PATTERN OF DEFORMATION ALONG THE AZORES - GIBRALTAR REGION

Anastasia A. Kiratzi and Constantinos B. Papazachos

Geophysical Laboratory, University of Thessaloniki, GR 540 06, Greece, Tel: +30 31 998486, Fax: +30 31 998528

ABSTRACT

The seismic moment tensor summation of recent shallow earthquakes, for the period 1939-1989, along the Azores - Gibraltar Ridge shows: 3 mm/yr of extension at N41°E along the Terceira Ridge and 5 mm/yr of compression at N139°E along the part of the boundary that extends east of Gibraltar. In the central part of the Azores-Gibraltar Ridge, that includes the Gloria Fault and extends up to the coastline of Iberia and Africa, the deformation is taken by E-W right lateral strike-slip motion at about 11 mm/yr. The results are in agreement with the expected motions from plate motion models. The rather fast strike-slip motion in the central part of the area, that includes the Gloria Fault, supports previous suggestions that this fault is an active transform fault.

INTRODUCTION

This study deals with the average deformation the seismicity of the last 100 years or so accounts for, for a part of the Africa-Eurasia plate boundary, that starts from the Azores triple junction at 30°W and extends up to the east of Gibraltar (9°E). Figure (1) summarizes the main features of the tectonics and of the bathymetry of the area studied (from Grimison and Chen, 1986). At the western part of the region, the Terceira Ridge joins the Mid-Atlantic Ridge in a ridge-ridge-ridge type triple junction between the North American, Eurasian and African plates. The eastern part of the Terceira Ridge terminates against the East Azores Fault zone near 24°W. Further to the east the plate boundary follows the Gloria Fault, which is considered part of the East Azores Fault zone, and at about 18°W, this fault zone diffuses into a region of complex bathymetry (Fig. 1). In this area the oceanic convergence becomes continental convergence as the plate boundary passes through the continental margins of the Iberia peninsula and Africa.

Previous attempts to study the tectonics and the deformation style of the region include the work of McKenzie (1972), Udias et al. (1976), Grimison and Chen (1986), Buforn et al. (1988), Jackson and McKenzie (1988), Westaway (1990), Udias and Buforn (1991). In the present paper, we estimate strain rates and relative velocities from the summation of the seismic moment tensors, which was not done before for the area west of Gibraltar.

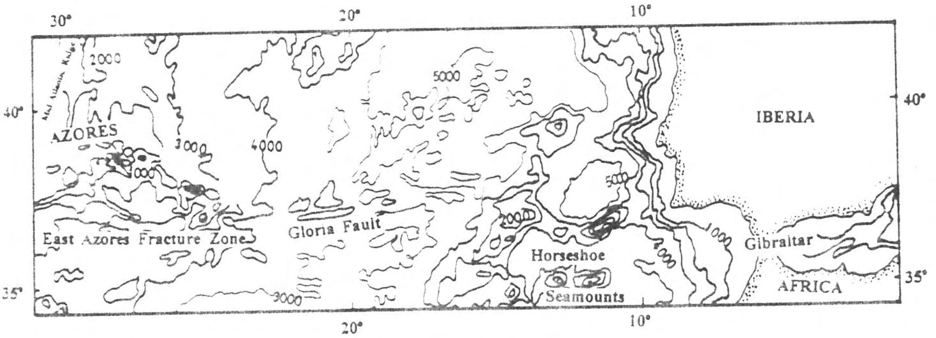

Fig.1 Bathymetric map, contour interval 1000m of the Azores-Gibraltar region with the important features marked. (from Grimison and Chen, 1986).

METHOD OF ANALYSIS AND DATA USED

The components of the strain rate tensor, ε_{ij}, and of the velocity tensor, V_{ij}, were calculated following the methodology described in Papazachos and Kiratzi, (1992); Papazachos et al., (1992), Kiratzi (1993). Folowing this approach the seismic moment rate M_o is calculated from Molnar (1979) which has the advantage that one can make full use of a complete record of seismicity spanning the present century as well as historical times. The main advantage of the method used here is the fact that one estimates the seismic moment rate from a complete record of seismicity that goes back in time at least 100 yrs. The catalogue of the fault plane solutions that is used to calculate the components of the tensor $\mathbf{F}_{ij}$, there is no need to be complete, but rather representative of the focal mechanisms of the events that occur in the area. As far as errors are concerned, in Papazachos and Kiratzi (1992) a most detailed error analysis was performed to estimate that a factor of 3 uncertainty is mapped in the strain rate results.

