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Geodynamic models for the Azores triple junction: a contribution from tectonics

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ABSTRACT

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The American, Eurasian and African lithospheric plates meet at the Azores triple junction. The nature of the northern and southern branches of the junction is well known and uncontroversial, the American plate is separated from Eurasia and Africa by the Mid-Atlantic Ridge (MAR). The western group of islands of the Azores archipelago (Flores and Corvo) lies on the American plate, just west of the rift, and their tectonic features agree with that location.

The nature of the third branch of the junction, to the east of the MAR, is however still controversial. Some authors believe that a ridge–ridge–ridge junction occurs in the Azores area and adopt the structure known as the “Terceira Ridge” (working as a simple rift boundary) as the third branch.

Another model proposes a triangular microplate in the Azores region bounded by the Mid-Atlantic Rift to the west, the East Azores Fault Zone to the south and a fault crossing S. Miguel and the Terceira islands to the northeast; in this model the fault zones are pure dextral strike-slip boundaries.

Both models would create space problems at Gloria Fault, a well-known pure dextral strike-slip structure. In the first model transtension would be necessary at Gloria Fault to accommodate plate motion, while the second would require a transpressive regime on that structure.

Neotectonic and seismotectonic data in the Azores indicate a transtensive regime in the central and eastern island groups in present and recent times. This is compatible with a “leaky transform” structure acting as the third branch of the junction in the Azores area, a model which has already been presented by several authors in the past. Stress trajectories deduced from neotectonic studies in some of the islands suggest that the main plate boundary passes between the islands of S. Jorge and Pico south of S. Miguel and joins Gloria Fault east of Santa Maria. This model and boundary location is also compatible with seismotectonic and magnetic data.

Introduction

Tectonic setting of the Azores archipelago

The American, Eurasian and African lithospheric plates meet in the North Atlantic at about 39°N, 30°W. The Azores archipelago is the result of the volcanic activity associated with the triple junction and comprises nine islands, the Formigas islets and some almost emergent submarine

volcanoes. The islands are aligned along a WNW–ESE direction, crossing the Mid-Atlantic Ridge obliquely. The western group of islands (Flores and Corvo) lies on the American plate, on the western flank of the ridge, while the islands of the central (Terceira, Graciosa, S. Jorge, Pico and Faial) and eastern (S. Miguel, Santa Maria and Formigas) groups link the ridge to the Gloria Fault at 37°N, 24°W (Fig. 1).

The Mid-Atlantic Ridge trends N10E north of the junction and has a mean NE–SW direction

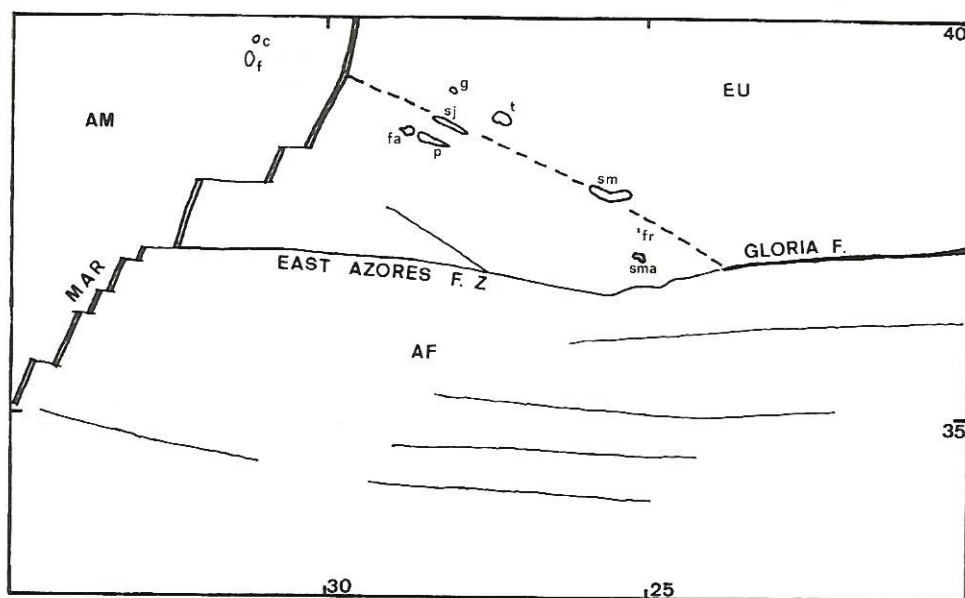


Fig. 1. Tectonic setting of the Azores (simplified from Laughton and Whitmarsh, 1974). *AM* = American plate; *EU* = Eurasian plate; *AF* = African plate; double line = Mid Atlantic Rift (*MAR*); dashed line = oblique structure of the Azores; heavy solid line = Gloria Fault zone; light solid lines = inactive East Azores Fault Zone and transform faults; *c* = Corvo; *f* = Flores; *g* = Graciosa; *t* = Terceira; *sj* = S. Jorge; *fa* = Faial; *p* = Pico; *sm* = S. Miguel; *fr* = Formigas; *sma* = Santa Maria.

south of that point as a result of a great density of transform faults cutting the ridge into small right-stepping segments. The nature of the third branch, linking the ridge to Gloria Fault, is still controver-

sial (Krause and Watkins, 1970; McKenzie, 1972; Laughton and Whitmarsh, 1974; Bonnin, 1977; Searle, 1980; Olivet et al., 1984).

