well as Kinemetrics SMA-1's. Some of the earlier events were also recorded by a 3-component digital station at Mina, Nevada. Data from the portable array and the permanent network are currently being integrated for a detailed study of this important sequence.

Preliminary results for earthquakes recorded during the initial part of the sequence indicate that the hypocenters were located along the southern ring fracture system of Long Valley caldera -- in a cluster about 7 km long trending N80W and dipping steeply to the north. Focal depths ranged from about 2 to 11 km, with a concentration in the 5-9 km range. The largest shocks, at 0138Z and 0324Z on 7 January had ML 5.2 and 5.4, respectively. The fault-plane solution for one of the events was consistent with right-oblique slip on a fault striking WNW and dipping steeply to the north. The largest events were preceded by foreshocks over a period of about one hour.

DEFORMATION ACROSS THE LONG VALLEY (CALIFORNIA) CALDERA FROM 1980 (POSTEARTHQUAKE) TO JANUARY 1983

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Geodolite surveys of a trilateration network that spans the Long Valley caldera were made in September 1980, October 1981 (3 lines only), August 1982, and January 1983 (8 lines only) as well as several times prior to the May 1980 Mammoth Lakes earthquake sequence. The observed deformation suggests magma injection of about 0.16 km^3 into a spherical source centered at a depth of 11 km between 1979 and September 1980 and an additional 0.07 km^3 between September 1980 and August 1982. Further deformation has occurred in the August 1982 to January 1983 interval but the data have not yet been analyzed.

SURFACE DEFORMATION IN THE LONG VALLEY, CALIFORNIA CALDERA SINCE 1975

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Reoccupation of an intra-caldera horizontal and vertical control network in the summer of 1982 revealed that the floor of the Long Valley caldera had undergone significant bulging and stretching since previous surveys in 1975 and 1978. The observed deformation was generally consistent with a radially symmetrical magma-chamber inflation model centered at a point slightly south of the center of the resurgent dome. Maximum measured deformation was recorded across the western and southern parts of the resurgent dome, where uplift of 35 cm and extensional strains of 25 to 50 microstrain were encountered. Maximum uplift at the center of the bulge was estimated to be about 45 cm.
Remeasurement of an expanded electronic distance measurement (EDM) network in early December 1982 showed virtually no further horizontal charges above the level of measurement uncertainty. However, EDM measurements during mid January 1983, immediately after an earthquake (maximum M 5.6) swarm in the southern caldera moat, revealed significant changes in the distribution and magnitude of horizontal strains. Most of the network lines that had accumulated maximum extensional strains during the period 1978-1982 showed either no significant change or a modest reversal of strain (shortening). Supplementary lines newly established in the summer of 1982 characteristically indicated a moderate shortening of as much as eight microstrain, except for short (< 5 km) lines between points within and 3-5 km north of the concentrated band of January earthquake epicenters in the southern caldera moat. These short, epicentral-area lines typically showed extension of 5 to 10 microstrain during the period mid-December 1982 to mid-January 1983.

GROUND TILT SINCE MAY 1982 AT LONG VALLEY CALDERA, CALIFORNIA

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Ground tilt at Long Valley caldera has been monitored by precise leveling (dry tilt) since May 1982, when five stations were installed on the resurgent dome and in the southern moat of the caldera. The network has since been expanded to 10 stations concentrated in the southern moat, the site of numerous earthquake swarms since May 1980. Measurements at monthly intervals indicate a zone of outward tilting centered on the southern part of the resurgent dome, 2-4 km north of Casa Diablo Hot Springs. Although this pattern is most apparent for the measurement interval spanning an intense earthquake swarm that began on January 6, 1983, some stations have tilted progressively in the same pattern since May 1982. This observation suggests that the January 1983 seismic swarm was a continuation of the process responsible for uplift and extension of the resurgent dome since 1978, and that this process may be continuing episodically.

GRAVITY VARIATION IN THE MAMMOTH LAKES, MONO LAKE AND OWENS VALLEY, CALIFORNIA REGIONS

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Forty gravity stations were established in the Mammoth Lakes, Mono Lake, and Owens Valley regions in August, 1982. A subset of 21 of these stations was reoccupied in October 1982 and a subset of 10 stations was reoccupied in January 1983 shortly after an earthquake swarm containing two magnitude 5.7 events near Mammoth Lakes. A single base station at Mammoth Lakes was used for the entire network. The base station shows no significant gravity change with respect to absolute gravity reference sites in the Owens Valley and Pasadena, California. Little significant change is seen in the network between the August and October, 1982 measurements with the exception of the northernmost station near Lee Vining California, MLEQ06 = -23±8 microgals, and a station over the recent earthquake foci at Sherwin Creek campground EPIC = -13±6 microgals. Comparison of the January 1983 measurements with those of the August 1982 shows a continuation of the decreasing trend of the above, MLEQ06 = -39±6 microgals and EPIC = -21±7 microgals, with the addition of a significant change at a station near Casce Diablo Hot Springs, SHER = -21±5 microgals. No interpretation of the MLEQ06 change is put forward at this time until a full year's data is available. A preliminary interpretation of the continuous EPIC gravity decrease joined by the SHER decrease during the 1sat October 1982-January 1983 interval indicates a possible uplift of the southwestern boundary region of the Long Valley Caldera during the latter part of 1982 of 7 to 10 centimeters, assuming 2 to 3 microgals per centimeter for the distortion gravity gradient.

MONITORING HYDROTHERMAL ACTIVITY AT LONG VALLEY, CALIFORNIA

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Surficial thermal features and gas emissions at Long Valley have been monitored since May 1982. Hot springs, fumaroles, warm ground, and areas of intense hydrothermal alteration occur at Casa Diablo and Long Canyon on the resurgent dome, in the Hot Creek-Whitmore hot springs area west of the resurgent dome, and on Mammoth Mountain. The maximum observed surface temperature is 93°C in fumaroles at Casa Diablo and Long Canyon. Temperature and water level are monitored continuously at several hot springs and water wells located within the caldera. Hydrogen gas is continuously monitored from fumaroles at Casa Diablo, and soil gas at Laurel Canyon. Total gas composition is determined from samples collected biweekly from fumaroles at Casa Diablo; these samples consist largely of water vapor and minor amounts of CO_2, H_2, and H_2S. Changes in flow rates and gas discharge have been observed at hot springs and fumaroles accompanying or following the large earthquakes of each swarm during 1980-82. Vegetation kill, which has been observed since summer 1982 in the vicinity of Casa Diablo and Long Canyon, probably reflects the increased thermal stress.

MONITORING HOT SPRINGS AND SHALLOW GROUNDWATER IN THE LONG VALLEY CALDERA, CALIFORNIA

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Periodic measurements of temperature and water level in wells and discharge and chemistry of springs in the Long Valley caldera was initiated in 1972 as part of the U.S. Geological Survey's geothermal research program. In November, 1979, continuous recording of temperature and discharge of hot springs along Little Hot Creek was initiated by the U.S. Forest Service. Following the magnitude 6 earthquakes in May, 1980, additional monitoring of springs and wells was begun. Continuous recording of fluid pressure, temperature, and electrical conductivity in four wells and one hot pool and temperature and conductivity in seven hot springs is currently in progress. Data from one of the wells located within the zone of recent seismicity near the southern portion of the caldera ring fracture is being telemetered via satellite. Significant changes in hot spring discharge and temperature observed during the period of record have been of a temporary nature and probably reflect tectonic influences on rock permeability and porosity. Analysis of data from sites being continuously monitored should provide further evidence of the response of the groundwater system to tectonic and magmatic processes and may yield precursory indications of earthquakes and volcanic eruptions.

SYNTHETIC SEISMOGRAMS FOR TWO-DIMENSIONAL VELOCITY AND Q-STRUCTURE I

GENERALIZED ASYMPTOTIC RAY THEORY

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The propagation of high-frequency body waves in laterally inhomogeneous media can often be described using geometrical ray theory. Unfortunately, of course, singularities such as caustics, shadows, critical points, etc. have to be treated as special cases. To avoid these, several extensions of asymptotic ray theory have been developed. In Kirchhoff integral methods, the singularities are removed by introducing intermediate surfaces. Asymptotic ray theory is used to trace rays to and from the intermediate surfaces without singularities. The singularities at the receiver are produced by integrals over the surfaces. The Gaussian beam method removes the singularities by associating a finite width to each ray and integrating over rays. One method, Maslov asymptotic theory, uses the same ray tracing as in asymptotic ray theory, but considers the path in a phase space of position and slowness. Liouville's theorem guarantees that no singularities exist in phase space. Results in real space are obtained by Fourier transform, and, as the slowness and frequency transforms can be cancelled, no extra integrals are needed compared with geometrical ray theory. Only the results from geometrical rays are used but surprisingly, the method remains valid at singularities. Examples will be shown illustrating the formation of various geometrical and non-geometrical signals.

THE KIRCHHOFF-RAY THEORY METHOD FOR COMPUTATION OF SYNTHETIC SEISMOGRAPHS IN 2-D HETEROGENEOUS STRUCTURES

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Seismic reflection and refraction data consist essentially of observations of distinct groups of arrivals or "phases" which extend continuously over ranges of observation distance. In many cases the travel times and amplitudes of the phases can be explained by simple ray theory (RT). In other important cases, however, RT fails. For example, it fails to give reliable amplitudes in the vicinity of caustics and it does not predict any arrivals at all in shadow zones. In all such cases the amplitude varies rapidly in a direction orthogonal to the rays in some part of the wavefield. This results in a spreading or diffraction of wave energy in the orthogonal direction not taken into account in RT. In the Kirchhoff-ray method, RT is applied to obtain approximations to the Green's functions for propagation between pairs of points on a suitable succession of surfaces located between the source and receivers. The wavefield is then calculated on the successive surfaces by means of a generalised form of the Kirchhoff integral. The method effectively extends the applicability of RT to include diffraction effects. Among the advantages of the method are that the calculations may be carried out directly in the time domain and the results apply for sources of finite duration. It also provides a clear physical understanding of diffraction effects. The method will be described in detail and a number of examples illustrating its use will be given.

