Natural and man-induced destructive earthquakes in stable continental regions

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Keywords – earthquake activity, intracontinental regions, magnitude, seismic risks

Summary

Despite the real societal challenge posed by their important potential of destruction, the causes of infrequent moderate and large earthquakes in tectonically stable continental regions (SCR) are not yet well understood. Nevertheless, recent studies suggest that large earthquakes in SCR can be explained by transient perturbations of local crustal stress or fault strength because the tectonic loading on faults is very slow. In this paper, we assert that this new hypothesis is well supported by the observation that many moderate M_W 5.5-6.0 SCR earthquakes are shallower than similar events in active regions. Moreover, by using the basic principles of frictional fault reactivation, we explain why these temporary stresses play a more fundamental role in the initiation of large earthquakes in SCR than at plate boundaries. As these disturbances in stresses can be related to natural environmental phenomena, but also to human activities, we also debate about the potential role of man-made earthquakes in SCR seismicity and seismic hazard. This discussion highlights the need to better understand the contribution of man-made earthquakes in the observed seismicity.

Mots-clés – tremblements de terre, régions intracontinentales, magnitude, risques sismiques

Résumé

Malgré le véritable défi sociétal posé par leur important potentiel de destruction, les causes des rares grands tremblements de terre dans les régions continentales stables (RCS) ne sont pas encore bien comprises. Des études récentes indiquent que les grands tremblements de terre en RCS peuvent être expliqués par l'action de perturbations transitoires des contraintes locales ou de la résistance des failles parce que le chargement tectonique sur les failles est très lent. Dans cet article, nous soutenons que cette nouvelle hypothèse est supportée par l'observation que beaucoup de séismes modérés de magnitude M_W 5.5-6.0 dans les RCS ont une profondeur beaucoup plus faible que celle de séismes semblables en régions sismiquement actives. Par ailleurs, en nous basant sur les critères classiques de réactivation des failles, nous expliquons pourquoi ces contraintes transitoires joueraient un rôle beaucoup plus fondamental dans l'initiation des grands tremblements de terre en RCS qu'en limite de plaques. Ces modifications de contraintes dans la croûte pouvant être reliées à des phénomènes environnementaux naturels, mais aussi à certains types d'activité humaine, nous discutons la contribution induite par l'Homme à la séismicité et l'aléa sismique en RCS. Cette discussion met en lumière l'importance de mieux comprendre la contribution des séismes induits par l'activité humaine dans la séismicité observée.

Introduction

Most of the seismic activity and large earthquakes worldwide occurs at active plate boundaries. Nevertheless, rare moderate and large earthquakes with $Mw \geq 5.5\text{-}6.0$ also occur in regions unaffected by currently active plate boundary processes. Such regions where tectonic loading is insignificant are defined as stable continental regions (SCR) by Johnston (1989) (Figure 1).

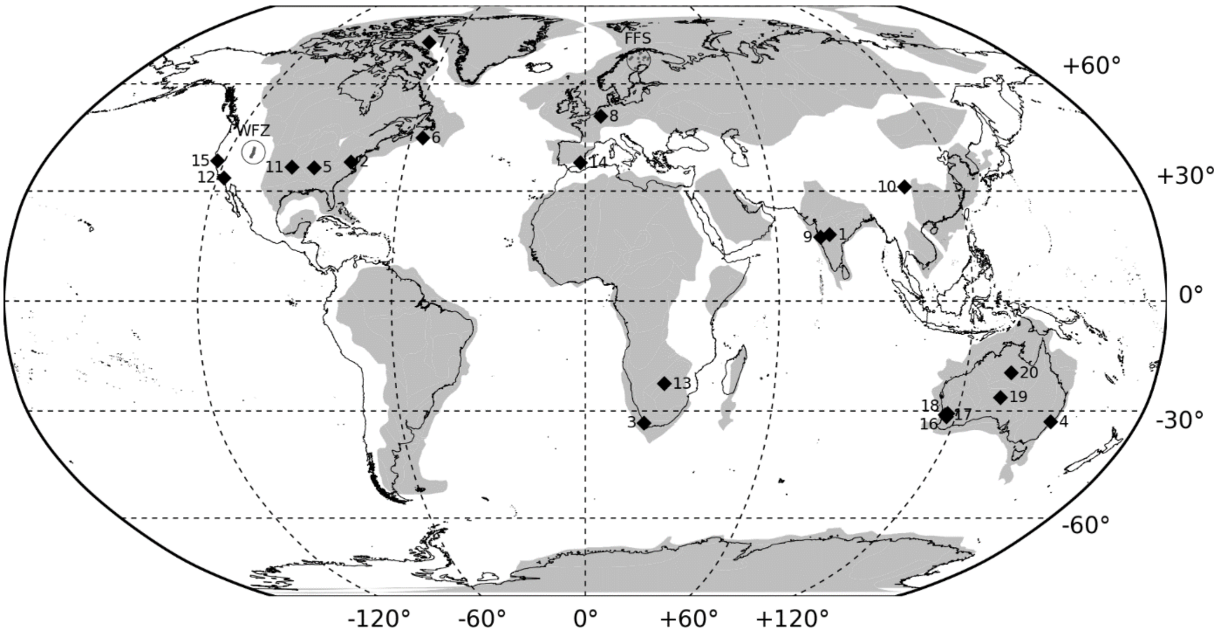

Figure 1: Stable continental regions

Stable continental regions defined by Johnston (1989) are indicated in grey on the world map. Black lozenges and associated numbers refer to the earthquakes mentioned in the text with these numbers in brackets. The two circles represent fault zone areas mentioned in the text: WFZ is the identifier of the Wasatch Fault Zone while FFS is for Fennoscandia Fault Zone.

