# Correlation of major eastern earthquake centers with mafic/ultramafic basement masses

by

M. F. Kane

## Abstract

Extensive gravity highs and associated magnetic anomalies are present in or near seven major eastern North American earthquake areas as defined by Hadley and Devine (1974). The seven include the five largest of the eastern North American earthquake centers. The immediate localities of the gravity anomalies are, however, relatively free of seismicity, particularly the largest events. The anomalies are presumably caused by extensive mafic or ultramafic masses embedded in the crystalline basement. Laboratory experiments show that serpentinized gabbro and dunite fail under stress in a creep mode rather than in a stick-slip mode. A possible explanation of the correlation between the earthquake patterns and the anomalies is that the mafic/ultramafic masses are serpentinized and can only sustain low stress fields thereby acting to concentrate regional stress outside their boundaries. The proposed model is analogous to the hole-in-plate problem of mechanics whereby stresses around a hole in a stressed plate may reach values several times the average.

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Earthquakes of the eastern United States are markedly lower in frequency and magnitude than those of the western regions, particularly as compared to the seismicity regime of the San Andreas fault of California. Because of the low damping of earthquake energy in the eastern United States, however, relatively high intensities are anticipated when compared with corresponding magnitudes of the western earthquakes (see e.g., Nuttlie, 1973). A second aspect of the eastern earthquake region which contrasts with that of western regions is the sparsity of readily identifiable major faults. To some extent this lack may be attributed to a thick cover of incompetent sedimentary strata, but nevertheless it seems surprising that ongoing studies have not uncovered direct evidence of major fault systems in the major eastern earthquake regions.

As part of the earthquake investigation program of the U.S. Geological Survey, aeromagnetic and gravity studies of the New Madrid, Missouri and Charleston, South Carolina earthquake areas were begun in 1972. Coverage of much of these regions was completed by 1975, although surveys in the New Madrid region are still underway. The initial efforts were directed towards discernment of linear magnetic or gravity features which could be attributed to major faults in the crystalline, presumably magnetic, basement rocks; but evidence of such features was not detected, at least not in the sense of readily apparent lineaments or discontinuities. It was recognized that major magnetic and gravity highs were present in the near-epicentral regions of both the New Madrid and Charleston areas, but coincidence seemed to be the most plausible explanation. Positive magnetic and gravity anomalies have now been identified, however, for the seven major eastern U.S. earthquake areas as defined by Hadley and Devine (1974), so that implications other than coincidence must be considered.

Figure 1 illustrates the comparison of earthquake epicenter areas with gravity anomalies for seven well-identified eastern North American earthquake regions. The dashed line shown on each map of the figure is the maximum contour line of total number per $10^4$ $km^2$ of earthquakes from 1800 to 1972 with intensity of Modified Mercali III or larger (Hadley and Devine, 1974). As explained by the authors the contours are "only.... a guide for estimating regional seismicity." Also shown is the earthquake of maximum intensity within each region. The fact that these largest earthquakes all fall within the maximum contour lines gives assurance that the contour lines also locate to some degree the areas of maximum energy release. The gravity contours indicate Bouguer gravity values and are taken from a variety of sources referred to in the figure caption.

An examination of the small scale maps of figure 1 shows that positive gravity anomalies of 10 mgal or greater and horizontal extents of more than 30 kilometers are present in each of the earthquake regions. The New Madrid, Missouri region (fig. 1a) is notable for two large circular anomalies which lie to the northwest and south of the zone of maximum epicenter frequency. The largest seismic event is also located between the highs. In the Charleston, South Carolina region (fig. 1b) the largest event and the center of maximum epicenter frequency both lie just to the east of a gravity high which has an easterly elongation. In the Cape Ann, Massachusetts (fig. 1c), Anna, Ohio (fig. 1e), and Attica, New York (fig. 1f) regions, the zones enclosed by the contour of maximum epicenter frequency are elongated, with one end of the zone overlapping the gravity high in each case. In each of these latter regions the event of maximum intensity lies near but outside the locus of the gravity high. In the Cape Ann area (fig. 1c) two events of approximately equal intensity are indicated with the second event lying to the north of the seismicity zone, well removed from any notable gravity high. The strongest known earthquakes of this region, however, occurred in the early and mid-eighteenth century and are approximately located in the region to the east of the gravity high (Richard Holt, written communication, 1976). In the Massena, New York (fig. 1d) and Baie St. Paul, Quebec (fig. 1g) regions the gravity highs are quite broad with local highs superimposed. The maximum frequency contour lies within the broad highs but the events of maximum intensity lie near but outside the superimposed gravity highs.

