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Intraplate earthquakes, regional stress and fault mechanics in the Central and Eastern U.S. and Southeastern Canada

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ABSTRACT

Utilizing 75 high quality individual earthquake focal plane mechanisms and 10 formal stress inversions we investigate the consistency of regional stress orientations in the central and eastern United States and southeastern Canada, the variation of relative stress magnitudes across the region and the compatibility of slip on optimally-oriented nodal planes with frictional faulting theory. To map faulting styles and relative stress magnitudes across the region of study, we utilize the high quality focal plane mechanisms to calculate the AΦ parameter (following Angelier, 1979; Simpson, 1997) that ranges from 0 (uniform horizontal extension with $S_V >> S_{Hmax} = S_{hmin}$) to 1.5 (strike–slip faulting with $S_{Hmax} > S_V > S_{hmin}$) to 3 (uniform horizontal compression with $S_{Hmax} = S_{hmin} > S_V$). We find that horizontal stresses become increasingly more compressive with respect to the vertical stress from the south-central United States (characterized predominantly by strike–slip focal mechanisms) toward the northeastern U.S. and southeastern Canada (predominantly thrust mechanisms). In a manner similar to the study by M.L. Zoback (1992a), which used a much smaller data set, we utilize the Mohr–Coulomb criterion to calculate the difference in orientation between the theoretically-optimal orientation of a fault plane (for various coefficients of friction, μ) and the focal mechanism nodal planes assuming that pore pressure in the brittle crust is hydrostatic. For the 75 focal plane mechanisms utilized in our study, the preferred (better fitting) nodal planes deviate on average only 7° in strike and dip from the theoretically-optimal planes for μ = 0.6. As such minor differences could represent small variations in the stress field (or uncertainties in the focal plane mechanisms), we conclude that nearly all earthquakes in the study region slip in a manner compatible with shear failure on pre-existing faults in the local stress field.

1. Introduction

Significant amounts of seismicity occur in intraplate regions throughout the world, often on tectonic structures such as pre-existing fault zones, sometimes associated with failed rifts, and ancient suture zones (e.g. Sykes, 1978). Intraplate seismicity in North America is frequently correlated with pre-existing faults which are optimally-oriented for reactivation in the current stress field (e.g., Zoback, 1992a; Zoback and Zoback, 1981). The stress field in the central and eastern United States (CEUS) and southeastern Canada is remarkably consistent on the lateral scale of 100 s of kilometers and is generally characterized by a horizontal, compressive, NE–SW trending maximum horizontal stress (e.g. Sbar and Sykes, 1973; Zoback and Zoback, 1980, 1991) thought to derive from buoyancy-driven forces such as ridge push (see Zoback and Zoback, 2007 for review) or from geoid perturbations and mantle thermal anomalies (Davies, 1999).

Second order stress fields, some of which may deviate from the large-scale regional field described above, are also observed across the CEUS. These stresses are generally driven by more localized buoyancy forces related to processes such as sediment loading and deglaciation or the presence of lateral lithospheric heterogeneities (e.g., Zoback and Mooney, 2003). The stresses generated by these processes may also contribute to the nucleation of intraplate seismicity in the CEUS and southeastern Canada. Since earthquakes are a direct result of stresses acting within the crust, analyzing seismicity in intraplate regions may yield valuable information regarding the current state of stress and physical conditions of the upper crust (pore pressure, fault friction) that is often unavailable from other sources. This information is essential to addressing potential seismic hazards in intraplate regions.

Earthquake focal plane mechanisms are often used to estimate the orientation of the three principal stresses (vertical stress (S_v), maximum horizontal stress (S_{Hmax}) and minimum horizontal (S_{hmin})) in the crust. The P-axis of the focal mechanism, which is defined as the

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bisector of the dilatational quadrants, is generally taken to represent the approximate orientation of S_{Hmax}, although it could significantly deviate from the true S_{Hmax} orientation in the absence of friction (McKenzie, 1969). In contrast to S_{Hmax} orientations estimated from individual focal mechanisms, a formal stress inversion of multiple earthquake focal mechanisms directly estimates the orientation of the three principal stresses and provides a more accurate S_{Hmax} orientation than the P-axis of an individual focal mechanism (Angelier, 1979; Gephart and Forsyth, 1984; Michael, 1984). The inversion procedure assumes a uniform stress field over the crustal volume containing all focal mechanisms used for the inversion and that shear slip occurs in the direction of maximum resolved shear stress (Bott, 1959).

In general, earthquake focal plane mechanisms are obtained from body-wave first-motions and polarizations (e.g. Khattri, 1973), body-wave amplitude ratios (e.g. Kisslinger et al., 1981), waveform modeling (e.g. Nábělek, 1984) or a combination of these methods. While the quality of an individual focal mechanism depends on the recording array geometry, seismogram signal-to-noise ratio and the accuracy of the earth velocity model, certain constraints generally yield higher quality and more reliable solutions. For example, because waveform modeling uses body-wave amplitude information and searches over a broader coverage of the focal sphere for a solution, it is often more powerful for constraining fault orientations than a focal mechanism created solely from P-wave polarities (e.g. Lay and Wallace, 1995). Solutions constrained by only P-wave polarities, for instance, may have several distinctly different nodal plane pairs (and slip configurations) that fit the data equally well and are highly dependent on recording array geometry. Consequently, we only consider high quality individual focal mechanisms constrained by waveform modeling in this study.

