Earth and Planetary Science Letters 381 (2013) 177–187

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

GPS and tectonic evidence for a diffuse plate boundary at the Azores Triple Junction

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ARTICLE INFO

Article history:
Received 14 March 2013
Received in revised form 29 August 2013
Accepted 31 August 2013
Available online 25 September 2013
Editor: P. Shearer

Keywords:
GPS and structural data
plate boundary
Nubia and Eurasia
Azores Triple Junction
Terceira Rift
Mid-Atlantic Ridge (MAR)

ABSTRACT

We use GPS, bathymetric/structural, and seismic data to define the pattern of present deformation along the northern half of the Azores plateau, where the Nubia–Eurasia plate boundary terminates at the axis of the Mid-Atlantic Ridge (MAR). New and existing campaign GPS velocities from the Azores islands reveal extension oblique to a series of en échelon volcanic ridges occupied by Terceira, S. Jorge, Pico, and Faial islands. In a frame of reference defined by 69 continuous GPS stations on the Eurasia plate, Terceira Island moves 2 ± 1 mm/yr away from Eurasia, consistent with the island's location within the Terceira Rift and plate boundary structure. The volcanic ridges south of the Terceira Rift move toward WSW at progressively faster rates, reaching a maximum of 3.5 ± 0.5 mm/yr (2-σ) for the Pico/Faial volcanic ridge. The hypothesis that the Terceira Rift accommodates all Nubia–Eurasia plate motion is rejected at high confidence level based on the motions of sites on S. Jorge Island just west of Terceira Rift. All of the islands move relative to the Nubia plate, with Pico Island exhibiting the slowest motion, only 1 ± 0.5 mm/yr (2-σ). Detailed bathymetry from the interior of the hypothesized Azores microplate reveals faults that crosscut young MAR seafloor fabric. These observations and the GPS evidence for distributed deformation described above argue against the existence of a rigid or semi-rigid Azores microplate, and instead suggest that Nubia–Eurasia plate motion is accommodated by extension across a ∼140-km-wide zone east of the MAR axis, most likely bounded to the north by the northern shoulder of the Terceira Rift. The MAR spreading rate along the western end of the Azores deformation zone (∼38.5°N–39.5°N) is intermediate between the Eurasia–North America rate measured at 39.5°N and the Nubia–North America rate measured at 38.5°N, consistent with the joint conclusions that the Nubia–Eurasia boundary is broad where it intersects the MAR, and the Azores Triple Junction is diffuse rather than discrete.

1. Introduction

The Azores Triple Junction is located at the western end of the Nubia–Eurasia plate boundary, where the North America, Eurasia and Nubia plates meet (Fig. 1). Although its existence has long been recognized, there is as yet no consensus regarding its location and the nature of deformation in the vicinity of the triple junction (e.g. Krause and Watkins, 1970; Searle, 1980; Miranda et al., 1991; Luís et al., 1994; Lourenço et al., 1998; Luís and Miranda, 2008). The triple junction is marked by a ∼15% decrease in MAR seafloor spreading rates from 39.5°N, where Eurasia–North America motion occurs, to ∼38.5°N, where Nubia–North America plate motion occurs (DeMets et al., 2010). Along the ∼100-km-long stretch of the ridge between ∼38.5°N and 39.5°N, the average seafloor spreading rate is intermediate between that for Eurasia–North America and Nubia–North America motion (DeMets et al., 2010), suggesting that either a rigid or nearly rigid Azores microplate rotates independently east of the MAR axis between ∼38.5°N and 39.5°N, or that distributed deformation occurs across a ∼140-km-wide zone east of the MAR axis.

In this study, we present and interpret GPS observations from sites in the Azores archipelago in the context of existing bathymetric/structural and seismic data to address three fundamental questions related to the Azores Triple Junction: (1) Is the Nubia–Eurasia plate boundary discrete or diffuse near the Azores Triple Junction and, by implication, is the triple junction discrete or diffuse? (2) Where is the present Nubia–Eurasia plate boundary in this region? (3) Is there an Azores microplate? Previous authors have used a variety of data to address some of these questions, including seafloor spreading magnetic lineations (e.g. Krause and Watkins, 1970; Searle, 1980; Luís et al., 1994; Luís and Mi-

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0012-821X/$ – see front matter
http://dx.doi.org/10.1016/j.epsl.2013.08.051

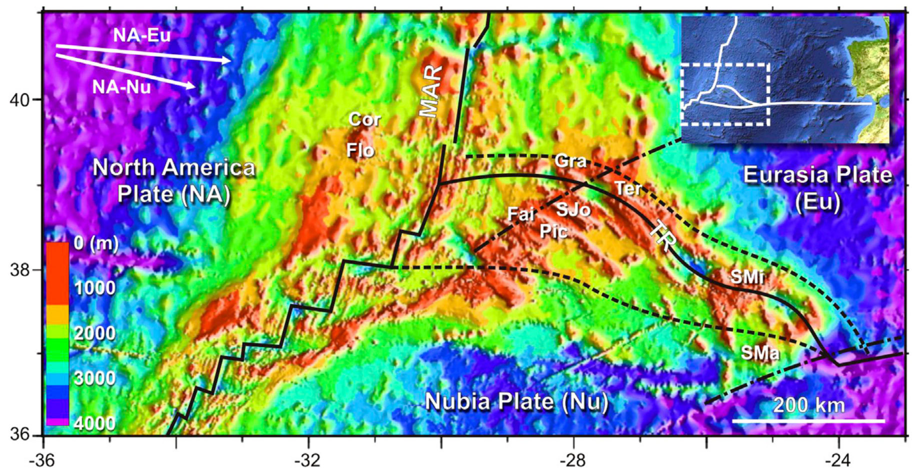

Fig. 1. Sketch illustrating the tectonic setting of the Azores Triple Junction. Inset on top right corner for location. Inset on top left corner for the kinematics of the Nubia and Eurasia lithospheric plates (DeMets et al., 2010). Dashed lines mark the boundaries of a hypothetical Azores microplate. Dash-dotted lines represent small circles around the MORVEL Nubia–Eurasia pole. The nine Azores islands are, from W to E, Corvo (Cor), Flores (Flo), Faial (Fai), Pico (Pic), S. Jorge (SJo), Graciosa (Gra), Terceira (Ter), S. Miguel (SMi), and Santa Maria (SMa).

