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Stress channelling and partitioning of seismicity in the Charlevoix seismic zone, Québec, Canada

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SUMMARY

The Charlevoix seismic zone in the St. Lawrence valley of Québec is historically the most active in eastern Canada. The structurally complex region comprises rift faults formed during the opening of the Iapetus Ocean, superimposed by a 350 Ma meteorite impact structure, resulting in a circular highly fractured zone. Although seismicity is localized along two steeply dipping planar rift-parallel zones, previous work indicates that most of the large-scale rift faults bound the low magnitude background seismicity rather than generate earthquakes themselves. In order to gain insight into the mechanics of the partitioning of this seismicity, a two-dimensional model of the Charlevoix seismic zone was built using the stress analysis code FLAC. The rift faults are represented by frictional discontinuities. The heavily fractured impact structure is represented by an elastic continuum of reduced modulus. Boundary displacements are used to generate a regional stress field with the major horizontal component in the direction of tectonic loading. Given a high strength, the rift faults have little effect on the stress patterns. Stress trajectories naturally flow around the crater of reduced elastic modulus, leaving the fractured area with lower stresses than the background level. However, when the rift faults have low strength, they are unable to support stress trajectories inclined to them, due to the resolved shear stress exceeding their strength. This prevents trajectories from flowing out of the rift, effectively channelling higher magnitude stresses into the region of the impact structure between the faults. Low-strength bounding faults can thus explain the localization of seismicity into linear bands, rather than distributed seismicity throughout the impact structure. It also explains how the rift faults act as boundaries to regions of low magnitude seismicity. These results indicate that the interplay between faults of varying strength and zones of differing elastic modulus can give rise to complicated stress patterns, and can explain many of the seismicity patterns observed in the Charlevoix seismic zone. This has implications for other intraplate seismic zones, as it shows an example of how regional weak faults can modify stress conditions around local structures and drive seismicity. The results are particularly relevant for other regions located within rifted crust, such as the New Madrid seismic zone, which possibly display evidence of stress channelling.

Key words: intraplate seismicity, Charlevoix, neotectonics, stress, Charlevoix seismic zone, impact structures, numerical modelling, rifted crust.

1 INTRODUCTION

Large earthquakes in intraplate regions are relatively rare; they account for only about 5% of the global seismic moment release (Célérier et al. 2005), however they have the potential to cause great damage and can pose significant societal risk. Our understanding of intraplate earthquakes is limited when compared to seismicity at the plate boundaries. The locations of earthquakes are not evenly distributed in continental interiors, rather they tend to cluster in smaller zones. Mazzotti (2007) outlined several end member geodynamic models to explain intraplate earthquake zones. These include the large-scale weak zone model in which crustal strain accumulates along weak paleotectonic structures, and the localized weak zone model, where earthquakes are confined to small areas of crustal weakness. The worldwide tendency of intraplate earthquakes to cluster around former rift zones (Sykes 1978) fits well with the large-scale weak zone model, however, the localized weak zone model is often invoked to explain the existence of small clusters of conspicuously high levels of seismicity such as the New Madrid seismic zone. This study examines one seismic zone that incorporates elements of both these models.

The Charlevoix seismic zone (CSZ) in the St. Lawrence valley of Québec, is historically the most active region in eastern Canada (Figure 1). Five earthquakes larger than magnitude 6 have been recorded in 1663, 1791, 1860, 1870, and 1925 (Adams & Basham 1991). The anomalously high level of seismicity in the CSZ, may be due in part to its unusual structural setting (Figure 2). The zone lies along a segment of an ancient rift that is superimposed by a meteorite impact structure.

1.1 Geological setting

The CSZ straddles the boundaries between three geological provinces (Figure 2), the Proterozoic Grenville Province to the northwest, the Cambro-Ordovician sedimentary rocks of the St. Lawrence Platform, which locally overlie the Grenville, and thrusted units of the Appalachian orogen to the southeast (Lemieux et al. 2003). Normal faults, formed during the opening of the Iapetus Ocean (late Proterozoic to early Paleozoic), extend into the Grenville basement and are associated with the northeast trending St. Lawrence paleo-rift system. These faults include the Gouffre North-West and St. Laurent faults that parallel the St. Lawrence river along its north shore, the Charlevoix fault, which lies under the river, and the South Shore fault, which does not outcrop on surface but is inferred from gravity and magnetic data (Lamontagne 1999) (Figure 2).

Extensive faulting due to a Devonian ($\sim$350 Ma) meteorite impact structure is also preserved in addition to the rift related faulting (Rondot 1971). The interior of the impact structure features much more varied fault orientations than the exterior. These include a polygonal set of normal faults around the centre of the impact that form graben and half-graben structures in which rocks of the St. Lawrence platform are locally preserved (Lemieux et al. 2003) (Figure 2A). Faulting related to the impact is estimated to extend to a radius of 28 km laterally and approximately 11-12 km below the surface (Rondot 1994). Major faults of the St. Lawrence rift system, such as the St. Laurent fault, cross the impact structure but are not significantly deflected by it, suggesting that they were reactivated post impact, possibly during the opening of the Atlantic ocean in the Mesozoic (Lemieux et al. 2003).

The current regional stress field of the Charlevoix seismic zone is dominated by the effect of ridge push at the Mid-Atlantic ridge, forming a fairly consistent NE-SW orientation of maximum compressive stress (S_H) throughout eastern North America (Zoback & Zoback 1991)(Figures 1 and 2).

1.2 Seismicity

Earthquakes in the CSZ are primarily thrust or combination thrust / strike-slip events (Lamontagne 1999). Hypocentres occur entirely within the Grenville basement rocks, concentrating mainly between depths of around 7 to 15 km but with some occurring as deep as 30 km (Leblanc & Buchbinder 1977). They cluster into two elongate zones parallel to the St. Lawrence rift faults and extend beyond the boundaries of the impact structure, particularly in the NE region (Figure 2). A cross-sectional view reveals that the NW cluster is aligned along a steeply SE dipping plane ($\sim$70°, Figure 2B). The similarity of the location and orientation of these clusters with the St. Lawrence paleo-rift led Anglin (1984) to suggest that seismicity was caused by the reactivation of rift faults. This conclusion is in agreement with the global correlation of intraplate earthquake clusters with ancient rift and continental suture zones (Sykes 1978). These features act as zones of weakness where earthquakes can be generated in the background regional stress field. However, this model is insufficient because it fails to explain the relative paucity of events in regions of the St. Lawrence just to the NW and SE of Charlevoix (See Figure 1). There is evidence from paleoseismic liquefaction studies that strong earthquakes have occurred within the CSZ area multiple times over the past 10,000 years, with no evidence of major earthquakes outside the zone (Ouellet 1997; Tuttle & Dyer-Williams 2008), suggesting that the seismicity is not simply migrating along the rift system over time. In addition, although focal mechanisms of larger events (e.g. 1925 $M6.2$, and 1979 $M5.0$) show SE dipping nodal planes consistent with slip along the rift faults (Bent 1992; Lamontagne 1999), detailed analysis of the smaller events reveals highly variable nodal plane orientations (Lamontagne 1999). Events also cluster away from high P wave velocity structures located at the projected locations of the main rift faults at depth (Vlahovic et al. 2003); thus the smaller events appear to form within a seismogenic volume bounded by the rift faults rather than being generated by them.

