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Thin-shell modeling of neotectonics in the Azores-Gibraltar region

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Abstract. We applied the thin-shell neotectonic modeling method to study the neotectonics of the Africa/Eurasia plate boundary in the Azores-Gibraltar region. The plate boundary consists of a simple fault system running from Azores to the Gorringe Bank where it branches along the Betics and Rift-Tell thrust fronts. Major faults in west Iberia and NW Africa have also been incorporated. Results are compared with seismic strain rates, fault slip rates and stress orientations. The best estimate for the fault friction coefficient is 0.1-0.15 meaning that the plate-boundary is only about 1/4 as strong as the adjacent lithosphere. The largest fault slip rates (>1.5 mm/yr) are obtained along the Gloria fault (strike-slip), and the Betic (transpressive) and Rif-Tell (compressive) thrust systems. Whereas tectonic activity in the Atlas region is comparable to that obtained along the plate boundary, the fault slip rates in the west Iberia fault systems are one order of magnitude less.

Introduction

Differential motion between the Eurasia, Iberia and Africa plates during the evolution of the North Atlantic region generated weak zones that subsequently acted as plate boundaries. Deformation was accommodated by thrusting, strike-slip and extensional structures according to variations of the prevailing tectonic regime. One of these major structures is the Azores-Gibraltar zone, which accommodated most of the left lateral motion between the Africa and Eurasia plates during the late Jurassic to middle Cretaceous. Activity resumed in the Eocene when the present convergence and right lateral motion between Iberia and Africa began (Srivastava et al, 1990).

Plate kinematic studies show that the tectonic regime in the current plate boundary changes progressively from transtension in the Terceira Ridge to transpression in the Gorringe-Gibraltar region, with only the Gloria fault zone acting as a pure right lateral strike-slip boundary (Grimison & Chen, 1986; Buforn et al., 1988, Fig.1). Relative plate velocities range from about 2.4 mm/yr near the Terceira Ridge to 4.8 mm/yr in the eastern segment (to the east of 13°W). The low relative velocities result in relatively low seismicity. The distribution of earthquakes indicates that strain rate is concentrated in the Azores and the Gorringe-Gibraltar regions while the Gloria fault segment is almost inactive; however, the catalog may not be long enough to give a true image of this slow-moving boundary. In the western segment earthquakes delineate a well defined plate boundary, but in the eastern segment the plate boundary appears more diffuse and spreads out over a wider region.

In a recent study Jiménez-Munt et al. (2000) used a thin sheet approach to analyse the possible geometry of the plate boundary and the role of lateral variations of the average lithospheric viscosity as well as the most plausible boundary conditions. They suggest that a bifurcation of the plate boundary (one branch in south Iberian and the other one in north Africa) extending from the Gorringe Bank towards the Alboran region could explain the measured stress orientations, slip vectors and seismic strain rates.

In this study, we approach the same problem using a very different modeling tool: the program SHELLS introduced by Kong and Bird (1995). Differences between the programs are summarised in Table 1. Our goal is to test whether the apparent weakness of the plate boundary seen by Jiménez-Munt et al. (2000) is real, or perhaps an artefact of a particular method of approximating fault zones.

One additional motivation for detailed study of this region is to determine the strength of an oceanic transform plate boundary. Low friction (or possibly low effective friction, due to high pore pressure) on transform faults has been inferred in California, Alaska, and New Zealand (Bird & Kong, 1994; Bird, 1996; Liu & Bird, 2000); it would be desirable to know if this weakness is confined to continental crust. If any oceanic transform faults are strong, the Azores-Gibraltar