Those moderate and large SCR earthquakes can be very damaging and at the origin of many fatalities. The most recent dramatic example is given by the M_W=6.1 1993 Killari (or Latur) [1] earthquake that occurred in central India and caused about 10,000 casualties (Seeber et al., 1996). Such damaging seismic events also occurred in many other continental areas considered as tectonically stable. Thus, Central Virginia was struck by a M_W=5.8 earthquake on 23 August 2011 [2] that caused widespread minor and moderate damage to buildings (Horton and Williams, 2012) and was felt over a very large area in eastern North America. Examples in other continents are the M_W=6.3 29 September 1969 Ceres earthquake [3] that caused considerable damage and nine deaths in southern Africa (Green and Bloch, 1971) or the M_W=5.3 28 December 1989 Newcastle earthquake [4] in south-eastern Australia, killing 13 and injuring more than 160 people and causing damage with an estimated cost around 4 billion Australian dollars (Sinadinovski et al., 2006). The largest earthquakes in SCR reach or slightly exceed M_W=7.0, like the 1811-1812 New Madrid events [5] that occurred in the middle of the North American continent (Hough et al., 2000). At the time of the earthquakes, their impact was weak because very few people lived in this area, but if similar events would occur today, they would cause an important number of fatalities, widespread destructions and a very important economic cost. Such large earthquakes also occur on passive margins. This was the case on the margin of eastern Canada with the M_W=7.2 1929 Grand Banks [6] and M_W=7.3 1933 Baffin Bay earthquakes [7] (Stein et al., 1979). The former seismic event triggered submarine landslides that generated a tsunami killing 27 people, destroying wharves, and displacing homes on the Canadian coast (Tuttle et al., 2004), indicating that despite their

occurrence offshore they can cause huge destructions on the coasts. This non-exhaustive list demonstrates the societal challenge associated to this seismicity in stable regions worldwide.
Earthquake activity and associated rare large earthquakes in SCR appear episodic, sometimes clustered on single fault zones that are active during relatively short intervals, and then migrates to other structures of similar strength (Crone et al., 1997). This is why Liu and Stein (2016) use the term "unanticipated" for the earthquakes in plate interiors by comparison to most large earthquakes at plate boundaries or active plate interiors that are or could be "anticipated" because their location and average recurrence is predicted by steady state plate motion and in some areas by the knowledge of long term earthquake records. Consequently, this lack of prospective in SCR makes a realistic evaluation of seismic hazard difficult.
Recently, Calais et al. (2016) explained the occurrence of large earthquakes in SCR at the light of their unanticipated spatial and temporal pattern and the lack of observed tectonic loading in these regions. These authors pinpoint the role played in their initiation by transient variations of fault strength or regional crustal stresses overlapping on the large scale intracontinental tectonic stress field. These disturbances can be related to short and long term local or regional variations of water at the ground surface or inside the crust. They also include surface Earth material loading and unloading like erosional or depositional phenomenon or the melting of ice sheets. The time-scale of these perturbations can vary from a few days to several ten thousand years while their spatial scale can range from a few km to a few thousand of km. Moreover, because of the very low tectonic strain rates in SCR, these large earthquakes release a significant part of the strain energy accumulated by the very long-term action of the intracontinental stress field (Craig et al., 2016). For that reason, this crustal strain energy reservoir can be strongly depleted after their occurrence and a very long time would be necessary to recover it. This would explain why large earthquakes and the associated seismicity in SCR do not necessarily repeat at the same location, in contrast to what occurs at plate boundaries where large earthquakes appear to recur more or less regularly on active faults.
These stress or fault strength disturbances at the origin of SCR earthquake activity can be related to natural environmental phenomena (see examples in Bilham et al., 2003; Calais et al., 2010; Craig et al., 2016; Gonzàlez et al., 2012), but also to human activities. This is attested by the rise of the number of observations and scientific papers concerning this man-made seismicity. The number of such seismic events significantly increased during the last 20 years due to the important development of underground industrial activities like shale gas and geothermal energy exploitation, or hydrocarbon storage and extraction, but also to a better-dedicated seismic monitoring (Gupta and Rastogi, 1976; Zoback and Harjes, 1997; Grigoli et al., 2017). A similar situation already occurred during the 1960th and 1970th years after the observation of some large earthquakes that followed the filling of large water reservoirs (Gupta and Rastogi, 1976). Two of the twenty four earthquakes with $M_W \geq 6.0$ that occurred in SCR between 1960 and 2008 (see earthquake catalog of EPRI, 2012) are related to large dams filling in areas where previous seismic activity was unknown. Hence, a consequence of the limited availability of strain energy in SCR would be that the occurrence of moderate or large earthquakes related to human activities in seismically inactive regions would represent an important societal issue. This also leads us to question whether some past earthquakes considered as natural and that occurred in regions where human activity largely modified stresses or water circulation in the upper crust would have been man-induced.
In this paper, we first discuss the destructive character of moderate SCR earthquakes and whether the shallow focal depth and larger stress drop of many moderate SCR earthquakes

compared to similar earthquakes in active regions could partly explains the dramatic impact of recent moderate SCR earthquakes. Secondly, we use the basic principle of frictional reactivation of faults to illustrate the differences between large earthquakes in regions where crustal strain rates are significant and SCR where the tectonic loading is close to zero. Thirdly, we discuss the possible relationship between the magnitude of large SCR earthquakes and the dimensions of the transient stress perturbations at their origin. Finally, we examine the contribution of man-made activities in the triggering of moderate and large earthquakes, considering whether it could be an issue equally important as natural seismic activity in some SCR.

