Tectonophysics 633 (2014) 115–125

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

The 1998 Faial earthquake, Azores: Evidence for a transform fault associated with the Nubia–Eurasia plate boundary?

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A R T I C L E I N F O

Article history:
Received 19 March 2014
Received in revised form 4 June 2014
Accepted 22 June 2014
Available online 28 June 2014

Keywords:
Azores Triple Junction
1998 Faial earthquake
Transform fault
Block rotation and fault termination
Faial Graben
Terceira Rift

A B S T R A C T

With very few exceptions, M > 4 tectonic earthquakes in the Azores show normal fault solution and occur away from the islands. Exceptionally, the 1998 shock was pure strike-slip and occurred within the northern edge of the Pico–Faial Ridge. Fault plane solutions show two possible planes of rupture striking ENE–WSW (dextral) and NNW–SSE (sinistral). The former has not been recognised in the Azores, but is parallel to the transform direction related to the relative motion between the Eurasia and Nubia plates. Therefore, the main question we address in the present study is: do transform faults related to the Eurasia/Nubia plate boundary exist in the Azores? Knowing that the main source of strain is related to plate kinematics, we conclude that the sinistral strike-slip NNW–SSE fault plane solution is not consistent with either the fault dip (ca. 65°, which is typical of a normal fault) or the ca. ENE–WSW direction of maximum extension; both are consistent with a normal fault, as observed in most major earthquakes on faults striking around NNW–SSE in the Azores. In contrast, the dextral strike-slip ENE–WSW fault plane solution is consistent with the transform direction related to the anticlockwise rotation of Nubia relative to Eurasia. Altogether, tectonic data, measured ground motion, observed destruction, and modelling are consistent with a dextral strike-slip source fault striking ENE–WSW. Furthermore, the bulk clockwise rotation measured by GPS is typical of bookshelf block rotations observed at the termination of such master strike-slip faults. Therefore, we suggest that the 1998 earthquake can be related to the WSW termination of a transform (ENE–WSW fault plane solution) associated with the Nubia–Eurasia diffuse plate boundary.

1. Introduction

The Central Azores Islands (Faial, Pico, S. Jorge, Graciosa and Terceira islands, Figs. 1 and 2) were born during the Quaternary at the Azores Triple Junction (ATJ), more specifically within the boundary between the Eurasia (Eu) and Nubia (Nu) plates. The ATJ is currently of the rift–rift–rift type. The Middle-Atlantic Rift makes the northern and southern arms, and the eastern arm is made of the Terceira Rift (TR), which connects to the Gloria Fault and the Azores Gibraltar Fault Zone in the east (Fig. 1). According to DeMets et al. (2010), there should be an Azores microplate interacting differently with the neighbouring Eu and Nu plates (Fig. 1): the Azores–Eu motion should be dextral oblique extension, and the Azores–Nu motion should be dextral strike-slip along an ENE–WSW direction. Based on GPS, tectonic and seismic data, Marques et al. (2013) concluded that the Nu–Eu boundary in the Azores is not discrete, and therefore the existence of an intervening Azores microplate is unlikely. Instead, the boundary is diffuse in its western half, with deformation accommodated by a ca. 150 km wide strip extending south of the western half of the TR. This has major implications in the distribution of strain, because maximum extension (approximately ENE–WSW) should be similar all over the diffuse boundary. The general structure in the diffuse boundary (Central Azores) is that of a sequence of WNW–ESE grabens and horsts (Fig. 2): the Graciosa and Terceira islands grew inside the TR; the Pico–Faial volcanic ridge sits on the master fault bounding the Faial Half-graben in the north; and the S. Jorge Island developed in the middle of a narrow graben, the S. Jorge Graben.

