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# EARTHQUAKE SOURCE MECHANISMS AND PLATE TECTONICS

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This review and the accompanying references will be concerned mainly with earthquake source studies pertinent to plate tectonics. Studies on geological problems, lithospheric flexure and mantle convection are discussed in other reviews in this volume.

In the earlier stage of the development of plate tectonics, the distribution of earthquakes and the geometrical configuration of earthquake source mechanisms played an important role. As more sophisticated techniques for retrieving earthquake source parameters (synthetic seismogram method for both body and surface waves, inversion method, matching filter method, etc.) were developed, emphasis in the last four years was placed on the determination of not only the geometry of the source but also more quantitative parameters such as the stress drop, the amount of slip, the complexity, the strength of non-isotropic components, and the spectral characteristics. Also significant emphasis was placed on intraplate earthquakes and events on continental plate boundaries.

The results for the individual earthquakes are of fundamental importance for developing and constraining various plate tectonics models. For example, a number of mechanism solutions have been included in the new synthesis of global plate motion [Minster and Jordan, 1978]. Since it is not practical to review the results for the individual events, a fairly complete list of the papers pertinent to the source mechanism study is prepared and listed in the reference.

The orientation and the magnitude of the stress associated with intraplate events are among the key parameters in constraining the driving mechanism of plates [e.g., Solomon et al., 1975; Richardson et al., 1976]. Richardson et al. [1976] found that intraplate stresses calculated for models in which viscous drag at the base of the lithosphere acts in the direction of absolute plate velocity are in much poorer agreement with observed stresses than are those for models in which drag resists plate motions.

Sykes [1978] summarized the distribution of intraplate earthquakes and of igneous rocks in a plate tectonic framework. One of the conclusions is that intraplate earthquakes tend to be concentrated along preexisting zones of weakness within areas affected by the youngest orogenesis that predates the opening of the present oceans.

Because of the difficulty of determining the fault dimension of intraplate events, the estimates of stress drop are still uncertain. Existing data indicate [e.g., Kanamori and Anderson, 1975; Richardson et al., 1977] that although the stress drop of intraplate events may be slightly (factor of 2 or 3) higher than that of inter-plate events, no order-of-magnitude difference exists between them. A relatively low stress drop, about 100 bars, for intraplate earthquakes is consistent with inferences from current models of the plate tectonic driving mechanism. Some questions have been raised about whether intraplate events represent the state of stress in the plate or the effect of local topographic features in the plate [Stein, 1978].

A large number of studies were made on seismotectonics of various regions. Papers on this subject are listed in the reference under category "Regional Tectonics". A recent development in this field is the study of continental tectonics [e.g., Molnar and Tapponnier, 1975; Bird et al., 1975; Chen and Molnar, 1977; Menke and Jacob, 1976; Armbruster et al., 1978; Chandra, 1978].

Armbruster et al. [1978] studied the northwestern termination of the Himalayan mountain front and found that the composite mechanisms of earthquakes in this area are compatible with the north-south convergence between the Indian and Eurasian plates inferred from plate tectonics.

Molnar and Tapponnier [1975] concluded on the basis of geomorphological and seismological evidence that the large-scale tectonics of Asia are a result of the India-Eurasia continental collision. They interpreted the marked decrease in the relative motion between India and Eurasia to be a result of the collision.

The amount of seismic slip along plate

boundaries has been determined from the seismic moment of large earthquakes [Kanamori, 1977]. A substantial discrepancy between the computed seismic slip rate and the rate inferred from the instantaneous plate motion has been found for some plate boundaries. This discrepancy suggests that either a large part of plate motion at plate boundaries is aseismic or the current plate motion is substantially different from that inferred from plate tectonics. For several earthquakes, evidence has been presented for the existence of large amounts of aseismic motion suggesting that slip at plate boundaries does involve aseismic motion [Kanamori and Anderson, 1975; Thatcher, 1975; Sacks et al., 1978; Kanamori and Stewart, 1979]. On the other hand, hang-up of plate motion due to subduction of buoyant oceanic lithospheres has been suggested to account for the lack of great earthquakes along some plate boundaries (e.g., the Marianas) [Kelleher and McCann, 1976; Vogt et al., 1976].

The relation between large earthquakes and various global processes such as rotation of the earth, the earth's polar motion including Chandler wobble and transient plate motions has been a subject of vigorous research [Anderson, 1975; Press and Briggs, 1975; O'Connell and Dziewonski, 1976; Smith, 1977]. It appears that the effect of earthquakes, with their seismic component alone is too small to affect the earth's polar motion significantly. Wilson and Haubrich [1977] concludes that the earthquake portion of the Chandler wobble excitation is smaller than 25% while the contribution of meteorological variation appears to be not less than 25%. However, in view of the possible aseismic component of earthquake deformation, a causal relation between earthquakes and Chandler wobble should not be completely dismissed [O'Connell and Dziewonski, 1976].