1. The destructive character of moderate earthquakes in stable continental regions

Earthquakes can be very destructive and at the origin of many fatalities when they occur in highly populated areas. By noting that recent strong earthquakes are among the most deadly known seismic events, Bilham (2009) even suggests an increase of seismic risks and earthquake consequences caused by the spectacular increase of worldwide population in a very short time period. This will lead to a more critical situation in the next fifty years because earthquake-resistant building, despite being relatively successful in developed nations, is often neglected in developing countries. The reasons for this failure, even in regions at plate boundaries, are the poverty, often severe in the developing nations, the lack of awareness of the reality of the seismic risks and the short-term view of political perspectives or economic investments. In SCR, this ignorance is also clearly associated to the episodic, clustered and migrating character of intraplate seismicity, rendering uncertain the magnitude of future earthquakes that are also likely to occur in unexpected locations (Stein et al., 2009).
Curiously, many examples suggest that moderate SCR earthquakes with magnitude in the range 4.5 – 6.0 have often an impact far greater than events of similar magnitude in active regions of the world. As mentioned in the introduction, this was the case for the M_W=6.1 1993 Killari (or Latur) earthquake [1] in central India. This seismic event, with epicentral intensity VIII on the Modified Mercalli scale (Jain et al., 1994), destroyed 20 villages in a radius of 15 km and caused about 10,000 casualties. This particularly catastrophic impact is due to the nearly total collapse of traditional stone-and-mud buildings in the villages around the epicenter of an event that occurred during the night when most people were sleeping. The high seismic vulnerability of these dwellings is related to the heavy mass of their wood-plank roofs topped by a thick clay layer to protect them from rain and heat (Jain et al., 1994). Even if the types of buildings are different in other intracontinental regions worldwide, there is an incontestable consistency in their seismic vulnerability, which is often such that buildings cannot safely support intensity grades as low as VII. A typical example of this widespread vulnerability, even in developed regions, are the consequences of the M_W=4.6 1983 earthquake [8] that occurred in the historical city of Liège in Belgium. This small seismic event damaged more than 16,000 buildings, mainly old low-rise masonry buildings sharing two walls (Plumier, 1985). The most visible damage was the fall of chimneys, bricks or ornamental features that caused further damage to roofs and many cars in the streets. Fortunately in this particular case, the earthquake occurred during the night; if it would have occurred at daytime, the falling of these objects would have caused more dramatic human consequences than the identified two deaths and dozens of injuries. Another effect of the significant damage in many houses was that more than 1000 people became homeless, which caused significant logistical problems.

It is difficult to explain the difference of the observed impact between moderate earthquakes in SCR and in more active regions only by a difference in building vulnerability. As earthquake resistant design is not yet applied in many regions worldwide both in SCR and in seismically active zones, the damage should be expected to be relatively comparable in these different areas, even if building methods are not necessarily similar. Of course, in regions of more frequent damaging earthquake, buildings should be often more resistant to shaking by the experience of the destruction of the weakest parts of the structures and their replacement after destructive events. Moreover, the impact of destructive earthquakes is also depending on other factors like the season and the time of the day of its occurrence, the density of housing, the local geotechnical conditions etc. The victim number and the risks associated to industrial facilities also strongly depend of rescue organization and preparedness. However, two seismic source parameters despite their great variability are recognized to be different in SCR by comparison to seismically active regions: focal depth and stress drop. These differences could partly explained the damage importance in SCR compared to seismically active regions because they favor higher strong ground motions for earthquakes in SCR than seismic events of similar magnitudes in active regions.
In active continental regions, the nucleation zone of earthquakes extends from a very shallow depth to the brittle-ductile transition inside the crust at depths where temperatures reach 300°C, typically between 10 and 20 km (Scholz, 1988). Moderate and large earthquakes are generally initiated at the base of this seismogenic layer. By studying earthquake focal depth in SCR, Klose and Seeber (2007) evidenced a bimodal distribution, which is different to this classical distribution. Part of the SCR earthquake ruptures are confined to the upper 10 km of the crust while the other part is in the range 20 to 35 km. Klose and Seeber (2007) observed that many large SCR earthquakes nucleate on reverse faults at less than 5 km deep and that 80% of the seismic moment is released in the uppermost 7 km of the crust, which is shallower than in more active regions. Therefore, being closer to the ground surface than in seismically active regions, many moderate SCR earthquakes would have a stronger impact in the epicenter area. In section 6, we discuss whether this depth distribution could be related to some generic characteristics of earthquake activity in SCR.
Moreover, earthquake stress drop is another source parameter that can directly influence spectral amplitudes of ground motion generated during earthquakes. Classical works of Mc Guire and Hanks (1980) and Hanks and Mc Guire (1981) established a direct proportionality between peak ground accelerations (PGA) and stress drop. In the context of our study, it is interesting to note that Kanamori and Anderson (1975) already pointed out a difference of stress drop between earthquakes along plate limits and in plate interiors by studying scale relationships between earthquake rupture area and seismic moment. More recently, Allmann and Shearer (2009) evaluated stress drop from seismic time histories for about 2000 moderate and large earthquakes between 1990 and 2007 and evidenced that stress drops are two times higher for intraplate (~ 6 MPa) than for interplate earthquakes (~ 3 MPa). Hence, even if their dataset included very few events from SCR, their analysis supports a possible influence of stress drop on the more destructive character of SCR earthquakes.