NOTES ON TWO ASYMPTOTIC METHODS OF COMPUTING BODY-WAVE SYNTHETIC SEISMOGRAMS FOR LATERALLY VARYING MEDIA

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For a velocity function which is continuous or nearly so the choice between the EWKBJ (Maslov) method and the EKH (Extended Kirchoff-Helmholtz) method is largely a matter of taste. Both require the tracing of large numbers of rays but significantly more ray tracing is required for the EKH method. The mathematics of the EKH method are simpler than those of EWKBJ-only elementary concepts are involved - but the computer code needed for EKH may be longer and more complicated than the code for EWKBJ.

For a velocity function which is discontinuous, if only refracted arrivals are to be modeled the discontinuities can be smeared over a short distance to give a velocity function treatable with EKH or EWKBJ. Reflection branches won't be correctly modeled by such an approach.

To include both reflections and refractions one can modify the standard form of the Kirchoff-Helmholtz method that has long been used by explorationists. In this standard form rays are traced from each source and receiver down to each reflector surface and the reflector surfaces are the surfaces of integration. Refractions can be included by using many reflectors separated by zones of constant velocity and by using plane wave elastic reflection and transmission coefficients at each interface. This method is more expensive than the methods for continuous velocity functions because of the far greater number of integration surfaces. The amount of ray tracing required is about the same as for the EKH method.

WAVE PROPAGATION THROUGH IRREGULAR LAYERS USING BOUNDARY INTEGRAL EQUATION APPROACH

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The Boundary Integral Equation (BIE) approach has proven extremely useful for wave propagation problems involving irregularly shaped layers. The BIE formulation takes advantage of known wave propagation properties within an individual layer, leaving only the interactions at the layer boundaries to be treated numerically. This essentially reduces the problem by one spatial dimension and represents a concise treatment of the pertinent physics involved. The resulting system of singular boundary integral equations is much smaller than the corresponding system of equations using the Finite Difference or Finite Element approach, but the block diagonal matrices are much more dense.

Two methods are presented for dealing with these dense matrix equations. First an approximate Kirchhoff technique is derived in which only local values of the wave field are allowed to interact with the layer boundaries and the propagation through multi-layered structures is accomplished by cascading up and down through the stack to get higher order reflections. Since the Kirchhoff approximation is not valid for critical reflections and some diffraction effects, a second and more complete BIE solution technique has been developed which iteratively deals with the singular matrix equation from a perturbation point of view with respect to known flat layer solutions. Comparisons are presented between the Kirchhoff solution and the iterative BIE solution showing the inadequacies of the Kirchhoff approximation and the convergence aspects of iterative BIE approach.

SCATTERING OF PLANE HARMONIC SH-WAVE BY DIPPING LAYERS OF ARBITRARY SHAPE

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Antiplane strain model for scattering of plane SH waves by dipping layers of arbitrary shape is investigated by using indirect boundary integral method. Dipping layers are of finite length perfectly bonded together. Material of the layers is assumed to be homogeneous, linearly elastic, and isotropic.

Presented numerical results incorporate variation in number of layers, angle of incidence, frequency of incident wave, material properties, and shape of the layers. It is shown that the presence of dipping layers may cause very large amplification of surface ground motion. Presented results indicate that surface displacement amplification depends upon number of parameters, such as: location of the observation point at the surface of the half-space, geometry and material properties of the layers, angle of incidence, and frequency of incoming wave. Change in any of these parameters may change significantly the surface response pattern.

A COMPARISON OF METHODS FOR AMPLITUDE DETERMINATION IN THREE DIMENSIONAL RAY TRACING

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Ray theoretic methods are probably the most efficient and widely used methods for solving wave propagation problems in laterally inhomogeneous media. Such methods generally rely on some form of geometric optics to obtain amplitudes associated with individual ray arrivals. Unfortunately, the failure of the geometric optics approximation at caustics and in diffraction problems in general often renders ray theoretic solutions invalid for a number of geophysically interesting problems.

Recently, several authors have proposed methods to extend the validity of ray theoretic solutions. These have included the three dimensional WKBJ method of Frazier and Phinney, its extension using Maslov asymptotic theory by Chapman, and the Gaussian beam method of Cerveny. In this paper, we compare the results of geometric optics with results obtained using these other asymptotic methods for both simple cannonical models and realistic geophysically interesting models. Results indicate that these asymptotic methods do provide a useful extension of the optics solution in the neighborhood of caustics, but are of limited utility in complex media where diffraction effects are important.

CALCULATION OF TWO-DIMENSIONAL SYNTHETIC SEISMOGRAMS USING DISK RAY THEORY

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Disk Ray Theory (DRT) methods are used to calculate synthetic seismograms for two-dimensional velocity- and Q-structure models. Ray tracing provides time, distance, geometrical spreading, slowness and amplitude factors corresponding to raypaths for all phases of interest in the model. Reflection and transmission coefficients and attenuation due to Q are included in the amplitude factors. These ray-amplitude data are summed along the travel time curve for each phase using appropriate weighting functions to synthesize wave propagation. Comparison of DRT synthetics with Modified Reflectivity Method (MRM) synthetics for one-dimensional models shows excellent agreement of amplitude and waveform in all areas of the record section except near critical points were amplitudes agree reasonably well, but the phase of the DRT seismograms is distorted. Pure head waves, multiples, reflections, P to S converted waves and radial as well as vertical component arrivals can be calculated with the DRT method. Comparison of DRT seismograms with Finite Difference synthetics for a two-dimensional model also confirm the accuracy and utility of the DRT method. The method is computationally efficient and allows modeling of wave propagation in complex geologic structures. The major limitation of the DRT method is the difficulty of ray tracing in certain velocity models.

STUDIES OF THE APPARENT ATTENUATION OF ACOUSTIC AND ELASTIC WAVES IN RANDOMLY LAYERED MEDIA

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We show that the work of O'Doherty and Anstey (1971) can be used to deduce the apparent attenuation of acoustic waves in randomly layered media:

$$\frac{A(\omega,x)}{A(\omega,0)} = \exp\left(\frac{-\omega x}{2\,\bar{v}\,Q(\omega)}\right)$$

$$Q^{-1}(\omega) = \frac{1}{2}\left(\frac{\sigma_I}{\bar{I}}\right)^2 \frac{\omega h}{\bar{v}}$$

Here $A(\omega,x)$ is the amplitude spectrum of the initial pulse of the transmitted wave at angular frequency ω after having propagated a distance x. The medium is characterized by its mean velocity $\bar{v}$, its mean impedance $\bar{I}$, and r.m.s. fluctuation σ_I, and has randomly independent layers of velocity v and thichness h. This formula is valid for wavelengths longer than one layer thickness. The affect of shear wave interactions on the apparent attenuation is examined through numerical calculation.

ATTENUATION FOR SEISMOGRAMS OBTAINED BY THE CAGNIARD-PEKERIS METHOD

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Attenuation and dispersion are included in synthetic seismograms obtained by a Cagniard-Pekeris formulation for the problem of a point source in a layer over a half space. The solution is decomposed into generalized rays and the effects of attenuation and dispersion are incorporated in an ad hoc manner in the frequency domain. The effects of the viscoelastic interfaces are taken into account by corrections to the reflection coefficient for an elastic media. The results are illustrated with synthetics for a model simulating a weathered layer over a half space. Both the SH and P-SV cases are treated.

REFLECTIONS FROM SECOND-ORDER DISCONTINUITIES

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In laterally homogeneous models, the transformed solution is usually found using the fundamental matrix approach. Various techniques have been developed to extend the Haskell matrix method to inhomogeneous layers. The WKBJ and Langer asymptotic expansions have both been used to develop the fundamental matrix. Both these methods have been used in iterative solutions to study low-frequency reflections from gradient inhomogeneities. In this paper, we point out that although the zeroth-order Langer solution predicts non-zero reflections from second-order discontinuities, they are inaccurate. Either the first-order asymptotic or iterative solution must be used to model second-order discontinuities accurately. Numerical examples for typical second-order discontinuities calculated using various methods will be shown.

INTRAPLATE SEISMOTECTONICS I

Some Results on the Intraplate Earthquake Activities in Alaska

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The strongest earthquake (magnitude 7.3) instrumentally documented in western Alaska occurred in 1958, near Huslia in the Koyukuk River basin. Other events of moderate size which have occurred in the different parts of western Alaska are of magnitudes 5.6 (1926), 6.25 (1928), 6.5 (1950), 6.0 (1964), 6.0 (1965) and 5.2 (1966). The second one of these events was located offshore in the Chukchi Sea. The rest were located about 10 km, 50 km, 60 km, 40 km, and 15 km, respectively, from the southern coastline of Kotzebue Sound, from the northern coastline of Norton Sound, from Port Clarence, Norton Bay and Hotham Inlet. Recent seismicity studies using a local seismographic network in western Alaska revealed a significant earthquake activity for both the onshore and offshore areas. An earthquake of magnitude 5.2 has been located in 1981, about 140 km northwest of Kotzebue. Several linear trends in the recently observed earthquake distribution patterns closely follow mapped traces of geologic features, principally faults. Seismicity of this part of Alaska is interpreted to be of the intraplate type.

