Deep brittle-ductile transition, water percolation into the mantle and reactivation of weakness zone: new insights of the seismicity on St. Paul Transform System, Equatorial Atlantic

Guilherme de Melo[1], Aderson do Nascimento[1], Marcia Maia[2], Julie Perrot[2], Alexey Sukhovich[2], Jean-Yves Royer[2], and Thomas Campos[1]

[1]UFRN
[2]CNRS

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Abstract

Four transform faults and three intra-transform segments located at Equatorial Atlantic form the Saint Paul Transform System (SPTS), with a long-offset of 630 km. In the northern transform, the 200 km long and 30 km wide Atoba Ridge is a major topographic feature that reaches the sea level at the St. Peter and St. Paul Archipelago island (SPSPA, 00º 55 '0' 'N and 29º 20 "43"W). The islets have an average uplift rate of approximately 1.5 mm/year. The southern and northern flanks of the Atobá Ridge are marked by a series of large thrust faults visible in the bathymetry and clearly imaged through seismics and correspond to an exceptionally serpentinized mantle. We have determined the hypocentral location of 62 minor-moderate earthquakes of SPTS, with magnitudes 1.9 [?] M [?] 5.3. The earthquakes occurred in 2013 and were recorded by a seismometer installed in SPSPA and three autonomous hydrophones deployed during the COLMEIA cruise. The HYPOCENTER software and Seismic Analysis Code (SAC) were used for data analysis and hypocenter location. The depth range is from 0.2 to 17.5 km and are concentrated in three different zones: the East Shear Zone (ESZ), the Atoba Ridge Zone (ARZ) and the Central Fracture Zone (CFZ). A seismogenic zone with a deep britle-ductile transition was identified in SPTS, with hypocenters reaching 18 km beneath the seafloor. We observed that this lithospheric structure presents relation with the offset age and controls the maximum hypocentral depths of oceanic transform faults. Besides, the earthquakes indicated the existence of a broad serpentinization depth reaching 18 km beneath the ARZ. This was interpreted as the effect of deep water percolation into the mantle in the SPTS, which caused a fluid-mantelic rocks interaction and allowed the expansion of faults into the mantle. Some hypocenters were located in the central fracture zone (CFZ) segment of SPTS and their depths reached 8.8 km beneath the seafloor. We interpreted this seismicity as reactivation of a weakness zone existent in CFZ due to the transpressive load-induced stress originated in Atoba Ridge.

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Guilherme de Melo[1]*, Aderson do Nascimento[1], Marcia Maia[2], Julie Perrot[2], Alexey Sukhovich[2], Jean-Yves Royer[2], Thomas Campos[3]

1-Department of Geophysics, Federal University of Rio Grande do Norte, Natal, RN, Brazil; 2-Institut Universitaire Européen de La Mer, UBO, Plouzané, France, 1-Department of Geology, Federal University of Rio Grande do Norte, Natal, RN, Brazil;