The Charlevoix impact crater is another structural feature which seems to play an important role in the seismicity of the region. Although most earthquakes larger than magnitude 4 occur outside or on the periphery of the impact zone, when smaller event locations are considered, there is a dramatic increase in activity inside the crater relative to the region surrounding it. Figure 3 shows an analysis of the depth distribution of earthquakes in the region directly below the crater relative to the area around it. Both regions show a bimodal distribution of earthquakes with a deep peak at $\sim$23 km. However, beneath the crater there is both a large increase in the total number of events, as well as a general shallowing of the events. Such a significant difference strongly suggests that the lower magnitude events are related to the impact structure.

In general, meteorite impact structures are not known to be associated with anomalously high levels of neotectonic seismicity (Solomon & Duxbury 1987). Charlevoix and the Vredefort crater in South Africa are the only two large seismically active impact structures, and the Vredefort seismic events are almost entirely related to deep gold mine rock bursts (Solomon & Duxbury 1987). However, the seismicity in Charlevoix is confined primarily to the region where the rift zone and impact structure overlap, suggesting that the two features together interact in such a way as to concentrate seismicity. Earthquakes occur along faults related to the impact structure, but only in those regions bounded by the larger rift faults.

The observed seismicity characteristics of the CSZ suggest that both the rift faults and the impact structure play an important role in the generated earthquake patterns. Large events appear to be related to slip along rift faults outside the boundaries of the crater; and small events primarily occur within or below the crater, but only in the region bounded by the rift faults. It appears that neither structural feature on its own would be sufficient to explain seismicity. However, the combined effect of both features is not clear. This study, through the use of numerical stress analysis, explores a possible mechanism by which the structural features interact with far-field tectonic forces to produce local stress perturbations compatible with observed earthquake patterns.

2 NUMERICAL APPROACH

The intention of using numerical stress analysis models is not to replicate all observations, rather they are used to explore mechanisms by which major structures might interact with each other in a regional stress field. In light of this, a simplified model using the two-dimensional finite difference continuum code FLAC (Itasca Consulting Group Inc. 2005) is used. Models can include a small number of discontinuities or interfaces that are given specific constitutive properties, allowing separate continuum zones to interact with each other.

The model geometry is shown in Figure 4. The crust is represented as a two dimensional elastic continuum, with a density of 2700 kg/m^3 and with a background bulk, and shear modulus (herby denoted collectively as M_B) of 73 GPa and 44 GPa, respectively, following the physical parameters used by Assameur & Mareschal (1995). Next, a series of parallel linear discontinuities are introduced, which are assigned Mohr-Coulomb strength parameters (cohesion and friction) to represent the rift faults. The heavily fractured impact structure can be considered a “zone of weakness”. Using the well-established concept of an equivalent continuum for fractured rock, the zone is represented by a continuum of reduced elastic modulus (e.g., Fossum 1985). Although we do not know the equivalent modulus of the 30 km radius impact zone, it is tested with elastic moduli (both bulk and shear, denoted M_C) of 1/2 and 3/4 the value of the surrounding rock to determine the influence of this parameter in the overall mechanics of the system.

The internal stress field in the model is generated by applying displacements to boundary gridpoints over a series of timesteps (i.e., boundary velocities). These displacements are applied in the direction of tectonic loading, and boundary gridpoint velocities perpendicular to this are set to zero (Figure 4). Provided these velocities are small enough to maintain model stability, an internal stress field is generated in a similar manner to far-field tectonic compression. The orientation of the applied boundary velocities relative to the orientation of the faults was chosen based on a smoothed regional stress field map from the world stress map project (Heidbach et al. 2008).

3 MODEL RESULTS AND ANALYSIS

The models were run with a variety of values of elastic moduli and fault strength. Since the true values are not known, a range of values were used to explore the effect of reasonable changes in these parameters on model behaviour compared to observations. The elastic modulus of the impact crater was modified within the range of 50% to 100% of the background modulus values, which is within the limits of effective modulus due to randomly oriented fractures in two dimensions (Fossum 1985). The friction angle of the faults was tested at values of 90° (locked), 15°, and 5° with no cohesion. The low values are meant to account for the effects of fault gouge and pore fluid pressure. Contour plots of computed magnitude of deviatoric stress and orientation of S_H are shown in Figures 5 and 6, respectively.

3.1 Effect of modulus

Column A of Figures 5 and 6 show the results of the models with fault friction set to 90°, which is equivalent to removing the faults from the model. By using this column as a reference, the effect of progressively lowering the modulus of the crater zone on the predicted deviatoric stress and orientation of S_H can be observed. With no modulus contrast (A1), a uniform stress field is generated, with S_H oriented parallel to the loading direction. As the impact zone modulus is decreased in rows 2 and 3, a partitioning of stress magnitude develops that intensifies as the modulus contrast increases. The behaviour follows that known for stress around soft inclusions. The magnitude of stress in the crater interior is lower than the background level because the lower modulus requires less stress for the same amount of strain (Figure 5). This lower stress magnitude is achieved by diverting stresses around the crater (Figure 6), which also results in high stress magnitudes concentrating in lobes on either side of the crater.

3.2 Effect of fault strength

The effect of fault strength on the state of stress in the model is shown in row 1 of Figures 5 and 6. Lowering the fault strength has very little impact on the magnitude of deviatoric stress (Figure 5), however, at very low friction angles (5°) the faults affect the orientation of S_H. If the faults are sufficiently weak they are unable to support the resolved shear stress of the applied stress field, in which case they slip and stresses rotate toward an orientation parallel to the faults (Figure 6, C1).

