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THE INTERSECTION MODEL FOR INTRAPLATE EARTHQUAKES

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ABSTRACT

The tectonic cause of intraplate earthquakes has remained enigmatic. As newer data became available, several common features were apparent for intraplate earthquakes occurring in a wide variety of geologic terranes. These have been incorporated in the intersection model. Seismicity occurs near the intersection of, and by the reactivation of, preexisting zones of weakness. The intersections are the foci of anomalous stress build up in response to the ambient stress field due to plate tectonic forces. This anomalous stress build-up is relieved by strike slip motion on a suitably oriented fault and, due to kinematic adjustment, is followed by vertical or horizontal movement on the intersecting fault. The intersection model has several elements that complement other models proposed to explain intraplate earthquakes.

INTRODUCTION

Intraplate earthquakes occur much less frequently than those at plate margins. Although they have a larger potential for destruction, their cause and nature are not well understood. In many locations of intraplate earthquakes high quality seismic networks have been in operation for a little over a decade. The pattern of epicenters located before the installation of permanent or portable networks tended to be diffuse. However, with network deployment and the collection of additional geophysical, geologic and seismicity data, it is becoming possible to define the seismogenic features and their temporal and spatial pattern of seismicity. In central and eastern United States, where historical data cover only two or three hundred years, a comparison of epicentral locations determined by seismographic networks and those based on historical records indicates a stationary pattern of seismicity (at least in the short historical span).

Intraplate earthquakes occur in a variety of geological terranes, and in rocks of different ages. A review of various case histories of intraplate earthquakes where high quality data are available suggests that they have many common features. They do not occur randomly; they occur by the reactivation of identifiable, preexisting zones of weakness in response to an ambient plate tectonic stress field. From a purely rock mechanics sense we would expect shear failure to occur on a suitably oriented preexisting fault more easily than by fracture of intact rock. Evidence of reactivation of preexisting faults is found at several locations, e.g. the reactivation of preexisting faults in the New Madrid area (Illies, 1982; Braile *et al.*, 1986), the Rhine Graben (Ahorner, 1975; Illies and Greiner, 1978) and the Charlevoix and Miramichi seismic zones (Hasegawa, 1986).

By preexisting zones of weakness, I do not mean weak, heavily deformed fault zones such as the San Andreas fault zone; rather, I mean inherently strong edges of blocks, dikes, etc., which provide suitable planes on which adjacent rock masses can move against each other. Although we would expect fault gouge to be present between rock masses that move against each other, direct evidence for it is lacking.

Based on these observations, I propose an empirical model, the intersection model, to explain the location of intraplate earthquakes. Many models have been suggested to explain these earthquakes; see e.g. Talwani (1983, 1985, 1988) and Dewey (1985) for reviews of some of the proposed models. The proposed intersection model has many elements that complement one or more essential elements of the other models, and it is likely that some of the physics involved in the localization of intraplate earthquakes at intersections may also be applicable to other models.

BASIS FOR THE MODEL

The configuration of the faults and other tectonic features for five intraplate earthquakes are shown schematically in Figure 1. In each case the sense of displacement on the faults was obtained from focal mechanism solutions. In order to compare them, the figures were arranged so that in each case the direction of maximum horizontal compression (S_H) was along the abscissa. Although the quality of geophysical and seismological data vary considerably from one location to another, these figures are representative of the actual situation. The earthquakes were chosen to cover a magnitude range from 5 to 8. Geographically the earthquakes occurred in the United States, China, western Europe and western Africa in rocks of disparate ages -- from Pre-Cambrian to Mesozoic. The objective was to show the similarity in the geometry of the features and their independence from geography, lithology or age.

In the New Madrid seismic zone the epicenters of instrumentally located microearthquakes define linear trends, which, together with the results of focal mechanism studies, were used by Russ (1982) to define a simple geometric framework to explain the Lake County uplift. In Figure 1A (modified from Russ, 1982) the two NE trends (SW from Ridgely and NE from Lilbourn) are both associated with dextral faulting, whereas the NW trend between these two towns,

.d along the axis of uplift, is associated with reverse ıulting. Recent data (Stauder *et al.*, 1988) suggest that .eismicity in the NW segment extends farther to the NW and SE. Nuttli (1973) located the three great earthquakes in the 1811-1812 sequence based on intensity data. His locations would be consistent with the events occurring on each of the three fault segments. It is also possible that the intersections of fault segments which are associated with a large number of small events (Figure 2) are the locations where a seismic sequence starts. The seismicity then spreads along a fault terminating in a main shock.

