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Seismotectonics of Portugal and its adjacent Atlantic area

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Abstract

A study of focal mechanisms of earthquakes and stress indicators are presented for Portugal and its adjacent Atlantic margins. Recently Riberio et al. (1996) published a work on this subject. In this study, we introduce new focal mechanisms of nine earthquakes. We use these results together with 12 other focal mechanisms and the main tectonic features in the region to define more accurately the type of mechanism and the stress pattern of the region. All the focal mechanisms used in this study differ partially but are compatible with the regional stress field. The stress indicators resulting from focal mechanisms and other geological and geophysical data show that the Portugal continental and its Atlantic margins are under horizontal pressure in NNW–SSE direction, with a greater proportion of strike-slip and reverse-oblique mechanisms for the whole area. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: seismicity; focal mechanisms; stress indicator; Portugal; seismotectonics

1. Introduction

The western continental margin of the Iberian Peninsula is divided in two main regions of complex bathymetry separated by the Nazaré submarine valley (NV) (see Fig. 1). The northern region comprises the Galicia Bank (GlB), the Vigo (VS) and Porto (PS) seamounts and few small submarine valleys. The region located southwards of the Nazaré submarine valley is characterised by a different geomorphological feature with smaller seamounts and larger submarine valleys: Tejo (TV), Sado (SV) and São Vicent (SV) submarine valleys are the most prominent ones (Fig. 1). Westwards of cape of São Vicent (CSV) is the Gorringe Bank (GB), a geomorphological feature whose highest summit reaches 25 m below sea level (Fig. 1). The Gorringe Bank is one of the main seismogenic source for the Iberian Peninsula and North Africa region (Moreira, 1985; Buforn et al., 1988a).

So it is to be emphasized that the region under study is deeply affected by the movements between the African and European plates whose western boundary, from 24°W to 5°W, is the Azores-Gibraltar fault. The Gorringe Bank divides this important fault in two sectors. The first one, from 24°W to 13°W ends very near the western boundary of Gorringe Bank and it is very well-known as Gloria fault (GF). This boundary is characterized by a strike-slip fault with right-lateral motion (Buforn et al., 1988a). The second one, from 13°W to 5°W, where Gorringe Bank belongs, has a diffuse seismicity, a complex bathymetry and also a large positive gravity and geoid anomaly (Souriau, 1984). It is an ocean–ocean N–S convergence area with a very slow rate of about 4 mm/year (Argus et al.,

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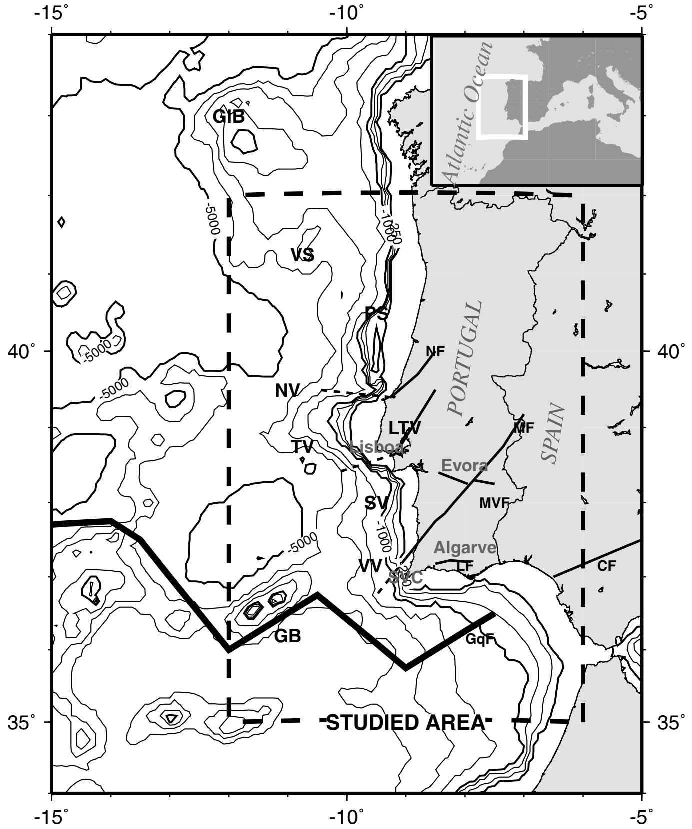


Fig. 1. Studied area and some important accidents (GB: Gorringe Bank; GqF: Guadalquivir Fault; GlB: Galicia Bank; VS: Vigo Seamount; PS: Porto Seamont; NV: Nazaré Valley; TV: Tejo Valley; LTV: Lower Tejo Valley; SV: Sado Valley; LF: Loulé Fault; VV: São Vicente Valley; SV: São Vicente; MVF: Moura-Vidigueira Fault; MF: Messejana Fault; CF: Cadiz-Alicante Fault). Batymetric contours are in 250 and 1000 m intervals.

1989). This zone of convergence becomes a zone of continental collision in the western Mediterranean region. Here, there are some NE–SW alignments that can be considered as a continuation of active faults in the Iberian Peninsula such as Messejana (MF), Guadalquivir (GqF) and Cadiz-Alicante (CF) faults (Fig. 1).

The geographical area covered by this study includes part of the Portuguese mainland and its adjacent Atlantic region, which belongs to the western and southern margin of the Iberian Peninsula. This area is limited by the parallels 42.0°N and 35.0°N and by the meridians 12.0°W and 6.0°W; Fig. 1 shows the general location of the studied area.

In this paper we present the study of nine shallow seismic events located in the Portuguese mainland and its adjacent Atlantic margins. Fault plane solutions and stress field are determined and discussed together with available seismological and geological data existing in this area.

2. Seismicity and tectonics

Portugal can be considered to have a moderate seismicity characterized by small events ($M < 5.0$) and occasional moderate/large/major ($5.0 \leq M < 7.8$) earthquakes. Epicentres of earthquakes for the period 1988–1997 for Portugal and its adjacent Atlantic area taken from the Seismicity Data File of the Instituto de Meteorologia (IM, Portugal) are shown in Fig. 2. This file is based on the Earthquake Catalogue for the period 1988–1994 of the IM (Senos et al., 1995) and the database for the period 1995–1997 of the