INTRA-PLATE EARTHQUAKES IN NORTHERN SVALBARD

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Two concentrated seismic zones have been delineated in the Svalbard archipelago using a regional telemetered seismic network operated cooperatively by Saint Louis University and the Norwegian Polar Institute. The southern zone was located within the network, but the northern zone was situated at a distance of about 200 km to the north and could not be studied in any detail. During the summer of 1982, a temporary network of four microearthquake recorders was installed on the island of Nordaustlandet to obtain more accurate locations than had been possible in earlier work. It is found that the earthquakes occurred along two separate north-south trending faults extending from the northern interior of the island of Nordaustlandet into the offshore continental shelf. In contrast to the seismic zone in southeastern Svalbard, these northern earthquakes are situated along well-mapped faults and appear to be consistent with them in orientation and sense of motion. Preliminary analysis of the first motion arrivals for these earthquakes suggests a right lateral movement along the faults. The fault-plane solutions obtained to date for both the northern and southern zones are consistent with a NE-SW trending regional compressive stress throughout Svalbard.

SEISMICITY PATTERNS AND TERRANE-MOSAICS IN THE SOUTHEASTERN U.S.

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The spatial pattern of seismicity in the southeastern U.S. is puzzling. It contains elements both parallel (southern Appalachians) and transverse (Piedmont in VA and SC-GA) to the regional geologic structure. Those patterns, based on historical seismicity data, have now been confirmed by several years of network monitoring. The network results are also beginning to define multiple map-patterns of seismicity: a linear zone in the Appalachians (Giles County, VA), diffuse areas in the Piedmont province (VA, SC, GA) and a clustering habit in the Coastal Plain province (Charleston, SC locale).

Regionally, the crust thins from over 50 km beneath the Appalachian Mts. to some 30 km at the continental margin. These gross thicknesses are well established, but the detailed variations that accomplish the thinning are unknown. Also, significant depth-to-basement changes are suspected to occur in the same area, again in an unspecified manner.

Recently, a specific model of the Appalachian orogen as a mosaic of suspect terranes have been proposed. Suspect terranes are pieces of crustal and lithospheric material of various sizes and origins that have been accreted to a continental margin at some time in the geologic past. If such a terrane-mosaic model is valid, then each member terrane could present a different structural province to the ambient, regional stress field. Thus, the resulting seismic activity could change character in different terranes as differing "targets of opportunity" (favorably oriented and/or sufficiently weak structures) are reactivated. Such may be the case in the southeastern U.S.: the seismicity there appears to be spatially associated with the proposed terranes.

THE CENTRAL VIRGINIA SEISMIC ZONE - SEISMICITY AND SUBSURFACE GEOLOGY

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Combined geologic and geophysical studies are defining the geologic framework of current seismicity in central Virginia. The geologic studies are developing a 3-dimensional geologic framework in terms of faults and surfaces of appreciable rigidity contrast. Regional structural, petrographic and isotopic data, together with detailed surface geologic mapping along the VIBROSEIS survey profiles, are used to interpret the subsurface geology.

More than 150 km of 12- and 24-fold VIBROSEIS data were obtained during 1981-82 using a single Y-1100 vibrator and a 48-channel MDS-10 recording system. Data processing was on a VAX 11/780 computer using Digicon DISCO software. Excellent reflections on migrated sections were obtained to depths of about 8 km from 2 different overthrust volcanic lithofacies, as well as from lower Paleozoic unmetamorphosed rocks above a sole-fault that is at a depth of 8-10 km. That sole-fault can be traced eastward from beneath the Blue Ridge to a point some 40 km west of Richmond. The seismic profiles show listric faults that splay from the sole-fault. Several faults extend from mapped surface positions into the subsurface according to the seismic reflection data.

Network monitoring results (1978-82), along with special relocation studies on larger, pre-network events (1966-77), have yielded a composite data base of 43 well-located earthquakes ($-0.6 \leq M \leq 3.6$) in the zone. Seven of those events have both accurate focal-depths (±5 km) and are within 5 km of the VIBROSEIS profiles. All 7 are spatially correlated with either the sole-fault or one of the listric splay-faults. This important preliminary result needs to be confirmed by additional focal-mechanism, geology and VIBROSEIS studies.

CONJUGATE THRUST FAULTING DURING THE MIRAMICHI, NEW BRUNSWICK EARTHQUAKE SEQUENCE OF 1982: ITS GEOMETRY, GEOLOGICAL CONTROL, SURFACE EXPRESSION, AND MECHANISM.

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Field surveys by the EPB (and others) followed the January 9th (M5.7 and 5.1), January 11th (M5.4) and March 31st (M5.0) Miramichi earthquakes. 265 well-located aftershocks M≤4.0 occurred near 47.00°N, 66.60°W, concentrated in an area 4 km NS x 6 km EW with depth from 0 to 7 km. In EW cross section they suggest a "V" trend with limbs about 2 km thick. The aftershock distribution is consistent with conjugate ruptures, March 31st and possibly January 9th on the east limb and January 11th on the west limb. Composite first motion studies reveal thrusting on N to NE trending faults controlled by a regional stress field that is EW trending and horizontal, and they suggest the aftershock faults intersect at right angles at depth but steepen upwards towards the surface on each limb of the "V", giving an angular "U" shape. The N-trending bedrock crack found in May has 25 mm of thrust (west side up) displacement and is consistent with the composite solutions.

Important and unusual features of the earthquake sequence that will be discussed are the: 1) geological controls bounding the extent of seismicity, 2) conjugate nature of the ruptures, 3) 2-km thickness of aftershock activity on each limb, 4) position of main rupture planes within aftershock activity, 5) lack of a major surface rupture and the minor nature of observed faulting, 6) large numbers of aftershocks following the M5.4 and 5.0 compared with the M5.7 and other eastern Canadian earthquakes, and 7) relative size of and 57-hour delay between M5.7 and 5.4 events. A plausible history of the sequence will be presented to account for the observations.

SURFACE WAVE ANALYSIS OF THE MAGNITUDE 5.7 MIRAMICHI, NEW BRUNSWICK, EARTHQUAKE OF 09 JANUARY 1982

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Well-defined P-wave first motions (on short-period records) and surface-wave analysis of the fundamental mode Love and Rayleigh waves indicate P-nodal solutions that are similar to estimates based on aftershock activity. Moreover the preferred results are close to a mean of previously reported calculations that are based on both the forward and reverse (moment tensor inversion) techniques applied to body waves. Previously reported results (abstracts) for the westward dipping (more tightly constrained) P-nodal plane for the largest (M 5.7) event are as follows: strike 185-205°; dip (upwards in an easterly direction) 35-65°; rake 70-130°; focal depth 6-10 km; seismic moment 1.5-6.0 x 10^{24} dyne-cm; stress drop 40-120 bars; and fault area 22-32 km^2. The comparatively sparse distinct P-wave first motions and surface-wave records of the larger aftershocks are being compared with those of the largest (M 5.7) event to determine whether or not there are significant differences in source mechanisms.

SEISMIC PARAMETERS OF THE 1982 ARKANSAS EARTHQUAKE SWARM

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The number of recorded events of the 1982 earthquake swarm in north-central Arkansas now exceeds 20,000. Preliminary characterizations of this data set include:

(a) A non-migrating source volume of dimensions ~ 8 km^3.
(b) Predominately strike-slip faulting in response to NE-SW maximum horizontal compressive stress.
(c) A total strain energy release of approximately 10^{18}-10^{19} ergs (equivalent magnitude ~ 4.8).
(d) Extremely episodic seismicity with bursts of high activity separated by weeks of relative quiescence. However, no major reactivations comparable to the initial activity have occurred.

Imbedded in the overall swarm activity are several dozen foreshock/mainshock/aftershock sequences that among themselves exhibit large variations in number and time span of foreshocks and aftershocks. Recordings of these sequences are complete to magnitude -2 thus providing the opportunity for a systematic study of the earthquake cycle. Such a study is now underway and initial findings will be presented.

MICROEARTHQUAKE TRENDS IN KANSAS AND NEBRASKA

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During the past five years approximately 100 microearthquakes in the local magnitude range 1 to 3 have been located by the 9-station Kansas seismograph network. The largest event in Kansas since network startup had maximum MM Intensity VI with an M_{bLg} of 3.3, and was located on a trend that has developed in northern Kansas along the northwestern margin of the Midcontinent Geophysical Anomaly. Other trends in Kansas mimic historical seismicity very closely along the Nemaha Ridge and the Central Kansas Uplift.

A pocket of activity ($\sim$ 50 events/year > magnitude 0) has been noted on the Central Kansas Uplift in Nebraska just north of the Kansas border. The 8-station Sleepy Hollow network was established to determine whether these earthquakes are being induced by secondary recovery operations in the Sleepy Hollow oil field. During the past two years, however, we have noted that the Sleepy Hollow earthquakes lie at the perpendicular intersection of the Central Kansas Uplift and a trend of microearthquakes that extends northeastward some 350 km across Nebraska. This intersection of two trends at Sleepy Hollow suggests that some of the earthquakes may be tectonic rather than induced.

In order to more closely examine the northeastward trend across Nebraska, we established a 6-station regional telemetered network in central and eastern Nebraska in December, 1982, under Nuclear Regulatory Commission funding. The earthquake trends in Kansas and Nebraska will be more closely evaluated with these additional stations in the future.