3.3 Combined effect of modulus and fault strength

When both fault strength and impact crater modulus are lowered (the diagonal of Figures 5 and 6), the two effects combine in a non-trivial manner. The most conspicuous effect is the partitioning of stress magnitude in the interior of the crater bounded by the faults (Figure 5, C3). Within the impact structure the region bounded by the faults is at a higher state of stress than the region outside the faults. The reason for this partitioning can be explained by examining the stress orientations (Figure 6, C3). Stress orientations well away from the faults are similar to the model with locked faults (A3), however, stress orientation closer to the faults is perturbed and tends to rotate parallel to the strike of the faults, similar to model C1. The result is that stress trajectories in regions between the faults are now forced to align parallel to the faults, which effectively channel higher magnitude stresses into the interior of the crater, as opposed to the periphery of the crater.

The partitioning of stress in the interior of the crater requires the presence of two or more weak faults. When a model is constructed with just one of the faults with low strength, there is no such partitioning of stress magnitude (Figure 7). In this single fault model there are still local perturbations of stress orientation in the vicinity of the fault. However, since there is no region bounded on both sides by faults, stresses can simply flow around to the other side of the crater. Channelling, resulting in a higher stress zone, does not occur.

4 DISCUSSION

The results of the model show that although the individual effects on the stress field are simple, the combined effect of a high contrast in elastic modulus as well as a series of weak parallel faults can result in complex stress partitioning. The presence of weak faults bounding both sides of the rift zone prevents stresses from flowing around the impact structure and effectively channels higher magnitude stresses into the interior. In order to relate this stress model to seismicity, further analysis is required. If the assumption is made that stress magnitudes correlate directly with seismicity potential, it is expected that most earthquakes would occur around the lobes of high stress at the sides of the impact crater. This does not agree with observations. However, there are other factors in addition to the state of stress that can affect seismicity, such as variations in the brittle strength of the rock, or the presence of pre-existing faults and fractures.

One approach to estimate where seismicity might occur is to compare the results to a similar structural model that is known to have very few seismic events. An obvious choice for this would be to compare it to other impact structures around the world, which are overwhelmingly aseismic (Solomon & Duxbury 1987). What sets Charlevoix apart from these other impact structures is that it also has the rift faults running through the crater. Based on this information an assumption can be made that a model in which the rift faults are locked (i.e., model C1 of Figures 5 and 6) should produce a stress field that is seismically stable. A better indication of the potential for seismicity can be determined by examining the difference in the stress fields between a model with just the impact zone, and another with the weak faults included. This is achieved through the use of “grid algebra” by subtracting the predicted values of deviatoric stress between the two models, which should highlight areas of stress magnitude change relative to a stable model. As Figure 8 shows, the combination of weak rift faults and a soft zone results in an increase in stress in the region of the impact zone between the rift faults, while the regions outside the faults result in little change or a reduction in stress levels. In these regions of increased deviatoric stress we expect a corresponding increase in the potential for earthquakes. The comparison of the red area of Figure 8 with a map of earthquakes in the Charlevoix area (Figure 2) reveals a good correlation with observed seismicity.

As discussed earlier, the difference in orientation of the rift faults relative to the applied stresses was chosen to be 10° based on the smoothed regional stress map (Heidbach et al. 2008). However, due to uncertainty in this value, variations in the angle were tested to see if there was any noticeable effect of the regions of increased seismicity potential (Figure 9). The results show that although small changes in the orientation of the faults do effect the magnitudes of stress change, the main effect of increased deviatoric stress between the faults relative to regions outside still remains. This test also highlights the subtle effect of asymmetry in the system caused by the rift not running straight through the centre of the impact crater, but offset to one side. This asymmetry results in extension of the zone of increased seismicity potential along the rift to the north of the crater at the expense of the region to the south. The effect is observed in all the models, but is most clearly shown by the model at 5° to the applied stress (Figure 9). This may partially explain the higher concentration of events to the northeast of the crater relative to the region to the southwest (Figure 2A).

Pre-existing zones of weakness are often used to explain regions of persistent intraplate seismicity. These weak zones can either have a large extent, or be very localized (Mazzotti 2007). Both of these end-member models have been used to explain the seismicity in the Charlevoix seismic zone. Leblanc et al. (1973) proposed that the seismic activity may be due to the impact structure becoming active under postglacial uplift strain. Adams & Basham (1991), noting the absence of earthquakes at other meteorite craters in Canada, attributed the seismicity primarily to the St. Lawrence rift system. Many others, however, associated the earthquakes with a combined effect of the rift faults and impact structure, either by the reduction of the rift fault strength caused by the meteorite impact (Anglin 1984; Lamontagne 1987) or by increased fluid pressure brought into the impact crater via the rift faults (Lamontagne 1999). This study's models similarly incorporate both features, however they differ in that the seismicity is a result of a stress concentration caused by their interaction rather than by local weakening of the structures. The impact structure is a localized weak zone which concentrates most of the low-level continuous seismicity, however, the large-scale weak rift faults act as the locus for most of the larger, but less frequent events, and are required in order to act as a conduit to concentrate stresses into the interior of the crater.

4.1 Limitations of model

The simplification of the model to two dimensions raises a number of issues that must be addressed in order to justify the modelling approach. Perhaps the most significant limitation is that because we are confined to two dimensions we are unable to represent the true three dimensional shape of the crater. In three dimensions the crater would have a bowl shape, with limited depth extent. By treating it as a two dimensional problem we are effectively modelling the crater as a column of weak material. The two lobes of high stress observed in the model on the sides of the crater are largely an artifact formed as a consequence of this simplification (Figure 5). In two dimensions, stress flowing around the crater is confined to the horizontal plane, and must therefore concentrate around the perimeter of the crater. In three dimensions stress would also be able to flow beneath the crater, spreading out and reducing the concentration effect. In our analysis, this problem is minimized by observing the differences in stress between two models rather than the total stress field. The bowl shape of the crater also presents a problem for explaining the presence of earthquakes below the crater. The maximum depth of faulting related to the Charlevoix impact is estimated to be approximately 12 km (Rondot 1994). Analysis of the depth distribution of earthquakes indicates that although a large number of events occur within this depth, a significant portion extend below the crater (Figure 3). This cluster of seismicity can still be explained under the framework of the stress channelling model by considering the behaviour of stress in the slab of rock between the rift faults. In this situation the stress channelling effect should restrict most of the flow of stress within the plane of the dipping slab. Stress can still flow down below the crater, however, only within the boundaries of the faults. This effectively reduces the problem to a two dimensional geometry, where we would expect a lobe of high stress below the crater. If the bounding faults are sufficiently strong, however, stress flowing around the crater will be able to cross faults and benefit from the geometric spreading effect, reducing the possibility of large concentrations, and therefore, seismicity.