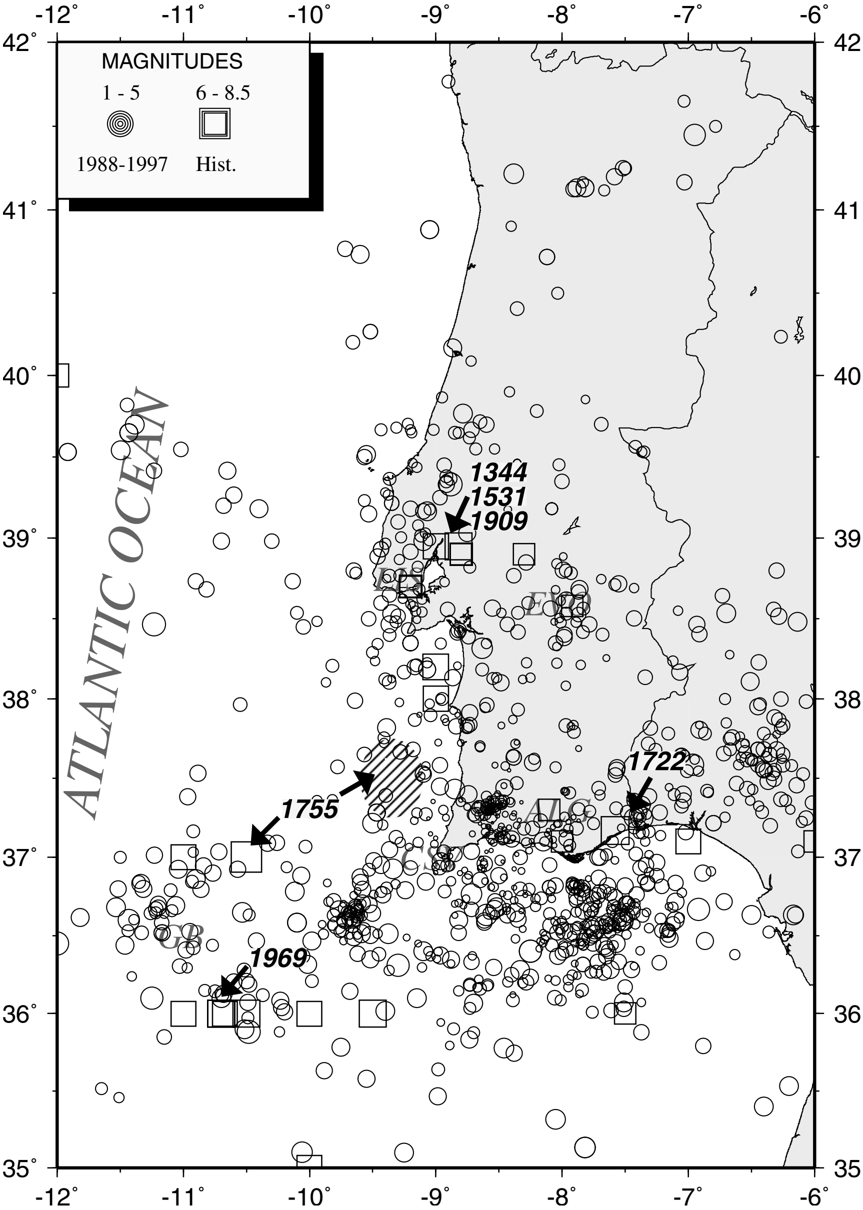


Fig. 2. Instrumental seismicity (1988–1997) and location of the most important historical earthquakes (1344–1970) of Portugal (see text for more details).

same institute regularly (monthly) published in IM's Preliminary Seismological Bulletins. Earthquakes from historical times to 1987 for Portugal and its adjacent Atlantic area also shown in Fig. 2 are taken from Sousa et al. (1992). Fig. 2 shows epicentres scattered all over the territory and recent seismic events with small magnitudes ($M < 5.0$) and epicentres concentrated along the Algarve coast and in the region near the city of Évora. Elsewhere, according to the seismic history, the Tavira earthquake of 27 December 1722 ($M = 7.5$) located offshore the coast of Algarve generated a tsunami along the coast of Algarve from

Faro to Tavira (see Mezcua, 1982). The northern and central part of Portugal are characterised by a low seismicity ($M < 5.0$) except Lower Tejo Valley region (LTV), which exhibits the relatively high seismic activity. At least three important historical earthquakes, plotted in Fig. 2, have occurred in this zone in 1344 ($M_s = 6.0$), 1531 ($M_s = 7.1$) (Martins and Mendes Victor, 1990; Sousa et al., 1992) and 23 April 1909 ($M_w = 6.0$, $M_s = 5.9$) (Teves-Costa et al., 1999). The southern part of Portugal is the region with the most significant seismicity and can be divided into two areas: (1) the Atlantic adjacent zone; and (2) the continental zone. The first one is characterized by more intense seismic activity associated with the convergence between Eurasian and African plates. The southwest of cape of São Vicent area, where the earthquakes of 28 February 1969 ($M_s = 8.0$; Buforn et al., 1988a) and 1 November 1755 (so-called Lisbon earthquake, $I_o = \text{X–XI}$; Baptista et al., 1998a; Martinez Solares et al., 1979) occurred, is probably the most seismically active zone (see Fig. 2). The epicentre location of the 1755 Lisbon earthquake is still uncertain as shown in Fig. 2. Recently Baptista et al. (1998b) suggest from numerical modelling of historical data, that the 1755 tsunami earthquake probably generated on the continental shelf. This probable seismogenic zone extends between the Gorringe Bank and the Portugal coast (see Fig. 2). According to the Portugal southern mainland neotectonic map (Cabral and Ribeiro, 1988) it is possible to identify the following main active structures (Fig. 1): (a) the Messejana fault (MF), with an extension of 500 km crossing all of the southern region with NE–SW orientation and which is probably associated with the Azores-Gibraltar fault; (b) close to the city of Évora, the Moura-Vidigueira fault (MVF) has a WNW–ESE strike; and (c) the Loulé fault (LF), located in Algarve with an approximately W–E orientation, probably responsible for large historical earthquakes (Fig. 2). These tectonic faults are partially correlated with the seismic activity in Évora region and Algarve (Moreira, 1985).

A seismic study between 1900 and 1990 in the western zone of the Iberian Peninsula has revealed four zones of high seismic strain release (Martins and Mendes Victor, 1993): (1) the Lower Tejo Valley (maximum 6.4×10^{22} erg/km^2); (2) the Gorringe Bank zone (maximum 4.5×10^{22} erg/km^2); (3) the southern Algarve (maximum 4.0×10^{21} erg/km^2); and (4) the area around the city of Évora (maximum 1.4×10^{21} erg/km^2). The southern region of Portugal (mainly the Algarve) and the Lisbon region (including the Lower Tejo Valley region) are the zones that have suffered the greatest number of disastrous earthquakes (Fig. 2).