In general the gravity anomalies and hence their sources tend to be peripheral to the earthquake maximum frequency contour. Since this contour encloses for the most part the earthquake of maximum intensity, this relation also indicates that the sources of the gravity highs lie outside the region of maximum strain energy release.

Figure 2 illustrates a more precise comparison of earthquake incidence and gravity anomalies for the New Madrid, Missouri and Charleston, South Carolina regions. The earthquake plot for the New Madrid region (fig. 2a) (Stauder and others, 1976) represents cumulative seismic events from June 29, 1974 to March 31, 1976. Events in the patterned zones fall too closely together to be shown individually. In figure 2a the earthquake epicenters are located for the most part between the two prominent gravity highs to the north and south of the earthquake zone. There is a suggestion of an arcuate zone to the southeast of the northern gravity high. Earthquakes are sparse or lacking in the immediate vicinity of the gravity highs. In the Charleston area (fig. 2b) the earthquakes (A. C. Tarr, written communication, 1976; C. E. Dutton, 1886) fall to the east of the gravity high which in detail has the shape of a sharp nose (Long and Champion, written communication, 1976). In both areas depths to the earthquakes generally fall in the range of 5 to 15 kilometers (A. C. Tarr, written communication, 1976; William Stauder, oral communication, 1976).

In reviewing possible causal relationships between the gravity anomalies and the earthquakes we have considered isostatic effects, intrusive activity, and anomalies in the distribution of regional stress. Isostatic effects would appear to be too small since the loads represented by the gravity highs are small compared with surface loads imposed by topography. Intrusive activity might be a factor but the anomaly in the Baie St. Paul region is associated with mafic masses of Precambrian age, seeming to rule out this possibility for at least one of the regions. Of the three factors, the most plausible one would seem to be a relationship between the distribution of the regional stress field and crustal lithology.

In a study of the relations between rock type, stress, and mechanical failure, Byerly and Brace (1968) concluded that serpentinized gabbro and dunite, limestone, and porous tuff failed by creep rather than by stick-slip, a small scale analog to earthquake-like failure. In considering the gravity anomalies in the region of the earthquakes shown in figure 1 plausible sources of the anomalies are large masses of mafic and/or ultramafic rock imbedded in a crust of generally more silicic rock. If these masses are serpentinized, they may, as suggested by Byerly and Brace's results, deform continuously by creep rather than intermittently by stick-slip under changing regional stress. The behavior of the stress in the host rock enclosing these masses might, therefore, be similar to that which occurs in a rigid plate near a hole or plastic plug. Timoshenko and Goodier (1951, p. 78-82) show that the stress is localized at the margin of a hole in a plate to values several times the applied stress. The thrust of this model is that large rock masses with distinctive deformation contrasts may distort regional stress fields in much the same fashion as distinctive magnetization and density contrasts distort the magnetic and gravity fields.

The role of serpentine in the mode of deformation of the San Andreas fault has been commented on by Allen (1968). He notes the "great abundance" of serpentine in the part of the fault zone characterized by creep and suggests that the creep may be related to the presence of serpentine. Although the geometry of the model described above and the San Andreas fault zone are greatly different, the two situations may be linked by the unusual deformation properties of serpentine.

The stress concentration near holes in plates is dependent, among other things, on the direction and type of stresses, shapes of the holes and on the relative location of plate boundaries. The arcuate zone (fig. 2a), for example, might be analogous to the high stress zone that exists between a hole-in-a-plate and a nearby plate boundary. In this case a boundary may be indicated by the southwest-trending zone of earthquakes that lies to the southeast of the arcuate zone (fig. 2a). As such it would represent a fault influenced to a greater or lesser extent by the location of serpentinized mafic/ultramafic masses near either end. Similarly the earthquakes near the eastern nose of the gravity anomaly in the Charleston region (rig. 2b) might be analogous to high stress zones associated with the ends of narrow cracks in plates when tension is applied normal to the crack.