Although many of the events in the CSZ indicate NE–SW compressive stress direction, some indicate orientations at high angle to this with NW–SE oriented compression (Mazzotti et al. 2006). Within the crater the discrepancy between the modelled orientation of S_H and the inferred compressive direction from individual focal mechanisms may be partially due to the omission of the fine detail of the complex faulting brought out by using the more simplified equivalent continuum representation. The presence of several pre-existing faults can result in complex perturbations in the stress field orientation and magnitude, however, the average stress field throughout the zone should be relatively consistent with the regional field (e.g., McKinnon 2006).

Another limitation of the model is its inability to explain the larger magnitude earthquakes ($M > 4$) , which tend to occur within the rift zone but just outside the impact structure (Stevens 1980; Lamontagne 1999). These large earthquakes have focal mechanisms that are consistent with reverse sense reactivation of the major rift faults. This is not possible in our model due to the simplification of the problem to two dimensions; displacement on the rift faults is confined to strike slip. The localization of the large earthquakes outside the crater rather than in its interior may be due to the availability of large continuous rupture surfaces, which may not exist within the heavily fractured impact zone. The local clockwise rotation in the orientation of S_H to the NE and SW of the impact structure, caused by the flow of stress around the crater (Figure 6), would increase the resolved shear stress on the faults in these areas. This provides some indication of the process of generating large events just outside the crater as opposed to farther along the rift away from the crater, however, because non-strike slip is not represented in the model the result would need to be examined using 3D models. The focal mechanisms of these large events tend to have the inferred compressive direction oriented NW-SE, which is at high angles to the regional stress field. This orientation is consistent with modelled displacements associated with glacial rebound (e.g., Wu & Mazzotti 2007), and with GPS measured displacements indicating convergence across the St. Lawrence river (Mazzotti et al. 2005). However, our models omit this source of strain and focus only on the far-field tectonic stresses. Despite these limitations, the stress channelling model provides a mechanism to explain much of the low-level continuous seismicity.

4.2 Implications

Despite the unusual structural setting of the Charlevoix seismic zone the results of these models are relevant for other intraplate areas. The models show how different scales of structures, both local and regional, can interact with each other when loaded tectonically, producing complicated stress patterns. The results are particularly relevant for regions associated with rifted crust, which account for over half of intraplate earthquakes (Schulte & Mooney 2005). The models indicate that weak parallel faults can act as conduits to channel stresses onto intersecting structures. This same mechanism could be invoked to help explain some of the concentrations of seismicity found in other ancient rifts.

One major difference that sets Charlevoix apart from other intraplate seismic zones is that the active structures involved are not simply a small number of discrete faults. Rather the CSZ comprises a distributed damaged volume resulting from a meteorite impact. It is this difference that makes it an ideal location to illustrate the effect of stress channelling by parallel rift faults. In the early stages of a seismic zone study, the initial focus of the investigation is often to determine which structures are "active". In Charlevoix because the structures generating seismicity are distributed throughout the crater, the investigation shifts to explain why only part of the crater is active (Figure 10A). This draws attention to the rift faults which, although possibly not currently active themselves, clearly have an important role in partitioning seismicity. In an alternative scenario the active structures could be a small number of discrete faults rather than an impact crater (Figure 10B). In this situation linear trends of seismicity clearly define which structures are seismically active. Seismicity could still be truncated by the rift faults, however, if they are aseismic or only periodically active and not in the seismic record, then their role is more subtle and could easily be missed, leading to an incomplete model.

The Charlevoix models show that some apparently aseismic structures can have a major role in partitioning stress in a rift environment. Evidence for similar processes may be found in the New Madrid seismic zone (NMSZ) in the eastern United States (Figure 11). The NMSZ is the site of the largest intraplate earthquakes on historic record in 1811-1812 (Grana & Richardson 1996), and is a region with continued seismic activity. The earthquakes are contained within the NE-SW trending Reelfoot rift which formed during the opening of the Iapetan Ocean, the same event which created the St. Lawrence rift. The active structures are interpreted as two rift-parallel right-lateral strike-slip faults with the northeastern arm forming the northwest boundary of the rift and the southeastern arm trending along the centre of the rift (Cox et al. 2006). These two strike-slip faults are connected by a left stepping reverse slip fault called the Reelfoot thrust. Seismicity along the Reelfoot thrust extends beyond the southeastern arm and is truncated by the southern margin of the rift, which experiences much less seismic activity (Figure 11)(Cox et al. 2001). Although the trend of the rift is oblique to the average regional orientation of S_H (approx. 80°, Ellis 1994), many stress orientations inferred from focal mechanism data within the seismic zone lie subparallel to the strike of the rift (e.g. Ellis 1994; Horton et al. 2005). The truncation of seismicity by the relatively aseismic rift margin is similar to the behaviour at the Charlevoix seismic zone. Combined with evidence of stress rotation within the Reelfoot rift, this provides compelling evidence that stress channelling is active in the NMSZ, and may be a contributing factor in the continued seismicity there.

5 CONCLUSIONS

Mazzotti (2007) describes a number of models to explain intraplate earthquakes in North America including the localized weak zone model, where earthquakes are confined to small areas of crustal weakness, and the large-scale weak zone model, where crustal strain is concentrated on major paleotectonic structures. Our model of the CSZ shares components of both of these models: the large-scale weak zone represented by the Iapetan rift structures interacting with the stress perturbation associated with the localized impact structure weak zone. The rift faults act as a conduit to concentrate higher stresses into the weak impact crater. Both components are required to generate the observed pattern of low-level seismicity.

Despite some of the limitations of the stress channelling model, such as its failure to explain the largest earthquakes of the Charlevoix seismic zone, it provides a potential mechanism for much of the low level continuous events frequently observed in the area. Using a very simple model incorporating only a few faults of varying strength and zones of differing elastic properties we are able to produce stress patterns that can explain many of the observed seismicity characteristics of the CSZ. These include why the earthquakes are localized into linear bands, rather than distributed throughout the impact structure, and how the rift faults act as boundaries to the seismicity.

The Charlevoix seismic zone's unique structural setting makes it an ideal location to show the role of weak bounding faults on altering the stability of intersecting structures. These large-scale weak faults can not only form the locus of intraplate seismicity but can act as natural boundaries for local stress volumes, and can form conduits for concentrating stress. Similar models involving stress channelling between rift faults could be invoked to explain earthquake concentrations on the Reelfoot thrust fault of the New Madrid seismic zone, on which seismic activity is truncated by the margins of the Reelfoot rift. Given that more than half of intraplate earthquakes occur within rifted crust, it is likely that this mechanism can be invoked elsewhere.