The data used in the present study are epicenters and magnitudes of shallow earthquakes for the period 1898-1991 collected from various sources that mainly include the ISC bulettins, the catalogue of Tsapanos et al., (1990) which is entirely based on international catalogues, Pacheco and Sykes (1992), as well as information on the historical seismicity collected from published papers (i.e Munoz and Udias, 1988; Udias and Buforn, 1991).

Figure (2) shows the distribution of the fault plane solutions along the Azores-Gibraltar Ridge, listed and referenced in Table I for each area separately. The parameters of these solutions have been all collected from published papers, especially from the work of Grimison and Chen (1986, 1988) that used inversion of body waves or the Harvard bulletins.

Figure (3) shows the distribution of the seismicity along the Azores - Gibraltar Ridge for the period 1898 - 1991. For this time period we have determined sub-periods that our data set was complete over a certain magnitude threshold, in the manner explained in Papazachos and Kiratzi (1992). This complete record of seismicity was used for each area to determine the parameters "a" and "b" of the Gutenberg-Richter relation. Only earthquakes with $M \geq 5.0$ were considered in the analysis. Some smaller events shown in figure (3) were only used to define the dimensions of the three areas examined, as these are outlined in the figure. The length, the width and the azimuth of each deforming volume were calculated from a least squares' fit to the epicentral data (Papazachos and Kiratzi, 1992).

Starting from the west, the first area extends along the Terceira Ridge from the Azores triple junction up to about 24°W. The second area, starts from the western end of the Gloria Fault and ends near the coast of Iberia at about 9°W, where the ocean-ocean convergence ends. The third area starts from the coastline of Iberia and Africa and ends at about 9°E, that is, it includes the continental segment of the plate boundary. This separation in three areas was based on the tectonic regime, the distribution of the seismicity and of the focal mechanisms as well as on the bathymetry.

Figure (4) shows the applied Gutenberg-Richter relation for each region and the values of a,b parameters are given in table I for each area. Figure (5) shows the moment-magnitude relation based on the available data (table I). Assuming that the slope of the line, c, (see eq. 3), equals 1.5 (Kanamori and Anderson, 1975) the value of constant d (eq. 3) was found equal to 16.35.

ESTIMATED SEISMIC STRAIN RATES

Table II lists the components of the strain rate and of the velocity tensors as well as the corresponding eigenvalues and eigenvectors for each deforming zone separately. The coordinate system 1:North, 2:East, 3:Down is used throughout this paper.

Azores

Eight fault plane solutions listed in table I, were used in the moment tensor summation. The focal mechanisms show predominantly normal faulting in planes that follow the trend of the Terceira Ridge. In some of the fault plane solutions, however, the strike-slip component is very strong (i.e. event of January 1, 1980). The maximum magnitude for this area was assumed to be 7.1 that is the magnitude of the mainshock of the May 8, 1939 sequence. The length and the width of the deforming volume were taken equal to 680 Km and 220 Km, respectively, while the azimuth of the deforming zone in respect to North was found equal to 120°. The thickness of the seismogenic layer, consisting of young oceanic crust, was assumed to be 15 km based on the depth estimates of the events studied by inversion techniques. The seismic moment rate determined from Molnar (1979) equals $0.24*10^{19}$ Nm/yr. The summed tensor, $\mathbf{F}_{ij}$, corresponds to a focal mechanism with strike 124°, dip 46°, rake -94° with the P axis with strike 291° and plunge 87° and the T axis with strike 37° and plunge 1°. As seen from table II the largest component of the strain rate tensor is ε_{33} which indicates crustal thinning (it has a negative sign) over a 15 km thick volume, at $1.0*10^{-8}$ /yr. The dominant mode of deformation is extension at N41°E at 2.8 mm/yr. One should also note the