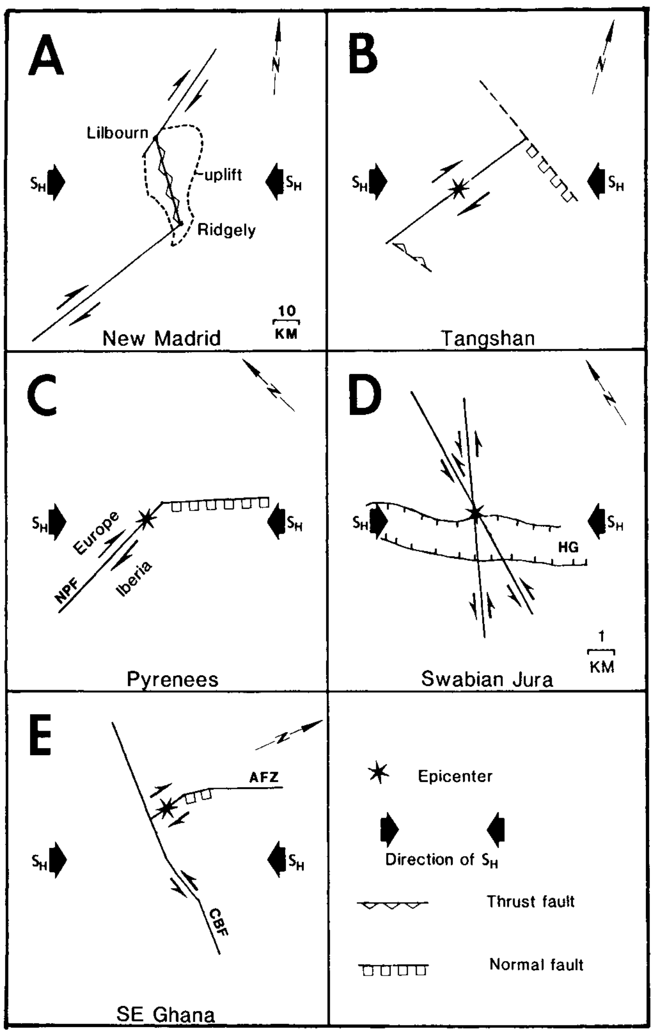

Fig. 1. Schematic illustration of seismotectonics/earthquake sequences. A) New Madrid (Russ, 1982). B) Tangshan, China (Butler *et al.*, 1979). C) Pyrenees (Gagnepain-Beyneix *et al.*, 1982). D) Swabian Jura (Turnovsky and Schneider, 1982). E) SE Ghana (Bacon and Quaah, 1982). The main shock (asterisk) results from a release of stress concentrated at the intersection due to plate tectonic forces (thick arrow). The strike slip motion associated with the main shock is followed by thrust (New Madrid, Tangshan), normal (Tangshan, Pyrenees, SE Ghana) or strike slip (Swabian Jura, SE Ghana) faulting on adjacent faults.

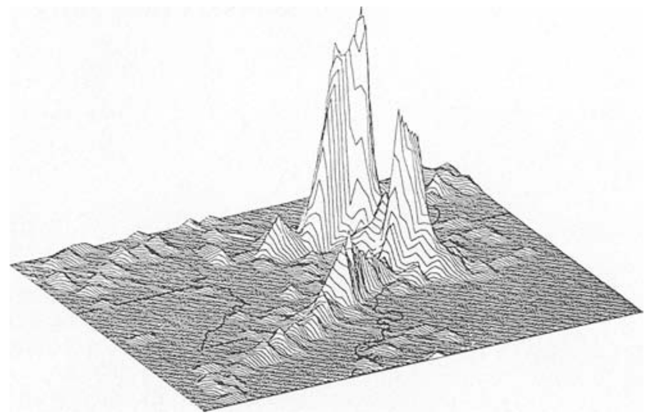

Fig. 2. Computer generated plot showing the number of earthquakes in the New Madrid seismic zone. The height of the peak is proportional to the number of events (from Johnston, 1982). Note the two peaks in activity at the intersections of the two NE fault segments with the central NW segment. The thick lines outline the state boundaries.