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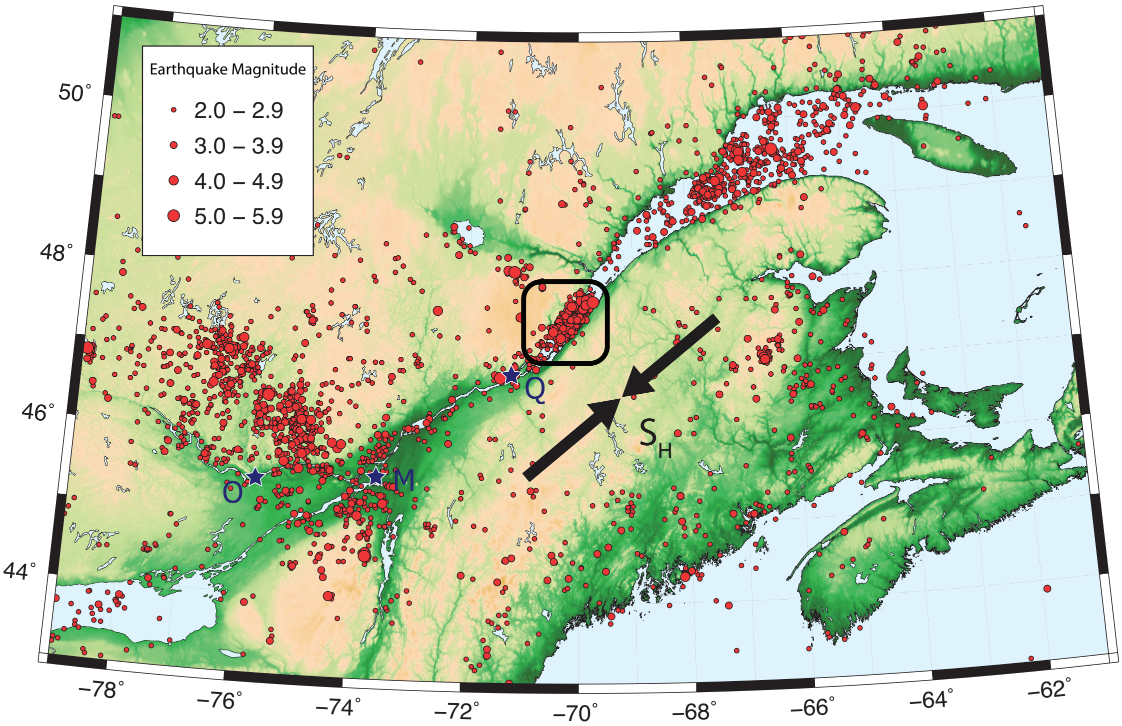

Figure 1. Seismicity map of eastern canada, showing the location of the Charlevoix seismic zone (Earthquake data from the Geological Survey of Canada for the period 1985-2007). Inverted arrows show the dominant orientation of maximum compressive stress (S_H) (Zoback & Zoback 1991). Abbreviations: Q: Québec City; M: Montréal; O: Ottawa.

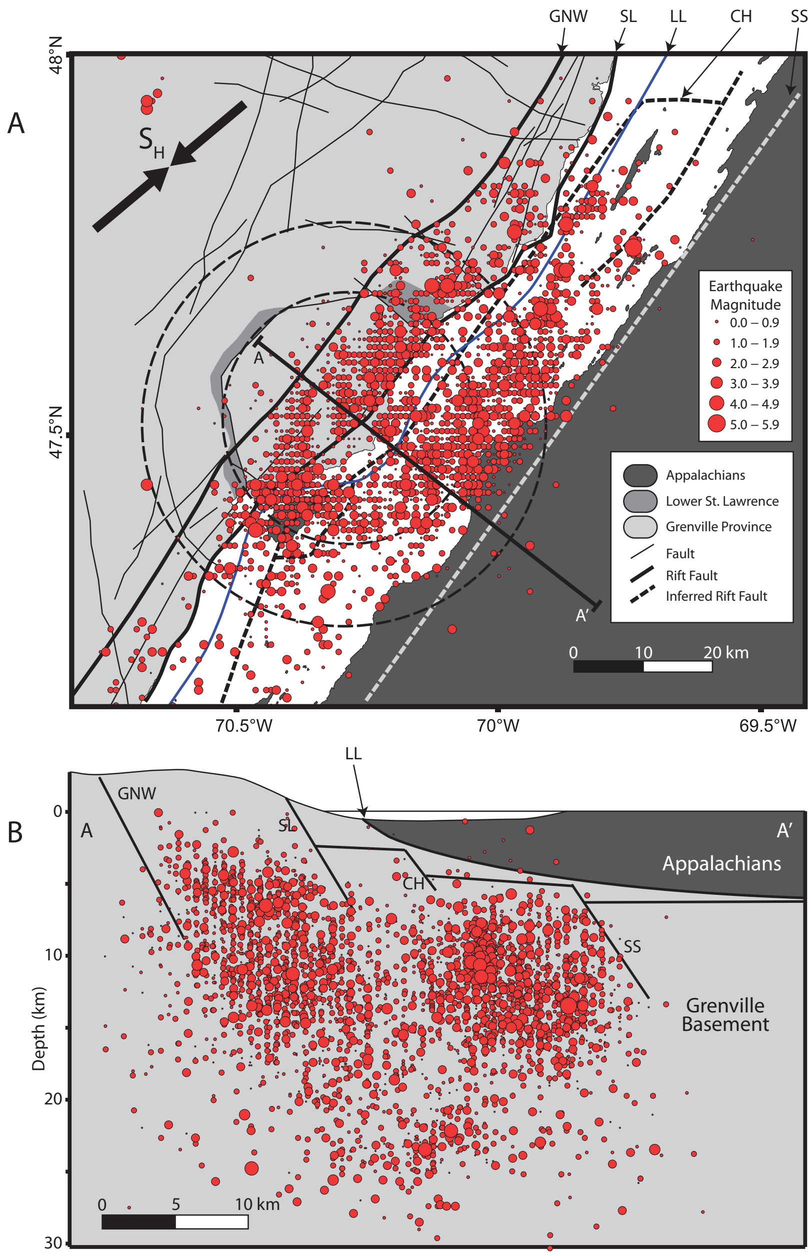

Figure 2. A – Seismicity and structural geology of the Charlevoix seismic zone (modified from Vlahovic et al. 2003). Abbreviations: GNW: Gouffre North-West fault; SL: Saint-Laurent fault; CH: Charlevoix fault; SS: South shore fault; LL: Logan's line (Appalachian deformation front), S_H: Maximum horizontal compressive stress orientation. B – Schematic cross-section showing seismicity across the St. Lawrence river, with geology based on the work of Lamontagne (1999). Earthquake hypocentres group into two long clusters which appear to be bounded by faults associated with the St. Lawrence rift (Earthquake data from the Geological Survey of Canada for the period 1985-2008).