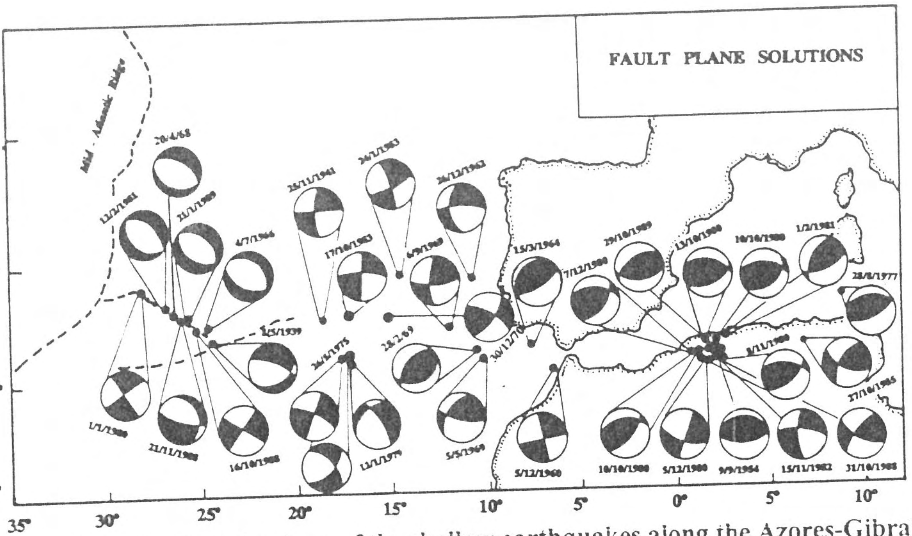

Fig.2 Distribution of the focal mechanisms of the shallow earthquakes along the Azores-Gibraltar Ridge.

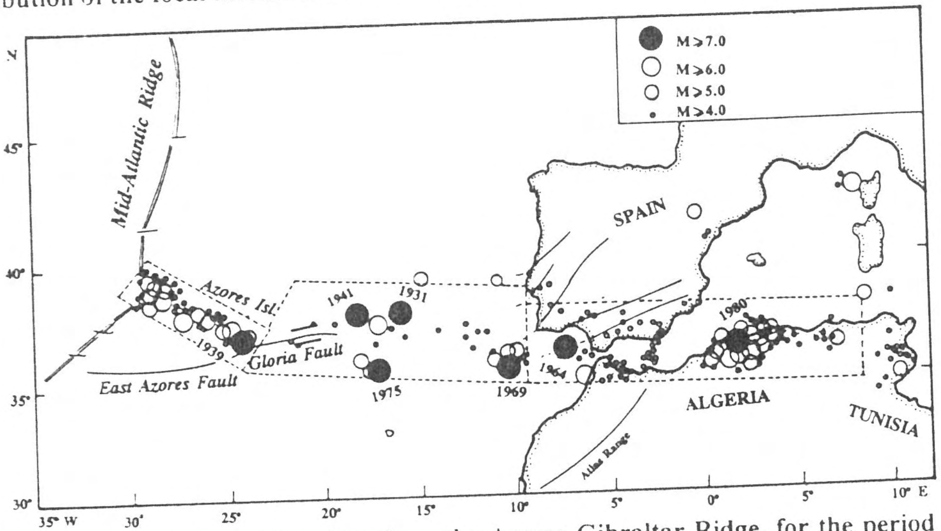

Fig.3 Distribution of shallow earthquakes along the Azores-Gibraltar Ridge, for the period 1898-1991. Th
three regions studied are also shown.

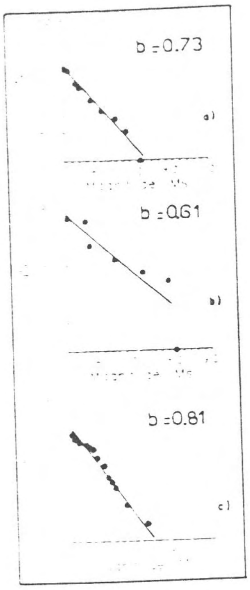

Fig.4 The Gutenberg-Richter relation for each of the three regions studied. afor Azores, b for the central part, 24°W-9°W and c for the eastern part, Gibraltar to 9°E.