2. Large earthquakes at plate boundaries and active plate interiors

Large earthquakes are defined as the ones for which the rupture propagates over the whole thickness of the brittle crust (Sibson, 1983; Scholz, 1988, 1990). The magnitude of the smallest earthquakes for which the whole seismogenic layer is ruptured ranges from 5.5 to 6.0

(Meghraoui et al., 1999). Along a major active fault zone, such moderate earthquakes rupture only a short section of the fault. Of course, if the rupture propagates along several fault segments, which is common for large earthquakes at plate boundaries, their magnitude can be greater than 7.0 and even reach 7.8-8.0 along continental strike-slip faults like the San Andreas Fault in California or the North Anatolian Fault in Turkey. The largest observed magnitudes greater than 9.0 occur during large mega-thrust earthquakes in subduction zones. At plate boundaries and active plate interiors, large earthquakes and their recurrence result from the localized accumulation of tectonic stress on long-lived active faults in a steady-state system where a balance is achieved between the rates at which strain accumulates and is released on faults (see Kanamori and Brodsky, 2004). In these regions, the accumulated elastic strain along the whole length of a fault zone during the seismic cycle allows several adjacent fault segments to be similarly stressed and hence to be ruptured during the same earthquake. This is why large plate boundary earthquakes may reach magnitudes up to 8.0.
The current paradigm for the earthquake process is based on these observations at plate boundaries. There, steady relative plate motions create a progressive increase with time of the shear stress τ acting on the faults. These faults do not move as long as τ stays smaller than $\mu_S(\sigma_n - P_f)$[1] in their weakest part (Figure 2A). When a fault is reactivated during a large earthquake, it releases part of the strain energy accumulated by the relative plate motion since the previous large earthquake along the fault portion on which the slip occurs. Therefore, after the occurrence of the event and due to the continuity of the plate motion, a new earthquake cycle begins and new elastic strain energy is progressively rebuilt over the whole length of the ruptured plate boundary until the next large event.

3. The criterion of frictional fault reactivation: natural and man-made induced earthquake activity

Nevertheless, as already noticed by different authors like Sibson (1990), this criterion of frictional reactivation of an existing fault in the current stress field implies that fault instability could also occur because the fluid pressure P_f increases, reducing the effective normal stress on the fault, or the normal stress on the fault σ_n decreases by a modification of fault loading (Figure 2A).
The importance of fluid pressure in the earthquake generation process is widely accepted in the scientific community. The first direct evidence comes from reservoir-induced seismicity. There are numerous examples of earthquakes occurring after the first impounding of a nearby man-made reservoir (Gupta and Rastogi, 1976). The largest observed reservoir-induced earthquake is the 10 December 1967 Koyna earthquake [9] in India with a magnitude M_W=6.3. However, discussions about the possible triggering of the 12 May 2008 M_W = 7.9 Wenchuan (China) earthquake [10] that killed 90,000 people, by the impoundment of a large water reservoir in 2005 open the possibility that higher-magnitude man-induced earthquakes could occur (Ge et al., 2009; Zhou et al., 2010). Talwani and Acree (1985) described these reservoir-induced earthquakes as resulting from a diffusion process of pore pressure that reduces fault strength or also possibly creates a chemical effect in reducing the friction coefficient of the fault. Fluid injection during mining and oil recovery also causes higher fluid pressure that is at the origin of seismicity (Zoback and Harjes, 1997). The most illustrative example is the

[1] σ_n is the normal stress on the fault, μ_S is the static coefficient of rock friction and P_f the fluid pressure in the rock mass.

dramatic increase of the seismicity in central United States since 2008, mainly due to the injection of waste-water resulting from oil and gas extraction. This seismicity produces a significant hazard in Oklahoma (Brooks et al., 2017). The strongest earthquake occurred in 2016 and reached M_W=5.8 [11] (Chen et al., 2017). Some analyses also suggest similar industrially induced seismic activity at plate boundaries. For example, Hough and Page (2016) provide evidence that moderate earthquakes in the Los Angeles Basin, including the 1933 M_W=6.4 Long Beach earthquake [12] could be related to the oil boom between 1915 and 1932. Observations on the role of fluids in the initiation of natural earthquake activity are more complicated than for induced seismicity by human activities because, while the location and the fluid volumes and pressures from induced activity are relatively well-known, the natural fluid reservoirs are not so easy to capture. Nevertheless, the role of fluid of natural origin in the initiation of earthquake activity was also the subject of different studies during the recent years. For example, pore pressure variations have been proposed to explain the observation of rainfall-triggered earthquake activity in the Staufen Massif (SE Germany) (Hainzl et al., 2006), as well as the spatial and temporal evolution of the 1997 Umbria-Marche seismic sequence in central Italy (Antonioli et al., 2005) or the fluid-driven earthquakes on the Irpinia fault also in Italy (Amoroso et al., 2017). More recently, Gardonio et al. (2018) suggest that the April 2017 M_W 6.5 Botswana earthquake [13] that occurred at a depth of 29 km would have been activated by a transient pulse of fluids from a deep source. In this case, the fluid movement would have been evidenced by two foreshock swarm-like sequences.

Some environmental processes like ground water volume variations, melting of large ice sheets and erosional or depositional phenomena can be at the origin of surface loading or unloading modifying crustal stresses and favoring fault slip reactivation. For surface loading or unloading with horizontal dimensions of ten to a few tens of km, stress modification is directly related to the change of the lithostatic pressure. Thus, Gonzàles et al. (2012) explain the shallow M_W=5.1 earthquake [14] in Lorca (SE Spain) on 11 May 2011 by groundwater extraction from a nearby aquifer. Craig et al. (2017) also evidence that recent seismicity variations in the New Madrid Seismic Zone (central United States) are the direct consequence of elastic stresses induced by water loading changes in the upper Mississippi embayment. On their side, Kraner et al. (2018) identified a natural seasonal nontectonic loading in the Napa region of North California, making faults more likely to slip during the summer. They infer that this loading could potentially have triggered the M_W=6.0 24 August 2014 South Napa earthquake [15].