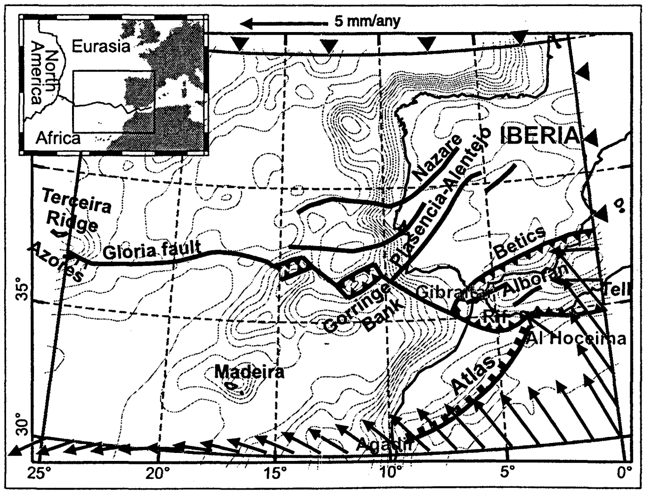

Figure 1. Zone of study, modelled faults, boundary conditions and mesh.

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Table 1. Modeling Methods

	Jiménez-Munt et al. (2000)	This paper. Kong and Bird (1995)
Program:	UHURU	SHELLS
Algorithm:	finite-difference	finite-element
Model shape:	flat-Earth (thin-plate)	spherical-Earth (thin-shell)
Elastic strain:	included	excluded
Crustal heat production:	exponential with depth	constant
Friction model:	isotropic	Coulomb
Fault model:	weak zones	fault elements

system would be expected to be, because (1) the lithosphere here is relatively old, cold, and thick; (2) the relative plate motion is slow, which permits more time for healing between earthquakes; and (3) the relative motion is transpressive, which according to Coulomb friction theory should enhance the resistance to sliding.

Methodology

SHELLS, the thin-shell neotectonic modeling program used in this study, has been described by Kong and Bird (1995). In this approach, the horizontal components of the momentum equation are solved using a 2-D finite element grid, and only the horizontal components of velocity are predicted. The radial component of the momentum equation is represented by invoking the isostatic approximation. Therefore, vertical normal stress at any point is assumed equal to the weight of overburden per unit area. The method incorporates some 3-D characteristics since volume integrals of density and strength are performed numerically in a lithosphere model with laterally varying crust and mantle-lithosphere layer thicknesses, heat flow and elevation.

Given a strain rate, the deviatoric stress is evaluated separately for each of three flow-laws: frictional faulting, dislocation creep (power-law), and Newtonian creep (linear). The mechanism giving the lowest maximum shear stress is presumed to dominate at that point. Frictional faulting stress is evaluated under an assumption of hydrostatic pore pressure and no cohesion,

$$\sigma_f = \mu_f\left(-\sigma_n - \mathrm{P}_w\right)$$

where σ_n is normal stress, μ_f is the coefficient of friction, and P_w is the pore pressure. The coefficient of friction is the same in the continuum parts of the crust and mantle-lithosphere layers, but a lower value is usually assigned in fault elements.

Input Model

We used regional elevation data and available deep seismic and surface heat flow data to determine the lithospheric structure and thermal regime under the assumptions of steady state and Airy isostasy in the manner of Jiménez-Munt et al. (2000). However, in this study we incorporate all the major faults comprising the Azores-Gibraltar plate boundary and also those affecting the interior of the Iberian and northwest African continental domains.

The selection of faults relied heavily on studies by Buforn et al., 1988; 1995; Kaz'min et al., 1990; Ribeiro et al., 1996; Tortella et al., 1997 and the tectonics maps of the Spanish 'Instituto Geográfico Nacional' (IGN, 1992) and 'Instituto Geológico y Minero de España' (IGME, 1980). Faults known to be active (from on-land geology or seismic reflection profiling) were included if over 100 km long. Other possible fault lineaments at sea were included if they met at least two of three criteria: topographic lineament, seismicity lineament, and/or gravity lineament. Faults roughly parallel to the expected direction of relative plate motion were assigned dips of 90°, while faults roughly perpendicular to expected relative plate motion were assigned dips of 65° for normal faulting (west of 23°W) or 25° for thrusting (east of 16°W). The assignment of non-vertical dip does not require that fault to be active in a purely dip-slip mode. Also, each fault included in the grid may be inactive in a particular solution if the shear tractions on it cannot overcome friction.