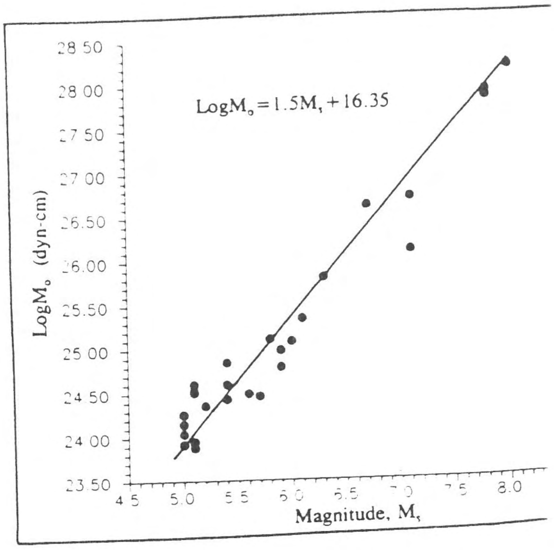

Fig.5 The moment-magnitude relation applic to the area. The seismic moments and magnitudes are listed in table I.

existence of a component of compression at N131°E occuring at 1 mm/yr. This geometry of the deformation results to left lateral shear at a rate of less than 1 mm/yr.

Central part (Gloria Fault to 9°W)

Eleven fault plane solutions were used in the calculations listed in table I. The event of Febr. 28, 1969 was modeled by Grimison and Chen (1986) with two sources with different fault plane solutions. We included in the calculations the focal mechanisms of each sub-event as an independent solution.

The Gloria Fault itself has very low seismicity and in fact has not been reported as the site of any major earthquake since at least 1400 A.D. (Udias et al., 1976; Buforn et al., 1988; Munoz and Udias, 1988). East of the Gloria Fault, up to about 9°W, the focal mechanisms indicate strike-slip motion in nearly E-W trending planes with the possible exception of the large event (Ms 7.8) in May 26, 1975. The maximum magnitude was assummed 8.0, that is, the magnitude assigned to the great November 25, 1941 event (Pacheco and Sykes, 1992). Actually, this is the largest event of the whole Azores-Gibraltar Ridge for this century. The Portugal earthquake of February 28, 1969 is the largest to occur in the area since the installation of the WWSSN network and occurred very close to the hypothetical epicenter of the great Lisbon earthquake of 1755 (as referenced in Buforn et al. 1988 from a Spanish publication).

Table I

Information on the focal parameters of the earthquakes used in the analysis, listed for each area separately.

AZORES

(Parameters of the Gutenberg-Richter relation: a, for 1 yr=3.28, b-value=0.73).

Date	h:m	ϕ°N	λ°E	h(Km)	M_s	M_o(Nt.m)	str	dip	rake	Ref
8/ 5/1939	01:46	37.00	-24.50	-	7.1	-	41	35	-154	3
4/ 7/1966	12:15	37.50	-24.70	10.0	5.4	$4.0*10^{17}$	126	56	-90	4
20/ 4/1968	10:18	38.30	-26.77	15.0	5.1	$4.0*10^{17}$	302	54	-90	4
1/ 1/1980	16:42	38.82	-27.78	12.0	6.7	$4.2*10^{19}$	330	82	5	5
12/ 2/1981	01:50	38.47	-26.75	10.0	5.1	$3.2*10^{17}$	141	42	-80	8
16/10/1988	06:15	37.46	-25.33	10.0	5.1	$8.9*10^{16}$	33	90	0	8
21/11/1988	16:55	37.93	-26.14	11.0	5.4	$7.1*10^{17}$	109	73	-114	8
21/ 1/1989	02:52	38.09	-26.18	10.0	5.1	$3.4*10^{17}$	131	41	-87	8

CENTRAL PART

(Parameters of the Gutenberg-Richter relation: a, for 1 yr=2.60, b-value=0.61)