When the spatial dimensions of the varying stress anomaly are larger (several hundreds of km), flexural stresses can play a more prominent role. This is the hypothesis of Craig et al. (2016) who interpreted the series of M>7.0 earthquakes that are attested in Fennoscandia by fault scarps formed around 9.5 ka ago as resulting from the reduction of normal stress when the ice sheet was rapidly melting (Figure 1). Calais et al. (2010) also explained the large Holocene earthquakes that occurred in the New Madrid region by an upward flexure of the lithosphere caused by an intense erosional event that occurred between 16 and 10 ka BP.

Of course, other processes modifying the stress state on faults can trigger earthquakes. A well-known mechanism is the change of static Coulomb stress by a fault rupture that affects other faults in the vicinity (King et al., 1994; Stein, 1999). Seismic waves from distant earthquakes can also create sustained groundwater pressure changes sufficiently important to trigger seismicity (Brodsky et al., 2003). Moreover, intracontinental areas are 3-D volumes in which the loading of faults is more complex than at plate boundaries because diffuse fault systems have to collectively accommodate slow tectonic strain rates, and large earthquake ruptures modify stresses on neighboring faults and/or alter tectonic loading at larger distance (Liu and Stein, 2016).

4. The criterion of frictional fault reactivation: differences between active regions and SCR

Fault reactivation by fluid pressure and loading or unloading as described in the previous section occur both in SCR and in seismically active regions. Nevertheless, their role in the seismic activity seems different in the two types of regions. They appear fundamental in the genesis of SCR earthquake activity, while their contribution in active regions is less important and partially hidden by the action of tectonic strains. This difference can be easily conceived when considering the criterion of frictional fault reactivation (Figure 2A).

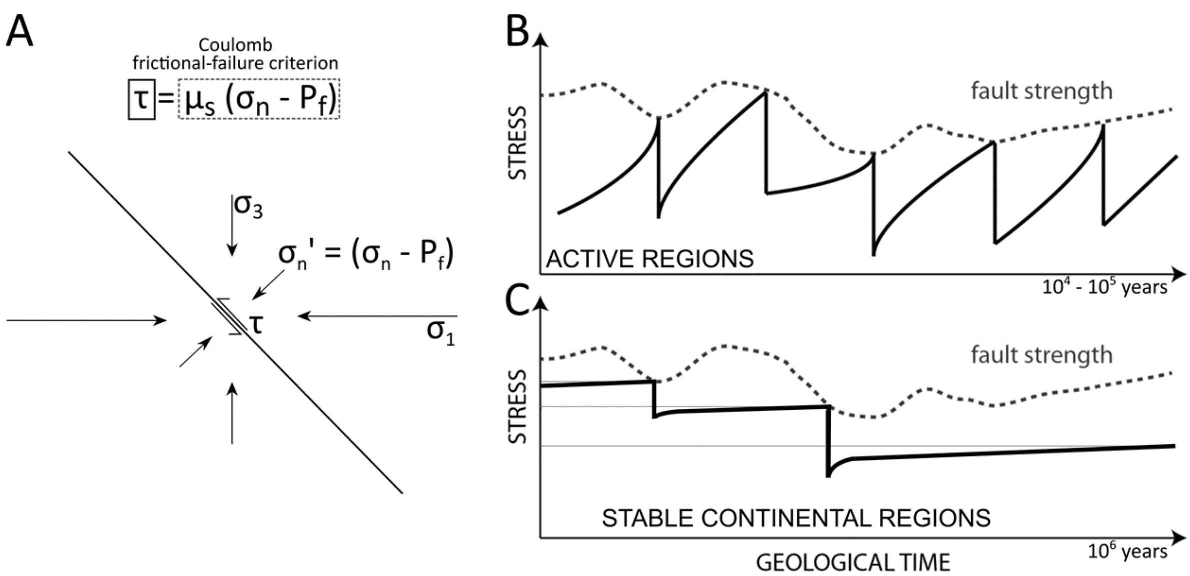

Figure 2: Frictional reactivation of an existing fault in the current stress field

A) *Classical expression of the Coulomb frictional criterion*: σ_n and τ are the normal and shear stresses on the fault determined from σ_1 and σ_3 that are the largest and the smallest principal stresses acting in the crust, μ_S is the static coefficient of rock friction and P_f the fluid pressure in the rock mass.
B) *Stress changes and large earthquake cyclicity along active faults in seismically active regions [modified from Kanamori and Brodsky, 2004]*.
C) *Stress changes and rare earthquake occurrences in SCR [modified from Calais et al., 2016]*.
   In this simplified figure, the term "Fault strength" is associated with the second member of the frictional criterion equation. Dotted lines represent its evolution with time and include time variation of μ_S, σ_n and P_f. The solid line corresponds to shear strain loading variation on the fault.