OBSERVATIONS OF MICROSEISMIC AND TILT ACTIVITY INDUCED BY FLUID INJECTION AND WITHDRAWAL FROM DEEP RESERVOIRS IN WESTERN COASTAL LOUISIANA

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Microseismic and ground subsidence monitoring arrays have been installed around two geopressured-geothermal gas wells in the Gulf Coast region of western Louisiana. Each well site is instrumented by seismometers, tiltmeters, and first-order levelling arrays. The seismometer arrays consist of eight short period seismometers within an approximately 25 square kilometer area centered about the wells. First order levelling arrays provide approximately 2 km of levelling data that are collected monthly. Tilt data are collected periodically from low sensitivity tiltmeters and continuously transmitted and recorded in digital format for high sensitivity tiltmeters. The planned high-volume brine withdrawal and gas-depleted brine injection program completed a Phase I test at one of the wells in February 1982; the Phase I test is currently underway at the second well.

A marked increase in the occurrence of microseisms was recorded upon commencement of withdrawal activities. This activity contrasts with the quiescence observed during the preceding year. The onset of microseismic activity was almost immediate, but decayed gradually, lasting several months after reservoir withdrawl activities were finished. The microseismic events are often characterized by a single arrival that apparently travels with a velocity near the shear-wave velocity taken from logs of nearby wells. A temporal correlation is also suggested between well activities and ground surface responses observed in first order levelling and tilt data.

THE SEISMICITY OF EAST TEXAS[1]

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The area of the East Texas Basin in the vicinity of the Mt. Enterprise fault zone has been known to be seismically active during the past century. A likely earthquake occurred in 1891 at Rusk, TX. In 1957, a series of four events occurred nearby, two of which were recorded instrumentally.

A small seismic-monitoring network of up to five stations was installed in 1981 by the University of Texas to investigate the level of seismic activity as part of the Gulf Coast Salt Dome portion of the Nuclear Waste Isolation Program. During the first year of operation, six locatable earthquakes were recorded; three of these were felt. The two largest events (June 9, 1981, near Center, and November 6, 1981, near Jacksonville) had magnitudes of 3-3.5. it is possible that even these felt events would not have been classified as earthquakes, had the nearby seismic stations not been operating. All of the locatable events occurred near the Mt. Enterprise fault zone, over an east-west segment covering 90 km. The Mt. Enterprise fault zone is confined to the upper 5 km of the sedimentary section. Because of station geometry, we cannot determine if the earthquakes occurred at those shallow depths, or in deeper "basement" rock instead.

In addition to these locatable earthquakes, several hundred events of undetermined origin were recorded (not including frequent sonic booms and explosions). Most of these events occur in swarms during the daytime. The possibility that these events, and maybe the recent larger earthquakes as well, are associated with fluid injection is being investigated.

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SOME ASPECTS OF THE SEISMICITY OF SWITZERLAND: 1964-1982

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Instrumental seismicity in the Swiss region for a 19-yr period (1964-1982) has been systematically re-analyzed and reprocessed. Reprocessing consisted of hypocentral relocation with improved techniques and discrimination of quarry blasts and other artificial seismic events. The resulting epicenter map shows broadly scattered earthquake activity throughout Switzerland with significant epicentral clustering in several areas, including: (1) the vicinity of Basel, Switzerland, where seismicity is presumed to be related to tectonic deformation along the southern margin of the Rhine Graben, (2) the Valais region (SW Switzerland), and (3) the Rheintal region (E Switzerland). In the latter two regions, densely clustered earthquakes correlate with areas marked by distinct isostatic gravity anomalies and high relative uplift rates. Strike-slip focal mechanisms in the Swiss region agree with the contemporary tectonics, characterized by NNW-SSE to NW-SE compression. Comparison of our instrumental data set with pre-1964 instrumental seismicity and historical seimsicity since 1000 A.D. suggests a relatively constant spatial pattern. One exception is an area in the central Swiss Alps near Visp-Brig where the absence of instrumental seimsicity contrasts with the meizoseismal location of several historic earthquakes.

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INVESTIGATION OF SEISMICITY IN THE SWISS-AUSTRIAN BORDER AREA

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The seismic history of northeastern Switzerland is characterized by pronounced earthquake-activity in the Rhine Valley between the Lake of Constance and the city of Chur. This analysis of historic and recent earthquakes reveals a low average b-value of 0.64, but 1.2 for the last 20 years. Most mechanisms of earthquakes in this area show thrust faulting in contrast to the predominating strike slip faulting in other areas of Alpine and preAlpine Switzerland. Distinct seismogenetic zones can be defined for the evaluation of seismic hazard. An intensity of VII to VIII (MSK-scale) was derived for a probability level of 0.001 P.A. Special effort was made to precisely relocate earthquakes using explosions as master events and operating portable seismic stations in the area.

TOPOGRAPHY AND ITS ISOSTATIC COMPENSATION AS A CAUSE OF THE SEISMICITY OF THE APPENNINES

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The load generated by the Appennines and its isostatic adjustment is simulated on an elastic spherical model, and an estimate made of the maximum shear stress field produced. For this purpose a load on a shell with isostatic compensation is considered showing that the couple effect associated with the displacement of the compensation greatly increases the maximum shear stress as

compared with the case of no displacement.

When the results of the present study are compared with those obtained from seismicity and from the gravity anomalies of the Appennines it is found that the largest earthquakes in the region and the most seismically active part of the region are in the region of the largest shear stress and the region's large gravity anomaly gradient. A pattern recognition study of the correlation between large earthquakes and gravity anomalies confirms this result.

The case of a load on a spherical cap not isostatically compensated is also considered; the findings in this case are in agreement with Jeffrey's results for a half space although in our case the largest value of the maximum shear stress occurs at a shallower depth. This case is of interest for those continents where the isostatic compensation is not complete.

LONG VALLEY CALDERA: RECENT ACTIVITY II

EARTHQUAKES AND MAGMA INJECTION AT MAMMOTH LAKES, CALIFORNIA

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P-wave fault-plane solutions for 44 events of the 1978-1982 Mammoth Lakes, California, earthquake sequence show consistent strike-slip mechanisms for events with focal depth less than 9 km and primarily oblique or normal faulting for deeper events. The shallow earthquakes are distributed in an irregular-shaped zone extending 30 km in a NW-SE direction and 25 km from north to south; lineups of events clustered in time suggest that this zone is being subjected to brecciation along a large number of NW and NE trending fractures. Strike of the two planes of the P-wave fault-plane solutions for shallow events are concentrated in directions N10E and N75W, and T-axes for events at all depths are strongly grouped in a NE-SW direction. The deeper shocks are located in a northerly trending zone 25 km long and about 5 km wide.

These observations are consistent with crustal extension along the NNW-trending Sierra Nevada frontal fault zone, with deeper shocks resulting from normal or oblique movement on east-dipping, NNW-striking faults and shallow events reflecting conjugate right- and left-lateral shear on nearly vertical fractures striking respectively WNW and NNE. The strike-slip mechanisms may be associated with the formation of clusters of magma-filled dikes at depth less than 9 km, based on an earthquake swarm model proposed by Hill (1977).

MECHANISMS OF THE MAY 1980 EARTHQUAKES NEAR LONG VALLEY CALDERA, CALIFORNIA: EVIDENCE FOR DIKE INJECTION

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A reanalysis of the three largest earthquakes that occurred near Long Valley caldera in eastern California on May 25 and 27, 1980, indicates that they were probably caused by magma injection along nearly vertical surfaces and not by slip on faults. Several previous investigators have reported difficulty in explaining both

the long-period surface waves and the locally recorded short-period body waves from these events with conventional source models. They attributed this difficulty to: (1) complex sources, not representable by single fault models (2) artifacts of the analysis methods used, or (3) effects of wave propagation through hypothetical complex structures beneath the caldera. The data (150-200-s Love-wave amplitudes, Rayleigh-wave amplitudes and phases, and short- and long-period P-wave first motions: Given, Wallace, and Kanamori, 1982) agree almost perfectly, however, with the predictions for a compensated linear-vector dipole-equivalent-force system with its principal extensional axis approximately horizontal and trending N. 65° E. Such a mechanism is just that expected for magma injection along dikes striking N. 25° W., which is the approximate strike of numerous faults in the area.

SPECTRAL CHARACTER OF "TREMOR" IN LONG VALLEY, CA DURING 1980-1983

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Occurrences of "spasmodic tremor" at Long Valley, CA, have been suggested by Ryall (EOS, 1982). Whether these unusual swarms are actually of volcanic origin, or, instead, represent intense bursts of normal tectonic earthquakes is crucial for assessment of the hazard, and remains an open question at this time. Recent work by Fehler and Chouet (GRL, 1982) at Mount St. Helens, Washington, suggests a spectral discriminant between spasmodic-harmonic tremor (magma-fluid flow resonance) and intense earthquake swarms (stick-slip source). At Mount St. Helens low-frequency events precede eruptions, and these events have spectral peaks near 1-3 Hz due to a fluid resonance mechanism. Stick-slip source events have flat spectra out to corner frequencies of 20-40 Hz. Also, high-frequency events characteristic of brittle fracture are readily distinguishable by bandpass filtering.

Since 1979, the California Division of Mines and Geology has been operating digital event recorders (Sprengnether DR-100's) in the area. Brief high-quality digital samples of several suggested occurrences of spasmodic tremor have been recorded, including the most recent 7 January 1983 M5.5 swarm, which occurred at the time of writing this abstract. This unique dataset is being analyzed for spectral content and wave character, and the results and implications relevant to the hazard as well as insights into tectonic/volcanic processes behind continued earthquake activity at Long Valley will be presented.