Date	h:m	ϕ°N	λ°E	h(Km)	M_s	M_o(Nt.m)	str	dip	rake	Ref
25/11/1941	18:03	37.50	-18.50	-	$8.0^{(7)}$	$15.7*10^{-20(1)}$	177	79	-6	3
26/12/1962	08:58	39.30	-10.60	15.0	5.7	-	180	47	-3	3
28/2/1969	02:40	36.01	-10.57	29.0	$7.8^{(7)}$	$8.4*10^{20}$				5
1st source				32.0		$3.0*10^{20}$	70	44	113	5
2nd source				22.0		$4.5*10^{20}$	14	82	-12	5
5/5/1969	05:34	36.00	-10.40	50.0	5.5	-	108	80	130	4
6/9/1969	14:30	36.94	-11.89	41.0	6.0	$1.2*10^{18}$	86	86	160	4
30/12/1970	20:57	37.22	-14.93	25.0	5.0	-	40	70	25	4
26/5/1975	09:11	35.98	-17.56	25.0	$7.8^{(7)}$	$7.0*10^{20(2)}$	290	68	180	4
26/5/1975	20:19	36.04	-17.56	35.0	5.5	-	58	64	-148	4
12/1/1979	14:49	35.55	-17.19	5.0	5.0	$1.4*10^{17}$	330	74	-123	8
24/1/1983	16:34	39.48	-14.44	34.0	5.8	$1.3*10^{18}$	342	80	-6	5
17/10/1983	19:36	37.59	-17.41	14.0	6.3	$6.5*10^{18}$	272	80	180	5

EASTERN PART

(Parameters of the Gutenberg-Richter relation: a, for 1 yr=4.04, b-value=0.81).

Date	h:m	ϕ°N	λ°E	h(km)	M_s	M_o(Nt.m)	str	dip	rake	Ref
9/ 9/1954	01:04	36.20	1.60	-	6.5	-	254	30	90	6
5/12/1960	21:21	35.60	-6.50	15.0	6.2	-	73	86	-178	3
15/3/1964	22:30	36.20	-7.60		$7.1^{(7}$	$0.13*10^{20}$				3
1st source				14.0		$8.6*10^{18}$	50	64	74	4
2nd "				20.0		$7.0*10^{18}$	23	64	122	4
28/8/1977	09:45	38.24	8.19	15.0	5.0	$1.8*10^{17}$	62	62	82	8

10/10/1980	12:25	36.16	1.40	10.1	7.1(7)	$5.1*10^{19}$	53	51	90	8
10/10/1980	15:39	36.25	1.61	10.0	6.1	$2.2*10^{18}$	58	43	81	8
13/10/1980	06:37	36.31	1.59	2.0	5.2	$2.3*10^{17}$	63	42	69	8
8/11/1980	07:54	36.12	1.38	4.0	5.1	$7.6*10^{16}$	44	55	59	8
5/12/1980	13:32	35.87	1.68	15.0	5.0	$1.1*10^{17}$	21	89	-29	8
7/12/1980	17:37	36.06	1.30	25.8	5.7	$2.9*10^{17}$	39	66	57	8
1/2/1981	13:19	36.43	1.68	10.0	5.4	$2.7*10^{17}$	64	52	112	8
15/11/1982	20:07	35.60	1.34	10.0	5.0	$8.3*10^{16}$	274	70	-169	8
27/10/1985	19:35	36.43	6.78	10.0	5.9	$6.2*10^{17}$	117	71	160	8
31/10/1988	10:13	36.40	2.68	10.0	5.6	$3.1*10^{17}$	103	55	167	8
29/10/1989	19:09	36.78	2.44	6.0	5.9	$9.6*10^{17}$	91	48	119	8

Key to the references

1 Brune and King, 1967, 2 Lynnes and Ruff, 1985, 3 Buforn et al., 1988, 4 Grimison and Chen, 1986, 5 Grimis and Chen, 1988, 6 Udias and Buforn, 1991, 7 Pacheco and Sykes, 1992, 8 CMT Harvard determination.

The length and the width of the deforming volume are 1200 Km and 300 Km, respectively and the azimuth this zone is 93°. The depths of the events of these area indicate that some occurred beneath the very old Atlan ocean floor with focal depths as large as 40 to 50 km. For this part only the thickness of the seismogenic layer w assumed to be 30 km, based on the depth estimates of the largest and best studied events of the area, and on fig. of Grimison and Chen (1986), who plotted the focal depth versus age of the oceanic lithosphere.

The seismic moment rate is $0.20*10^{20}$ Nm/yr, which is the highest for the three areas of the Azores-Gibralt Ridge. The summed moment tensor, $\mathbf{F}_{ij}$, corresponds to a focal mechanism with strike 96°, dip 88° and rake 162 the P axis with strike 143° and plunge 8° and the T axis with strike 50° and plunge 16°.

