PRESENT-DAY CRUSTAL STRESS FIELD FROM GCMT FOCAL MECHANISMS BASED ON THE SLIP MODEL

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Summary

The Slip Model is applied to the Global Centroid Moment Tensor database to determine the present-day state of stress. Thus, from each focal mechanism the horizontal shortening direction (Dey) and the shape factor of the strain ellipsoid (k`), defined as the relationship between the maximum horizontal shortening and the vertical axis, are calculated. Additionally, this method proposed the neoformed plane from the calculated nodal planes. In this study, to determine the stress configuration at crustal scale, only depths < 40 km are included. Focal mechanisms are grouped in reverse, strike-slip and normal, to analyse its distribution and to determine the b-parameter from Gutenberg-Richter law. Finally, global shape factor and horizontal shortening direction maps are presented.

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Introduction

From early 80´s the World Stress Map project has stablished the foundations of the present-day stress analysis. Thus, Zoback and Zoback (1980) published the first article compiling data and describing first order stresses, based on focal mechanism, well bore breakouts, drilling-induced fractures, in-situ stress measurements and young geologic data. During that time different authors (Zoback, 1992; Heidbach et al, 2018 and references therein) have improved the database, including new data and refining the quality parameters. However, in some specific tectonic environments, focal mechanisms were used previously to determine stress at crustal scale (Isacks and Molnar, 1971). Originally, focal mechanisms were determined by first arrivals. This methodology is limited by the availability of seismic stations and its locations, which may determine an inaccurate definition of nodal planes. From early 70´s the Harvard Centroid Moment Tensor project, presently Global Centroid Moment Tensor (https://www.globalcmt.org/), calculate focal mechanism solutions for earthquakes magnitude > 5 Mw. (Dzienowski et al., 1981; Ekström et al., 2010). As a result, geoscience community has access to a homogeneous database, temporally sufficient, to estimate crustal stresses.

The aim of this work is to analyse the CMT global database from 1976 to 2009. Firstly, the type of focal mechanism, in function of principal stress orientation, and shortening direction are estimated by the Slip Vector method (De Vicente, 1988). Based on the obtained populations, the b parameter from Gutenberg-Richter law is calculated for normal, reverse and strike-slip. Finally, present day stress regime, determined by the shape factor, global map and horizontal shortening direction maps are presented.

Methodology

The Slip Model, proposed by De Vicente (1988), based on the slip model of triaxial deformation (Reches, 1983), is used for the calculation of the orientation and the shape factor of the strain-stress ellipsoid. This method assumes two important restrictions: 1) The main axes of brittle deformation (strain) and the principal stresses are parallel, and 2) One of the strain–stress axes is vertical. The method provides a value of the shape factor of the strain ellipsoid ($k' = ey/ez$, ey maximum horizontal shortening, ez vertical axis) and the maximum horizontal shortening trend (Dey) for every individual focal mechanism. Additionally, this method allows the selection of the neoformed plane, which can be assigned as causative of the earthquake. (De Vicente, 1988). K´ parameter shows possible values between $+\infty$ and $-\infty$. De Vicente et al. (2008) and Olaiz et al. (2009) proposed a methodology to plot the shape factor in a continuous map, for a straightforward interpretation It was scaled up by a logarithmic scale into the interval 0 (uniaxial compression) and 300 (uniaxial extension) (150, pure strike-slip).

Results

The CMT catalog includes 30.422 events (Mw>5.0). For this study, a 40 km depth cutoff has been stablished to avoid deep subduction events that may mislead the analysis. Thus, 24.265 events are computed. A 47.3% of the registered earthquakes is related to reverse faults, while a 33.4% is strike-slip and only a 19.3% is extensional.

Most of the compressive earthquakes are located in subduction zones. However, some events appear in discontinuous ridges highly fragmented by transform faults. Also remarkable is the presence of intraplate events in both oceanic and continental crust. Strike-slip earthquakes are registered in all type of plate boundary. In intraplate environments appear associated to strike-slip corridors in Central Asia and Middle East. Finally, extensional registers are dominant in ridges but also in other regions as the African Rift, the U.S. Basin and Range or back-arck basins.

Gutenberg-Richter law express the relationship between the magnitude and the number of earthquakes. The relationship is expressed as: $\log N(m) = a - bm$, where N (m) is the number of events having a