randa, 2008), SONAR and marine bathymetry (e.g. Searle, 1980; Madeira and Ribeiro, 1990; Lourenço et al., 1998), bathymetric and seismic observations (Borges et al., 2007), and GPS (Fernandes et al., 2006). A key goal of this paper is to use a critical subset of observations to evaluate and refine the emerging view that Nubia–Eurasia plate motion is accommodated by deformation distributed across the northern half of the Azores plateau.

This paper is organized as follows. We first present and analyze the GPS observations that are the core of the study, including descriptions of newly estimated Nubia and Eurasia plate angular velocities in the ITRF2008 reference frame, and the resulting Nubia–Eurasia relative angular velocity. We next describe relevant bathymetric observations and the information they suggest about the character and location of regional deformation, albeit over time scales significantly longer than for the GPS observations. Finally, we discuss the implications of the GPS velocity field in the context of bathymetric/structural observations and seismic data.

2. GPS data

The GPS observations used in this study consist of the following: (1) new measurements at 35 campaign sites on Faial, Pico and Terceira islands (shown by red circles in Fig. 2A), (2) measurements at 117 continuous sites on the Nubia and Eurasia plates (Figs. 3 and 4), and (3) velocities for 15 GPS stations on S. Jorge Island from Mendes et al. (2013). Procedures for processing the new campaign and continuous data are described below.

2.1. Campaign GPS data

The Azores central group GPS geodetic–geodynamic network was established in 2001 in the aim of STAMINA and SARAZORES projects (Navarro et al., 2003; Catalão et al., 2006). It consists of 35 rock-anchored benchmarks on Faial, Pico and Terceira islands (14, 8 and 13 marks, respectively), with an average spacing of 5 km (Fig. 2A).

The principal data used for this study, from 35 stations on Faial, Pico and Terceira islands (locations shown in Fig. 2A and listed in Table 1), were acquired during seven surveys from 2001 to 2013. During each survey, every benchmark was occupied for two-to-four 24 h sessions with a sampling rate of 30 s and elevation mask of 15°. During each survey, at least six stations were observed simultaneously and one station per island was measuring continuously (FAIM for Faial, TOMA for Terceira and PPIL for Pico). For this

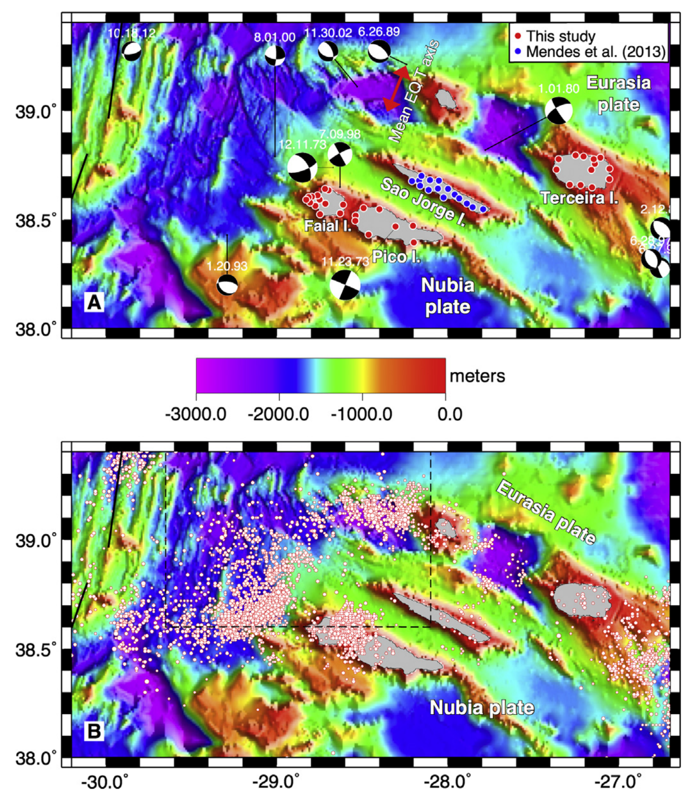

Fig. 2. A – locations of GPS sites used for this study and earthquake focal mechanisms for the study area. Bathymetry is a 1-km-resolution grid from J. Luis (http://w3.ualg.pt/~jluis/misc/ac_plateau1km.grd). Legend indicates source of the GPS velocities for Faial, Pico, S. Jorge and Terceira islands. Earthquake focal mechanisms are from the global centroid-moment tensor catalogue (Dziewonski et al., 1981; Ekstrom et al., 2012) and Borges et al. (2007 – labeled 11.23.73 and 12.11.73). Double-headed red arrow shows the average tension axis direction for the focal mechanisms of earthquakes in the diffuse deformation zone (29.5°W–27.5°W). B – epicentres of M > 1 earthquakes for the period 1998–2013, from the Portuguese IPMA catalogue, scaled by magnitude. Dashed rectangle indicates the region shown in Fig. 6. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

12-yr-long time series, each station was visited at least four times and observed for at least eight 24-h sessions.

GPS phase observations were analyzed using GAMIT software version 10.4 (Herring et al., 2010). The processing and analysis were made in two-step approach according to Dong et al. (1998).