Figure 1B taken from Butler *et al.* (1979) shows schematically the inferred seismotectonics of the M_S 7.7 Tangshan, China earthquake and its aftershocks. According to the authors, the main shock, associated with dextral motion on a NE striking fault, was followed by thrusting events to the south, and later by a large aftershock associated with normal faulting on a NW structural boundary.

The February, 1980 magnitude 5.1 event occurred in a seismically active zone at the northern edge of the Pyrenees range (Figure 1C) (Gagnepain-Beyneix *et al.*, 1982). The main shock and most of the early aftershocks occurred on the E-W North Pyrenees fault (NPF) -- a possible transform fault separating European and Iberian blocks. The early aftershock activity migrated to the east and west along the NPF, and was associated with right lateral strike slip faulting. Subsequently, the aftershocks migrated to the southeast (along a NW-SE preexisting fault) and were associated with normal faulting.

Focal mechanism studies by Turnovsky and Schneider (1982) of the September, 1978, magnitude 5.1 earthquake in Swabian Jura in southwestern Germany, and its aftershocks revealed two dominant directions of faulting ($N7^o$E and $N22^o$E). The main shock and most of the aftershocks were associated with left lateral strike slip faulting. The main shock occurred near the NW flank of the shallow Hohenzollern graben (HG) and its junction with the two underlying deep NE trends (Figure 1D, modified from Turnovsky and Schneider, 1982).

Historically, SE Ghana has been the site of several destructive earthquakes including the magnitude 6.5, 1939 Accra earthquake. Bacon and Quaah (1981) found that the current seismicity was concentrated near the intersection of the NNE trending Akwapin fault zone (AFZ in Figure 1E) and the almost E-W, offshore, Coastal Boundary fault (CBF). The AFZ, a possible suture zone of Pan-African age is thought to be the landward extension of the Romanache fracture zone (RFZ) (Blundell, 1976). The 1939 event was located teleseismically SE of the intersection and was associated with dextral faulting on a N-S fault plane. Based on field evidence and isoseismal data, these authors argued that the epicenter was on the AFZ and to the north of the junction (Figure 1E). The location of an event in 1969 was not well constrained and may have been associated with sinistral faulting on the CBF, whereas recent seismicity (1977-80) was located further north on the AFZ and was associated with normal faulting.

Common Features

In all the examples above, chosen for their diversity (and several others in the literature), intraplate earthquakes occurred by the reactivation of preexisting zones of weakness, and the main shock was located near the intersection of two or more faults. The main shock was associated with strike slip faulting, the sign of which (dextral or sinistral) depended on the orientation of the fault with respect to S_H. The aftershocks were associated with large components of normal, reverse or strike slip motion, depending on the orientation of secondary faults, and the sense of kinematic adjustment that followed the main shock.

Laboratory Data

The results of some photoelastic experiments by Pain (1979) as reported by Ma *et al.* (1982) are shown in Figure 3. He studied the stress build-up in rocks with parallel and intersecting fractures under uniaxial compression. The contour values indicate the magnitude of the stress. He found that the stress build-up depended on the length of the fracture, size of the locked area and duration of the applied stress. Other factors being the same, the stress amplification at the intersections was significantly greater than at the ends of single faults (Figure 3). Many other laboratory workers have observed the anomalous build-up of stress near the edges of fractures (e.g. Duda, 1985; Bombolakis, 1968; Shamina *et al.*, 1985). However, unlike Pain's experiments, they did not compare this stress build-up with that at intersecting fractures.

Summary

So we have a three-fold basis for the proposed model. A review of several case histories in different geologic settings and where good geophysical, geological and seismological data are available, the intraplate earthquakes appear to nucleate near the intersection of preexisting zones of weakness (Figure 1). For at least one case, where detailed seismicity data are available, there are a large number of earthquakes located where the fault segments intersect (Figure 2). Finally, the results of photoelastic experiments also suggest that intersections are the loci of anomalous stress build-up (Figure 3).

These observations were used to propose the intersection model for intraplate earthquakes. (Other indications of anomalous stress build-up near intersecting faults are in the rock mechanics and mining literature and will not be presented here because of space limitation.)