3. Fault plane solutions and stress indicators

Fault plane solutions, based on short-period (SP) P-wave first motion polarities, have been determined for nine earthquakes, four in the Portugal mainland and five in the adjacent Atlantic region. These solutions correspond to seismic events recorded by digital and analogic instruments between 1989 and 1998 by the Instituto de Meteorologia (IM, Portuguese national seismological network) with magnitudes greater than 4.0 except for the event of 1997 (event 20, Table 1) whose magnitude is 3.6. This earthquake was located by the Évora local network (Borges et al., 1999) and presents 15 polarities with a good azimuthal coverage (even 20 in Table 1). In some cases the data from the Portuguese national network was complemented with SP data from the national networks of Spain and Morocco. The number of observations for each event ranges from 15 to 30. Earthquakes parameters are given in Table 1. Fault plane solutions have been determined using a computer program based on the algorithm of Brillinger et al. (1980). This algorithm determines the maximum likelihood function, and it estimates the orientation of the principal stress axes (P and T), nodal planes, and their standard errors (Udias and Buforn, 1987) for the nine new solutions. Take-off angles have been estimated for regional distances from a regional crustal model (Senos et al., 1995).

The reliability of the solutions has been estimated by the values of the standards errors of P and T-axes, the score (S) and the number (N) of seismograms. The fault plane solutions with a good quality are based on standard errors of the axis orientation less than 15°, $S \geq 0.8$ and $N \geq 15$. Events 6, 12, 13, 19, 20 and 21 have well-constrained solutions with small values of standard errors (less than 15°) for axes and nodal planes; events 14, 17 and 18 have standard errors between 16 and 54°. All solutions correspond to

Table 1

Hypocentral data and fault-plane solutions of the studied earthquakes (*Φ*, *Θ*: azimuth and plunge of the *P* and *T*-axes; *N*: number of polarities; *S*: score)

Event no	Date (yr/mo/da)	Lat (°N)	Lon (°W)	Depth (km)	Magnitude (M_L)	Nodal plane			*P* Axe		*T* Axe		*N*	*S*
						Strike	Dip	Rake	*Φ*	*Θ*	*Φ*	*Θ*		
6	80/11/13	39.3	−11.7	15	4.0	358 ± 4	54 ± 4	−11 ± 6	323 ± 4	32 ± 5	221 ± 6	18 ± 4	12	1.0
12	89/04/08	39.3	−8.9	12	4.7	191 ± 3	75 ± 6	79 ± 6	290 ± 8	29 ± 4	86 ± 13	59 ± 5	30	1.0
13	89/09/23	38.3	−8.6	25	4.0	21 ± 2	46 ± 8	82 ± 4	117 ± 10	1 ± 6	214 ± 7	84 ± 5	15	0.8
14	89/11/02	36.8	−8.7	40	4.5	180 ± 40	75 ± 20	8 ± 43	135 ± 32	5 ± 36	43 ± 22	16 ± 37	15	0.9
17	93/02/16	36.6	−8.6	26	4.3	17 ± 12	33 ± 21	34 ± 26	326 ± 25	22 ± 28	202 ± 52	54 ± 3	24	1.0
18	93/06/22	36.4	−8.3	15	4.4	37 ± 13	62 ± 19	40 ± 16	159 ± 21	4 ± 13	230 ± 54	48 ± 10	25	1.0
19	94/09/24	36.7	−7.8	52	4.3	274 ± 8	70 ± 10	126 ± 11	338 ± 14	17 ± 15	226 ± 16	51 ± 8	29	1.0
20	97/01/19	38.7	−7.8	13	3.6	101 ± 8	59 ± 9	172 ± 11	322 ± 13	17 ± 7	61 ± 14	27 ± 7	15	1.0
21	98/07/31	38.8	−7.9	5	4.0	95 ± 2	70 ± 5	180 ± 3	318 ± 8	14 ± 1	52 ± 9	14 ± 2	15	1.0

strike-slip or reverse faulting mechanisms with a component of strike-slip motion, except for the events 12 and 13 where the reverse motion is quasi pure. In Fig. 3, the graphic representations of the new solutions using the equal area projection of the lower hemisphere of the focal sphere are represented. The corresponding focal parameters and their associated errors are given in Table 1.

In addition to the fault plane solutions determined in this paper, we have selected from the literature, 12 focal mechanisms of shallow earthquakes with magnitudes greater than or equal to 3.5 that occurred in the