Undoubtedly, the model of the hole-in-a-plate, if valid, is greatly oversimplified, since the masses are more analogous to plastic plugs and geologic bodies are three dimensional. Uncertainties are also present in other aspects of the data including the precise cause of the gravity anomalies, the directions and type of stress, the shapes and orientations of the anomalous masses, and the dimensions and boundaries of the host rock in which the anomalous masses are embedded. The only densities, however, which could reasonably explain the high positive gravity amplitudes, are those associated with mafic or ultramafic rocks. At present there is no direct evidence of serpentinization.

Perhaps the major question that arises about a relationship between mafic basement masses and stress field distribution is why other regions in eastern North America underlain by large positive gravity anomalies do not have associated earthquake activity. Lack of serpentinization would be the most obvious answer. Other answers include the lack of a sufficiently large or changing regional stress field or inappropriate geometric relations between the causative masses and stress field directions.

Our present evidence indicates for example, that most, if not all of the masses so far considered are at depths where they would be enclosed in highly competent basement. Mafic masses located in softer, less competent sedimentary strata that yield more easily would presumably not give rise to the same stress concentrations. It is also possible that the continental stress field, probably imparted by plate tectonic conditions, is strongly zoned in a regional sense. The southwest alignment of earthquake areas from the Gulf of St. Lawrence to the New Madrid region and the similar trend in the broad earthquake region of the Applachians exhibited by the seismotectonic map of Hadley and Devine (1974) may be an expression of a regional zoning of the continental stress field.

In summary, a correlation has been shown to exist between major eastern North American earthquake areas and the occurrence of mafic-ultramafic masses as evidenced by gravity anomalies. The converse, however, does not hold. A model has been proposed whereby stress is concentrated near the margin of these masses much in the same manner as stress concentrations occur near the margins of defects or holes in plates under stress. This model has major implications for the consideration of eastern North America seismicity inasmuch as it suggests that larger earthquakes are restricted to relatively local areas. The model may also explain why major through-going faults of continental or subcontinental dimensions are not evident in eastern North America. Presumably the faults associated with the localized stress zones would be similarly localized and of relatively small dimensions, perhaps 10 kilometers or less in length.

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## Figure captions

Figure 1. Gravity and seismicity data for seven major earthquake regions in eastern North America. Seismicity data after Hadley and Devine (1974). Gravity data in a and b from Am. Geophys. Union, Spec. Comm. Geol. Geophys. Study Continents (1964); Gravity data in c and d from Kane and others (1972); gravity data in e from Heiskanen and Uotila (1956); gravity in f from Revetta and Diment (1971); gravity data in g from Thompson and Garland (1957).

Figure 2. Gravity and contemporary epicenter data for the New Madrid, Mo. and Charleston, S.C. earthquake areas. Sources of gravity data are given in Figure 1. Epicenter data in New Madrid, Mo. area from Stauder and others (1976). Epicenter data in Charleston, S.C. region from Tarr (written communication, 1976). Isoseismal boundary from Dutton (1888).