In active regions, the steady-state strain build-up caused by the tectonic loading controls the long-term global release of earthquake seismic moment and the cyclical nature of large earthquakes (Figure 2B). Nevertheless, temporal variations of fault strength would modulate the duration of the seismic cycle. This effect has been studied in the moderately active U.S.

plate interiors by Hetzel and Hampel (2005), who showed that the increased slip rate observed in the paleoseismic record on the moderately active Wasatch fault in the U.S. state of Utah (WFZ in Figure 1) since about 17 ka could be explained by the natural regression of Lake Bonneville and the melting of glaciers in the nearby mountainous area. Therefore, it seems logical to consider that the anthropogenic activity would have a similar effect as the natural activity by triggering moderate or large earthquakes that would have naturally occurred later in the course of the current seismic cycle. In this context, man-made induced seismic activity, as that suspected by Hough and Page (2016) in the Los Angeles Basin at the beginning of the 20th century, could be seen as a real part of the current activity on specific faults that would have likely been otherwise released by natural earthquakes. Kao et al. (2018) defends a similar idea based on different scenarios about the possible evolution of induced seismicity in Western Canada. Barbour and Pollitz (2019) considered these scenarios as plausible but discuss their basic underlying physical assumptions.

In SCR, as tectonic strain rates are nearly zero, the role of tectonic stress would be limited to building an elastic strain reservoir by its long term action. This reservoir, if sufficiently supplied, provides the strain energy required to generate the seismic activity and occasionally large earthquakes. However, the timing of these rare large earthquakes is independent of the tectonic loading on the fault, and is rather directly controlled by the natural and (or) man-induced transient disturbances of local stress or fault strength (Calais et al., 2016) (Figure 2C).

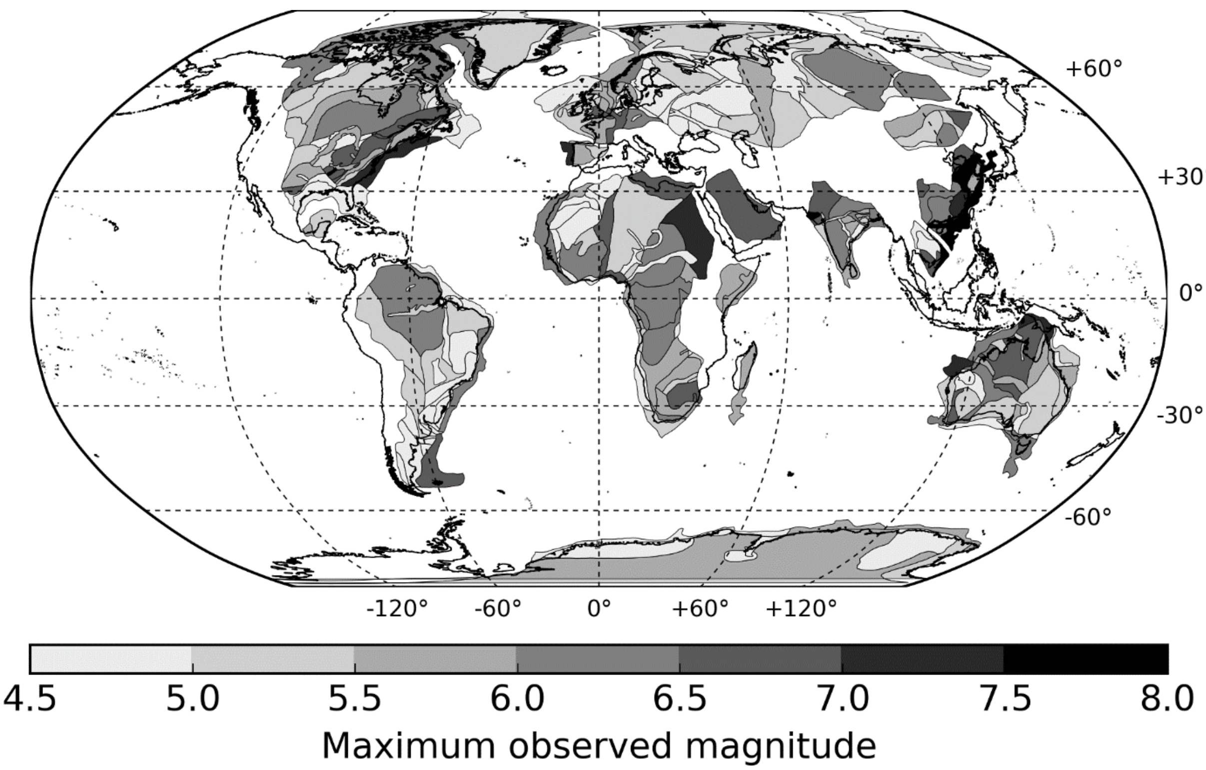

Figure 3. Observed maximum magnitude in SCR domains [EPRI et al., 2012]

The criterion of frictional reactivation of a fault is a simple qualitative means to roughly evaluate whether a fault can be reactivated by modifying the acting stress and/or fault strength conditions. Hence, it allows us to evidence the respective roles of elastic strain accumulation and transient disturbances of local stress or fault strength in large earthquakes occurrence and related seismicity, which are different in SCR compared to seismically active areas. In contrast, it does not furnish any information on the possible extension of fault areas on which the earthquake rupture will propagate and hence on the possible magnitude of the earthquakes, which are fundamental questions in seismic hazard and risk assessment.

5. Large earthquake magnitude in stable continental regions

The magnitude of the largest possible earthquakes in a given region is related to the dimension of the fault zones capable to be ruptured by large earthquakes and of the lithospheric volume in which tectonic loading is homogeneous. At plate boundaries or in active plate interiors, the known seismicity and the study of active faults often include in their records these largest earthquakes.