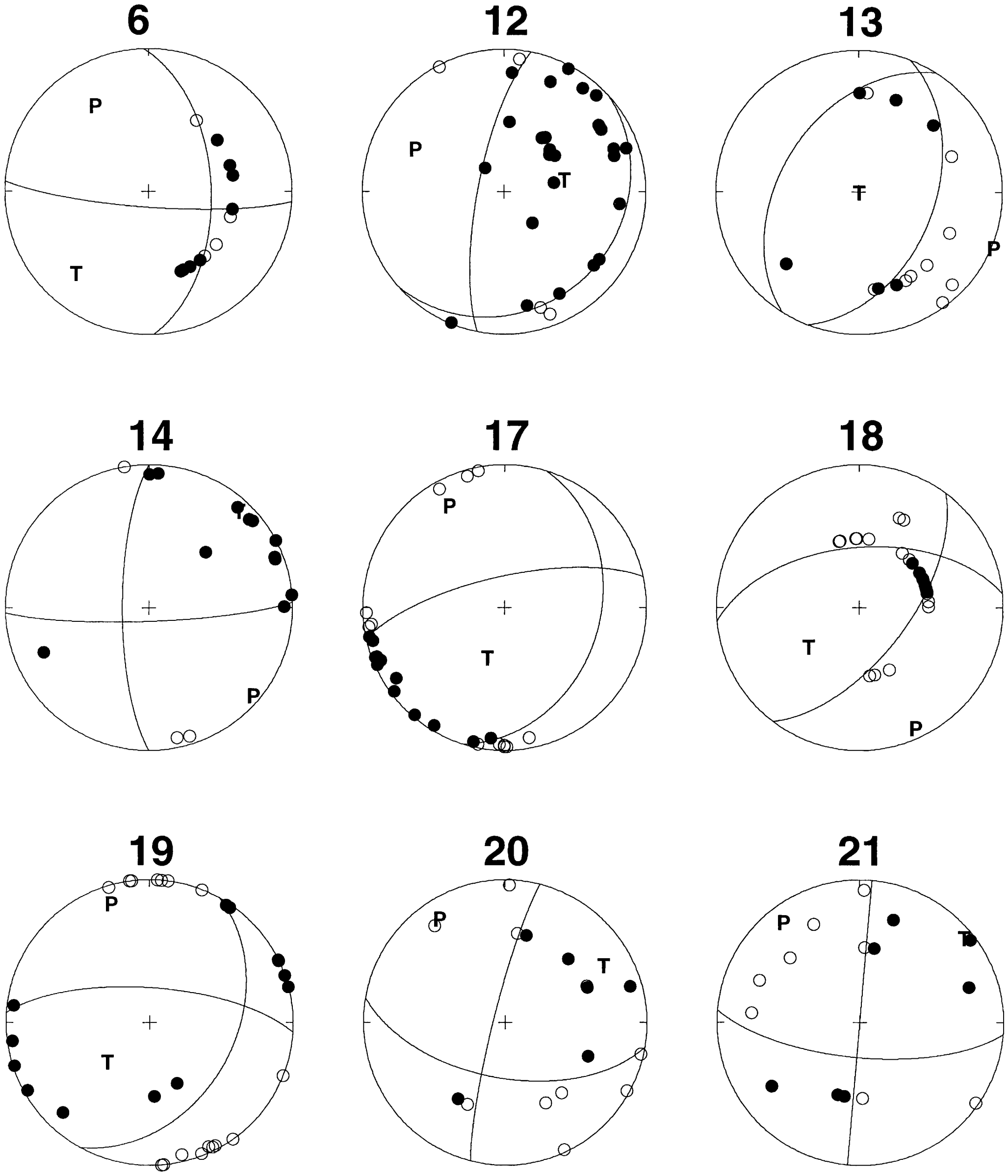


Fig. 3. Focal mechanism solutions of the studied events (lower hemisphere equal area projection; black circles correspond to compression and white circles to dilatation).

Portugal mainland and its adjacent Atlantic region during the period 1960–1990. They are listed and referenced in Table 2. However, two earthquake focal mechanisms presented by Ribeiro et al. (1996) are not included in this study: the earthquakes of 18 August 1980 ($m_b = 4.5$) and 12 October 1986 ($M_L = 3.7$). We completely recalculated the mechanism of the 1986 earthquake and we consider it poorly constrained by the stations; the available data are not well distributed azimuthally. For the 1980 earthquake the score given by Ribeiro et al. (1996) is not satisfactory ($S = 0.65$). It is obvious that the seismotectonic interpretation from low magnitude events could not be a representative of the general stress trend of the zone. However, if the totality or a sufficient number of focal mechanisms used have the same trend, some interpretations could be inferred. The 21 focal mechanisms used in this study are mapped in Fig. 4. Most of the solutions are strike-slip, reverse or oblique and we will analyse the different regions separately starting with the Évora region.

Earthquakes 9, 20 and 21 located near Évora city present strike-slip motion with planes striking NS and EW. In this area, there are no observed faults corresponding to focal planes obtained for these three events (Fig. 5a). The correlation between seismicity, tectonic faults and focal mechanisms present in this area is therefore problematic. However, a general trend of epicentres in a N–S direction is present near the city of Évora (Fig. 2) and agrees with one of planes obtained for the three focal mechanisms, showing a N–S trending, nearly vertical fault plane with horizontal *P*-axes.

On the right bank of the Tejo river, near the coast line, earthquakes 10 and 11 located to the northern part of Lisbon present normal fault motion in contrast to the events 12 and 13 to their north and south, respectively, which are reverse fault motions with planes striking NNE ≯ SSW (Fig. 5a). Given the weak magnitude of events 10 and 11 (4.0 and 3.7), it is probable that these events are associated with a local tectonic motion. The event 12 presents reverse motion and may be associated with some short reverse faults with NNE–SSW trend, offshore of the coast, that possibly form a part of the Lower Tejo Valley fault system (LTV). The earthquake 13 located near Alcácer do Sal shows a reverse fault motion with planes striking NNE–SSW, which may be associated with the Deixa-o-Resto fault (DRF, Ribeiro et al., 1996) (Fig. 5a).

The southern part of Portugal and its adjacent margin are dominated by oblique faulting with dominant reverse motion for 3, 4, 5, 17, 18 and 19 (Fig. 5b). Fault plane solutions 1, 7, 8, 14 and 15 correspond to vertical strike-slip motion. These events, except the event 1, are located in the vicinity of the coastline. All of these earthquakes may be related to the main plate

Table 2
Hypocentral data and fault-plane solutions used in this study (Φ, Θ: azimuth and plunge of the *P* and *T*-axes; *N*: number of polarities; *S*: score; BUFa: Buforn et al. (1988a); BUFb: Buforn et al. (1988b); MOR: Moreira (1991); BOR: Borges (1991); RIB: Ribeiro et al. (1996); IGN: Instituto Geográfico Nacional (Spain))

Event no	Date (yr/mo/da)	Lat (°N)	Lon (°W)	Depth (km)	Mag	Nodal plane			*P* Axe		*T* Axe		*N*	*S*	Ref.
						Strike	Dip	Rake	Φ	Θ	Φ	Θ			
1	60/12/05	35.6	−6.5	15	6.2 M_s	73	86	−178	298	4	28	1	14	0.71	BUFa
2	62/12/26	39.3	−10.6	5	5.7 M_s	180	47	−3	145	30	38	27	38	0.79	id
3	64/03/15	36.2	−7.6	12	6.1 M_s	56	71	75	158	24	304	61	56	0.89	id
4	69/02/28	36.1	−10.6	22	8.0 M_s	231	47	54	165	3.7	68	64	65	0.85	id
5	69/05/05	36.0	−10.4	29	5.5 M_s	324	24	142	194	28	335	55	24	0.88	id
7	86/09/25	36.8	−8.9	–	4.3 M_L	7	70	−10	325	21	232	7	–	–	MOR
8	86/10/20	36.9	−8.6	37	4.8 M_L	180	37	3	147	33	29	36	36	0.89	BUFb
9	87/06/04	38.5	−8.1	8	4.4 M_L	262	84	−162	127	17	35	8	–	–	MOR
10	87/08/05	39.2	−9.1	10	4.0 M_L	110	49	−119	311	69	220	0	11	1.0	BOR
11	88/05/22	38.9	−9.2	20	3.7 M_L	285	38	−160	125	45	242	24	11	1.0	RIB
15	89/12/20	37.3	−7.4	23	5.0 M_L	351	77	10	305	2	215	16	40	0.77	IGN
16	90/05/26	38.4	−11.7	68	4.6 M_L	138	79	−12	94	16	184	1	38	0.73	BOR