The response of the viscous asthenosphere to the transient displacement caused by a large earthquake has been studied in order to determine the constitutive law for the asthenosphere and its effective viscosity [Anderson, 1975; Melosh, 1976; Savage and Prescott, 1978; Thatcher and Rundle, 1979]. Anderson [1975] used a simple model of an elastic lithospheric plate riding on a viscous asthenosphere to show that most of the plate motions near plate boundaries occur during short periods of time after a large decoupling earthquake. This accelerated plate motion may have a significant effect on the excitation of Chandler wobble.

Melosh [1976] used a migration pattern of the aftershocks of the 1965 Rat Is. earthquake to determine the constitutive law for the asthenosphere and concluded that a nonlinear constitutive relation $\dot{\varepsilon}$ (strain rate) $\sim$ $\sigma$(stress)$^n$ ($n = 3$ to $4$) is most appropriate. However, Savage and Prescott [1978] argue that a linear model is capable of producing the observed migration pattern. In order to resolve this problem, direct measurements of transient deformation after a large decoupling earthquake would be extremely important.

Rundle and Jackson [1977] and Thatcher and Rundle [1979] used a viscous asthenosphere model to explain the time dependent deformation after the 1906 San Francisco earthquake and the 1946 Nankaido earthquake.

Development in the method of earthquake location (e.g., master-event method, relative-location method, joint-hypocenter determination) allowed a very high resolution analysis of the geometry of various seismic zones, in particular Benioff zones [Billington and Isacks, 1975; Barazangi and Isacks, 1976; Engdahl, 1977; Isacks and Barazangi, 1977; Cardwell and Isacks, 1978]. One of the significant results is the discovery of lateral segmentation of Benioff zones in South America. Isacks and Barazangi found a remarkable correlation between a nearly flat Benioff zone beneath South America and the absence of Quaternary volcanoes.

James [1978] proposed an alternative model in which the Nazca plate dips at an angle of about 30°. This model is based on the depth of the upper boundary of the descending plate inferred from converted seismic phases and on the anelasticity structure of central Peru [Snoke et al., 1977; Sacks, 1977]. James argued that whether the Benioff zone beneath central Peru is flat or not is not yet resolved.

Mechanism studies of great earthquakes suggest that truly great earthquakes occur only in subduction zones without actively opening back-arc basins while subduction zones with active back-arc basins are completely lacking in great earthquakes. Uyeda and Kanamori [1979] interpreted this correlation in terms of either a difference in the degree of intra-plate coupling or a difference in the velocity of the landward plate.

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# EARTHQUAKE PREDICTION

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Earthquake prediction, hardly taken seriously as science in the United States before 1971, reached fledgling status in the period 1975 to 1978. By late 1974, most U.S. researchers in seismology were agreeing that earthquakes might be predictable on a scientific basis. Cautious optimism had in fact turned to rampant enthusiasm among some workers as evidence accumulated for many possible earthquake precursors and the theory of dilatancy seemed to explain most observations (see summaries by Bolt and Wang, 1975; Healy, 1975; Kisslinger and Wyss, 1975). Slower progress since 1974 has dampened the euphoria felt by some but a much more solid and broad foundation for a Prediction Program has now been constructed and a number of important cornerstones laid.

A new sense of urgency and relevancy for prediction research was created in December, 1975, when Castle et al. (1976) presented evidence that the elevation of a 12,000 square kilometer area in southern California had increased by 15 to 25 cm during the 1960's. Because this uplift lay astride a section of the San Andreas fault that has been essentially aseismic since a devastating earthquake in 1857 and because uplifts have been reported before other damaging earthquakes (e.g. Castle et al., 1974), the ominous suggestion was made that this uplift could be precursory to the next great California earthquake. Although scientists could not and still cannot be sure that the uplift is a precursor, concern was expressed from households in the uplifted area all the way to the White House and research scientists were suddenly asked to interact closely with public leaders, news media, and the general public. Staff of the U.S. Geological Survey (USGS) were invited to brief the President's Advisory Panel on Anticipated Advances in Science and Technology. The Director of the USGS met with the staff of the Governor of California to discuss implications of the observed uplift. The USGS and the National Science Foundation (NSF) were asked to transfer, for one year, $2.6 million from other programs over to earthquake research related to the Southern California Uplift and to develop a rationale for a national Earthquake Hazards Reduction Program (EHRP). A panel, convened by the President's Science Advisor, issued such a rationale (anonymous, 1976), which, together with the initiatives of Congress and the feeling of most seismologists that substantial progress was possible, helped bring about a threefold increase in funds during 1978 (Hamilton, 1978). Funding for earthquake prediction increased to a national level of $15.8 million, and the level of effort in the whole Earthquake Hazards Reduction Program funded by the USGS and NSF rose to a total of $53.2 million including prediction, hazards assessment, earthquake engineering, induced seismicity, fundamental studies of earthquakes, and research on how to stimulate the utilization of scientific results by the general public as well as studies of the socioeconomic impact of predictions.

Continued analysis of the uplift showed that between late 1972 and early 1974 the area of uplift increased to more than 50,000 square kilometers and the maximum uplift reached 45 cm (Castle, 1978; Holdahl, 1977). Then, by 1976, the whole area subsided to less than 50 percent