THE CDMG AUTOMATED STRONG-MOTION PROCESSING SYSTEM AND THE MAMMOTH LAKES DATA

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An automated scanning digitizer has recently been installed at the California Division of Mines and Geology (CDMG) as part of the Strong-Motion Instrumentation Program. The system is patterned after that of Trifunac and Lee at the University of Southern California. The film accelerogram is scanned by a horizontally-travelling photodensitometer while mounted on a rotating drum. The digitized

accelerogram is reconstructed from the resulting gray-level matrix by a curve-follower algorithm.

Various tests and modifications have been made in the course of certifying system performance. The resolution of some problems in the Phase 1 processing and improvements in the Phase 2 filtering has reduced system noise levels to near or below that estimated for the original hand-digitizing procedures at CIT.

The Mammoth Lakes strong-motion data was the first data processed by the system. This is an extensive set of records from several free-field and structural stations (1/4 to 1 g peak acceleration, epicentral distances from 2 to 25 km). The earthquakes recorded include the four M > 6 events in May 1980, two M > 5 events in September 1981, and the two M > 5 events in January 1983. Particular data discussed includes that from the heavily-instrumented Long Valley Dam, which includes co-located optical (SMA) and electrical (CRA) systems. High-amplitude spikes similar to those in the Bonds Corner record from the 1979 Imperial Valley earthquake are present in the left-abutment records. As yet unexplained, these spikes are shown to not significantly affect the computed displacements.

MAGNETIC MEASUREMENTS ACROSS THE LONG VALLEY CALDERA, 1972-1983: A COMPARISON WITH OBSERVATIONS AND MECHANISMS DURING THE MATSUSHIRO EARTHQUAKE SWARM

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Repeated magnetic measurements have been made since 1972 with a 32-site array in upper Owens Valley. The array extends around Mono Lake, across the Excelsior Mountains, and down the Owens Valley. In 1976, the array was extended from Bishop across the Long Valley Caldera to Mono Lake. One or two sets of data have been obtained each year at each of the site pairs. Following the first Mammoth Lake earthquakes in 1978, recording portable magnetometers were also installed in Round Valley and along the Hilton Creek fault to the approximate center of the Long Valley Caldera. Periods of continuous recording (typically 5 days) have occurred each year since 1978, usually when measurements in the larger array are being repeated. The result of most significance in both of these data sets is a 3 to 4 nT field increase at sites on the southwest side of the caldera and along the Hilton Creek fault. This general field increase apparently started in 1977-1978 and has continued in a systematic manner since then. Simple tectonomagnetic models which incorporate an increasing pressure source at a depth of about 5 km would generate a field change similar to that observed across a zone to the southwest of the caldera. This picture would, of course, be complicated by simultaneous strain activity on the Hilton Creek fault. Thermal demagnetization may also be occurring but would generate changes opposite in sense to those observed. The preferred explanation of these and similar observations during the Matsushiro earthquake swarm in Japan is in terms of inflation of a shallow magma chamber within a crust containing preexisting horizontal shear stresses. A reversal in sense of the magnetic changes should indicate decreasing source pressure and herald a subsequent decrease in seismicity as observed at Matsushiro.

HIGH RESOLUTION RECORDING OF AFTERSHOCKS OF THE JANUARY 1983 MAMMOTH LAKES, CALIFORNIA EARTHQUAKES.

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Following the main shocks of the Mammoth Lakes, California, earthquakes of 6 January 1983, (PST), 120 portable seismographs were dispatched to Mammoth Lakes to be deployed at close intervals in and near the epicentral area. The first deployment, on the night of 8 January 1983, placed the instruments at 100 meters intervals in a linear array within the Long Valley Caldera. Twenty three located events were concurrently recorded during two half hour recording windows. Field playbacks suggest that the array traverses the nodal plane of many of the events.

A second deployment on the night of 10 January 1983 sought to use the aftershocks as sources for a seismic refraction profile to the north of the epicentral area. Instruments were placed at intervals of 160 meters along a 17.5 km profile on highway 395 beginning 25 km north of the Mammoth Lakes. Many of the instruments re-occupied sites used for a multiple reversed and overlapping explosion profile in the summer of 1982. Of 24 events located during the recording period, four or five were of sufficient magnitude to be recorded across the array. A seismic record section of one of these events displays a prominent secondary arrival that may be a reflected phase from beneath Long Valley Caldera.

PROPERTIES OF MAMMOTH LAKES, CALIFORNIA, EARTHQUAKES FROM DIGITAL SEISMOGRAPH DATA

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As part of a program to use natural events to profile simultaneously in four directions from the region of highest seismicity near Mammoth Lakes, we have studied the distribution and properties of these earthquakes. From a ten-day snapshot of activity obtained with 12 three-component triggered digital seismographs, we have so far found that station residuals are in general inversely related to elevation, and that poorly received S correlates both with positive station residuals and with locations in the Long Valley caldera. Shear waves can pass under the Long Valley caldera. The Minimum Apparent Velocity technique (Matumoto, 1977) appears to be usable for obtaining an estimate of local velocity vs. depth in the region of highest seismicity. Expected structural offsets are visible in unusual apparent velocities, and values within recognized structural provinces are internally consistent. The region of highest seismicity lies south of the Long Valley caldera, in the region of historic highest activity, and is contained in a volume of about 1,000 km^3. These earthquake sources are adequate for profiling to PmP ranges (120 km) with an efficient field program, and compressional arrivals from these earthquakes are as impulsive as those of the best 700-kg shots of the USGS in 1982.

SEISMIC PROFILING USING EARTHQUAKE SOURCES NEAR MAMMOTH LAKES, CALIFORNIA

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In a prototype study, we have employed 12 digital seismographs to profile in four directions from the most active seismic volume near Mammoth Lakes, California. The western profile crosses into the Basin and Range province, the south profile extends through Owens Valley as does the north profile, which corrses the Long Valley caldera, and the profile to the west crosses the highest part of the Sierra Nevada. In this study, which extended to 80 km along each of the arms of the profile, the seismographs were leapfrogged over each other, spaced at 10 km intervals, and left on site for about 10 days. The source dimension, about 10 km on a side, and the seismometer spacings are thus about equal. In most cases, about 200-300 locatable events were recorded during each observation period. We expect that record sections can be produced with that many earthquakes, and that some of the procedures used for interpretation of high-density explosion profiles will be directly applicable to tectonic studies in these locally complex regions.

TELESEISMIC TRAVELTIME ANOMALY AT MONO AND INYO CRATERS, CALIFORNIA: A DIKE-FORM LOW-VELOCITY BODY?

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Traveltime residuals for distant earthquakes recorded at 16 stations around Mono and Inyo Craters, California, may be caused by a vertical sheet of low-velocity material beneath the craters. Events from the southeast azimuth give relative traveltime delays at most stations northwest of the craters, and events from the northwest give delays southeast of the craters; the maximum variation in residuals from earliest to latest is 0.4 s. If this residual pattern is caused by such a body, then the body must extend from within 2 or 3 km of the surface to at least 25-km depth and run most of the length of the chain of craters. No approximately spherical low-velocity body like the one under Long Valley, just south of this area, can be seen in these data. Once analysis is complete, the seismograph array used can be expected to resolve three-dimensional velocity structure in the region of Mono and Inyo Craters to a depth of about 30 km.

PRECURSORY CHANGES IN VOLCANIC ACTIVITY PRIOR TO GREAT EARTHQUAKES

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Although many investigators have noted changes in seismic activity prior to several great earthquakes, these changes are not uniquely identifiable. In order to determine if there are similar changes in other easily observed parameters, I have examined changes in volcanic activity prior to several great earthquakes in the circum Pacific area. The great earthquakes considered occurred in this century and volcanic activity for about one hundred years prior to the occurrence of these earthquakes was examined. This examination shows that at some time prior to the occurrence of great earthquakes, there is a sudden in-

crease in volcanic activity on the landward side of the rupture zones of these earthquakes. Furthermore, this increase in volcanic activity occurs at a time which depends on the magnitude of the impending great earthquake. A further examination shows that this increase in volcanic activity occurs a few years before the noted increase in seismic activity in the rupture zones of these great earthquakes. This suggests that a sudden increase in volcanic activity followed in a few years by significant seismic energy release can be identified with greater confidence as a precursor and as such utilized for long term forecasting purposes. These data also suggest a spatial relationship between the area of increase in volcanic activity and the epicenter of the impending great earthquake.

SYNTHETIC SEISMOGRAMS FOR TWO-DIMENSIONAL VELOCITY AND Q-STRUCTURE II

SYNTHETIC SURFACE-WAVE SEISMOGRAMS USING FINITE-ELEMENT TECHNIQUES

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Two distinct approaches exist for the synthesis of surface-wave seismograms using finite-element techniques. The equation of motion is

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F(t)\} \qquad (1)$$

Here, [M], [C], and [K] are related to the material properties of the model, $\{F(t)\}$ is the known time-history of the forcing loads, and $\{u\}$ is the vector of unknown displacements.

The time-dependent approach assumes initial values for $\{\ddot{u}\}$, $\{\dot{u}\}$, and $\{u\}$ at t_o, and then uses difference equations to solve for $\{u\}$ at a time $t_o + \Delta t$. The desired time-history of motion is obtained by repeating the calculations for subsequent increases in time until the seismogram is complete (e.g., Martel, GJ 61, 659-677, 1980).