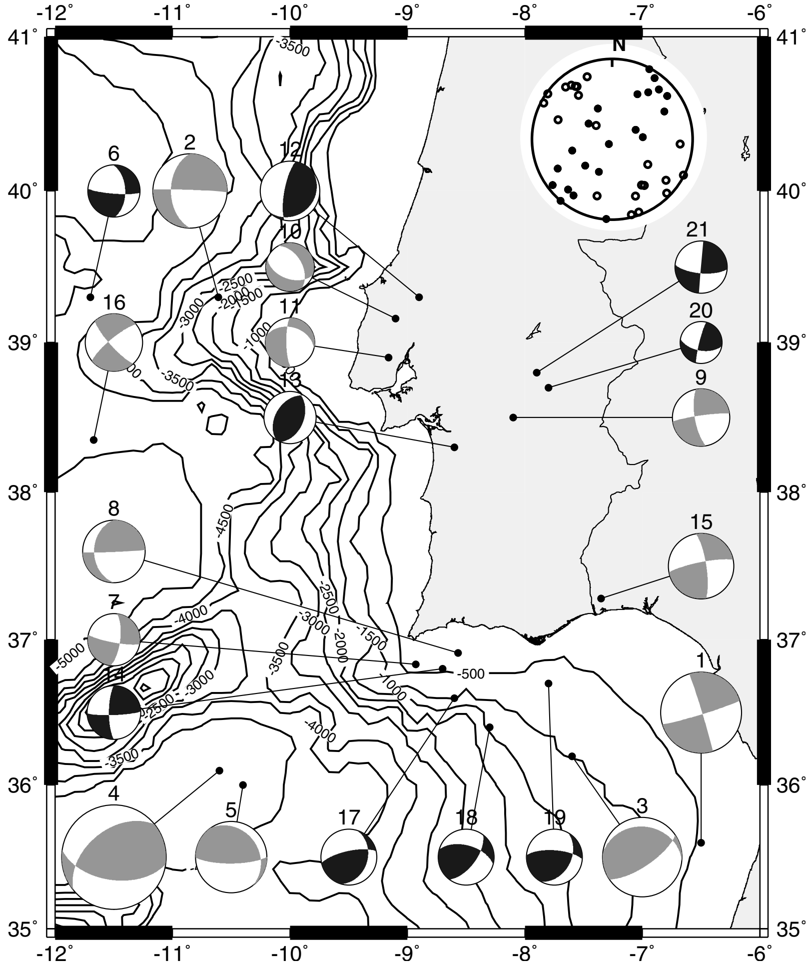


Fig. 4. Fault plane solutions of selected events located in the studied area obtained by different authors (see Tables 1 and 2). Black mechanisms are those calculated in this work (Table 1).

boundary or to some of its secondary features. Event 15 could be associated to the Loulé fault (LF, Fig. 1) according to Mezcua and Rueda (1997). Nevertheless Terrinha (1997) attributes this earthquake to a hypothetical fault (Guadiana fault) located near Guadiana River. ‘Hypothetical’ because the Guadiana fault (GFZ, Fig. 5c) has not been mapped until present. The tectonic model for the Algarve basin, formed by the four major extensional transfer faults presented by Terrinha (1997) and including the Guadiana fault, are compatible with the fault plane solutions 7, 8, 14 and 15 where one of planes strike about N–S with left-lateral movement (see Fig. 5c).

The general map of focal mechanism, combined with the stereographic projection of *P* and *T*-axes show that the stress orientation of *P*-axes is mainly NW–SE (centre) to NNW–SSE (south) (Fig. 4). In Fig. 6, the Frohlich diagrams (Frohlich, 1992) are presented: the upper triangle corresponds to focal mechanisms of earthquakes between 37 and 40°N and the lower triangle between 35 and 37°N. In the continent and its west adjacent Atlantic margins (37–40°), strike-slip and oblique mechanisms are predominant whereas in the southern part (35–37°) reverse mechanisms are predominant. This change in stress orientation is confirmed by triangle diagrams (see Fig. 6) and the horizontal projections of *P* and *T*-axes (see Fig. 7), which indicates that the orientation of *P*-axes for earthquake mechanisms in the Portugal mainland and its adjacent Atlantic area is mainly NW–SE to NNW–SSE. In contrast, most *T*-axes change from a subvertical orientation southward in the oceanic domain, to a subhorizontal orientation northward in the continental (Évora region) and oceanic domain (Fig. 7). Due to the absence of earthquake focal mechanisms between 37 and 38°N, it is difficult to assure that this N–S change in stress is progressive or sudden. However, the whole region is under horizontal compressional stress in a NW–SE direction (Fig. 4). This is in agreement with the results obtained by Bezzeghoud and Buforn (1999) for the whole Ibero-Maghrebian region and with the orientation of the principal axis of stress along the Eurasian–African plate boundary. This distribution of *P* and *T*-axes is dominated by low-magnitude events, but it can be a representative of the general stress trend of the region for the following reasons. Firstly, there are a sufficient number of events which have the same trend; and secondly all the low-magnitude events have a trend similar to the moderate 1960, 1962 and 1964 (events 1, 2, 3, Table 2, Figs. 4 and 7) earthquakes ($M_s = 5.7$ to $M_s = 6.2$) and to the large 1969 Gorringe earthquake ($M_s = 8.0$) (event 4, Table 2, Figs. 4 and 7).