Velocity boundary conditions were taken from Jiménez-Munt et al. (2000); for a detailed study with different boundary conditions and Euler poles see this previous work. Therefore, we allowed no motion of the northern boundary and eastern boundary north of 37.5°N (establishing the Eurasian reference frame). The southern boundary and the eastern boundary as far North as 34.5°N were moved according to the Africa/Eurasia pole of Argus et al. (1989), located at 18.8°N and 20.3°W with an angular velocity of 0.104°/Ma. The eastern boundary between 34.5°N and 37.5°N, the Alboran domain, has a westward velocity equal to that of the Africa plate. The western boundary of the model, which faces the Mid-Atlantic Ridge, was left free of anomalous tractions; it was subjected only to normal tractions from the lithostatic pressures expected under a mid-ocean spreading ridge.

Results and Discussion

Several models were tested, with fault friction values between 0.01 and 0.85 (Fig. 2). In a model with a fault friction of 0.85, there is no distinction of rheology between the fault elements and the continuum elements around them, so most faults are inactive. In the models with low fault friction, most of the relative plate motion is absorbed in the plate boundary fault system.

These models were scored by comparison of their predictions to 92 principal stress directions collected in the 1997 version of the World Stress Map (WSM97; Mueller et al., 1997). Only stress data west of 5°W were used in scoring

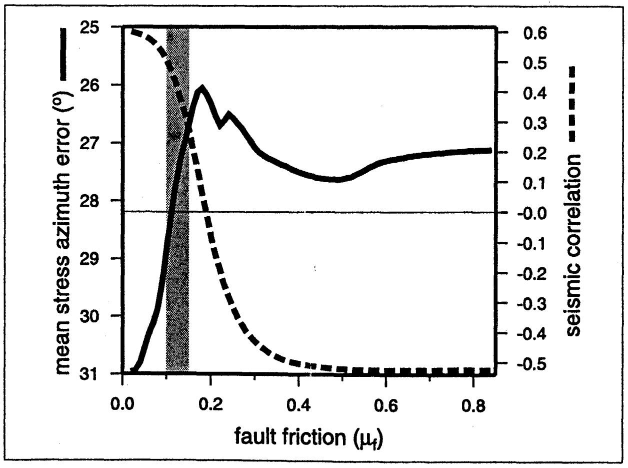

Figure 2. Mean stress azimuth error and seismic correlation for different fault frictions. The optimal model is that with high seismic correlation and low stress azimuth error. Ideally, both curves would be have maxima at the same value of fault friction, but they do not. The grey strip indicates the best compromise values for the fault friction.

because we expect at least the easternmost 20% of the model region to be perturbed by inaccuracies in the boundary conditions. The mean error in predicted stress direction varied from 25.5° to 31°, with the lowest values indicating a preference for fault friction of 0.18.

Another test of model quality was the match or mismatch between the maximum absolute value of the predicted principal strain rates and strain rates inferred from the earthquakes of the Historical Hypocentre Catalog (ISC, 1993), between the years 1964-1991. Earthquake moments were converted to strain-rates as we did in the previous work (Jiménez-Munt et al., 2000). We use the time window of the catalog and a lithosphere volume bounded by an arbitrary seismogenic depth of 20 km (as we compare relative, not absolute, values of the strain rate the magnitude of this variable will not affect our correlation) and a Gaussian spatial footprint with 60 km radius. In the model, fault-related strain rates were calculated by averaging the velocities of nodes across the fault to make velocity continuous and recomputing strain rates from the result. Both the model results and the seismic strain rates were further smoothed by 16 iterations of diffusive node/element averaging on the finite element grid to remove the smaller wavelengths. Finally, correlation was tested between the logarithms of the two smoothed strain rates to avoid the dominance of the largest single earthquakes. The strain rate derived from earthquakes has some limitations; one is that it doesn't take in account the ductile deformation and the other one, that the seismic catalog covers a short time window. However, until geodetic velocities are determined, it will be the best objective measure of strain rates available.