The time-harmonic approach assumes a harmonic wave with a known frequency ω and known displacements $\{u_I(\omega)\}$. Equation (1) then reduces to

$$\{[K] - \omega^2[M] - i\omega[C] + [S] - [R_2]\}\{u\} = \{[\dot{S}] - [R_1]\}\{u_I\} \qquad (2)$$

where [S], $[R_1]$, and $[R_2]$ are known matrices related to boundary conditions (Drake, BSSA 62, 1241-1258, 1972). Equation 2 is solved for $\{u\}$ by standard techniques; analysis of $\{u\}$ yields the amplitudes and phases of all modes propagating in the structure. If equation 2 is solved for a number of frequencies ω_1, ω_2, ... ω_n, the resultant spectra may be transformed to the time domain to obtain a seismogram.

The ability of the finite element method to model inhomogeneous materials and complicated boundary conditions is an advantage over other numerical and analytic procedures.

FINITE-ELEMENT MODELING OF ACOUSTIC AND ELASTIC WAVES

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On the basis of the concept of the principle of virtual work and the Gurtin's variation principle of initial-boundary-value problems, the finite-element solutions for acoustics and elastodynamic transient problems have been successfully formulated. The spatial and temporal domains were initially discretized by the finite-element method. Since the temporal discretization generally can be considered homogeneous, it is equally valid and convenient to carry out time integration by the implicit or explicit time integration scheme of the finite-differences method. Although the implicit scheme is unconditionally stable, and the explicit scheme is only conditionally stable subject to the Courant-type of conditions, the demand of "stability" and "accuracy" limits the choice of the optimal time step for a given finite-element domain.

The finite-element method as developed provides advantages over the more conventional finite differences, chiefly as follows: (1) simple and accurate modeling of arbitrary seismic sources, (2) ease of applying homogeneous and inhomogeneous boundary conditions, (3) great flexibility in modeling any spatial irregular geological media, and (4) perhaps most importantly, errors are averaged over the elements throughout the domain in question.

The finite-element algorithms developed at Aldridge are proven to be numerically stable, fast-convergent, and without artificial suppression, and these algorithms can be used to solve the two- and three-dimensional foward problems of acoustic waves and elastic waves (both compressional and shear), scattering, and diffraction from more realistic and complex geologic media.

LOVE WAVE DISPERSION ACROSS SUBDUCTION ZONES BY FINITE ELEMENT MODELLING

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The eigenproblem for Love waves across a subduction zone has been solved using the finite element algorithm previously developed for seismic waves through anomalous seismic structures. The two models constructed represent subduction slabs under Japan and the North Island of New Zealand. Fundamental-mode Love wave dispersion curves have been calculated for wave periods between 5 and 60 sec. Comparison with phase velocity curves for the adjacent ocean and island regions shows intermediate values for most of the period range. At a period of 20 sec, the subduction zone phase velocity curves give about 4.20 and 3.85 km sec^{-1} for the Japan and New Zealand zones, respectively. Energy reflection-refraction partition ratios have also been calculated. At 10 sec the percentage of transmitted energy in the fundamental Love wave is much greater across the New Zealand than across the Japanese subduction zone.

APPLICATIONS OF FINITE DIFFERENCE SYNTHETIC SEISMOGRAM MODELING IN LATERALLY HETEROGENEOUS ELASTIC MEDIA

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In principle, the finite difference (FD) approximation to the two-dimensional elastic wave equation provides a simple computational method for calculation of synthetic seismograms in laterally heterogeneous media. Explicit FD equations are solved for each grid point in the velocity model at each time step for the total propagation time. Well known grid spacing (10 points/minimum wavelength) and stability criteria $\Delta t^2 \leq \Delta H^2/(\alpha_{max}{}^2 + \beta_{max}{}^2)$ insure stable and accurate seismogram calculation, but result in large computer storage and computer time requirements for realistic models at useful frequencies. Additional difficulties arise from boundaries of the model, free surface conditions and introduction of the source time history. In spite of these problems, FD methods can now be routinely used for seismic modeling. Both synthetic seismogram and time history 'snapshots' can be calculated and displayed. Arbitrary source mechanisms can be introduced including a finite-length earthquake source. Comparison of FD and modified reflectivity synthetics for a layer over a half space model demonstrates the validity of the FD approximations. Calculation of FD synthetics for a variety of two-dimensional velocity models illustrates the utility of FD methods for seismic modeling and wave propagation studies.

LINEARIZED INVERSION OF TRANSMITTED ACOUSTIC WAVEFIELDS FOR MODULUS AND DENSITY PERTURBATIONS: COMPARISON WITH A LINARIZED TRAVEL TIME INVERSION TECHNIQUE.

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A linear relationship, in the frequency-horizontal wavenumber domain, between transmitted acoustic wavefields and two (or three) dimensional fractional perturbations in modulus and density in the adjacent medium can be obtained by using a Born approximation. These equations can be inverted with standard linear inverse methods. The linear relationship, in the horizontal wavenumber domain, between the gravity field and the density perturbations can be included in the inversion with arbitrary weight or as a constraint. This greatly reduces the strong negative trade-off between modulus and denisty perturbations which occurrs in the acoustic case. Examples comparing the performance of this wavefield inversion to that of a standard linearized travel-time inversion used in teleseismic P-residual studies will be given for some synthetic wavefields. Advantages of the whole wavefield inversion over the travel-time inversion include: 1) better spatial resolution, 2) the ability to model structure with dimensions near or smaller than the wavelength of the incident wavefield, 3) simultaneous modeling of modulus and density structure without ad-hoc assumptions about the relationship between these independent properties. Disadvantages are the breakdown of the approximation for structures much larger than the incident wavelength and the need to avoid spatial aliasing in the seismic recording array.

EXPERIENCE WITH FINITE DIFFERENCE SYNTHETIC SEISMOGRAM CALCULATIONS UTILIZING ELASTIC AND ACOUSTIC MODELS AND EXPLICIT AND IMPLICIT FORMULATIONS

DAUDT, C.R. and BRAILE, L.W., Department of Geosciences, Purdue University, West Lafayette, IN 47907

We have utilized the finite difference (FD) method for calculation of synthetic seismograms in two-dimensional velocity structures for both the acoustic and elastic wave equation and utilizing both explicit and implicit FD formulations. The acoustic calculations are far faster than the corresponding elastic wave approximations and, therefore, two-dimensional modeling with acoustic wave techniques represents an approach to rapid initial modeling of seismic data. Implicit methods are stable even for coarse grid spacings and large time steps. However, the increased complexity of the computer program and additional storage requirements, as well as grid spacing and time-step constraints due to inherent inaccuracy, make the implicit approach only slightly faster than the explicit calculations. In addition, the accuracy of absorbing boundary conditions is limited in the implicit formulation. Problems associated with absorbing boundary conditions, introduction of the seismic source, and accuracy and stability conditions are largely solved with the proper grid spacing and time step conditions utilizing the explicit acoustic or elastic FD formulation. We have calculated synthetic seismograms and associated time history 'snapshots' of elastic and acoustic wave propagation for a variety of one- and two-dimensional models. Comparison with other techniques and with theoretical results, indicates that a high degree of accuracy for full wave synthetic seismogram calculations can be achieved utilizing the explicit finite difference approach. The principal difficulty with the explicit FD calculations is the vast amount of computer time and storage necessary for synthetic seismogram modeling of realistic earth models at useful frequencies.

SYNTHETIC SEISMOGRAMS IN MULTILAYERED VISCOELASTIC MEDIA USING THE VESPA ALGORITHM

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An efficient and flexible algorithm called VESPA has been developed for generating complete synthetic seismograms in a parallel-layered half-space due to a variety of source types including directional point forces, explosions, ring loads of arbitrary azimuthal order and arbitrary second order moment tensors. VESPA uses a frequency-wavenumber integration approach without approximations or limiting assumptions for any number of viscoelastic layers. The algorithm has no instabilities at low or high frequencies, in the presence of thin or thick layers, or for near or far receiver distances. The adaptive integration scheme over wavenumber is highly optimized with large savings for uniformly spaced receivers. Interpretive features are provided such as suppression of various wave types from the complete solution and separation of waves traveling within different phase velocity windows. Applications for exploration geophysics are illustrated by simulating seismic shot records and multiple offset vertical seismic profiles. Applications for earthquake seismology are illustrated by simulating strong ground motions for a suite of earth models that differ only in near surface material properties (eg., Q and seismic velocities).

RESONANCES OF LOW-VELOCITY LAYERS WITH LATERAL VARIATIONS

Alan R. Levander and N. Ross Hill

Gulf Research & Development Company

Small lateral variations in the velocity or boundaries of a buried low-velocity layer allow far-field seismic energy incident on the layer to be scattered into the waveguide modes of the layer, something which cannot occur in the absence of lateral inhomogeneity. The energy trapped by this resonance mechanism can be much greater than the energy trapped by multiple reflections within a similar laterally homogeneous layer. The energy trapped in the waveguide modes can only slowly leak out of the layer by again interacting with the lateral inhomogeneities. Finite difference simulations of this effect for SH waves clearly show the excitation of the mode structure within the layer caused by scattering from the lateral perturbations. They also show the energy slowly leaking out of the layer and making the principal contribution to the coda of the signal recorded at the surface. This phenomenon may contribute significantly to the coda of body waves which have interacted with low-velocity zones in the crust and near-surface sediments.