With the exception of the very small area of the islands (Fig. 1), the Azores crust lies below sea level, which is a strong limitation to directly observe and characterise deformation. Moreover, appreciable surface rupture related to main tectonic and M > 4 earthquakes has not been observed within the islands. Even if there were minor surface rupture, the superficial effects of very slow deformation imposed by the hyper-slow differential motion between Eurasia and Nubia (ca. 4 mm/yr) would not survive, because erosion, sedimentation and volcanic rates are much faster than the tectonic rate. For instance, Costa et al. (2014) and Hildenbrand et al. (2008, 2012a,b) have shown that major periods of massive island destruction (mostly large-scale landslides and flank

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http://dx.doi.org/10.1016/j.tecto.2014.06.024
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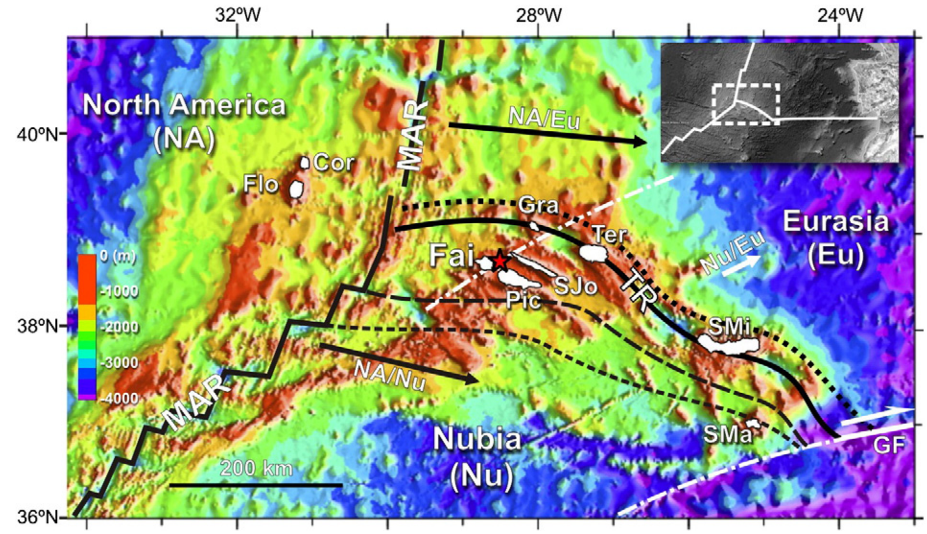

Fig. 1. Sketch of the general framework of the Azores Triple Junction. Black-rimmed red star marks the 1998 Faial earthquake. MAR and TR are the Mid-Atlantic and Terceira rifts, respectively. GF is the dextral strike-slip Gloria Fault. Full black arrows represent the velocity vectors of Eurasia (Eu) and Nubia (Nu) relative to North America (NA). Full white arrow represents the velocity vector of Eu relative to Nu. Dotted black line marks the northern shoulder of the TR, which represents the northern Nu/Eu plate boundary for both the diffuse boundary and the microplate scenarios. Black dashed and black long-dashed lines mark the southern boundaries of the hypothetical Azores microplate and the diffuse Nu/Eu plate boundary, respectively. White dash-dotted lines represent small circles around the MORVEL Nu/Eu pole (DeMets et al., 2010), which represent the transform direction related to the Nu/Eu boundary. From W to E, the Azores Islands are Flores (Flo), Corvo (Cor), Faial (Fai), Pico (Pic), S. Jorge (SJo), Graciosa (Gra), Terceira (Ter), S. Miguel (SMi), and Santa Maria (SMa).
Background image built with data retrieved from http://topex.ucsd.edu/marine_topo/mar_topo.html (Smith and Sandwell, 1997).

collapses) are intercalated with short periods of fast volcanic construction, which are able to mask intra-island evidence of the effects of large-scale tectonics occurring in the underlying plateau.