*gwsmelo@ufrn.edu.br

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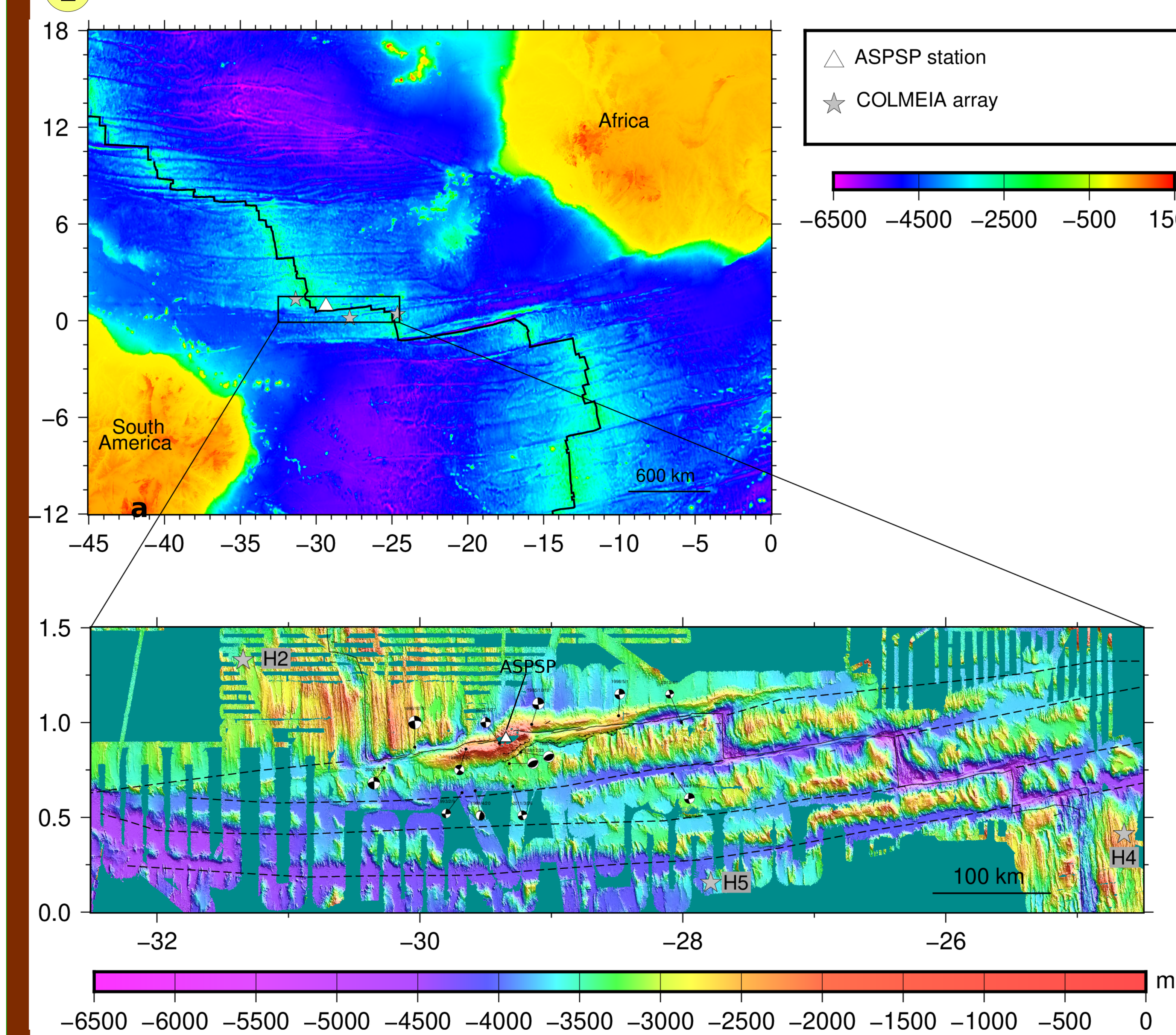


Introduction

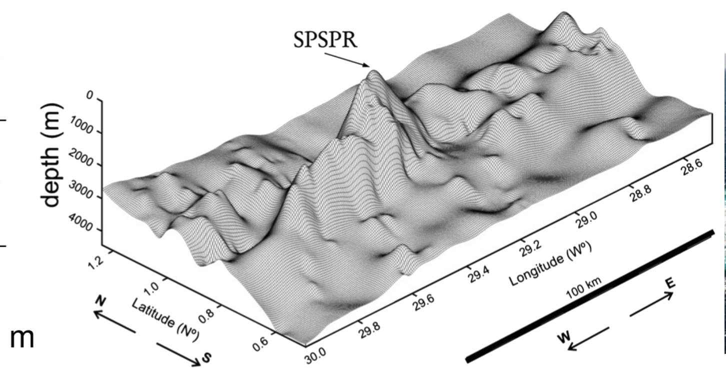
In Equatorial Atlantic, a complex multifault system of four transform faults, bounding three short intra-transform segments form thea St. Paul Transform System (SPTS) (Maia et al., 2016). SPTS is a complex group of four transform faults, bounding three short intra-transform segments located at the Equatorial Atlantic. In the northern transform fault of SPTS, the 200 km long and 30 km wide Atoba Ridge is a major topographic feature that reaches the sea level at the St. Peter and St. Paul Archipelago (SPSPA). We have determined the hypocentral location of 62 minor-moderate earthquake (>ML 1.6), using records of three hydrophones and one seismograph.

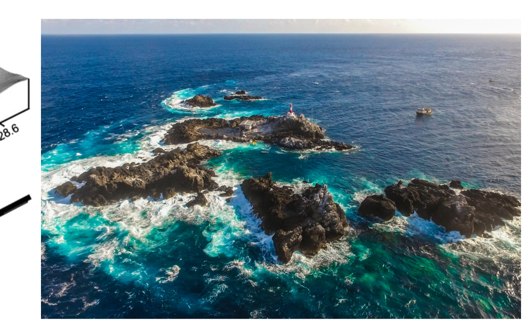
Geological Setting

In northern of SPTS, the transform present an offset with the two adjacent ridges segments in 630 km with a slow-spreading rate of 32 mm/year (DeMets et al., 2010; Maia et al., 2016). Along this segment is located the Atobá Ridge, a 200 km long and 30 km major tophografic formed for a push-up due to transpressive stress that started 10 million years ago (Maia et al., 2016). The sctructure is formed for exposed peridotite rocks, that reach until the sea level 3500 m above seafloor, in the SPSPA islets. The structure of islets is composed for peridotite mylonite and alkaline ultramafic with differents seperpentinization degree (Campos et al, 2010).