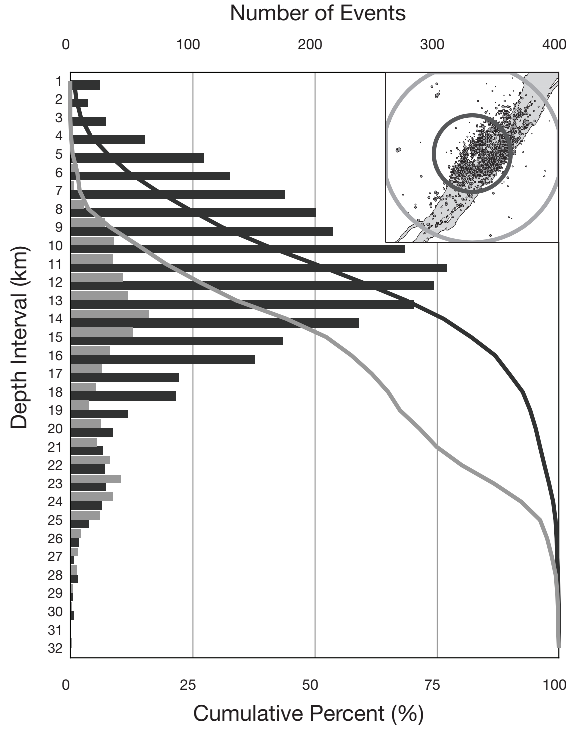

Figure 3. Earthquake depth distribution in two sub-zones of the Charlevoix seismic zone presented as number of events per 1 km interval (bars) and as cumulative percent (lines). The sub-zones are defined as epicentres within a 30 km radius from the centre of the impact structure (roughly the outer boundary of the crater, black) and from 30 km to 70 km from the centre (grey). Inset: Location map showing the two sub-zones. Shallow earthquakes are greatly enhanced in the inner zone relative to the outer zone.

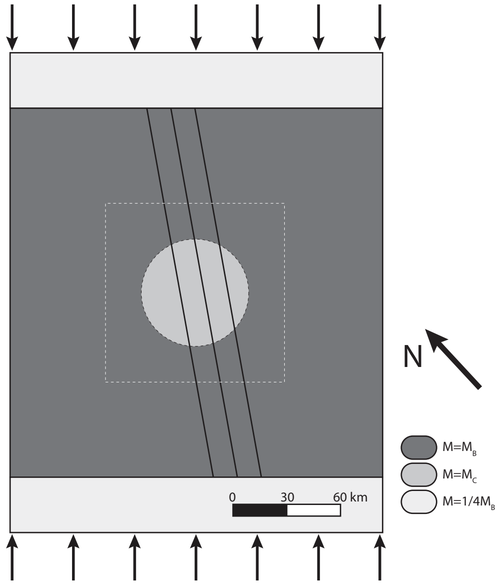

Figure 4. Model geometry of the Charlevoix seismic zone. The background moduli of the model (M_B) is given values of 73 GPa for bulk, and 44 GPa for shear modulus. The modulus of the crater (M_C) is varied from 50 to 100% of the background values. At the boundaries of the model soft zones with modulus 1/4 of the background values are added to reduce edge effects. The three black lines running through the crater represent the faults. The dashed square around the crater shows the boundaries of the contour plots of Figures 5 and 6. The two converging sets of arrows on the edges of the model represent the NE-SW oriented regional horizontal maximum compressive stress. North arrow indicates the relative orientation of the model with respect to the natural prototype.