As it is seen, from the results of table II the dominant mode of deformation is a right lateral shear of abou $2*10^{-8}$/yr corresponding to about 11 mm/yr of right lateral displacement across the region.

Straits of Gibraltar to 9°E

Fifteen focal mechanisms listed in table I were used in the calculations. For the event of March 1964 the foc mechanisms of the two sources were used in the moment tensor summation. The focal mechanisms indicate thru faulting, sometimes with strong strike-slip component, and with the P axes oriented in a NNW-SSE direction. Tl maximum magnitude was assumed to be 7.1 (Algeria event of October 10, 1980). The length and the width of tl deforming volume are taken 1500 Km and 300 Km, respectively, and the azimuth 93°. The thickness of tl seismogenic layer was taken equal to 15 km. The seismic moment rate is $0.42*10^{19}$ Nm/yr. The summed tensor, F corresponds to a focal mechanism with strike 239°, dip 40°, rake 88°, with the P axis with strike 150° and plunge and the T axis with strike 341° and plunge 84°. The results of table II indicate that the deformation is main expressed by compression at N139°E at 4.5 mm/yr. The small component of extension observed (1.4 mm/yr N49°E) is the result of the strike-slip component in some events. This geometry of the deformation causes dextr shear motion at 2.9 mm/yr.

Table II

Components of the strain rate tensor, ε_{ij},(in 10^{-8}/yr) and of the velocity tensor, v_{ij},, in mm/yr for the Azores-Gibraltar Ridge.

AZORES

Strain rates, $*10^{-8}$/yr	ε_{11}	ε_{12}	ε_{13}	ε_{22}	ε_{23}	ε_{33}
	0.73	0.66	0.00	0.34	0.05	-1.07
Velocity, mm/yr	v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}
	1.13	1.90	-0.00	0.59	0.02	-0.16

Eigenvalues of the velocity tensor:	**λ_i mm/yr**	**Azimuth°**	**Plunge°***
	2.78	41	0
	-1.06	131	-1
	-0.16	145	89

CENTRAL PART, GLORIA FAULT TO 9°W

Strain rates, $*10^{-8}$/yr	ε_{11}	ε_{12}	ε_{13}	ε_{22}	ε_{23}	ε_{33}
	-0.49	1.85	0.54	0.37	0.23	0.12
Velocity , mm/yr	v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}

-0.20	11.10	0.32	3.26	0.14	0.03

Eigenvalues of the velocity tensor: λ_i mm/yr	Azimuth°	Plunge°
-10.81	142	1
12.03	52	2
0.03	83	-88

EASTERN PART, STRAITS OF GIBRALTAR TO 9°E

Strain rates, $*10^{-5}$/yr	ε_{11}	ε_{12}	ε_{13}	ε_{22}	ε_{23}	ε_{33}
	-0.58	0.47	0.14	-0.05	-0.07	0.63
Velocity, mm/yr	v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}
	-1.89	2.92	0.04	-1.17	-0.02	0.09

Eigenvalues of the velocity tensor: λ_i mm/yr	Azimuth°	Plunge°
-4.48	139	1
1.42	49	1
0.09	97	-89

* *Extension has a positive sign, while compression has a negative one, positive or negative plunge indicates that the eigenvector points to the solid earth or above it, respectively.*

CONCLUSIONS AND DISCUSSION

Figure (5) is a sketch map to summarise the results. Along the Azores the deformation is expressed as extension at N41°E at a low rate of about 3 mm/yr. This is in fairly good agreement with Chase (1978), Minster and Jordan (1978), Searle (1980), DeMets et al., (1990) and Westaway (1990), whose models predict rates that range from 2.9 to 4.9 mm/yr with a spreading direction that range from N59°E to N63°E. The deformation in the central part of the Azores - Gibraltar Ridge, that also includes the Gloria Fault, is expressed by nearly E-W right lateral strike-slip motion, at a rate of 11 mm/yr. This sense of motion is consistent with the relative horizontal motion of Eurasia