Objectives

Our objective is to investigate the estimates the seismicity that occur along the St. Paul Transform System, in Equatorial Atlantic. Using earthquake data, we estimate the brittle-ductile transition depth along this transform fault, limit depth of serpentinization, and also show reactivation on weakness zones in the SPTS (de Melo et al., *in review*).





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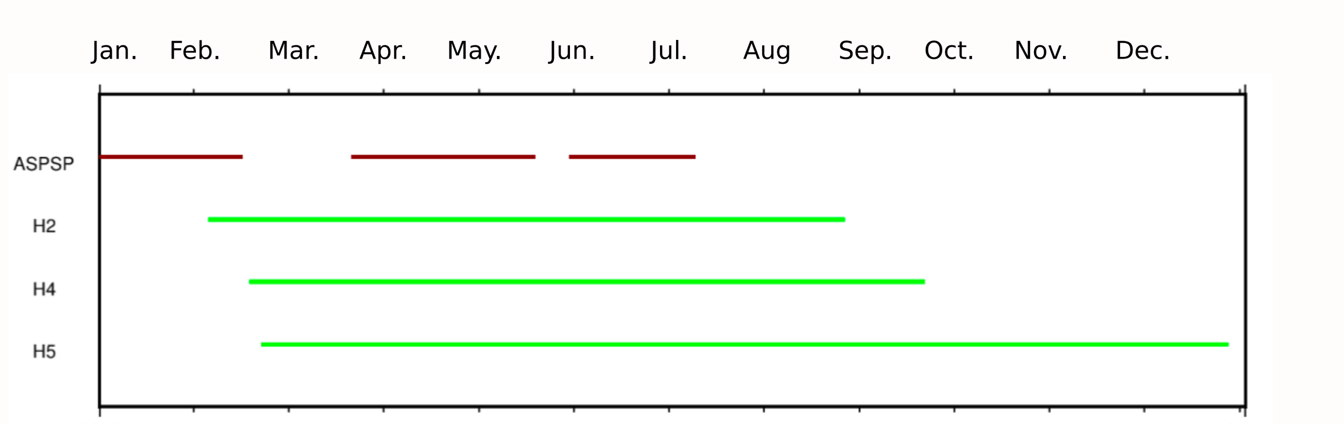
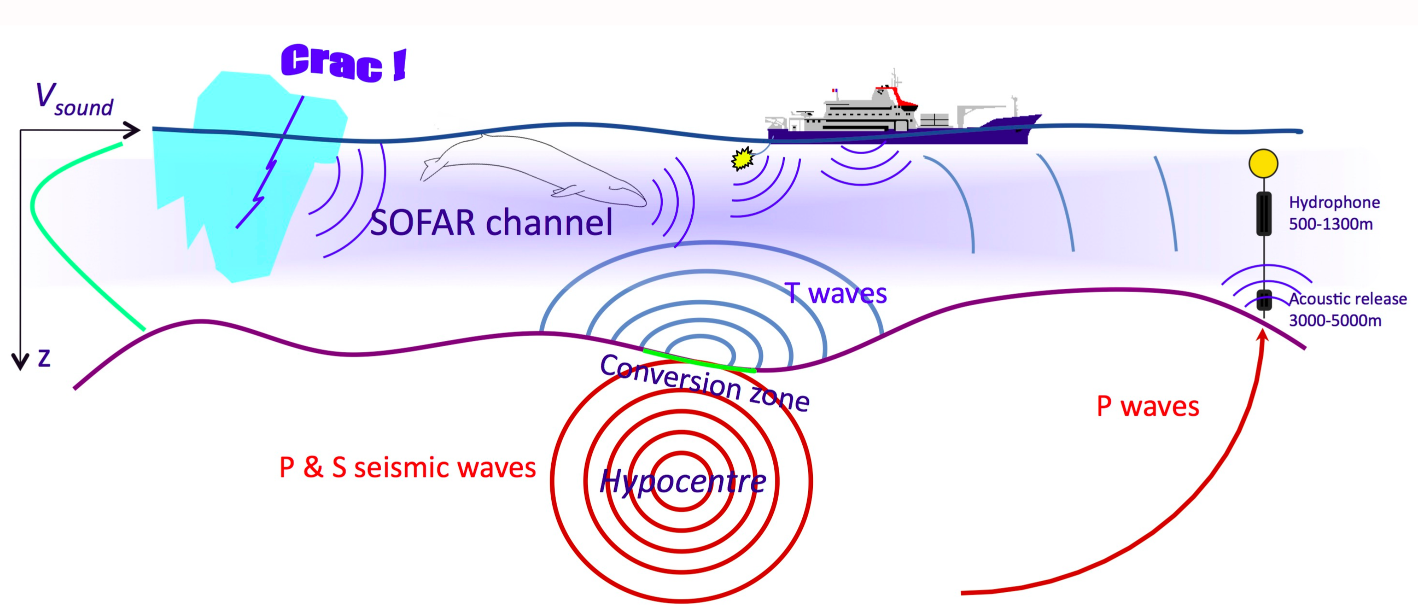
Data Aquisition