THE INTERSECTION MODEL FOR INTRAPLATE EARTHQUAKES

Many elements of this model are similar to that proposed by the author (Talwani *et al.*, 1979) and that proposed by Illies (1982). The earthquakes lie at or near the intersection of, and occur by the reactivation of, preexisting zones of weakness. One of these zones of weakness is regional in scale, and may include fissures, breccias, hydrothermal veins, etc. These are associated with sub-vertical discontinuities usually accompanied by, or offsetting, gravity and magnetic anomalies. The intersecting zone is not necessarily regional in scale, and may be local in nature, e.g. the boundary fault of a buried basin. Or, it may be long, such as a major tectonic boundary or ancient suture zone. The vertical intersection which forms the boundary of crustal blocks provides a locus of the large earthquake. The block boundaries often separate rocks with different rheological properties, and are associated with increased density of fractures.

Stress build-up on a fault plane has often been observed, and Kanamori's (1981) asperity model offers a possible explanation. However, unlike the asperity model, where stress concentrations occur at strong patches on a fault *plane*, here we envisage a stressed *volume*. The intersecting faults form a locked volume

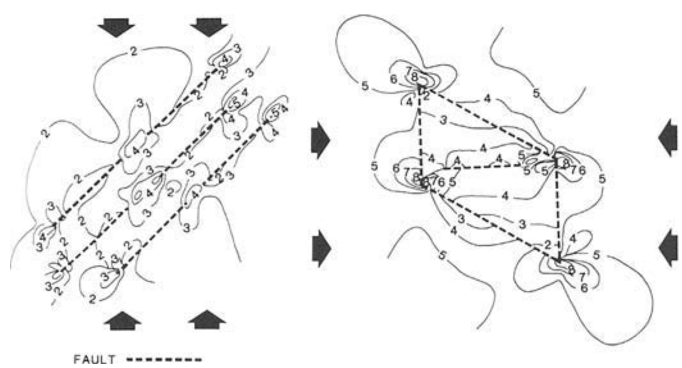

Fig. 3. The results of photoelastic experiments on rocks undergoing uniaxial compression. On the left is a rock with preexisting parallel fractures, on the right, a rock with intersecting fractures. The regions at the end of the fractures are locked. Solid arrows show the direction of uniaxial compression. The contours show the build-up of stress at the ends of fractures. Note the larger build-up when the locked portions are at the intersections of fractures (from Pain, 1979; quoted in Ma *et al.*, 1982).

where there is a stress build-up in response to the ambient stress field due to plate tectonic forces. The size of the anomalously stressed volume and the amount of stress build-up depend on several factors, including the length and depth extent of faults, their rheological properties, orientation with respect to S_H, etc. Because the movement on one fault is inhibited by the intersecting fault, stress large enough to generate major intraplate earthquakes can build up at intersections. (In the absence of intersections, faults can slip at a lower stress threshold, generating microearthquakes.) When the stress build-up is large enough to overcome the frictional and mechanical resistance at the locked fault, major intraplate earthquakes occur. The faulting usually starts on one fault plane in the vicinity of the intersection, and, due to movement on it, triggers movement on the adjacent fault. Although it is not clear why, the general observation is that in most cases, the main shock is associated with strike slip faulting. Due to kinematic adjustments, movement on the intersecting faults can be vertical (e.g. Tangshan, New Madrid, etc.) (Figure 4), or horizontal (Swabian Jura). The result over geologic times of continuous strike slip movement on a fault is not clear. It would tend to alter the fault geometry in the vicinity of the intersections, perhaps, by developing local depressions or uplifts. The intersections also help to localize seismicity, and as King (1986) noted, form the nucleation points of new ruptures.

COMPARISON WITH OTHER MODELS

In a recent review of the characteristic features of intraplate earthquakes and models proposed to explain them, Talwani (1988) suggested that the reactivation of preexisting faults occurs by one or more of three ways. These include a localized stress build-up on a potentially seismogenic feature due to the ambient stress field, the superposition of triggering stress and by mechanical and/or chemical means. The various models that have been suggested to explain intraplate earthquakes contain one or more of these elements.

Models in the first category include stress amplification near plutons (e.g. Campbell, 1978), the initiation and termination of seismicity at fault bends (King, 1986), the concentration of stress at intersections of seismogenic features (the intersection model) and stress build-up on faults due to localized strain in the mid-lower crust (Kunze, 1982; Zoback *et al.*, 1985). In the second category are triggering stresses due to glacial rebound (Stein *et al.*, 1979; Quinlan, 1984) and due to lateral variations in density (Goodacre and Hasegawa, 1980). In the third category which is an extension of the mechanism of reservoir induced seismicity (Talwani and Acree, 1985) to subcrustal depths, failure occurs by the reduction in strength of rocks by mechanical or chemical means. This is the hydroseismicity model of Costain *et al.* (1987).