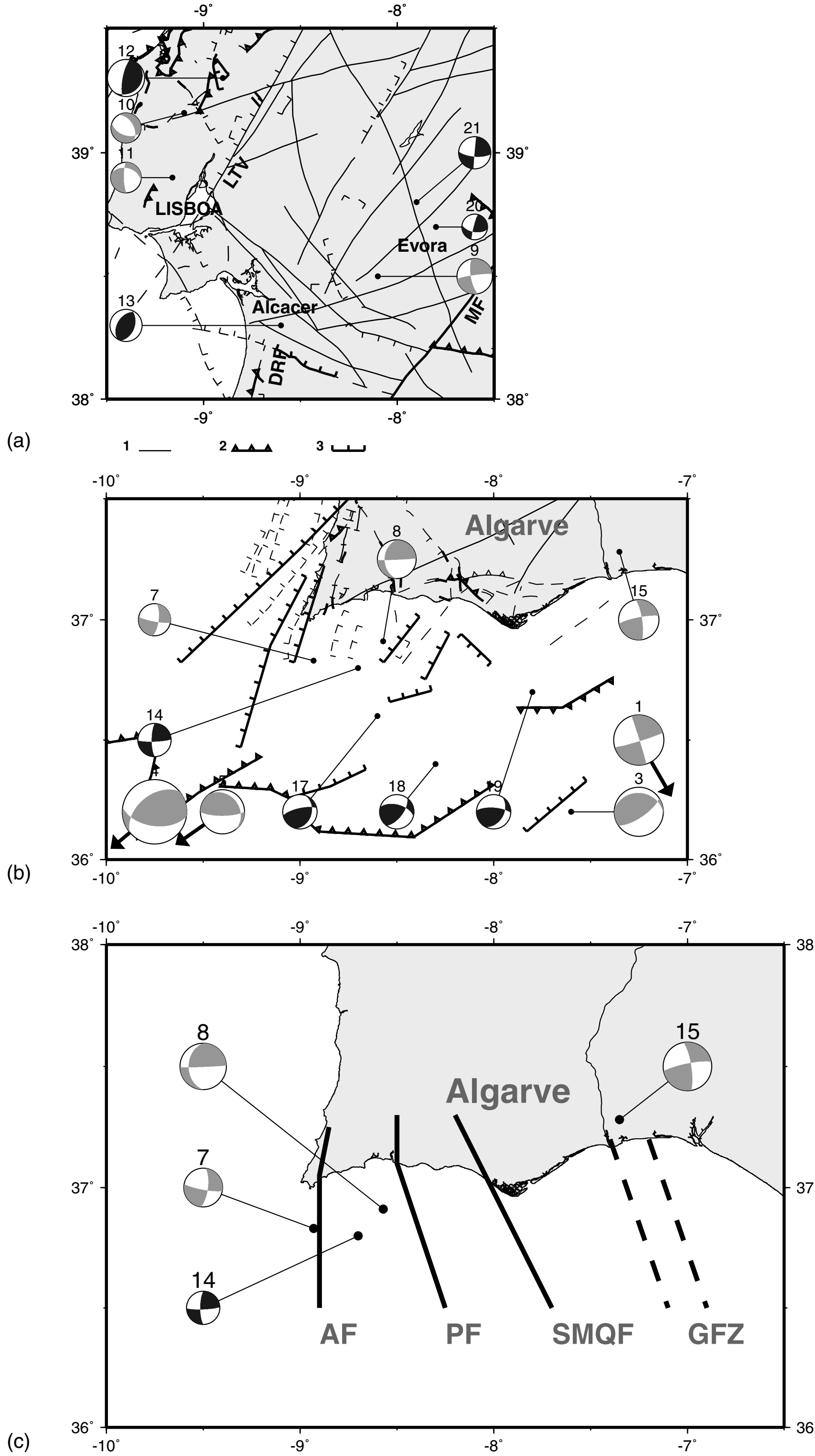
The values of S_{Hmax}, classified according to the Zoback criteria of quality (Zoback, 1992), are deduced from the nine earthquake focal mechanisms determined previously in this study. These values, listed in Table 3, are plotted in Fig. 8 together with 35 S_{Hmax} stress orientation obtained and compiled by Ribeiro et al. (1996) from three different categories (earthquake focal mechanisms, breakouts and geologic fault-slip data). This figure shows a complete view of all data of S_{Hmax} for Portugal mainland and its adjacent Atlantic area (Fig. 8). These 44 reliable stress indicators, according to the Zoback criteria, have a classification from A to C and show a mean S_{Hmax} azimuth of 135° with a standard deviation of 25%. It is important to emphasize that between the value of this S_{Hmax} azimuth and the geological and seismological data there is an average rotation of 20° clockwise and of 15° anticlockwise, respectively, whereas in the borehole elongation the results are remarkably consistent with the trend. The NNW–SSE direction of the S_{Hmax} is consistent for the whole area and agrees with the present collision motion between Africa and Eurasia plates.

As reported by Ribeiro et al. (1996) the stress indicators obtained for the Portuguese mainland and near offshore, suggest a rotation in time of the direction of maximum compression of S_{Hmax} from NNW–SSE in the upper Pliocene (fault-slip stress indicators) to NW–SE in the present time (focal mechanisms stress indicators). The distribution of S_{Hmax}, plotted in Fig. 9 shows this rotation of stress. Let us stress that the geologically observed fault-slip is poor and its dispersion relevant.

4. Discussion and conclusions

In Portugal, continental earthquakes are relatively small but provide seismologists with an opportunity to hone their emergency response routine. The fault plane solutions determined in this study, from polarity data, indicate that all events have similar strike-slip and oblique thrust faulting mechanisms. These mechanisms are similar to those of many other earthquakes located in the Betic-Rif zone and the Alboran Sea which have an oblique character (Bezzeghoud and Buforn, 1999). In Portugal, in the continental and adjacent Atlantic margins, the compressive seismic stresses in NW–SE direction, as derived from focal mechanism solutions are in agreement with the stress field expected in the area from the collision between African and Eurasian plates.

In the Western continental margin, a strike-slip movement prevails with a compressional stress in a WNW–ESE direction and extension in NNE–SSW direction. The faults of Nazaré, Tejo and Messejana, considered to continue into the Atlantic along submarine valleys (Moreira, 1991) could be associated with this movement. In the Évora region, results of focal mechanisms suggest NW–SE compression associated with an extensional component in the NE–SW direction. Ribeiro et al. (1996) sustain the hypothesis that the western Atlantic margin of Portugal is characterized by an incipient northward propagating subduction zone nucleating at the Gorringe submarine bank. This is a possible hypothesis but it is difficult to verify with the existing seismological data. The instrumental seismicity in this complex area is known only for one period of less than 40 years. The spatial distribution of earthquakes, shown in Fig. 2, is diffuse and no Benioff zone is evidenced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-8°
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-7°
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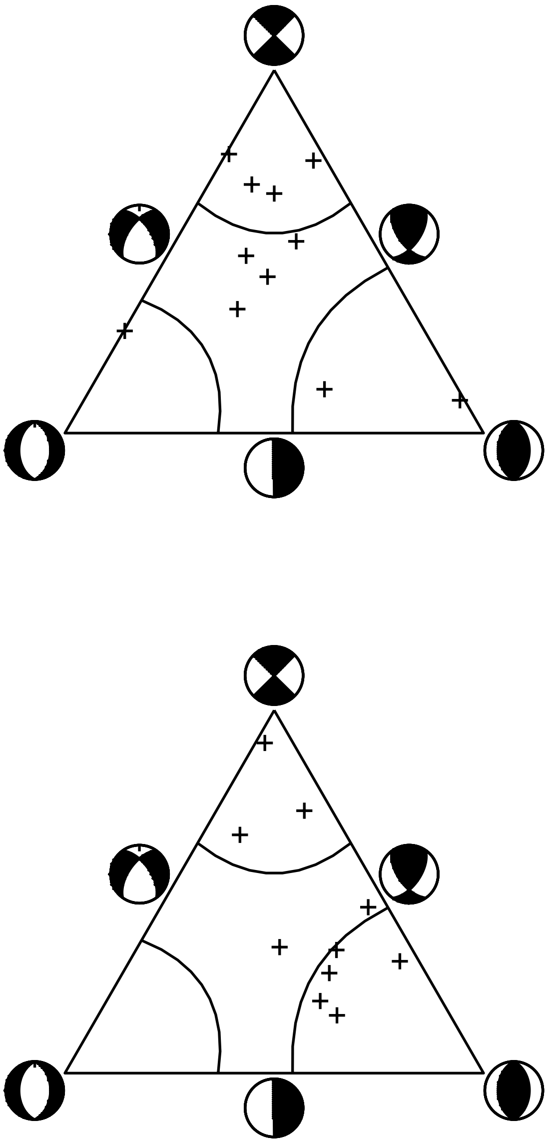