Seismic correlation values greater than 0.3 require fault friction values lower than 0.15. However, stress direction data indicate that misfits increase for very low fault friction values. Therefore, considering both sets of scores, the best model appears to be that with a fault friction coefficient between 0.10 and 0.15 (Fig. 2). Within this range, we have used a fault friction value of 0.12 to display predicted strain rates and tectonic regimes. This means that the plate-boundary transform is about 1/4 as strong as adjacent oceanic lithosphere, at equal strain-rates. It is worth noting that this friction coefficient is an intermediate value between those typically found for plate-interior faults and plate-boundary faults. Neotectonics studies from California and Alaska (Bird and Kong, 1994; Bird, 1996) found a friction coefficient between 0.17 and 0.25; locally in Cajon Pass the friction appears to be even less (Lachenbruch and Sass, 1992). In comparison, Bird (1998) studied a global model and proposed a friction coefficient of 0.03 for the plate boundaries; while Wang and He (1999) found effective friction of only 0.05 to 0.09 in two subduction zones. The previous study of this same region by Jiménez-Munt et al. (2000) found the fault friction coefficient changes from about 0.06 in the oceanic domain to about 0.3-0.6 in the continental domain. All of these values are significantly less than the value of 0.85 used to represent plate interiors. The reason for low fault friction is not known, although it may involve fluids at super-hydrostatic pressures.

Strain Rate and Fault Slip Rates

Fig. 3 shows that the maximum strain rate is localised over the plate boundary, from the Azores to Gibraltar, along the branch in the southern Iberian Peninsula, and along the branch in the north and north-west of Africa.

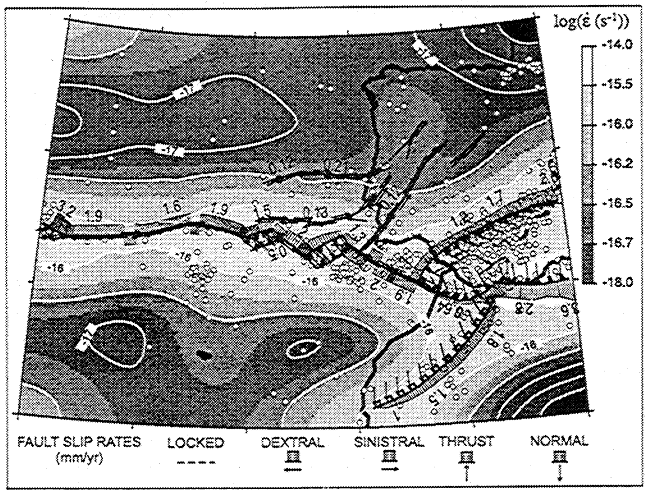

Figure 3. Predicted scalar strain rates and fault slip rates from the best thin-shell model. White points are epicentres from the ISC catalog.

Calculated fault slip rates along the plate boundary, from Azores to Gibraltar, range between 1.6 and 2.2 mm/yr, with some higher rates (3.2 mm/yr) near the Azores (Fig. 3). In the easternmost segment, the belt of high strain rates and high fault slip rates divides into one branch in the south of the Iberian Peninsula (Betics) and another in the north of Africa. The fault slip rates in the Betic cordillera are elevated, between 1.5 and 2 mm/year; this agrees qualitatively with the high number of earthquakes registered. The strain rates in the north of Africa, in the Rif and Tell cordilleras, are also high, with the maximum values in the Al Hoceima zone that expands towards the Atlas until Agadir. This concentration of high strain rate roughly coincides with historical seismic activity.