Earthquakes were analyzed using recorded data during six months (January-July) by a single seismographic station located on St. Peter and St. Paul Archipelago (ASPSP) and three hydrophones deployed in 2013 as part of COLMEIA cruise (Maia et al., 2016) that obtained records of P waves.



Analysis

SEISAN package was used in the analysis (Havskov and Ottemöller., 1999). P and S seismic waves were analyzed in ASPSP station, together the P waves recorded by the hydrophne array. Waveform data were bandpass filtered at 4-18 Hz in ASPSP station, and 2-12 Hz to the hydrophone. Back-azimuth and angle of incidence method (Havskov and Ottemöller., 2010) was used to estimated the hypocenter catalogue in ASPSP station. Angle of incidence were measured using Seismic Analysis Software (Helffrich et al., 2013). P waves recorded by the hydrophones were analyzed applying the travel time correction because the change solid-to-acoustic that occur in wave propagation. This delay was added to account for the length of the mooring cable, using a constant water velocity from the global ocean sound speed model (GDEM).



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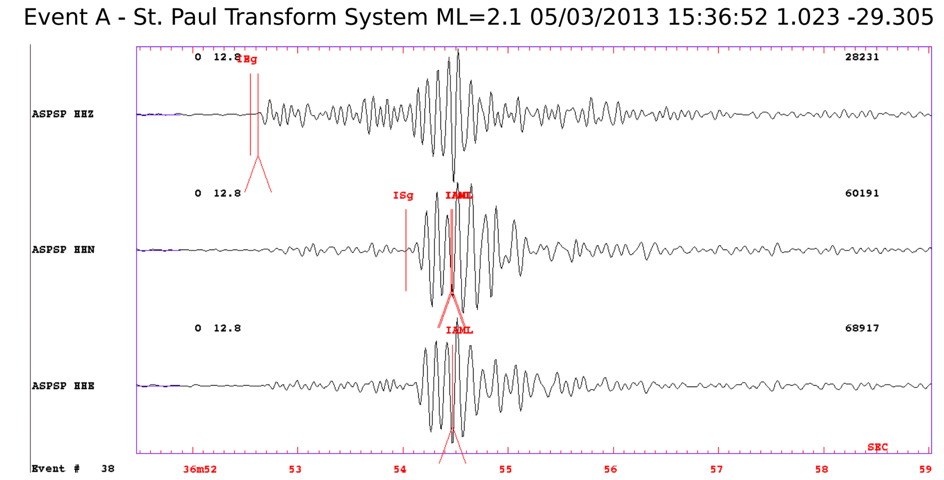
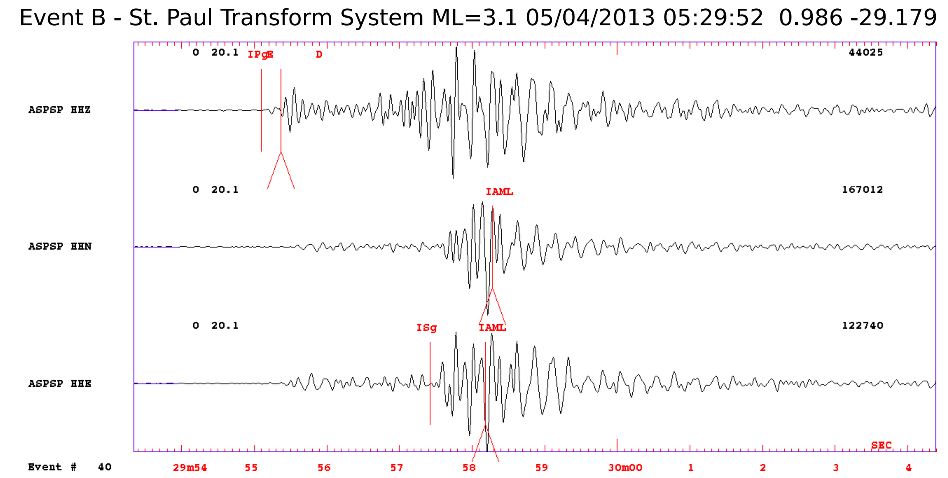
Earthquake catalog

62 earthquakes were recorded by the ASPSP station with magnitudes between 1.9 and 5.3 M. Among these, 15 events with M > 2.9 were recorded also by the hydrophone array. Example of these events are shown in **(a)**, **(b)** and **(c)** figures.