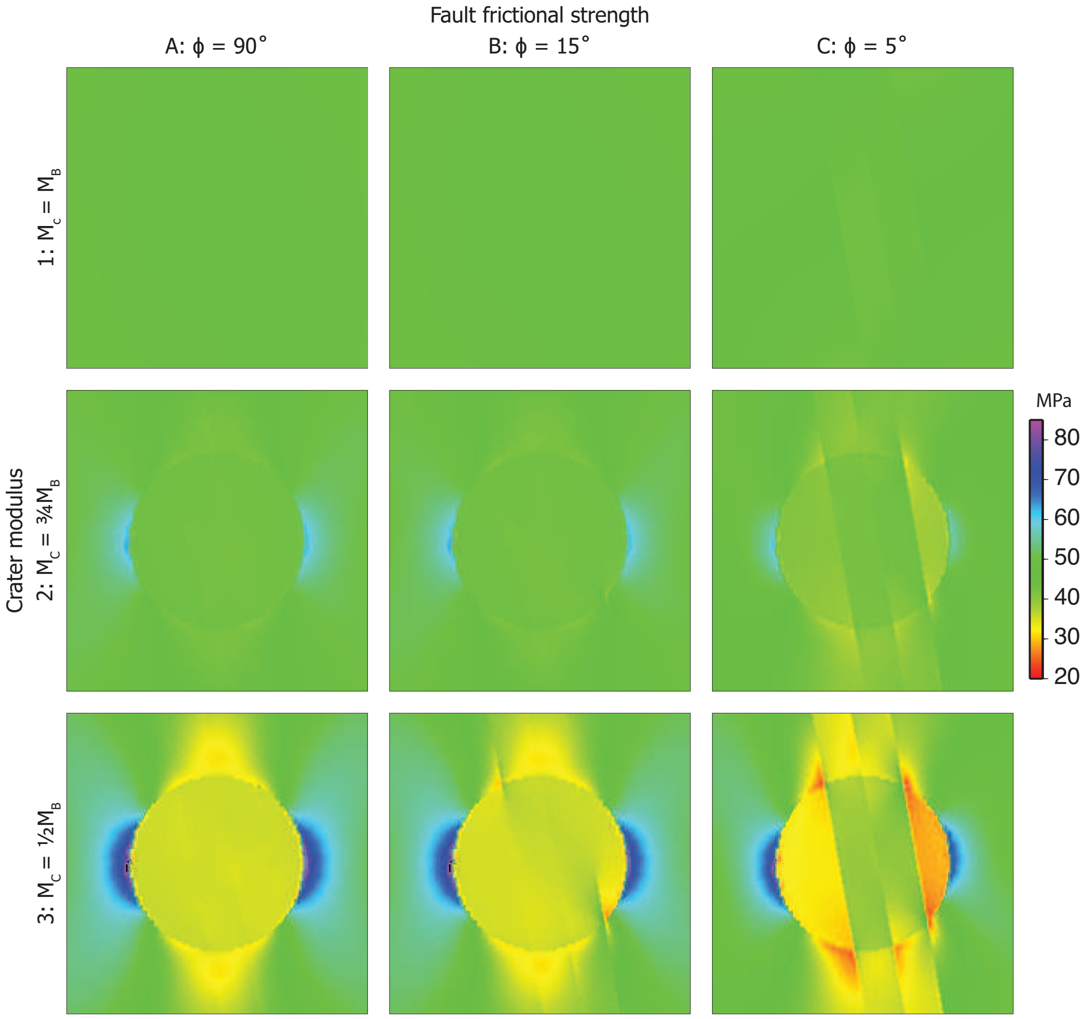

Figure 5. Contour plots of maximum deviatoric stress magnitude for varying values of Mohr-Coulomb fault friction angle (ϕ) and relative crater elastic moduli (M_C, both bulk and shear) compared to the surrounding rocks (M_B). A reduction in crater modulus results in a reduction of stress in the crater at the expense of stress concentration in two lobes on either side of the crater. In the absence of a large modulus contrast, a low fault strength has little effect on stress magnitude, however, when the two features are combined there is an added partitioning of stress magnitude in the interior of the crater.

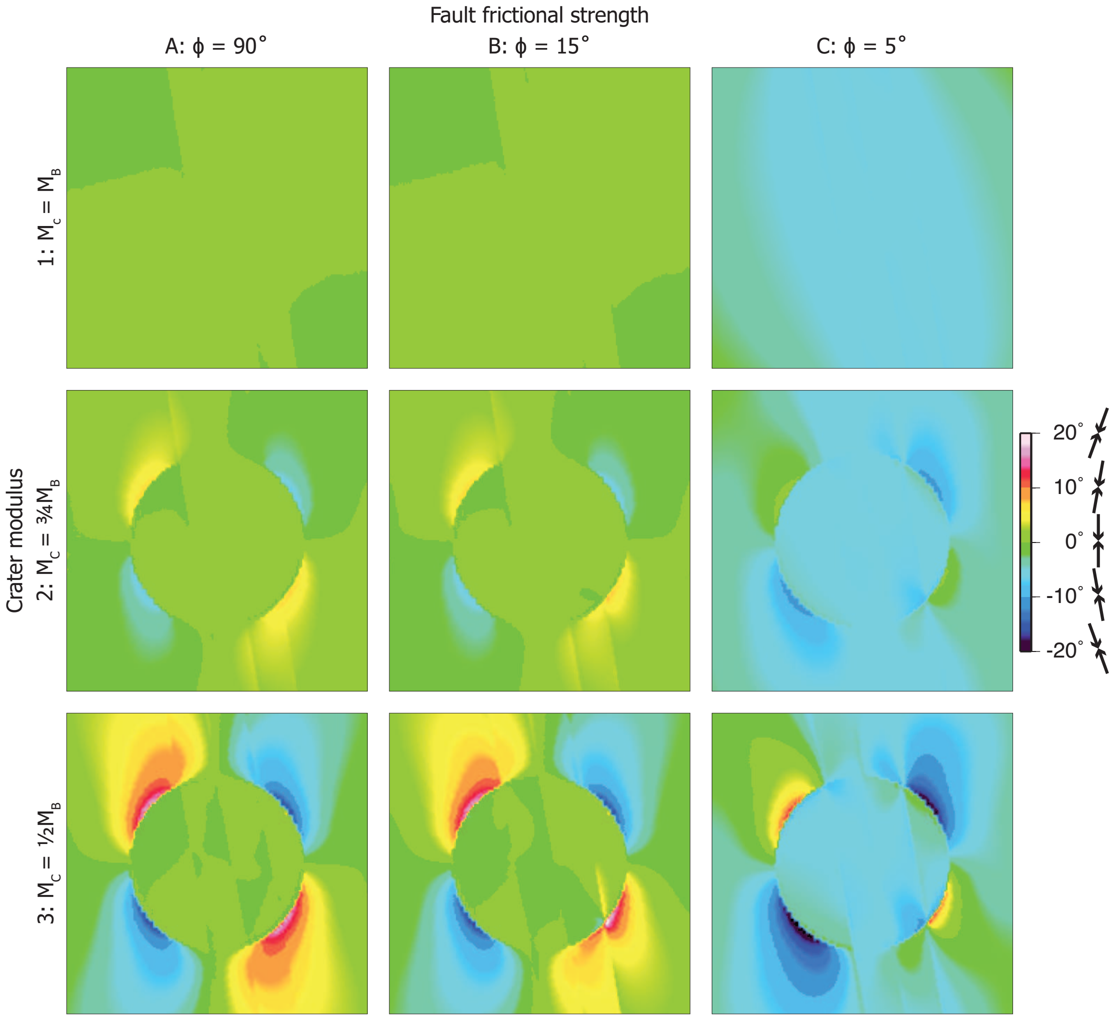

Figure 6. Contour plots of maximum compressive stress (S_H) orientation for varying values of Mohr-Coulomb fault friction angle (ϕ) and relative crater elastic moduli (M_C, both bulk and shear) compared to the surrounding rocks (M_B). Orientation is given relative to model loading direction, with clockwise rotation positive and counterclockwise negative. A reduction in crater modulus results in the stress field flowing around it, and a reduction in fault strength causes stress to flow parallel to them.

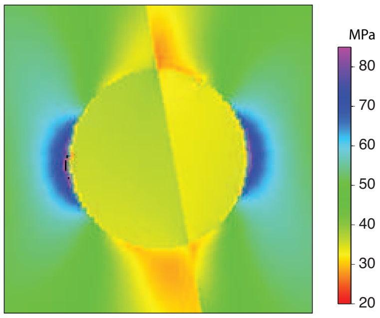

Figure 7. Contour plot of deviatoric stress showing the effect of only a single weak rift fault. The impact structure modulus is set to 50% of the background level and fault friction at 5°. In this case, since there is no region bounded on both sides by faults, stress simply flows around either side of the crater.