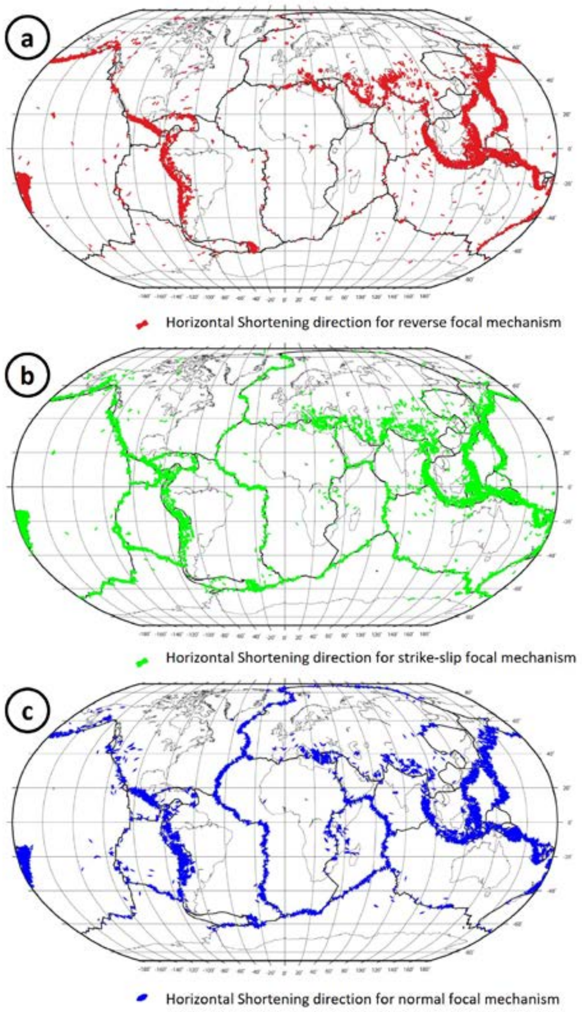

Figure 1 *Shortening direction obtained from Slip Model (De Vicente, 1988) for the Global Centroid Moment Tensor database (1976-2009). a) red: reverse, b) green: strike-Slip and c) blue:extensional.*

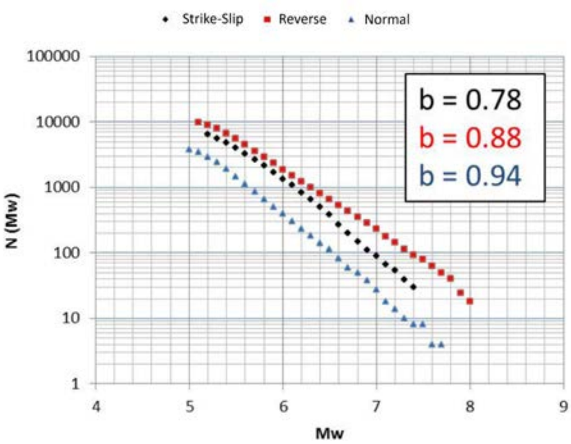

Figure 2 *b-parameter calculated for strike-slip (black), reverse (red) and normal (blue) populations, extracted from Centroid Moment Tensor catalogue for the period 1976 – 2009.*

magnitude >= M; a and b are constants. The parameter b is goes between 0.7 and 1.3 (Kin. In seismically active regions b is close to 1, although this value may varies depending on the heterogenous stress distribution and stress regime (Schorlemmer et al., 2005). The b parameter describes how seismic energy is released. Therefore, the higher the b value, the higher proportion of low magnitude events. Figure 2, shows the b parameter calculated for the previously selected populations. Higher b-parameter value (0.94) is obtained for the extensional events, while the lowest value is for strike-slip earthquakes (0.78), and reverse has an intermediate value (0.88).

The distribution of focal mechanism evidences that most of them are considered as reverse, with a wide geographical distribution. However, b-parameter is higher for extensional results. Thus, results imply that although earthquakes located at ridges are very frequent, its magnitude is lower than 5 and therefore not detectable for CMT catalog. For the reverse events, the slope of the Gutenberg-Richter, is gentler for the complete catalogue (Schorlemmer et al., 2005), evidencing the presence of larger earthquakes in subduction zones. However, if only crustal events are analyzed, b-parameter for strike-slip is lower, associated to continental scale strike-slip systems, affecting to the complete seismogenic crust.

Finally, figure 3 shows the global strain factor and Dey maps. Resultant data from Slip Model have been pondered in 1 grade-size blocks. Then, the values are interpolated in a 1º regular grid and finally plot in a 3º regular grid. Dey vectors are displayed considering the consistency of the orientation. Thus, a longer vector reflects more consistent results. Resultant maps are consistent with previous published maps, achieved from different approaches (Zoback, 1992;; Heidbach et al., 2018, Lund Snee and Zoback, 2020).

Main observations are:

- Stress trajectories and shape factor are consistent and stable in large scale regions (Zoback, 1992).

- Intraplate regions seem to be associated to reverse and strike-slip, especially in those area where crust is thicker than 40 km.

- Those areas where topography is recently raised as the Tibetan Plateau or African Rift, extensional regime is dominant.

- There is not clear relationship between oceanic crustal thickness and stress regime. Only Pacific Plate appears under compression due to scatter reverse events in shallower Moho areas.

- In oceanic ridge domains the dominant stress regime is extensional. However, it is heavily affected by strike-slip in those areas where the main ridge is segmented by transform faults. At this scale, spreading ridge velocity seems not to be governance the stress regime.