Fig. 6. Frohlich's diagrams, top triangle corresponds to focal mechanisms of earthquake between 37 and 40° and bottom triangle between 35 and 37°.

or detected by a specific hypocentral pattern. It is difficult to evaluate the existence of incipient subduction zone in the western Atlantic margin of Portugal because there are few stress data, in particular focal mechanisms. The few stress data in the oceans and the difficulty to evaluate the role of slab pull forces related to subduction zones has been already pointed by Wiens and Stein (1985) and corroborated from the World Stress Map global stress by Zoback (1992). In our case, an incipient subduction zone (of slow young oceanic plate) is still more difficult to evaluate. The strike-slip earthquakes observed along the western Atlantic margin of Portugal (Fig. 4) are not typical of subduction zones. Studies for the last 30 years has made it possible to establish that the principal seismic moment release at subduction zone (at the frictional interface) occurs by thrusting along the plate interface during great underthrusting earthquakes (e.g. Scholz, 1990). Otherwise, earthquake focal mechanisms presented in this study (1960–1998, Tables 1 and 2, Fig. 4), are consistent with the general direction of the quaternary compression, and they are in good agreement with the seismotectonics of the Ibero-Maghrebian region (e.g. Bezzeghoud and Buforn, 1999; Buforn et al., 1988a). The orientation of the stress obtained in Portugal mainland and its adjacent Atlantic area is controlled by the continental collision between Iberia and Africa in the eastern segment of the Azores-Gibraltar plate boundary (Figs. 4, 6 and 7).

The contact and stress orientation between Africa and Eurasia along the Azores-Gorringe zone, except for the Gloria fault zone, is well-defined by a fairly linear fracture in the E–W direction with the occurrence of large earthquakes of right-lateral strike-slip character (Buforn et al., 1988a). However, in the vicinity of the Portugal Atlantic margin, including the Gulf of Cádiz and the Strait of Gibraltar, the earthquakes are of moderate magnitude and the contact between the plates is more complicated. This complexity, probably due to the changes in the crust type from oceanic to continental, is evidenced by

Fig. 5. (a) Details of focal mechanisms and geological faults for the Lisbon and Évora region. 1: Geological lineation; 2: Reverse fault; 3: Normal fault. Dashed lines represent probable faults. Faults are from Cabral and Ribeiro (1988). DRF: Deixa-o-Resto Fault. See caption of Fig. 1 for other details. (b) Detail of focal mechanisms and geological faults for Algarve region. See caption of Fig. 5a for other details. (c) Tectonic model for the Algarve basin formed by the four major extensional transfer faults presented by Terrinha (1997) and focal mechanisms for this region. AF: Algezur fault; PF: Portimão fault; SMQF: São Marcos-Quarteira fault; GFZ: Guadiana fault zone.

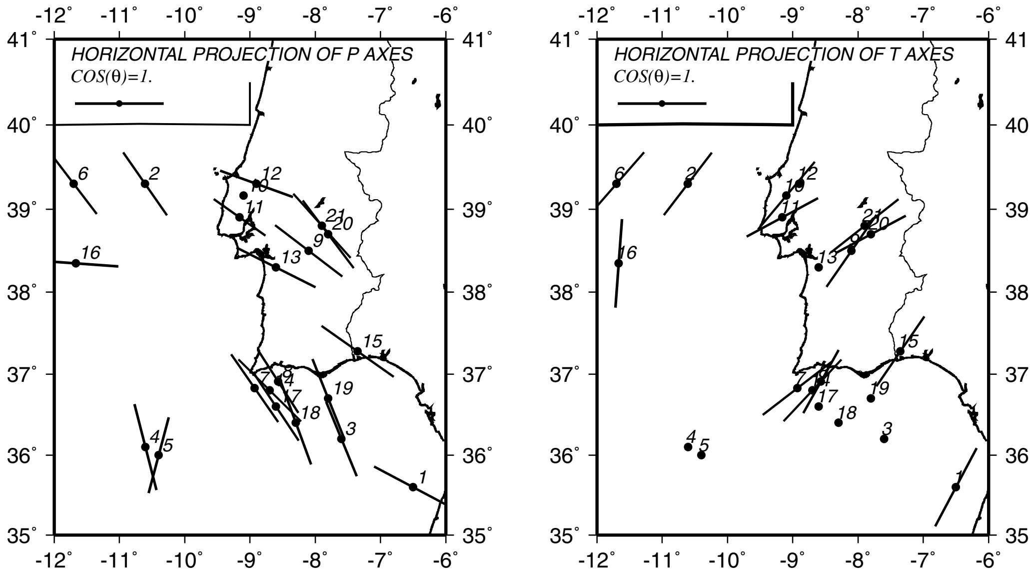

Fig. 7. Plot of horizontal projection of P (left) and T (right) axes. Length of lines is proportional to the cosine of plunge (cos θ).

multiple faults, diffused seismicity and by reverse and oblique faulting becoming predominant. From Gorringe Bank there are three main seismic alignments in NE–SW directions that could be interpreted as continuations of neotectonic active faults in the Iberian Peninsula: (1) Messejana, (2) Guadalquivir and (3) Alicante-Cádiz faults. However, the few earthquakes recorded in this area have small magnitude ($M < 5$) showing a non-uniform distribution of epicentres and no clear seismic activity is evidenced at present along the Messejana and Guadalquivir faults except along the Alicante-Cádiz fault where a significant seismic activity is continuous in time and space (Fig. 2, see also Bezzeghoud and Buforn, 1999). The focal mechanisms of the southern part of Portugal and its adjacent margin, presented in this study, could be associated with these faults or/and other secondary faults linked to them. This interpretation is based only on recent seismological data. To understand the seismotectonics and geodynamics of this zone it is fundamental to use other geological and geophysical information as well as historical and paleoseismic studies. For instance, a geodetic monitoring program in Portugal could provide a most complete and reliable data set on this problem. Nevertheless, in the present-day, these studies are almost non-existent and an effort must be made by the scientific community to solve this problem; especially with regard to the paleoseismic studies in the Iberian Peninsula. In this study, it was deduced that the Portugal continental and its Atlantic margins are under horizontal pressure in the NW–SE direction, resulting in strike-slip mechanisms to the north and in reverse and oblique faulting to the south with underthrusting of the Africa plate. This motion is consistent with the recent results given by Bezzeghoud and Buforn (1999), for the eastern part of Strait of Gibraltar (Betic-Alboran-Rif-Tell zone).