NUMERICAL WAVE ANALYSIS IN FAULTED BASINS ON THE CRAY 1

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Full P-SV transient wave fields are calculated numerically for 2-D inhomogeneous faulted basins typical of the Basin and Range province. Model scales are from 16 to 50 km in range and 7 km in depth, with near-surface frequency resolution of 3 Hz for Rayleigh waves and S-waves, and 6 Hz for P-waves. This scale and resolution requires discrete models with 30,000 to 100,000 nodes in the computational mesh--which are only feasible on vector computers such as the CRAY 1 (at least one order of magnitude faster than scalar machines for explicit wave calculations).

The present talk describes the suite of basin calculations for various cross sections and source types. Velocity seismograms over the basin and bordering bedrock are used to quantify surface and body wave interactions at the basin edge for a steep faulted flank, an echelon faulted flank and a shallow dipping flank. Two-point ray tracing in the inhomogeneous models allows a unique identification of phases in the seismograms. In addition, the talk provides an overview of explicit wave solver implementation on the new class VI computers (i.e., vectorization on the CRAY 1) and discusses the size and scale of 2-D and 3-D problems which can be economically solved now and in the near future.

INTRAPLATE SEISMOTECTONICS II

NATURE OF CONTEMPORARY FAULTING IN THE RIO GRANDE RIFT NEAR SOCORRO, NEW MEXICO

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A moving array of high-gain short-period seismographs centered near Socorro, New Mexico, detected ~1200 microearthquakes during 316 recording days from May 1975 through January 1978. Utilizing exceptionally sharp S as well as P arrivals, 336 hypocenters were obtained whose rms residuals were less than 0.1 seconds and whose epicentral and depth errors were less than 1.1 km. Hypocenters for this data set are all located beneath structural elements of the Rio Grande rift at Socorro; the Socorro basin, the Polvadera-Socorro-Chupadera Mountains horst block, and the La Jencia basin. The focal depths range from 4 km to 14 km with 90 percent at depths less than 11 km. The sharp cutoff in number at shocks between 11 and 14 km indicates a rapid change in the physical properties of the crust in this depth interval.

Constrained composite fault-plane solutions were obtained for microearthquakes within seven regions ranging in size from 5 to 50 km^2; two in the La Jencia basin, two in the horst block, and three in the Socorro basin. All solutions show dominantly normal dip-slip movement, and for six of the solutions the orientation of the T axis is consistent; N75E($\pm 10^{\circ}$s.d.), plunge 7.7°(2.8°s.d.). The dips of the nodal planes for these six solutions (average depth 9 km) range from 36° to 60° and average 45.7°. Projection of the nodal planes to the surface assuming curved faults which intersect the surface at 90° matches the surface geology somewhat better than planar projections. However, the possibility exists that the fractures along which the microearthquakes occur are totally unrelated to faults mapped at the surface.

CHARACTERISTICS OF A MICROEARTHQUAKE SWARM IN THE RIO GRANDE RIFT NEAR SOCORRO, NEW MEXICO

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A microearthquake swarm centered 14 km southwest of Socorro, New Mexico, was recorded by a digital seismograph (100 sps) within 3 km of the epicenters as well as by analog instruments at greater distances. The most intense activity during the swarm occurred from May 30 through June 2, 1977, with ~60 shocks ranging in magnitude (M_L) from approximately -1 to 2. Depths of focus, based on readings from digital data of direct P, direct S and a reflected S phase from a midcrustal magma layer, were found to be narrowly restricted; 9.74 ±0.06 (s.d.) km. Epicenters, on the other hand, were distributed in an ~N10E direction over a distance of ~0.6 km which, in conjunction with the hypocenter depths, indicates dominantly lateral migration of faulting during the swarm. First motion data do not tightly constrain the fault mechanisms, but they are compatible with lateral progression of normal faulting on a fault or closely spaced faults striking north. Ratios of the amplitudes of reflected S to direct S suggest minor differences in the dip or strike of rupture surfaces for individual shocks.

Spectra for all swarm events of $M_L < 0$ at the same station are nearly identical despite differences in amplitude on the order of 10 and differences in hypocenter location greater than the wavelengths of the signals recorded. As noted by others, these observations indicate that waveforms for very weak microearthquakes are independent of source strength and are less sensitive to changes in hypocenter location than station location.

EPISODIC EARTHQUAKE SWARMS ($M_L \leq 4.7$) NEAR SODA SPRINGS, IDAHO, 1981-82: CORRELATION WITH LOCAL STRUCTURE AND REGIONAL TECTONICS

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The Soda Springs area of SE Idaho lies within the Intermountain seismic belt (ISB) and is characterized by Pleistocene and Holocene basalt-rhyolite volcanism and contemporary swarm seismicity, including notable macroseismic activity in 1960 ($I_0 \leq$VII). A recent swarm episode between mid-September and mid-November 1982 peaked with a shock of $M_L 4.7$ on October 14, 1982. The swarm included more than 50 felt earthquakes and followed several shocks ($M_L 3$ to 4) beginning in September 1981. Following the largest earthquake on October 14, 1982, a dense network of 19 stations was operated in the epicentral area by the University of Utah and the U.S. Geological Survey for 11 days (Oct. 15-26). Approximately 2,000 small earthquakes were recorded--providing the best data yet available for resolving the geometry and source mechanism of swarm seismicity in this part of the ISB. Continuous temporal monitoring for this area ($M_L \geq 1.7$) is provided by the University of Utah's regional seismic network ($\Delta \geq 50$ km). Preliminary findings from the dense-network special study include: (1) epicentral alignment on the SW flank of the Aspen Range, SE of Soda Springs, along a 13-km-long zone trending ~N30°W and located a few km NE of and parallel to the NE boundary of the Bear River Valley; (2) planar-clustering of foci (near-surface to 10 km depth) defining an inferred fault ~N30°W, 85°NE, apparently not a valley-bounding structure; and (3) strike-slip focal mechanisms with one nodal plane (having dextral slip) in agreement with that defined by the planar-clustered foci. The NW trend defined by the seismicity parallels the structural grain of both pre-Neogene thrust-belt structure and younger basin-range structure in the area, which are transverse to the axis of the Snake River Plain nearby to the NW.

SEISMICITY OF THE EASTERN SNAKE RIVER PLAIN REGION, IDAHO (43.0°-44.5°N, 111.5°-114.0°W), OCTOBER 1972-JUNE 1982

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The Idaho National Engineering Laboratory (INEL) has deployed a network of short-period high-gain vertical seismographs since December 1971 to monitor earthquake activity on and about the eastern Snake River Plain (ESRP), Idaho. This paper summarizes the earthquakes located within a designated Special Study Area (43.0° - 44.5°N, 111.5° - 114.0°W) from October 1972 to June 1982. Seventy-eight events were located within the Special Study Area, with a Richter Local Magnitude (M_L) range of $0.8 \leq M_L \leq 2.7$. The mean M_L for these microearthquakes was 1.4. Only three small microearthquakes ($M_L \sim 1.0$) were detected on the ESRP. Fifty-nine microearthquakes were located northwest of the ESRP, primarily in the Birch Creek Valley - Beaverhead Range region. Sixteen microearthquakes were located southeast of the ESRP within the Special Study Area. The aseismicity within the ESRP can possibly be attributed to high crustal heat flow which allows aseismic creep to occur in response to regional tectonic forces, rather than earthquakes. The aseismic behavior of the Lost River, Lemhi, and Beaverhead Ranges northwest of the ESRP may also be associated with aseismic creep or possibly small strain accumulation rates. The very low seismic activity reported in this study is in agreement with the historical record of seismicity compiled for the ESRP region.

MECHANISMS OF THE MINING INDUCED SEISMICITY IN THE BOOK CLIFFS, UTAH

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The Book Cliffs of east-central Utah and the Colorado Plateau is one of the most seismically active areas in the intermountain United States. Several hundred seismic events induced by underground coal mining have been regionally recorded, with the largest approximately M_L 4. Based upon microseismic monitoring (Dunrud et al, 1973; Smith et al, 1974; Arabasz and McKee, 1982), two types of mining induced events are apparent: (1) rockbursts or coal bumps, which occur in the immediate vicinity of the mine; and (2) triggered earthquakes, which occur up to 2 to 3 km laterally from or below the mines.

Two-dimensional finite element modeling of a typical coal mine was performed to evaluate the in situ stress changes induced by mining. Stress increases up to 500 bars caused by stress redistribution and localization occur near pillars and mine faces. Such high stress concentrations are capable of fracturing intact rock and producing rockbursts. The analysis also suggests that the ridge and canyon topography in which the mines are located further concentrates the stresses (compared to a uniformly thick overburden) because lateral support is reduced by the canyons.

Up to 2 to 3 km below the mine, mining decreases the vertical compressive stress over large areas while the horizontal compressive stress remains relatively unchanged or is slightly increased. Such changes are a few bars or less and are thus only capable of triggering displacement on favorably oriented, pre-existing, reverse faults critically pre-stressed by tectonic compressive stresses. Focal mechanisms support the existence of such faults in the Book Cliffs and of a compressive stress field within the Colorado Plateau.

CONTEMPORARY SEISMICITY AND TECTONICS OF THE COLORADO PLATEAU INTERIOR

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The interior of the Colorado Plateau has historically exhibited a low level of small to moderate magnitude seismicity, consistent with the prevalent view of tectonic stablity. However, this observation is based upon a poor historical record and inadequate past seismographic coverage. The recent operation of a 16- to 24-station seismographic network in southeastern Utah in the plateau's interior has revealed low-level microearthquake activity in the vicinity of the network and has allowed improved definition of the seismicity within the plateau.