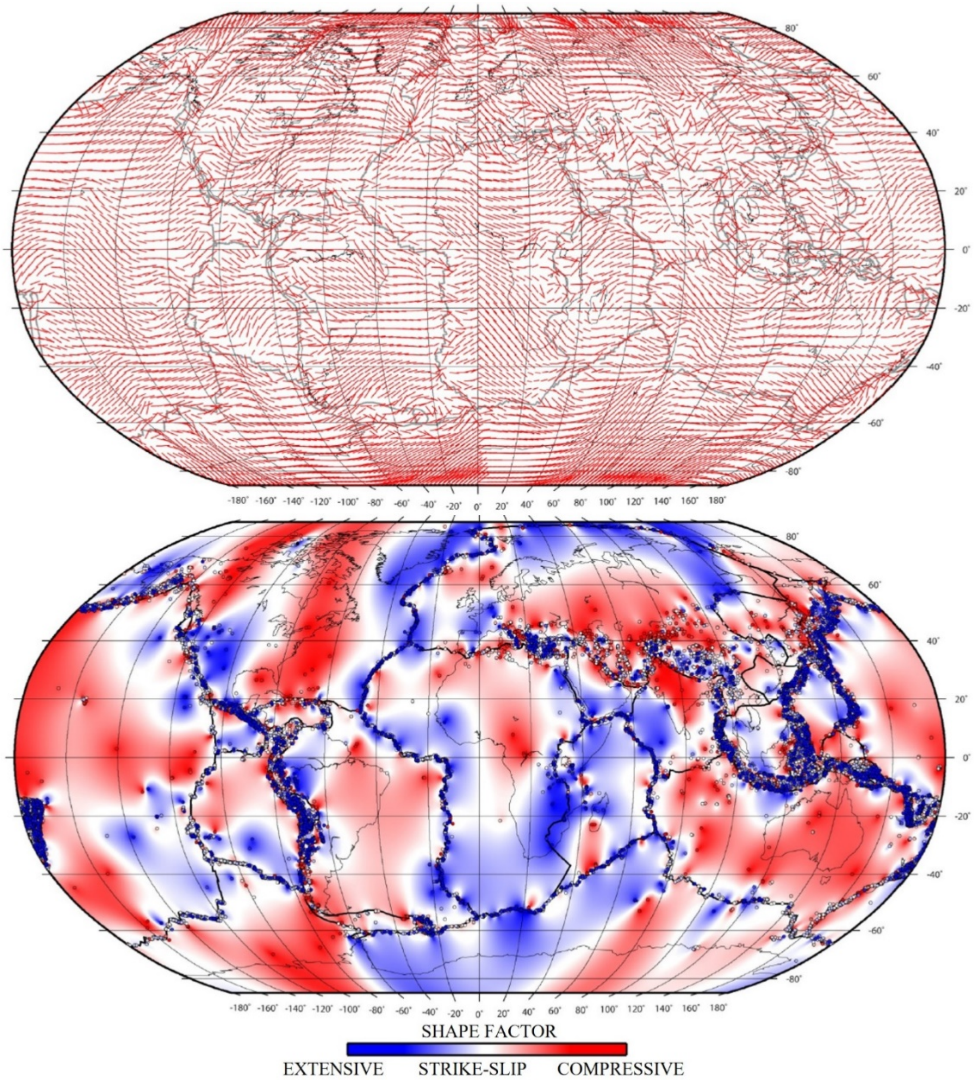

Figure 3 *Top: Continuous maximum horizontal shortening. Bottom: Continuous strain–stress regime map. Individual k´values and Dey calculated from the Slip Model (Reches 1983; De Vicente, 1988).*

Conclusions

Focal mechanisms from the Global Centroid Moment Tensor from 1976 to 2009 have been analyzed to determine the present-day stress state at crustal scale. In this study, the Slip Model is used to determine the horizontal shortening direction and the shape factor (k´).

Almost a 50% of the 24.265 evaluated earthquakes have been classified as reverse, whereas only a 20% are extensional, clearly concentrated, but not limited, to oceanic ridges.

The b-parameter obtained for the crustal events, is higher for extensional events, which implies very active extensional zones (e.g. oceanic ridges, African Rift, U.S. Basin and Range) but low magnitude earthquakes. On the other hand, b is lower for strike-slip, where only few events but high magnitude are registered.

Primary stresses, originated at plate boundaries, are conditioning tensorial state. Regional and local perturbations are observables with the proposed methodology only if earthquakes with magnitude bigger than 5 (Mw>5.0). Publications at regional scale, which include national networks (e.g. De Vicente et al., 2008; Olaiz et al., 2009) and well data are needed for a better characterization of present day stress field.

Results obtained by the Slip Model are consistent with previous models, in both, shortening direction and stress regime, besides to determine the more probable fault plane. Therefore, the proposed methodology reveals as a fast and reliable tool to evaluate present-day stress field.

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