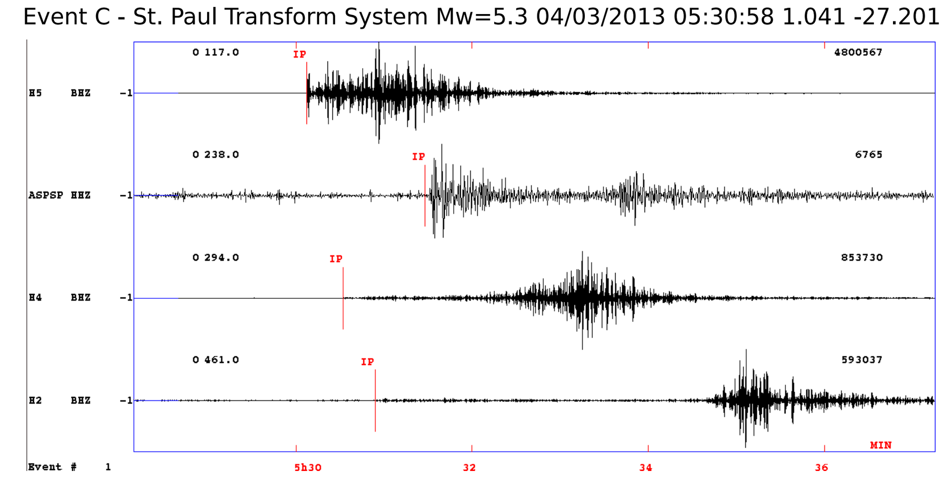
Event A - St. Paul Transform System ML=2.1 05/03/2013 15:36:52 1.023 -29.305



Event B - St. Paul Transform System ML=3.1 05/04/2013 05:29:52 0.986 -29.179



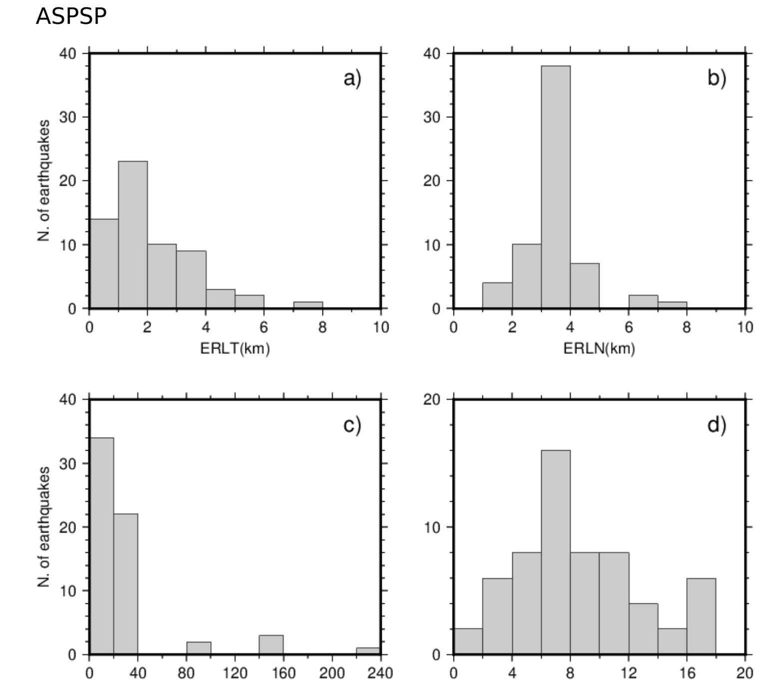
Event C - St. Paul Transform System Mw=5.3 04/03/2013 05:30:58 1.041 -27.201



