SEISMOTECTONIC ZONING USING THEORETICAL MECHANICS

by

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SYNOPSIS

Theoretical mechanics, based on theories of plasticity and elasticity, is a powerful tool for defining tectonic zones and style of deformation. The mathematical arguments of theoretical mechanics describe stress distributions which can be used to define fault patterns and areas of relative seismicity.

One applicable model of theoretical mechanics is the Prandtl cell, based on the theory of plasticity. Its mathematical arguments were applied to several geologic areas in the world. These areas have a distinctly different tectonic fabric and lower level of seismicity than the surrounding areas. The theory is consistent with observed tectonics and seismicity and may be used for prediction.

INTRODUCTION

Seismic zoning is required as a basis for the development of seismic design criteria. Sources of information for seismic zoning have included: locations and intensities of historical earthquakes, focal mechanism solutions of earthquakes, seismic moment and stress-drop calculations, and locations of active and potentially active faults. Other geological and geophysical data such as thermal, gravity, and magnetic gradients have supplemented the data base. These data provide bases for defining seismotectonic zones of specific seismicity, which in turn lead to the establishment of criteria for seismic design.

An additional and powerful tool for defining seismotectonic zones comes from theoretical mechanics. Models from theories of elasticity and plasticity were used to rigorously describe tectonic characteristics in two areas of the western United States; the results were extrapolated to seismically zone these areas[1]. Knowledge of the mechanics of deformation provides a better understanding of the nature of faulting and seismic activity. The theoretical models generated from theories of elasticity and plasticity can describe the magnitudes, distributions, and orientations of stress which result in faulting as well as the orientations of and sense of movement along those faults. The boundary conditions used to define the theoretical models come from the geological, geophysical, and seismological data base. This paper describes the application of a particular theoretical model described by Prandtl[2] based on the theory of plasticity, to describe the sesimotectonic setting of several geologic areas. The boundary conditions imposed by the geologic constraints required modification of Prandtl's original solution.

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THEORETICAL MODEL

The model is based on a two-dimensional analysis in theory of plasticity, Prandtl's compressed cell (Figure 1, I). A three-dimensional model might better explain the geologic and seismic data, but such a model could not be derived from the present knowledge of theory of plasticity. In addition, a three-dimensional model is not warranted with the available data.

The Prandtl cell consists of an ideally plastic mass compressed between two parallel rigid plates (Figure 1, I). As the plates are compressed, the plastic material flows in one direction and yields along two sets of isogonal trajectories of maximum shear stress (slip lines). Prandtl used the von Mises yield criterion; the slip lines are orthogonal cycloids. The orientation of and sense of movement along slip lines of the theoretical model are analogous to those of the faults in the geologic case.

Prandtl's original solution has been modified to accommodate different boundary conditions[3,4,5,6,7]. For example, the plates may be non-parallel; they may move toward or away from each other and the plastic mass may move toward or away from the apex of the wedge. The geometry of the slip lines is different for the four possible cases (Figure 1, II). The choice of the model to be applied depends on the boundary conditions prescribed by the geology (orientations of and sense of movement along the faults, regional stress distribution, direction of movement of the plastic mass, and so forth). The orientations of and sense of movement along the slip lines depend on (1) whether the plates move toward or away from each other and (2) whether the material between the plates moves toward or away from the apex of the wedge.

The distribution and magnitudes of the compressive stress along the boundary plates and along the open ends are shown in Figure 1. The value of the shear stress along the boundary is a constant and is the maximum shear stress. Consequently, the contact between a boundary plate and the plastic mass is a slip line; the important geologic implication is that faults can be used as boundaries for the theoretical models. The relative strike-slip movement along each family of slip lines within the plastic mass is the same as that along one of the boundaries into which those slip lines merge; the boundary is a member of that family of slip lines. Justification of the Prandtl cell to geologic cases, including choices of boundary conditions, is given elsewhere[5,6,7].

APPLICATION OF THEORETICAL MODEL TO SELECTED GEOLOGIC CASES

The theoretical model is applied to five geologic areas; other areas exist where the model also appears to fit the geology. The areas described below are listed in decreasing order of available geological, geophysical, and seismological data. The areas that are well documented fit the theoretical model very well. The areas that have relatively little information nevertheless provide certain necessary boundary conditions from which we can choose one of the four possible cases; future work may provide geologic information which could modify the proposed model but should not change the basic concept.

All of the areas to which the model applies have similar geologic characteristics. The tectonic fabric within each area is internally consistent and markedly different from that of the surrounding area. The age of faulting within the area is the same as the boundary faults. Each area has a lower level of seismicity than the boundary faults and the surrounding areas.