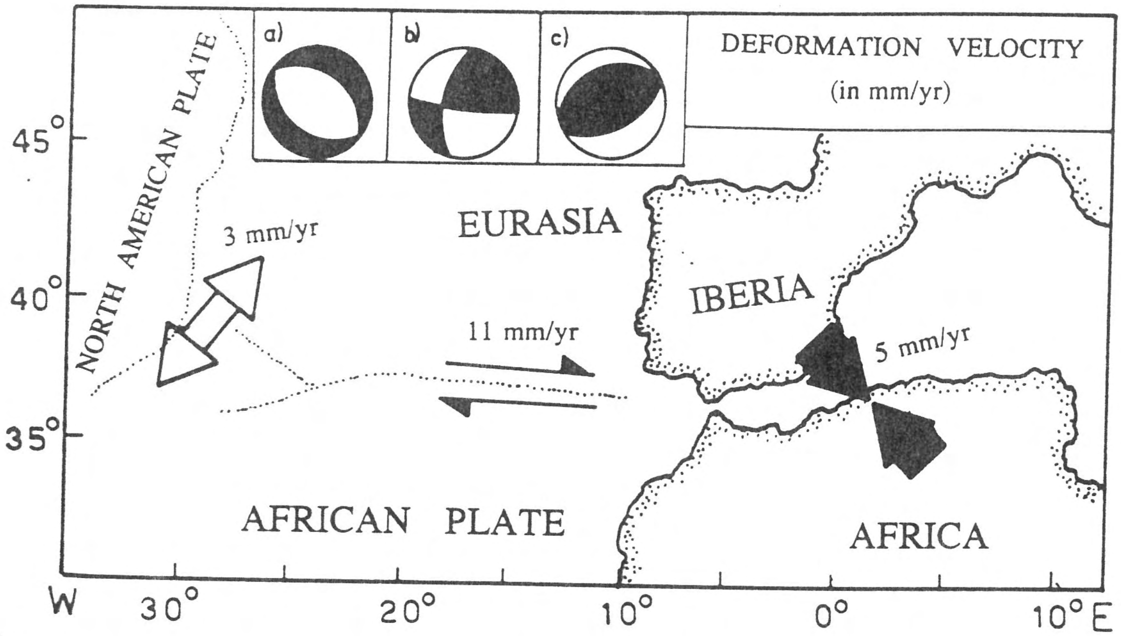

Fig.6 Schematic representation of the average velocity field along the Azores-Gibraltar Ridge, derived from the seismicity of the last 100 years or so. Converging arrows denote copression while diverging ones denote extension. The three focal mechanisms shown in the inset correspond to the equivalent double couple obtained from the summed moment tensor, F_{ij}, for each region, from west to the east.

towards east with respect to Africa. This strike-slip motion, of about 1 cm/yr, compared to the slow deformation (of a few mmm/yr) in the areas to the west and to the east, supports previous suggestions that the Gloria Fault should be considered as an active transform fault (Argus et al., 1989, Udias and Buforn, 1991). Actually, the tectonics resemble the picture we have in the Northern Aegean trough where the strike-slip motion of the North Anatolian Fault and the nearly N-S extension of the thin Aegean crust results in a mixture of normal and strike-slip faulting (Kiratzi 1991, 1993; Papazachos et al., 1991, 1992). Indeed, this is what we get along the Terceira Ridge, where the NNE-SSW spreading of the Ridge and the strike-slip motion from the Gloria Fault and the surrounding area, results in normal and strike-slip faulting in the area. Buforn et al., (1988) calculate that the slip rate of Eurasia-Africa at the area that extends from Gloria fault to about 13°W reaches 33.9 mm/yr. Further east, as we pass the Straits of Gibraltar up to Algeria the deformation is mainly expressed by compression at N139°E at 5 mm/yr. Our results are in good agreement with what is expected from plate motion models. NUVEL-1 Africa-Eurasia Euler vector (DeMets et al., 1990) predicts 6±1 mm/yr at N29±8°W convergence at Algeria (at 35°N, 2°E), slightly faster than the 4 mm/yr predicted by RM2 (Minster and Jordan, 1978).

At last, we would like to say that the main difficulty in studing the deformation along the Azores-Gibraltar ridge is the large repeat time of major events and the answer to the question whether the results reflect the deformation of longer periods of time or not. Unfortunately, we cannot answer this question and the present paper was an attempt to study the style of the deformation using the presently available data.

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