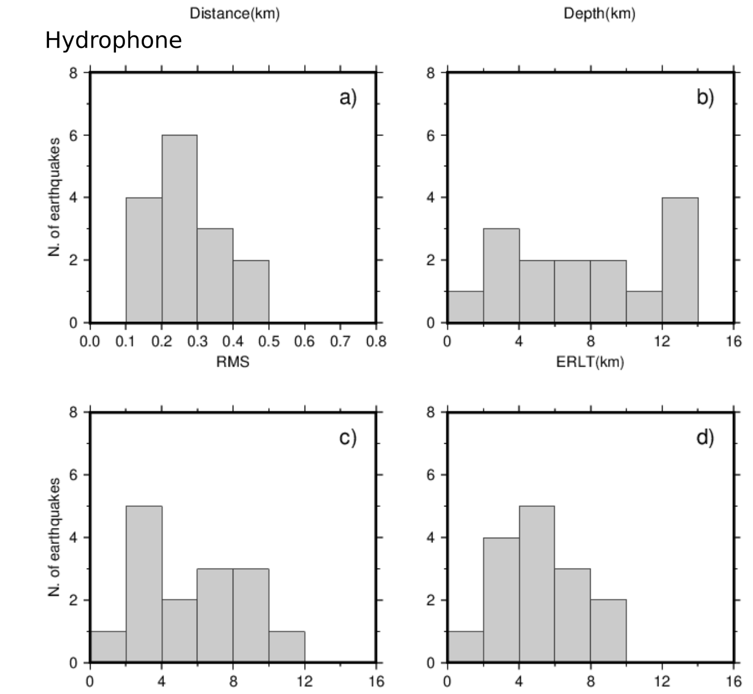
Hypocenter location

Earthquakes located by the ASPSP single station present error latitude (ERLT) from 1.5 until 4.5 km, and error longitude of 1.5 until 4.6 km (ERLN). The depth error (ERDP) was estimated with a uncertainty of +/- 3° to incidence angle, that presented error range 3-7 km. 15 events using hydrophone array together presented ERLT from 2.5 until 13.9 km, ERLN with range 1.4 until 9.7 and ERDP range 1.3-9.7 km. Then, the final catalogue is defined by the 15 events located together hydrophone and another 47 using only ASPSP station.

ASPSP



Hydrophone



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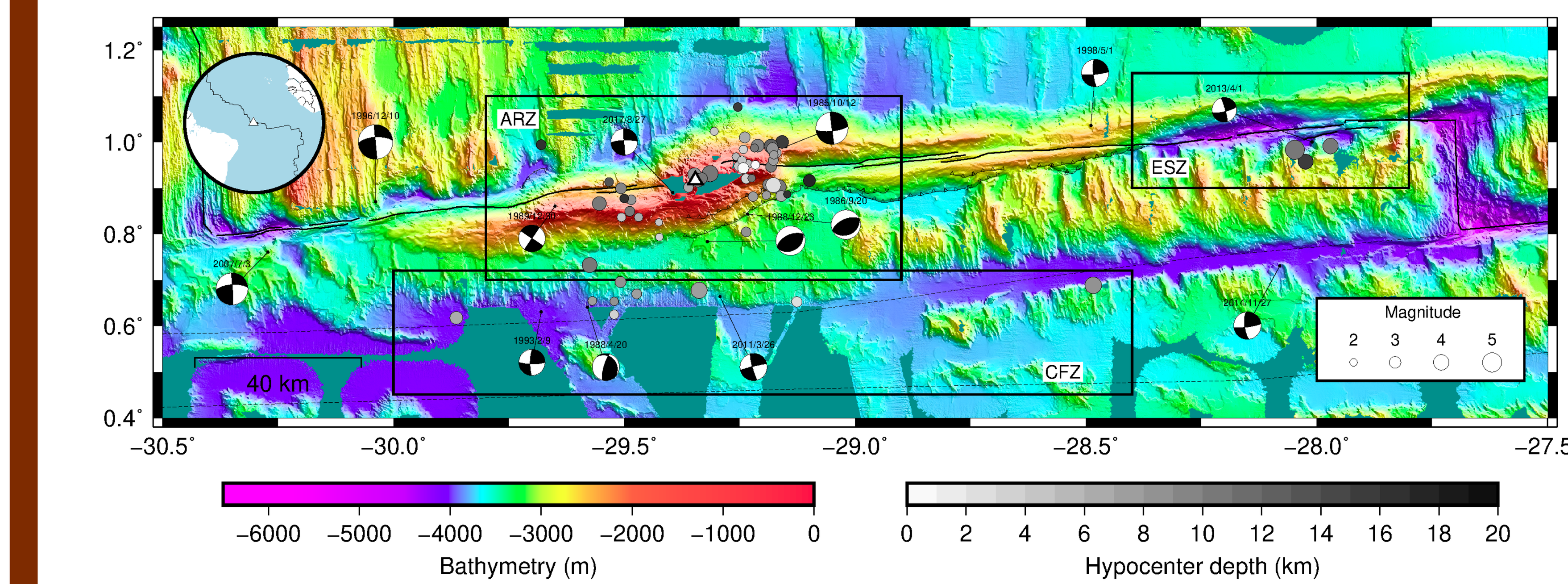
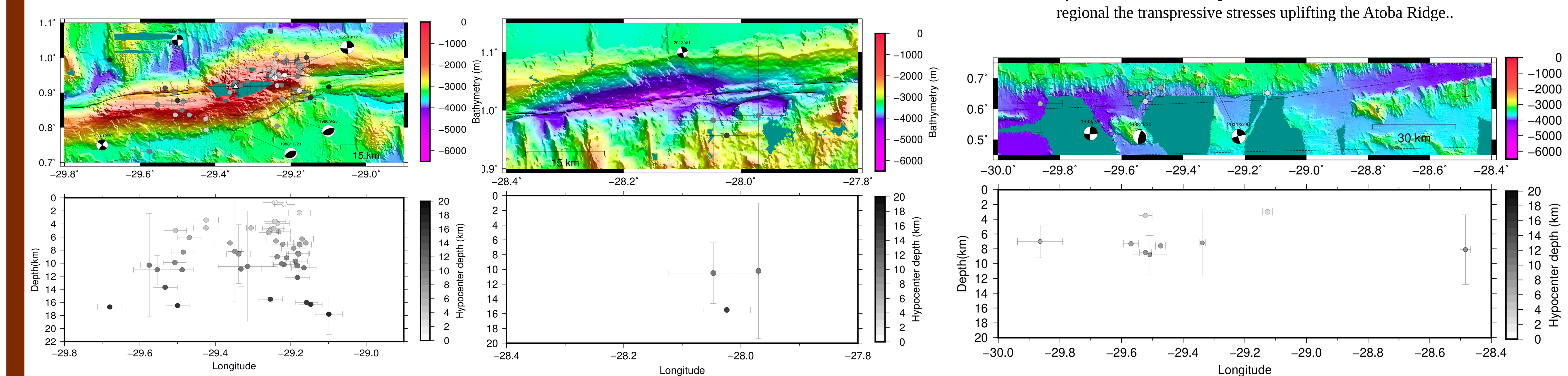