Since July 1979, an average of 8 microearthquakes per month have occurred in the vicinity of the network, M_L -1 to 2.4. Events have been widely distributed, with some temporal and spatial clustering, most notably along a stretch of the Colorado River southwest of Moab, Utah. Events appear to be occurring on pre-existing Precambrian basement faults that are being reactivated by the contemporary stress field. The Colorado lineament, a Precambrian wrench fault system which has been suggested to extend across the plateau, may be such a major zone of weakness. Focal depths of microearthquakes have ranged from approximately 2 km, the top of the basement, to 20 km. One significant exception is the localized occurrence of several events at the unusual intraplate depths of 30 to 58 km.

Network observations of the plateau interior outside southeastern Utah are consistent with a widely distributed, low level of seismicity of small to moderate magnitude. Several focal mechanisms have been determined that support the view that the plateau interior is being subjected to generally east-west tectonic compression bounded on the west, south and southeast by Basin and Range extension.

LINEAMENTS AT LISBON VALLEY, SOUTHEASTERN UTAH--IF FAULT RELATED, IS THE FAULT SEISMOGENIC?

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In the Lisbon Valley area, a preliminary active fault investigation was recently conducted to identify potential earthquake sources. Distinct co-linear lineaments, similar to those commonly seen elsewhere along active fault zones, were identified within the previously mapped Lisbon Valley fault zone, subparallel to but not coincident with mapped fault traces.

Additional work is needed to assess: (1) whether or not the lineaments are related to a fault, (2) if so, whether the most recent fault displacement cuts existing Quaternary deposits, and (3) if so, whether that displacement is seismogenic. The last question is raised by an evaluation of geologic history of the Lisbon Valley non-diapiric salt anticline, which indicates Cenozoic structural collapse (induced by salt dissolution) subsequent to anticlinal growth in Late Paleozoic/Early Mesozoic. Since the identified lineaments along the fault zone are located within the collapse area, active faulting here may be related to continuing collapse rather than tectonic earthquakes. Given the characteristics of contemporary seismicity and the compressive tectonic stress field of the Colorado Plateau (Wong and others, this meeting) tectonic or earthquake-related displacements are expected to be reverse, or lateral, or both; collapse-related displacements, by contrast, are expected to be normal.

CONTEMPORARY SEISMICITY AND TECTONICS OF THE SOUTH FLANK OF THE UINTA MOUNTAINS, UTAH

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Data recorded during 6 months of microearthquake monitoring in 1980, together with the record of historical seismicity, are used to interpret the contemporary tectonics of the south flank of the Uinta Mountains west of the Uinta River, Utah. Moderate levels of microearthquake activity are shown to be continuing in the epicentral area more than 3 years following the occurrence of a Richter magnitude 4.5 earthquake near Moon Lake, Utah, on 30 September 1977. Composite focal mechanism solutions and the distribution of hypocenters indicate the causative structure is a north-trending normal fault dipping about 40° east that is not expressed at the surface. Additional microearthquake activity was found to be occurring (1) in proximity to the South Flank fault, (2) just outside the array in an area of known bedrock faulting, and (3) randomly within the array. The resolution of these other data does not allow for a determination of their source characteristics.

In contrast to the simple but prominent physiographic boundary defined by the Wasatch fault, numerous researchers have noted that the structural boundary between the Basin and Range province and the Colorado Plateau and Middle Rocky Mountains provinces is complex and transitional and may be migrating eastward. Available crustal seismic refraction data, heat flow measurements, geologic evidence for young faulting, and the historic record of earthquake occurrence all support this concept of a dynamic transitional boundary between these major physiographic provinces. The microearthquake data recorded during 1980 indicate this transition zone extends at least 100 km east of the Wasatch fault or about 20 to 50 km further than was previously recognized.

VERTICAL MOVEMENT ON THE WASATCH FAULT ZONE, NORTHERN UTAH

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Comparisons of first-order National Geodetic Survey (NGS) level surveys on railroad routes along the Wasatch Mountains front between Salt Lake City and Ogden, Utah show that the Wasatch Fault zone experienced at least 80 mm of vertical movement between 1953 and 1967. Similar results are obtained from a comparison of 1958 NGS leveling with 1974 USGS leveling along an east-west line that crosses the fault zone near Ogden. Elevation change and surface tilt of 6 to 30 microradians occur across a zone about 12 km wide, with at least two-thirds of the tilt occurring in the Salt Lake Valley hanging-wall block and about one-third in the Wasatch Mountains foot-wall block. Beyond 6 km from the fault zone, no surface tilt is detected. The pattern of surface tilt suggests block movement with strain confined to the 12-km wide zone. The Salt Lake City to Ogden line shows that this contemporary deformation occurred along at least this 40-km segment of the mountain front.

The east-west line through Weber Canyon near Ogden was last leveled in 1978 by the USGS. The 1974 to 1978 comparison shows a minor tilt of about 1 microradian that involved more of the foot-wall block, and a total tilt of 10 mm down toward the Salt Lake Valley. These data suggest that an episode of rapid strain occurred between 1958 and 1967, with uplift rates of about 6 mm/yr. Between 1974 and 1978, the rates diminished to about 2.5 mm/yr and are more like the long-term Holocene rates reported in a 1980 study by F.H. Swan and others from exploratory trenching of the fault.

The possibility of survey errors and non-tectonic causes of surface tilt are being evaluated, but the magnitude and sense of surface tilt and the coincident results from two independent surveys argue that these are real tectonic movements along a strained normal fault zone.

HIGH-RESOLUTION SEISMIC REFLECTION PROFILES ACROSS LATE PLEISTOCENE AND HOLOCENE FAULT SCARPS IN THE EASTERN BASIN AND RANGE AND THE WASATCH FRONT, CENTRAL UTAH

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High-resolution seismic reflection profiles have been obtained across selected young fault scarps in Utah as part of an effort to better understand the size and subsurface geometry of the faults with which the scarps are associated. An 8 km-long east-west profile across a system of Holocene scarps on the east flank of the Drum Mountains northwest of Delta shows a strong doublet reflector at the west end of the line that is believed to be consolidated rock beneath the alluvium at an approximate depth of 61 m. This reflector is vertically displaced approximately 133 m across a 640-m-wide zone that is coincident with the westernmost major fault scarp. At the east end of the line, an approximately 1-m-high, west-facing fault scarp overlies a zone where the reflector is vertically displaced approximately 66 m. A 450-m-long reflection profile across a 1-m-high fault scarp near Clear Lake, south of Delta, contains numerous prominent reflectors that are displaced vertically about 300 m at a depth of about 2000 m across the fault. Published vibroseis data shows that this fault may be a major graben-bounding fault that extends downward to a major regional detachment fault. A 450-m-long reflection line across an east-facing, 3-m-high scarp at Scipio, Utah shows strong reflectors at an approximate depth of 185 m in the downthrown block that cannot be traced across the fault. Two parallel profiles approximately 0.7 km long, which cross the Wasatch fault zone at Kaysville, Utah show a complex system of faults with a well-developed, 280-m wide graben at the base of the fault scarp.

MICROSEISMICITY OF THE KAIBAB PLATEAU, NORTHERN ARIZONA

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During the summer of 1981, a six-week microearthquake survey was conducted on the Kaibab Plateau, Arizona to evaluate the nature and relationship of seismicity to mapped faults, sense of motion with respect to style of deformation, and changes in the orientation of the stress field from Basin and Range (BR) to Colorado Plateau (CP) tectonic provinces. The portable seismograph network was situated within the eastern portion of the geological and geophysical transition from BR to CP. Several high angle normal fualts which exhibit recurrent movement are mapped in the area including the Sinyala fault, West Kaibab system, and East Kaibab monocline. Portions of these faults exhibit late Quaternary displacement, but the lack of recent sediments limits the dating of the most recent surface rupture. Twelve smoked-paper recording instruments were deployed with a fifteen kilometer station spacing. Sixty usable events ($M \leq 2$), including three swarms were recorded. Preliminary results indicate these are shallow crustal events (depth $\leq$ 12 km) occurring near the intersection of the Sinyala and West Kaibab faults. Single event and composite fault plane solutions indicate high angle, normal faulting on east to east-northeast trending faults. Thus in the Kaibab Plateau, the BR to CP transition is marked by low to moderate shallow seismic activity and a north-northeast trending least compressive horizontal stress.

MICROSEISMICITY IN THE ST. GEORGE REGION, SOUTHWEST UTAH - NORTHWEST ARIZONA

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A 16 station portable seismic network was operated for 6 weeks during June and July, 1982 in the St. George area of SW Utah and NW Arizona. The objectives of the study were: 1) to observe the relationship of the seismicity to mapped faults, 2) to infer the style of deformation of the faults, and 3) to determine the orientation of principle stresses in relation to the Northern Basin and Range (NBR) and the Intermountain seismic belt (ISB). The study area is just west of the Hurricane fault system and may encompass the transition between the ISB and the NBR. The style of deformation changes from near vertical fault planes indicative of E-W extension in the southern ISB to normal and strike-slip faults with NW-SE extension in the NBR.

Vertical-component, smoked drum seismographs were employed in a roughly rectangular array with station spacings of 5-10 km. Instruments were moved systematically throughout the experiment, occupying 45 sites. Station spacing was decreased in areas of observed activity to improve location accuracy.

The northern parts of the Grand Wash and Washington faults were covered by the survey as well as a zone of E-W faults at about 37°30'N. The latter were the most seismically active within the area. Over 40 microearthquakes were recorded during the study in addition to several swarms, one of which lasted 3 days and included $\geq$ 40 events. From these events, fault plane solutions will be determined to clarify the style of faulting and the orientation of principal tectonic stresses within the study area.

AUTHOR INDEX

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