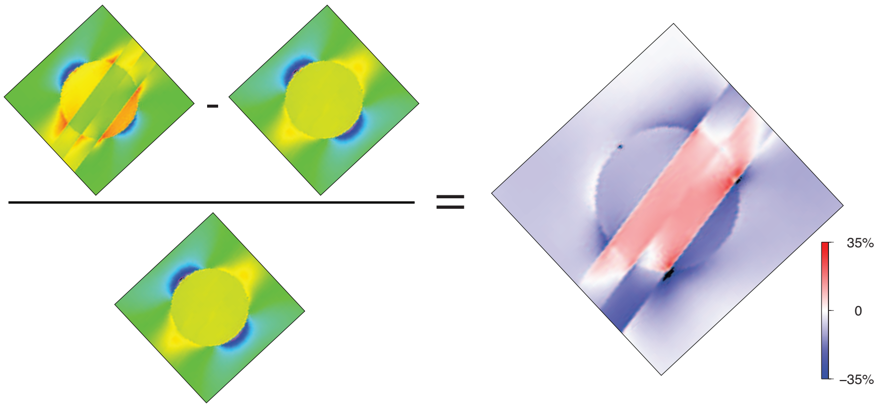

Figure 8. Grid algebra equation used to isolate the effect of weak rift faults and give a plot of change in deviatoric stress relative to the seismically stable locked rift model. The red area between the faults in the impact crater marks a region of increased deviatoric stress stress and can be considered a region of increased potential for earthquakes.

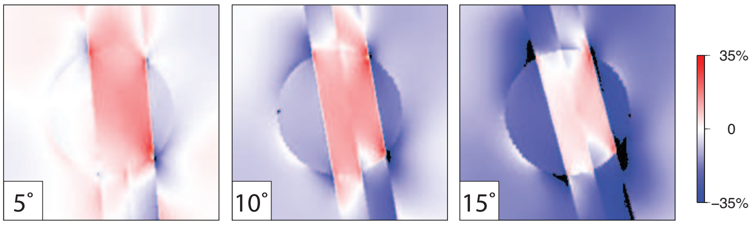

Figure 9. Contour plot of increased earthquake potential (as defined in Figure 8) for varied orientations of faults relative to the applied boundary stress. Note the extension of the zone of increased earthquake potential along the rift to the north of the crater, most apparent in the 5° model, which may explain the increased concentration of earthquakes compared to the southern region (see Figure 2A).

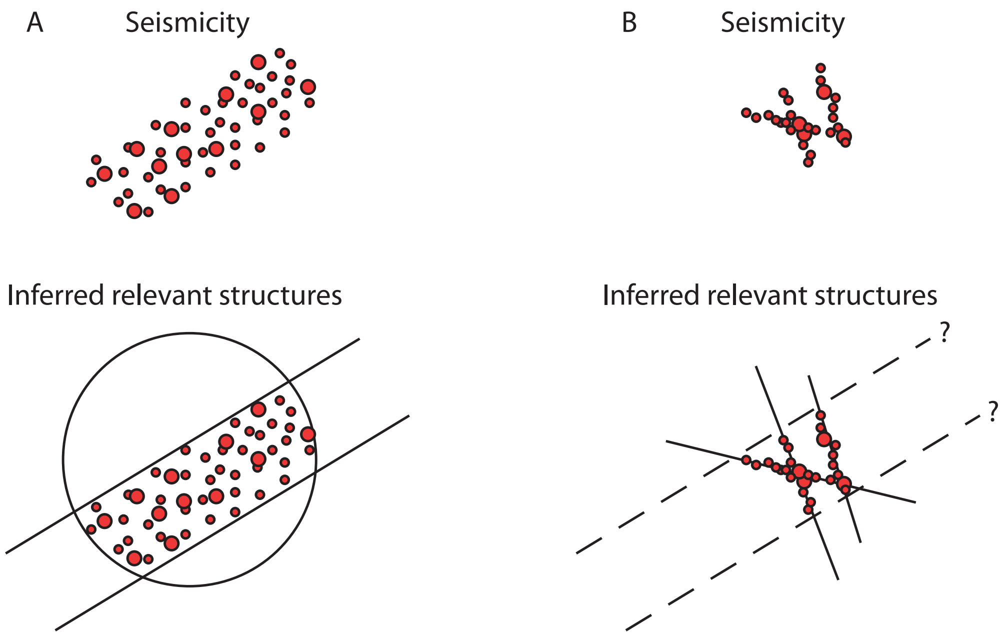

Figure 10. Cartoon showing the seismicity and relevant structures in two scenarios involving stress channelling within rift zones. A – Stress channelling into an impact structure producing a volume of seismicity with clearly defined boundaries at the rift boundaries, indicating their significance. B – Stress channelling resulting in partial reactivation of intersecting faults, in this example the rift faults are significant yet it is not clearly evident from the seismicity data.

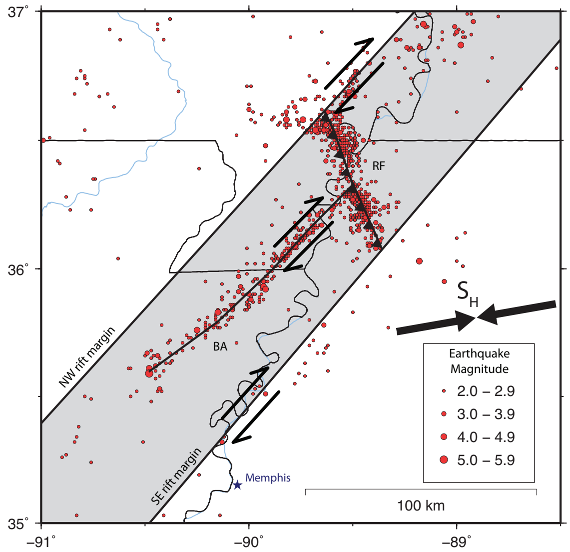

Figure 11. Earthquakes epicentres of the New Madrid seismic zone (1974–2008) with interpretation based on Cox et al. (2001). Abbreviations: RF: Reelfoot thrust fault; BA: Blytheville Arch; S_H: Maximum horizontal compressive stress orientation for the NMSZ area (Ellis 1994). Note that earthquakes along the Reelfoot thrust fault are truncated by the southeast margin of the Reelfoot rift. Proposed stress channel between the NE and SW rift margins is shown in grey. Seismicity data from the catalogue of Center for Earthquake Research and Information, University of Memphis.