Geodynamic

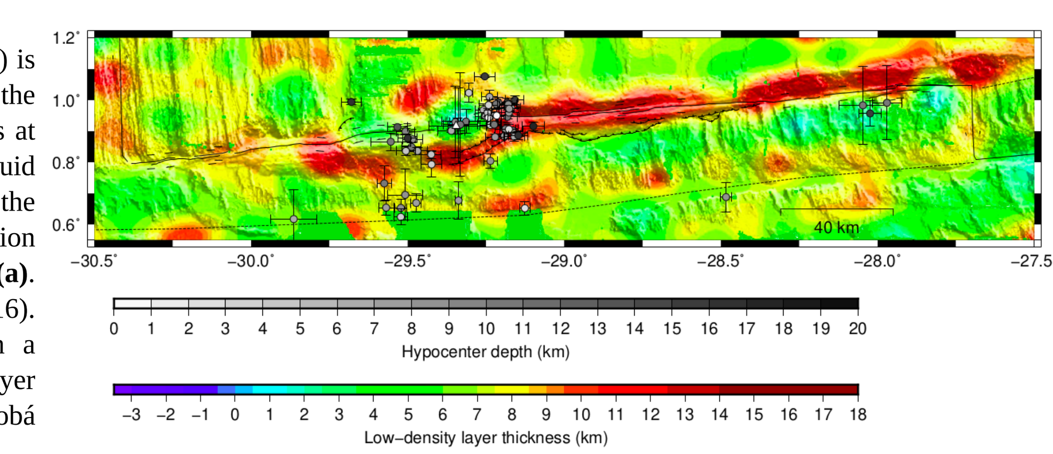
- 50 earthquakes with 0.2 km being the minimum depth and the maximum of 17.8 km were located in the Atobá Ridge Zone (ARZ) between longitudes 29.6º and 29.1º W. This high number is probably due to the high transpressive stress zone and the presence of a large number of faults that concentrate the deformation near the core of the push-up ridge.
- In the East Shear Zone (ESZ) were recorded only three earthquakes, with depths of 10.2 until 15.5 km. ESZ section is a deep basin crossed by the principal transform displacement zone, which is here more linear and less segmented than to the West of SPTS (Maia et al., 2016);
- Nine earthquakes were located at Central Fracture Zone (CFZ). They are distributed between longitudes 29.1º and 28.4º. These earthquakes possibly are linked to the reactivation of this segment of the fracture zone between the North and Central segments of the St. Paul Transform System, associated with possible zone of weakness reactivated due to the regional the transpressive stresses uplifting the Atoba Ridge..