Due to the "unanticipated" and infrequent character of moderate and large earthquakes in SCR, there are very few regions where this largest earthquake can be considered as being represented in the seismic records. This is why the first scientific effort to address the issue was to collect available information on SCR seismicity worldwide with the idea that there would exist a relation between the frequency and magnitude of large earthquakes and particular tectonic contexts (Johnston et al., 1994). In this way, grouping the information on large earthquakes for the same "types" of region allows to significantly improve statistics on the largest observed magnitudes. Hence, the SCRs around the world were subdivided in 255 different domains based on crustal age and type, age of the most recent extension, stress state, and the orientation of the tectonic structures relative to the present stress field (Electric Power Research Institute [EPRI] et al., 2012). EPRI et al. (2012) combined domains with similar tectonic characteristics worldwide into super domains considering that their common characteristics correlate with a similar Mmax, the largest possible earthquake magnitude (Figure 3).

The classification in domains and super domains is somehow representative of the geological history of the different SCRs, of the current intraplate stress field and of its action on inherited structures. Nevertheless, it does not take into account the actual processes described in the previous sections that could control the initiation of large earthquakes in SCR. In this context, we note that the earthquakes with a magnitude slightly greater than M_W=7.0 attested in Fennoscandia by fault scarps dating from the beginning of the Holocene (Muir-Wood, 1989) and the ones that occurred in the New Madrid region in central United States in 1811-1812 (Hough et al., 2000) could correspond to the largest known SCR earthquakes[2]. They also correspond to seismic events that would have been initiated by strong transient stress perturbations with a few hundred to thousands km of horizontal spatial dimension and time scales of several thousand years (Calais et al., 2010; Craig et al., 2016). Due to their comparable spatial dimension, we suggest an analogy between the action of these stress perturbations on the inherited SCR faults and the shear stress buildup on active faults in tectonically active regions. Of course, there are fundamental differences between the two different types of region. Among others, the stress perturbation in SCR is transient with duration not exceeding a few thousand years, concentrating large earthquakes and the associated seismicity in a short time window at the geological scale, while in seismically active regions, shear stress is

[2] Vanneste et al. (2016) note that the two SCR earthquakes with the largest observed magnitude in the catalogue NUREG-2115 (EPRI et al., 2012) are a M_W 7.9 earthquake in eastern China in 1668 and the largest 1812 New Madrid M_W 7.8 earthquake. These authors question the validity of the SCR status of the region where the China earthquake occurred and note that the magnitude of the largest New Madrid earthquake is revised downward (Hough et al., 2000).

progressively rebuilt after each large earthquake during far longer periods. We advocate that this difference could explain why the magnitude of the largest SCR earthquakes, slightly greater than M_W=7.0, appears to be lower than the maximum magnitude observed at continental plate limits. Indeed, Manighetti et al. (2007) suggest that a certain structural maturity is necessary for an earthquake rupture to break barriers between fault segments. Active faults at plate boundaries reach this maturity after a few seismic cycles. In contrast, inherited faults in SCR cannot reach the same level of maturity by the absence of long-term recurrent movements, which would imply difficulties for earthquake ruptures to propagate on fault lengths exceeding some tens of km, limiting the largest earthquake magnitude to values slightly greater than 7.0.

On the other hand, several 5.5 ≤ M ≤ 6.6 earthquakes occurred during the last decades in the cratons of Australia [16, 17, 18, 19, and 20] and central India, some with documented surface ruptures (Crone et al., 1997). These two areas exhibit stable crust where compressive stress regimes dominate. In Australia, the orientation of the maximum horizontal stress slowly changes inside the continent in relationship to the balance between plate driving and resisting forces from the margin of the Indo-Australian Plate (Reynolds et al., 2002). On the other hand, the northward motion of the Indian plate results in a compressive stress field inside the plate. This compressive tectonic stress is twice as large than this far-field stress in central India, where the 1967 Koyna [9] and 1993 Killari [1] earthquakes occurred, by the flexural stress resulting from the collision between India and Tibet (Bilham et al., 2003). Bilham et al. (2003) also noticed that the rate of flexural stress change is small, but likely sufficient to bring this part of the Indian plate closer to failure. Therefore, Australia and central India are typical SCR in which large scale regional transient stress perturbations like the ones that acted in Fennoscandia or presently in the New Madrid areas are currently absent. Here, we argue that large earthquakes on these faults would rupture relatively small fault sections, which correspond to their observed range of magnitude 5.5 ≤ M ≤ 6.5. This leads us to suggest that earthquakes in the range of magnitude 5.5 ≤ M ≤ 6.5 would possibly be representative of the largest possible earthquake in this particular type of SCR.

6. Earthquake focal depths in SCR

Klose and Seeber (2007) noticed that the depth distributions in SCR, with 80% of the seismic moment release in the uppermost 7 km of the crust, express significant and systematic differences compared to the ones in active seismic regions, which would be related to fundamental differences in crustal geo-mechanical properties. Nevertheless, most of the M_W > 4.5 earthquakes with well-determined fault geometries used in their analysis are reverse faulting events resulting from compressive stresses considered as relatively common in many intracontinental regions (Zoback and Zoback, 1980). Therefore, even if it includes most of the recent moderate and large earthquakes that occurred in SCR worldwide, their dataset is mostly representative of old cratons where far-field stresses originating from plate boundaries are dominant compared to other possible stress sources.

As suggested by Calais et al. (2016), SCR fault reactivation is mostly related to processes acting at the ground surface or in the upper crustal layers. These processes include loading or unloading of the crust, and natural or man-induced fluid pressure. Hence, we can suppose that they would have the potential to modify stresses or reduce fault strength near the top of the seismogenic layer and increase the instability leading to earthquakes closer to the ground surface. Classically, hypocenters of large earthquakes occur near the base of the seismogenic layer where shear strength is strongest and friction the most unstable (Scholz, 1988). Thus, this model would represent more the situation in seismically active regions than in SCR. Hence, despite the reduced data number, the analysis of the focal depth of large recent SCR earthquakes by Klose and Seeber (2007) would support the hypothesis of Calais et al. (2016).