Table 3
Stress indicator for focal mechanisms determined in this study (S_{Hmax}: azimuth of maximum horizontal stress axis; Q: quality ranking according to the Zoback criteria)

No	Date	S_{Hmax}	Q
6	80/11/13	323	C
12	89/04/08	290	B
13	89/09/23	117	C
14	89/11/02	135	C
17	93/02/16	326	C
18	93/06/22	159	C
19	94/09/24	338	C
20	97/01/19	322	C
21	98/07/31	318	C

The focal mechanisms and stress indicators

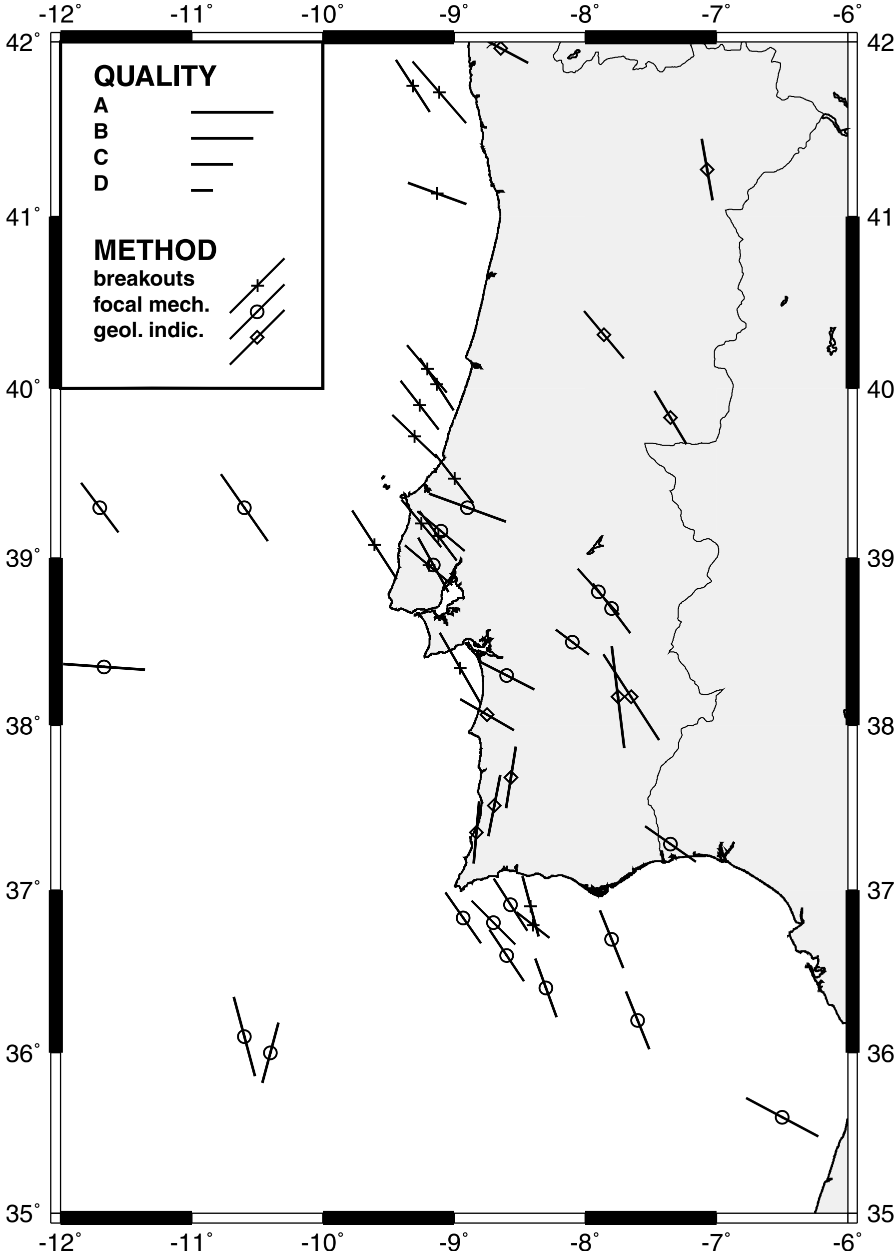

Fig. 8. Map of all stress indicators available in the studied area.

presented in this work suggest a rotation of the direction of maximum compression from Pliocene (NNW–SSE) to present (NW–SE) in accordance with the stress field data presented by Ribeiro et al. (1996). However, the dispersion of the fault-slip data deserves particular attention. This tectonic stress rotation could be due to local crustal structure, rheology and strength contrast as argued by Zoback et al. (1989) and Zoback (1992). Several examples of apparent rotation of S_{hmax} have been observed (e.g. Amazonas rift in Brasil) by Zoback (1992). Otherwise, Zoback et al. (1989) suggest that the continental margins strongly

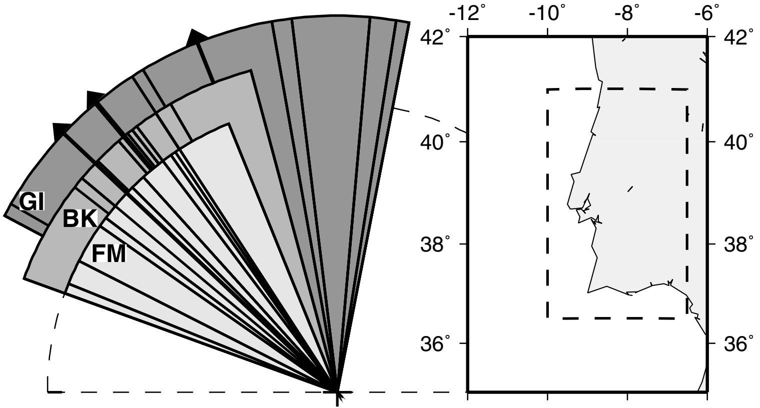

Fig. 9. Azimuth of S_{Hmax} for the three stress indicators in the geographic area limited by the dashed line. The arrows represent the mean azimuth of S_{Hmax} for Geological indicators (GI), Breakouts (BK) and Focal mechanisms (FM).

influence the tectonic stress orientation, and along the North American continental margin in particular. In our case, along the Portugal Atlantic margin as shown in Fig. 7, we do not have the same behaviour. The stress orientation NW–SE maintains itself excepts in two cases as follow: one fault-slip indicator located in the northwestern region of Portugal and, three others, in particular, located in the southwest near the continental margin indicating the N–S compression parallel to the continental shell. This singularity indicates a particular behaviour of the Portugal Atlantic margin.

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