5

Serpentinization

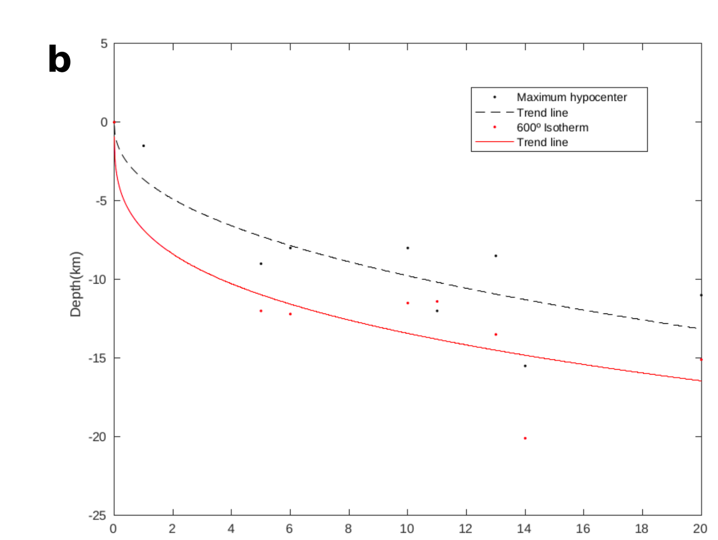
The thickness of the low density layer in the East Atoba (near 29º25'W) is highly variable, reaching 17 km. We identify a correlation between the crustal thickness of low density layer and the depths of the earthquakes at the Atoba Ridge suggesting that the deeper events may be linked to a fluid interaction with the mantelic rocks caused by water percolation down the thrust faults that border the push up ridge and the occasion a fluid interaction with the mantelic rocks and after the faults develops into the mantle. **(a)**. (Bonatti., 1976; Escartin et al., 1997; Roland et al., 2010; Maia et al., 2016). Maia et al (2016) showed that the density pattern correlates with a deepening of the 500-600°C isotherms and that the thick low density layer probably corresponds to serpentinized mantle rocks found in the Atobá Ridge and SPSP islets.

a



Britttle-Ductile Transition

b



The hypocenter depth can be controlled by the ~600°C isotherm, defining the brittle-ductile transition. This was discussed by several authors (Abercrombie and Ekström., 2001; Schlindwein and Schmid., 2016). We compare the 600ºC isotherm depth (in a plot of offset age against depth) reported by Boettcher and Jordan (2004), and the curve of the maximum observed hypocentral depth of St. Paul transform system. Considering the thermal lithosphere structure changes which occur when the isothermal limit depth (600ºC) increases as the fault length, we view a deep brittle-ductile limitation in the St. Paul Transform System (15-18 km).

c

Transform	Latitude(°)	Longitude(°)	Length(km)	Age Offset(m.y)	$Hypocenter_{max}$(km)	600°C Isotherm(km)	References
Oceanographer	35.150	-35.560	105	10	9	11.5	Cessaro and Hussong [1986], Bergman and Solomon [1988]
Hayes	33.630	-38.530	75	6	8	12.2	Bergman and Solomon [1988]
Kane	23.760	-45.680	150	11	8	11.4	Bergman and Solomon [1988]
Fifteen–Twenty	15.310	-45.940	180	13	12	13.5	Cleveland et al [2018]
Marathon	12.650	-44.660	80	5	8.5	12	Smith et al [2008], Cleveland et al [2018]
St.Paul(North Segment)	0.950	-29.000	310	14	15.5	20.1	Maia et al [2016], Hypocenter depth of this study
Chain	-1.240	-14.645	300	20	11	15.1	Abercrombie and Ekstrom [2001], Harmon et al [2018]

Conclusions

- Earthquakes occur regularly in the St. Paul Transform System with hypocenters reaching 17.8 km below the seafloor
- A thicker lithosphere in SPTS with a 600ºC isotherm limit situated in 15-18 km depth.
- The correlation between the low density layer and the hypocenter depths present an extensive serpentinization beneath the Atobá Ridge reaching depths of 18 km.
- Earthquakes at the CFZ possibly is caused by a reactivated zone of weakness, due to the regional transpressive stresses uplifting the Atoba Ridge that contributed to the reactivation of an otherwise inactive fracture zone.

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