7. The contribution of moderate and large man-induced earthquakes in SCR

We emphasized the role of fluid pressure and loading or unloading near the ground surface in the triggering of earthquake activity. Many examples of these influences in earthquake activity presented in section 3 concern environmental parameters modified by industrial processes, which demonstrates the possible role of human activity in the earthquake activity of a particular region.
Earthquakes triggered by human activity have mainly been recognized at least since the second half of the 20th century by the observation of seismic activity associated to the filling of artificial water reservoirs in many regions worldwide (Gupta and Rastogi, 1976). Moreover, earthquake activity induced by fluid injection for industrial purposes is becoming an important hazard topic in developed countries like Europe and North America since the beginning of the 21st century (Ellsworth, 2013; Grigoli et al., 2017).
The identification of man-induced earthquake activity is facilitated when it occurs in areas of weak or absent seismic activity. This is the case in central India where the 10 December 1967 M_W = 6.3 Koyna earthquake [9] occurred. It caused around 200 deaths and over 1500 injuries and is the strongest known earthquake associated to the filling of a dam reservoir. Evidence of the relationship between the earthquakes and the reservoir in Koyna is established because earthquake activity began soon after the reservoir filling that started in 1962, whereas no earthquake activity was previously known in the area, and induced earthquakes have continued to occur up to the present following the reservoir level variations (Gupta et al., 1997). The M_W=6.1 1993 Killari earthquake [1], which is the most recent deadly SCR earthquake (see section 1), occurred in the same area more or less 500 km to the east. It also occurred two years and half after the first impoundment of a nearby reservoir and one year after a swarm of seismicity very likely initiated by the reservoir filling. This leads Seeber et al. (1996) to suggest a possible man-made induced triggering of the earthquake. These two earthquakes are the largest observed in the stable Indian peninsula and are amongst the 24 earthquakes with M_W≥6.0 that occurred in SCR worldwide between 1960 and 2008 (see earthquake catalog of EPRI et al., 2012). This clearly suggests that the most hazardous part of the Indian peninsula seismicity would be directly controlled by reservoir-induced seismicity.
Another area where seismic activity increased recently in a dramatic way is the central United States, mainly due to the injection of wastewater from oil and gas extraction (Ellsworth, 2013). This activity includes several M_W > 5.0 earthquakes that caused significant damage (Keranen et al., 2013). Therefore, even if many wells are apparently aseismic, managing injection activities to reduce hazard was recommended to industrials (Mc Garr et al., 2015). For example, by installing “traffic-light” systems controlling seismic activity and establishing thresholds for reducing injection rates or stopping injection. Nevertheless, controlling industrial processes may not be sufficient in some specific cases, as indicated by Chen et al. (2017) who provided evidence that the largest event of M_W = 5.8 in Oklahoma [11] occurred as an interplay between injection, tectonic faults, and foreshocks, demonstrating the complexity of stress transfer processes inside the crust.

Only 78 earthquakes with magnitude $M_W \geq 5.5$ occurred in SCR worldwide between 1960 and 2008 (see earthquake catalog of EPRI et al., 2012). Davies et al. (2013) identified 6 SCR man-induced earthquakes in this range of magnitude for the same period. If we include the more recent earthquakes in Oklahoma their number would be 8. Therefore, even if the number of moderate man-induced earthquakes stays limited since 1960, it reaches around 10 percent of occurrence compared to natural earthquakes, which is far to be negligible.
In the examples of Oklahoma and central India, the evidence of the prominent role of man-induced seismicity is facilitated by the absence of previous seismic activity, allowing to suspect the link between earthquakes and human activity. In other stable regions worldwide, seismicity and large earthquakes are more continuous since historical periods. Therefore, establishing a link between earthquakes and current industrial activity in these regions is more difficult because the location and the timing of such seismic activity would not be necessarily coincident with the man-made activity and (or) could be hidden by the natural earthquake activity. This is why we advocate the idea that man-induced earthquake activity could certainly play a more significant role in the recent and present-day SCR seismicity than currently admitted.

8. Conclusion

It is difficult to dismiss the fact that man-made earthquake activity is currently at the origin of the main seismic hazard in some SCR, like the central United States or the Indian peninsula. In a more general way, we assume that it could be a hazard at least equally important as natural seismicity in some SCR, particularly where there is a lack of previous seismic activity.
Of course, natural processes explain the occurrence of the SCR seismicity before the advent of industrial processes able to trigger earthquakes, and would continue to be at the origin of a part, often significant, of the current activity in many other SCR. Since 1960, more or less 10% of moderate earthquakes with $M_W \geq 5.5$ that occurred in SCR have been attributed to human activities. In many regions worldwide, moderate shallow earthquakes can be very destructive and deadly. As large industrial projects can modify crustal stresses or fault strength, evaluating their possible consequences in terms of induced seismicity and associated vulnerabilities should be the rule. This includes not only evaluation of the strength of industrial infrastructures, but also of the different existing types of buildings in the concerned areas. This is particularly true for developing countries located in SCR with unknown seismicity.
Progressing in the understanding of SCR earthquakes needs to address the question of the different natural and man-induced processes modifying stresses in the crust and/or fault strength. This can only be done by investigating current and past moderate and large SCR earthquakes at the light of available contemporaneous relevant environmental data. A main objective would be to determine the factors to be considered for classifying SCR into domains in a way similar to what has been done by EPRI (2012).

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