We compile well-constrained focal mechanisms and formal stress inversions from the CEUS and southeastern Canada over the past ~20 years. We utilize these data to investigate the consistency of regional stress orientations, to map faulting styles and relative stress magnitudes across the region and to investigate the likelihood of shear failure on the more well-oriented nodal planes in the local stress field in the context of frictional faulting theory, in a manner analogous to M.L. Zoback (1992a) who worked with a much smaller data set.

2. Data collection

All individual focal mechanisms and focal mechanism inversions are compiled from publications and earthquake catalogs over the past ~20 years. Since the individual focal mechanisms will directly be used to calculate relative stress magnitudes and examine slip compatibility in our analysis, it is crucial that the mechanisms be well constrained. To ensure such quality, we only select mechanisms constrained by waveform modeling. Again, waveform modeling techniques provide a better constraint on fault orientations because they use a broader coverage of the focal sphere along with relative body-wave amplitudes to constrain solutions.

The study area includes the CEUS, with the western boundary corresponding roughly to the 105°W line of longitude, and southeastern Canada. A total of 52 individual focal mechanisms and 10 stress inversions (from Mazzotti and Townend, 2010) are compiled (Appendices A and B, respectively). Of the 52 new focal mechanisms, 24 indicate thrust faulting, 25 are strike–slip and 3 represent normal faulting regimes. All focal mechanisms have magnitudes greater than $M_w = 3.1$ with the maximum magnitude being $M_w = 5.2$. The Canadian earthquakes range in depth from 2 to 25 km with an average depth of 14.1 km compared to a depth range of 2 to 18 km with an average of 8.0 km for the CEUS earthquakes. We also include 23 of the focal mechanisms analyzed by Zoback (1992a) within this study area (Appendix C). In instances where a precise latitude and longitude location are not available for a data point, a location is estimated using the original data source.

3. Defining stress orientations and relative stress magnitudes

3.1. Stress orientations

The first objective in our analysis is to investigate the consistency of the maximum horizontal principal stress orientation throughout the study area as inferred from the P-axes of newly compiled individual focal mechanisms and the formal stress inversions. Fig. 1 illustrates the new data points overlain on the 2008 World Stress Map (WSM) database (Heidbach et al., 2008), which is essentially identical to the database used by Zoback (1992a,b). In general, the S_{Hmax} orientations inferred from the new focal mechanisms (shown by blue bars on the black and white mechanisms) as well as the stress inversions (dark green circles with dark green bars) are consistent with the overall NE–SW S_{Hmax} orientation seen over much of the CEUS and southeastern Canada. Moreover, the new data points are locally consistent with pre-existing data which often show slight variations from the regional stress orientation.

This said, in contrast to the broadly homogeneous S_{Hmax} orientation, several focal mechanisms and stress inversions appear to indicate locally variable S_{Hmax} orientations. For example, the stress inversion in central Virginia yields a S_{Hmax} orientation of 90°, which is a roughly 45° clockwise rotation from stress indicators just to the west (Fig. 1). Similarly, the six new individual focal mechanisms in the Wabash Valley seismic zone in southern Illinois have an average P-axis orientation of 77°, which is relatively consistent with the regional S_{Hmax} direction but differs from the local E–W S_{Hmax} orientation indicated by nearby breakout stress indicators in western Kentucky and the focal mechanism inversion in the New Madrid seismic zone in NE Arkansas. Four of the five new data points in the Charlevoix seismic zone and both new focal mechanisms (and the stress inversion) in the St. Lawrence seismic zone also display a significant clockwise S_{Hmax} rotation from the regional trend as inferred from nearby borehole breakout measurements.

3.2. Relative stress magnitudes

The second objective is to estimate the relative magnitudes of the three principal stresses at hypocenteral depths. First, we estimate the local S_{Hmax} orientation near each earthquake from independent stress measurements in the WSM database. This is inferred by averaging the S_{Hmax} orientation from the three nearest data points in the WSM, regardless of type. If the standard deviation of the average is greater than 25°, the average of the two nearest 'A' quality stress measurements is used. For all 52 earthquakes, the two nearest 'A' quality stress measurements are usually from either borehole breakouts or hydraulic fractures. Next, to constrain the orientations of the remaining principal stresses S_{hmin} and S_V, we assume that the three principal stresses are perpendicular to one other and oriented horizontally and vertically (Zoback and Zoback, 1980). In Fig. 2 of Mazzotti and Townend (2010), it is clear that one principal stress is near vertical in each of the ten areas where focal mechanism inversions were carried out.

With the stress orientations constrained, the relative magnitudes of the three principal stresses are then calculated. Prior to calculation, the guidelines from Zoback (1992b) were used to classify each focal mechanism as thrust, strike–slip or normal. For S_V, we assume a regional lithostatic gradient of 25 MPa/km, which corresponds to an overburden density of 2500 kg/m^3. Although rock densities increase with depth, and a higher gradient (27–28 MPa/km) may be more appropriate for the earthquakes of greater depth, we use the 25 MPa/km gradient since the majority of earthquakes examined in this study fall within the upper crust. More importantly, since only relative