The tectonic fabric of each area, boundary conditions, and so forth, are consistent with one of the four modifications of the Prandtl cell.

Mojave Desert Block, California

The first geologic area to which the theoretical model is applied is the Mojave Desert Block, southern California. Figure 2a shows the fault pattern; Figure 2b shows the theoretical model (Case B, Figure 1, II) superposed on the fault pattern. Details of the analysis are given elsewhere[6].

The pattern of seismicity indicated in Figure 2c shows a greater seismicity outside of and along the boundary faults than that inside the wedge. Very few earthquakes occur near the apex of the wedge compared to the open end. These distributions are all consistent with the mathematical solution of the theoretical model.

Lut Block, Iran

The fault pattern of the Lut Block is shown in Figure 3a; Figure 3b shows the theoretical model (Case C, Figure 1, II) superposed on the fault pattern. Details of the analysis are given elsewhere[7].

The pattern of seismicity indicated in Figure 3c is consistent with the mathematical solution of the theoretical model. The earthquake swarm near the apex of the wedge is biased by the 1968 Dasht–E–Bayaz earthquake.

Anatolia Area, Turkey

The fault pattern and seismicity of the Anatolia Area is illustrated in Figure 4. The theoretical model (Case B, Figure 1, II) fits the fault pattern.

The pattern of seismicity is consistent with the mathematical solution of the theoretical model. The model may also be used to predict the orientations of and sense of movement along as yet unrecognized faults within the wedge.

Pakistan Area: Herat Fault–Quetta–Chehan Fault

Although the geologic and seismic information for the area is relatively poorly documented (Figure 5a, b), the available data indicate that Case A (Figure 1, II) provides a good fit.

The pattern of seismicity and faulting can be predicted from the theoretical model.

West Tibet Area: Altyn Tagh Fault–Karakoram Fault

The geologic and seismic information for this area is also relatively poorly documented (Figure 5a, b). Here again, the available data indicate that Case A (Figure 1, II) provides a good fit.

The pattern of seismicity and faulting can be predicted from the theoretical model.

APPLICATION TO SEISMIC ZONING

Regional seismic zoning can be described for the areas discussed above. The area between the boundary faults has a level of seismicity lower than these faults and lower than the areas outside the boundaries. The boundary faults have a level of seismicity higher than the area outside the cell. The pattern of seismicity results from the modification of the regional stress by the boundary faults and the ensuing orientation of these stresses.

Orientations of and sense of movement along future faults within the boundaries will follow the orientations of the theoretical stress trajectories. If the area has one boundary fault more active than the other, the preferred orientations of future faults will conform to that family of stress trajectories which contain the boundary as a member[6].

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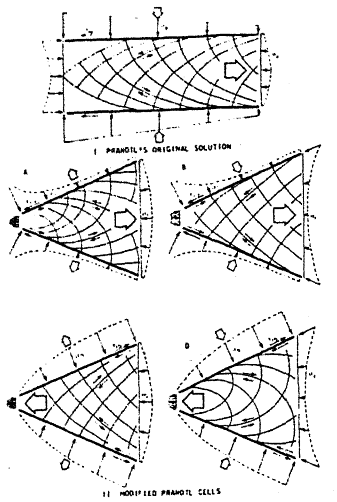

Fig. 1. Theoretical Models based on Prandtl's compressed cells (After Cummings 1976a with permission Geol. Soc. America, Ref. 6)

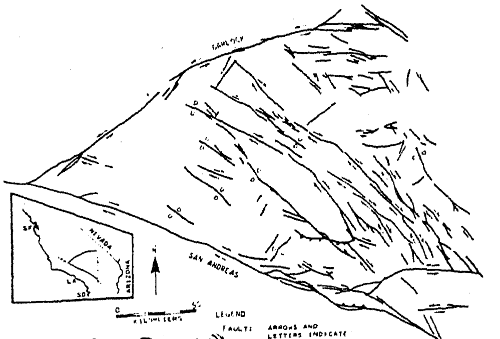

Fig. 2a. Fault Map, Mojave Desert Block, California (After Cummings 1976a with permission Geol. Soc. America, Ref. 6)