Figure 1

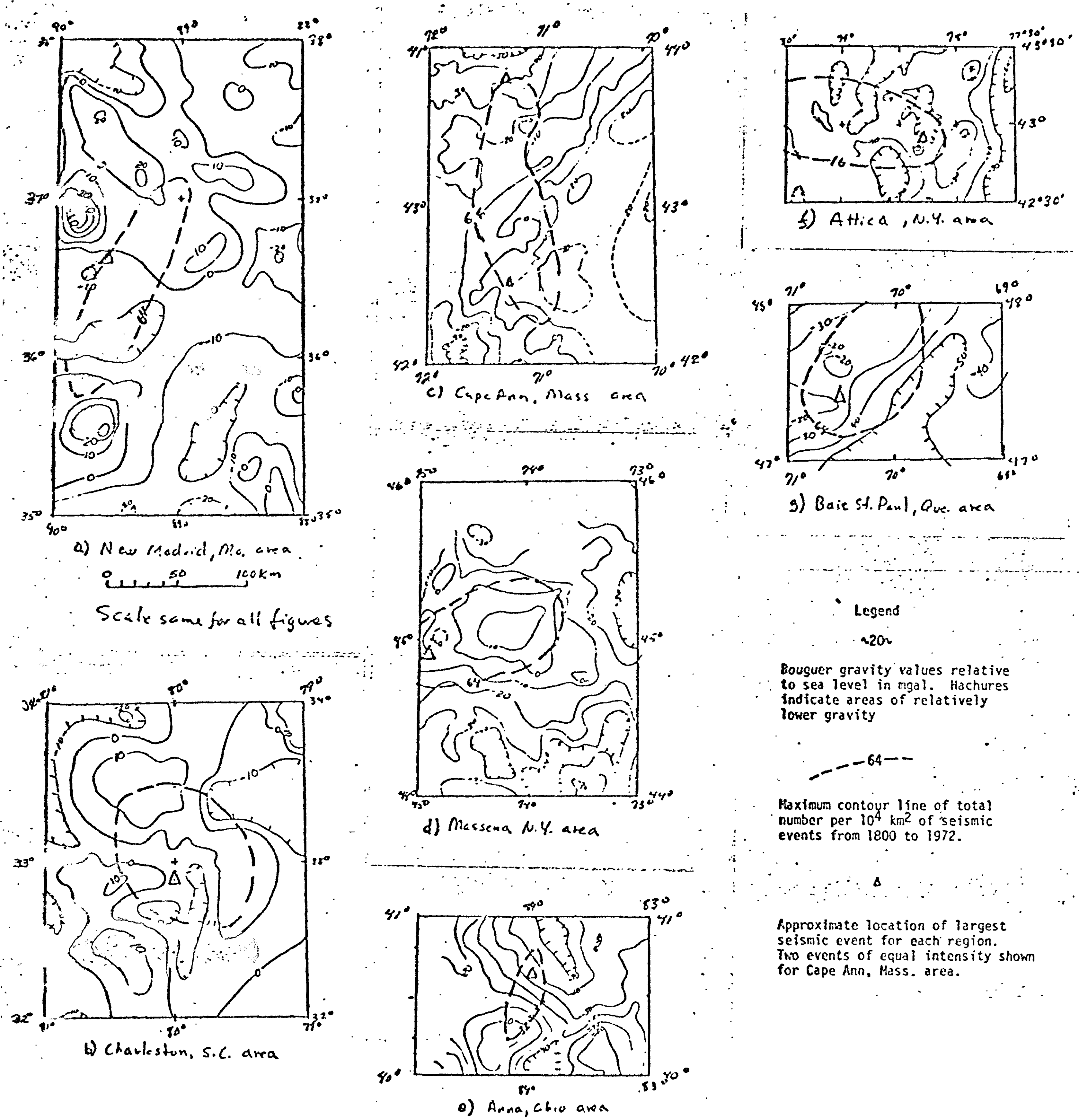
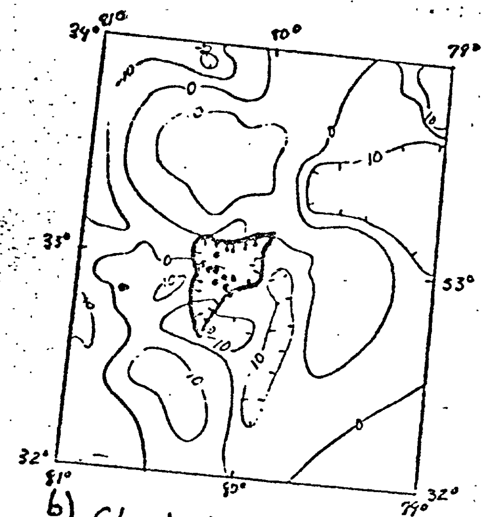

a) New Madrid, Mo. area
0 50 100Km
Scale same for all figures
b) Charleston, S.C. area
c) Cape Ann, Mass area
d) Massena N.Y. area
e) Anna, Ohio area
f) Attica, N.Y. area
g) Baie St. Paul, Que. area
Legend
20
Bouguer gravity values relative to sea level in mgal. Hachures indicate areas of relatively lower gravity
64
Maximum contour line of total number per $10^4$ $km^2$ of seismic events from 1800 to 1972.
Δ
Approximate location of largest seismic event for each region. Two events of equal intensity shown for Cape Ann, Mass. area.

Figure 2


a) New Madrid, Mo. area




b) Charleston, S.C. area

**Legend**

-20-

Bouguer gravity values relative to sea level in mgal. Hachures indicate areas of relative lower gravity.

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Location of well-determined recent seismic events.

Area where seismic events are too closely grouped to be shown separately.

Isoseismal zone of the 1886 Charleston, S.C. earthquake.