The major strike-slip faults modelled in the Iberian Peninsula are predicted to have low rates (0.1-0.2 mm/yr). These rates, in spite of the fact that they are low, may explain the seismicity alignment that runs through the westernmost part of Iberia and into the Atlantic (Nazare and Plasencia-Alentejo faults). They are strike slip faults with some thrust component on the Nazare fault (Ribeiro et al., 1990; 1996).

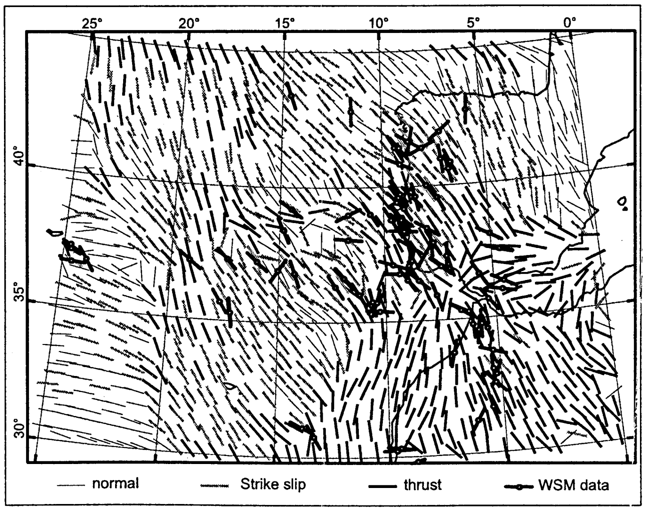

Figure 4. Most-compressive horizontal principal stress directions from the best thin-shell model, compared to data from the World Stress Map. Colour indicates stress regime.

The regional variation of the sense of slip includes thrust faulting in the easternmost segment (east of 13°W), changing westward to dextral strike slip, with normal faulting only near the Azores. This coincides with previous studies, which divided this plate boundary segment into three sectors (Kiratzi & Papazachos, 1995; Buforn et al., 1988; Grimison & Chen, 1986).

Stress Directions

Fig. 4 shows the maximum horizontal compression direction and tectonic regime (normal, thrust, strike-slip). The Africa/Eurasia plate boundary can be divided into three sections by regime. To the east of 12°W, the regime is thrust-faulting with NNW-SSE compression. These compressive axes rotate counter-clockwise to the west, along the Gloria fault, where there is a strike-slip regime, until near the Azores normal faulting occurs with NNE-SSW tension axes. This predicted variation coincides with the results obtained from seismicity data (Grimison and Chen, 1986; Buforn et al., 1988; Kiratzi & Papazachos, 1995; Medina, 1995), and studies done from seismic images (Sartori et al., 1994; Tortella et al., 1997).

The influence of the Iberian faults is that they provoke a rotation to the west of the compressive stress directions. This component to the west is higher to the ocean zone.

Conclusions

Using the thin-shell approach, we have approximately reproduced the tectonic regime and strain rate map of the Azores-Gibraltar part of the Africa/Eurasia plate boundary. We have seen that we need to reduce the strength of the plate boundary by about a factor of four (fault friction coefficient about 0.12) relative to adjacent lithosphere. Then the model is compatible with the stress data (WSM97) and the seismic strain rate calculated from the seismicity data.

We have predicted long-term-average fault slip rates and we are able to confirm that the regional strain is concentrated along the plate boundary. To the east of Gibraltar, the maximum strain is in the Betic and north African cordilleras, especially around the Al Hoceima seismic zone. High seismicity and strain rates are predicted all along the Atlas until Agadir. However, the faults in the Iberian Peninsula are characterised by relatively low rates of strike slip.

The relatively low effective friction inferred for this oceanic transform boundary is in the same range as was previously inferred for continental transform faults, indicating that the mechanism of fault weakening, whatever it may be, is insensitive to the petrology of the crust.

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