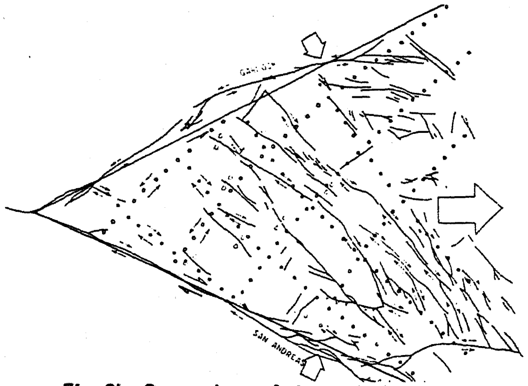

Fig. 2b. Comparison of theoretical model to fault pattern, Mojave Desert Block, California (After Cummings 1976a with permission Geol. Soc. America, Ref. 6)

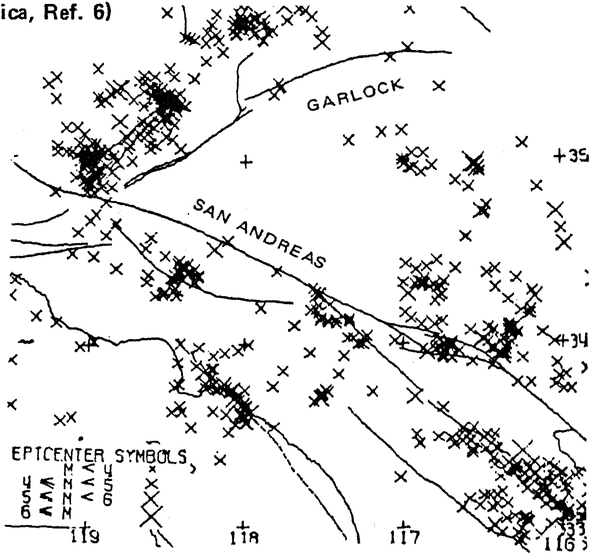

Fig. 2c. Epicenter Map 1932-1972, Mojave Desert Block and Vicinity, California (Ref. 8)

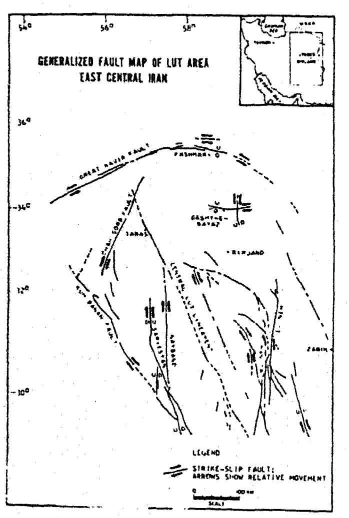

Fig. 3a. Fault Map, Lut Block, Iran (Ref. 9)

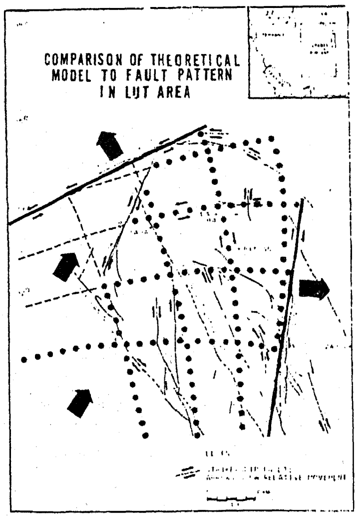

Fig. 3b. Comparison of theoretical model to fault pattern, Lut Block, Iran (Ref. 9)

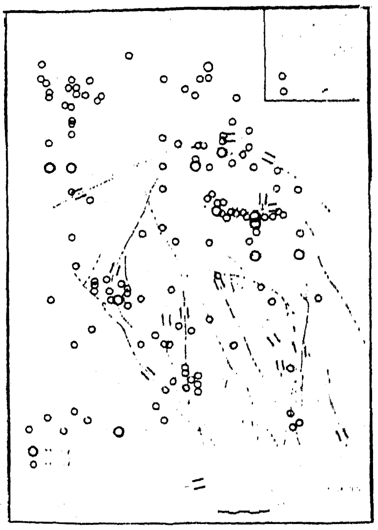

Fig. 3c. Epicenter Map 1900-1974, East-central Iran (Ref. 10)