The intersection model has many elements which are either in common with or complement the other models. For example, the model explains the localization of stress build-up. The source of additional stress may be because of anomalously high ductile strain in the mid-lower crust or due to deglaciation. If the crustal blocks formed by the intersections have large differences in rheology that would help in stress amplification due to their rigidity contrast, and also in the generation of gravitationally induced stresses. The increased fracture density at intersections (which has been noted at locations of petroleum and gold accumulations) also provides a means for groundwater to migrate to large depth -- an essential element of the hydroseismicity model.

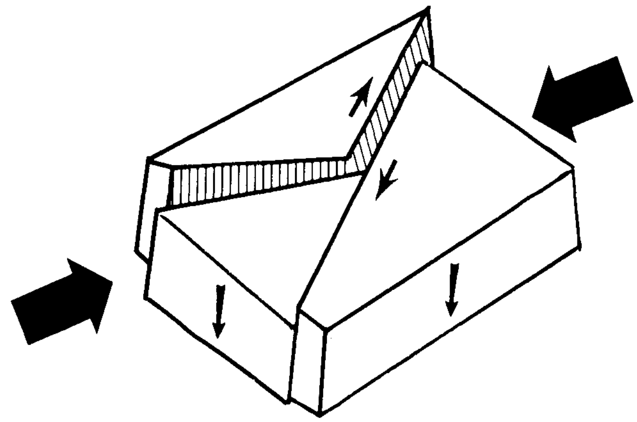

Fig. 4. Schematic diagram to show the relative motion of blocks formed by two intersecting faults. If the main fault undergoes strike slip motion, the adjoining block moves down due to kinematic adjustment. The large arrows represent the direction of maximum horizontal compression.

CONCLUSIONS

With the installation of seismic networks and following detailed geophysical and geological studies it has become possible to identify many common elements associated with the larger intraplate earthquakes. These empirical observations have led to the development of the intersection model to explain these earthquakes. The model provides for localized stress build-up due to the ambient plate tectonic stress field at zones of weakness. It accommodates or complements important elements of many of the other models suggested to explain these earthquakes. Although the background seismicity on the fault may be associated with strike slip, reverse or normal faulting (depending on the orientation of the fault with respect to S_H, focal depths, etc.) empirical data suggest that the main shock occurs by strike slip faulting. The reason why the main shock is almost always by strike slip faulting is not clear. Perhaps the large stress field build-up needed to trigger the main shock on steeply dipping faults can be most efficiently released by horizontal movement (or there is a lack of suitably oriented shallowly dipping faults). The movement on the adjacent faults is easier to explain -- it is essentially kinematic, it moves to occupy "space" created by movement on the main fault. The direction of strike slip faulting (dextral or sinistral) is controlled, as we would expect, by the orientation of the fault and the direction of maximum horizontal compression (S_H). However, there are cases where strike slip motion is not the mode of failure. A prominent exception is at Miramichi, where a series of events (M > 5) associated with thrust faulting occurred on two shallowly dipping fault planes which formed a V-shaped intersection in the vertical plane (Wetmiller *et al.*, 1984).

Another observation, for which, currently, I do not have a satisfactory explanation, is that the main shock occurs *near* the intersection on a fault suitably oriented with respect to S_H and not at the intersection itself. Perhaps it is because the intersection itself is "locked," and with the stress build-up it is easier for the fault to fail away from the locked portion. The observation of a large number of small shocks at the intersection (Figure 2) does argue for larger stresses there, perhaps acting on smaller asperities. Studies are currently underway to explain this analytically.

Other empirical data suggest that the observation of stress concentration at intersections may be applicable to the generation of smaller events. The magnitude 2.6 earthquake at Savannah River Plant was located at such an intersection (Talwani *et al.*, 1985). The model may also explain localization of some plate boundary earthquakes near their intersection with transverse structures.

As more data accumulate, and the model is further refined, we may be able to identify the geometrical characteristics of seismogenic faults -- in terms of their length, depth extent, orientation with respect to S_H, etc. The combination of these characteristic features with seismicity and stress data may prove to be a useful tool in seismic hazard assessment in intraplate regions where the ambient seismicity level is low.

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