The Azores earthquakes show a few characteristics that make the 1998 Faial shock unique: (1) it has been reported since the early 1930s that very rare earthquakes (i.e. of tectonic origin, and M > 4) have seemingly occurred inside the islands (e.g. Agostinho, 1931; Borges et al., 2007; Machado, 1959). In fact, no major intra-island tectonic earthquake has been recorded in the Azores since earthquakes can be measured instrumentally. Locally, earthquakes occur inside the islands, but they are mostly related to volcanism rather than tectonics, which is the case, for instance, of the ongoing seismic crisis in the S. Miguel Island (e.g. Silva et al., 2012). (2) From a total of 24 major earthquakes for which the focal mechanisms have been computed (e.g. Borges et al., 2007), very few tectonic and M > 4 earthquakes are strike-slip (4 out of 24), and by far the large majority shows normal fault kinematics (16 out of 24) (e.g. Borges et al., 2007; Buforn et al., 1988, 2004; Grimison and Chen, 1988; Hirn et al., 1980; McKenzie, 1972; Miranda et al., 1998; Moreira, 1985; Udías et al., 1976 for a synthesis). (3) The main fault trends associated with tectonic M > 4 earthquakes are the WNW–ESE and NNW–SSE trends. The exception to this most common scenario can be the Faial 1998 shock, because deformation propagated inland, and the main source fault is pure strike-slip. Furthermore, this peculiar earthquake occurred within the Pico–Faial volcanic ridge (although close to the northern edge) and it can be related to a different trend (ENE–WSW), overlooked in the Azores, although of probable large-scale tectonic meaning as argued in the present paper. These characteristics, together with the relationship with plate kinematics and strains, support and justify the importance of studying the 1998 Faial shock.

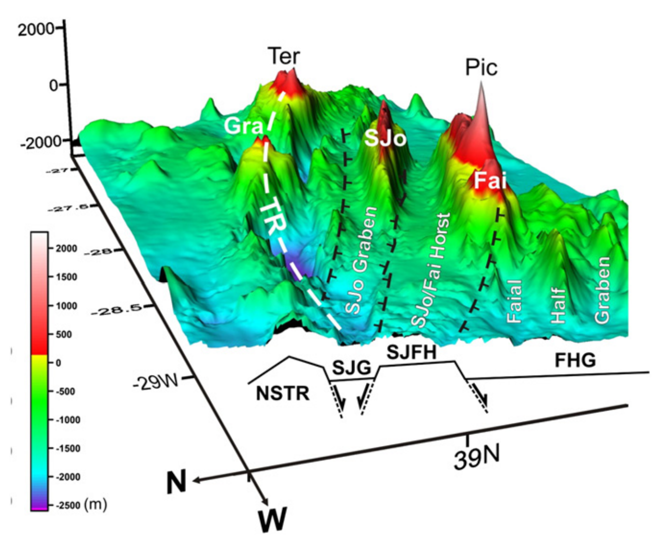

Fig. 2. 3D surface with interpreted main tectonic framework (viewed from WNW). TR is the Terceira Rift. Fai, Pic, SJo, Gra and Ter correspond to the islands of Faial, Pico, S. Jorge, Graciosa and Terceira, respectively.
3D surface built using topographic data available at http://w3.ualg.pt/~jluis/misc/ac_plateau1km.grd (Lourenço et al., 1998).

The TR is a ca. 620 km-long sigmoidal graben filled at regular spaces (ca. 80 km) by large-volume central volcanism making up islands and large seamounts (Fig. 1). Here we hypothesise that the regular spacing is due to concentrated volcanism at the intersection between the TR and transform faults related to the Nu/Eu plate boundary, thus making up privileged conduits. However, such transforms have never been recognised, which could be due in part to the low resolution of the bathymetry. Therefore, we looked for different evidence, in the form of earthquakes, like the 1998 Faial earthquake, which can be related to transform motion due to the Nu/Eu interaction in the Azores.

Given the premises and current knowledge outlined above, the questions we address in this article are: (1) which was the fault responsible for the earthquake? The sinistral NNW–SSE or the dextral ENE–WSW? (2) Which one is consistent (or inconsistent) with the known plate kinematics in the Azores? (3) What kind of fault is it? Are there transform faults associated with the Nu/Eu plate boundary? (4) What is the meaning of the measured ground deformation? (5) What are the sources of strain/stress? Our ultimate objective is a better understanding of strain (mostly faults) in the Azores Triple Junction, in terms of typology,