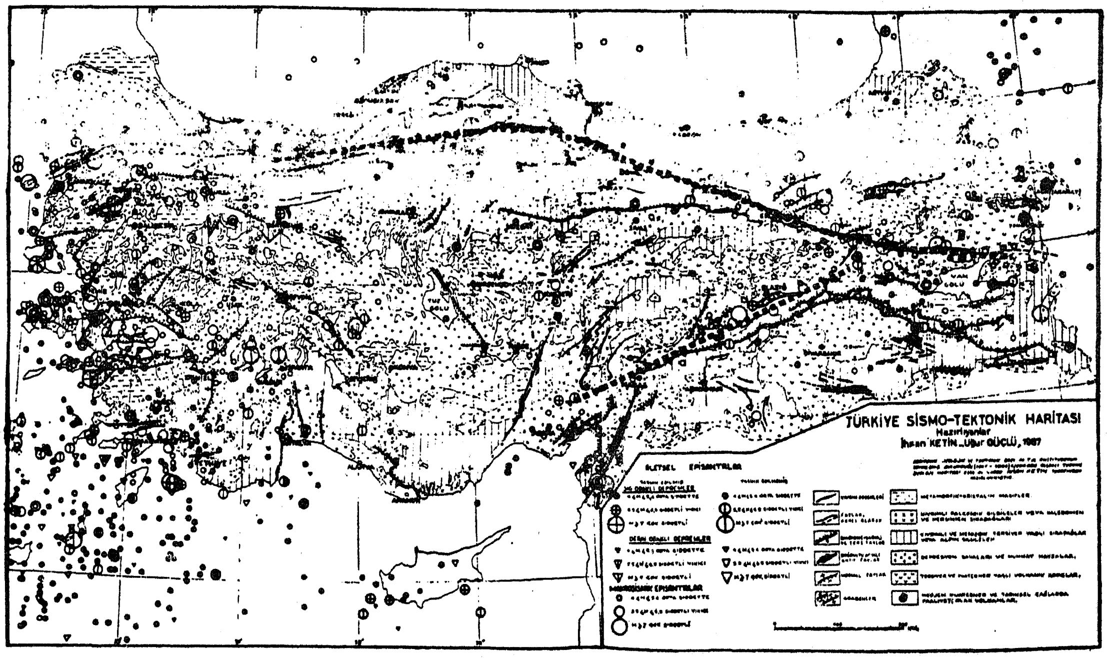

Fig. 4. Seismotectonic Map, Anatolia Area (Ref. 11)

Dashed lines indicate boundaries of model along the North and East Anatolia Faults

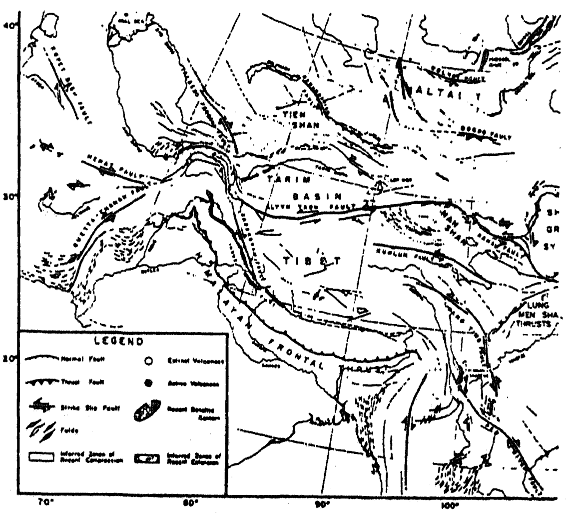

Fig. 5a. Tectonic Map, Pakistan-Tibet Region (Ref. 12)

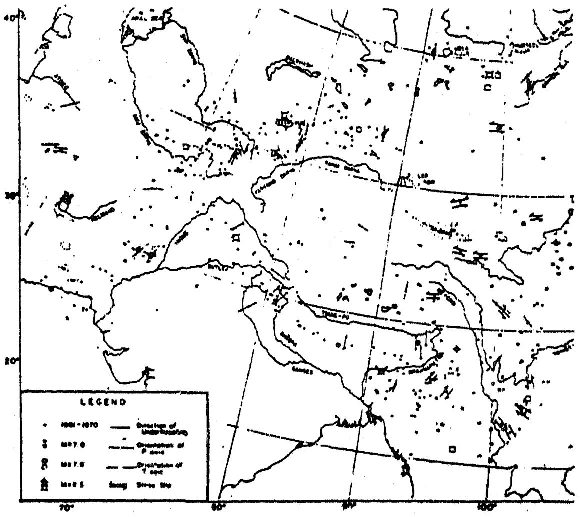

Fig. 5b. Epicenter Map, 1961-1970, Pakistan-Tibet Region (Ref. 12)

DISCUSSION

J.C. Stepp (U.S.A.)

How are the theoretical stress orientations derived from your model related to actually measured tectonic stress orientations ?

Author's Closure

With regard to the question of Mr. Stepp, we wish to state that we are not aware of any published or in-progress work that describes or cites either in situ or laboratory stress measurements for any of the geographic areas discussed in our paper. However, the many published fault plane solutions based on earthquake data are consistent with the orientations and sense of movement along the theoretical stress trajectories.