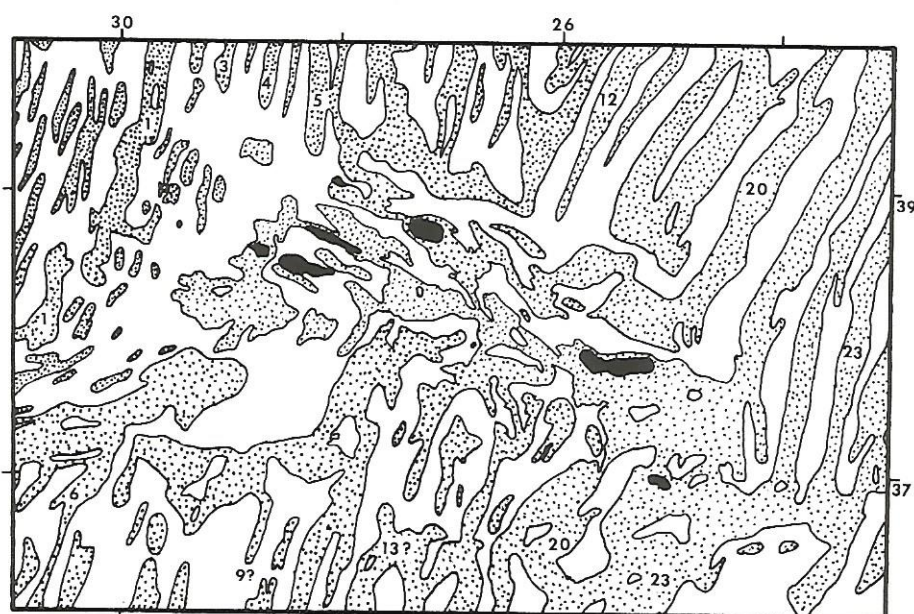


Fig. 2. Magnetic anomalies in the Azores area. Positive anomalies are stippled; numbers are anomaly identifications (from Searle, 1980).

Magnetic anomalies in the Azores

The magnetic anomalies in the Azores have a complex pattern (Fig. 2). Although well-defined anomalies parallel to the ridge are present there is a rhomboidal area in which the magnetic lineations are less clear and in which the WNW–ESE Azores trend is evident (Searle, 1980). The complexity of the lineations within the rhomboidal area may be the result of very young intrusions (along WNW–ESE fractures) in older crust, with the superposition of magnetic trends.

Seismicity in the Azores area

The frequency of seismic activity is high in the Azores area. Focal mechanism solutions (Fig. 3) from medium- to high-magnitude ($M = 4.8$ – 8.4) earthquakes show strike-slip solutions on transform faults and, on the Mid-Atlantic Ridge, some events with a normal faulting component. On the third branch of the junction, strike-slip solutions are dominant, but normal and reverse faulting mechanisms are also present (Udias, 1980; Udias et al., 1986; Bufo et al., 1988). On Gloria Fault, two events (18 and 19) have pure dextral strike-slip solutions on an E–W structure. Solution 21 has no

E–W nodal plane but it may be explained by a NNW–SSE left-lateral structure, conjugate with Gloria Fault. Event 20 is not on Gloria Fault.

Estimations based on historical records indicate that at least three earthquakes reached an intensity of XI (Modified Mercalli Scale): May 4, 1614 on Terceira, July 9, 1757 on S. Jorge and June 13, 1758 on Graciosa. Machado (1949) estimated a magnitude of 7.4 for the 1757 earthquake, which caused 1000 deaths among a population of 5000.

Recorded volcanic eruptions

Volcanic activity has been reported in the Azores since the discovery of the islands in the 15th century. From 1439 to present times, 33 events have been recorded (Fig. 4) (Zbyszewski, 1963; Weston, 1963/1964; Zbyszewski, 1976; Forjaz, 1988), but many submarine eruptions must have also occurred without being detected.

Isotopic age determinations

Some isotopic age determinations on volcanic rocks from the Azores are available (Fig. 5) (Abdel-Monem et al., 1968, 1975; Féraud et al., 1980, 1984; Azevedo et al., 1986; Forjaz, 1988).

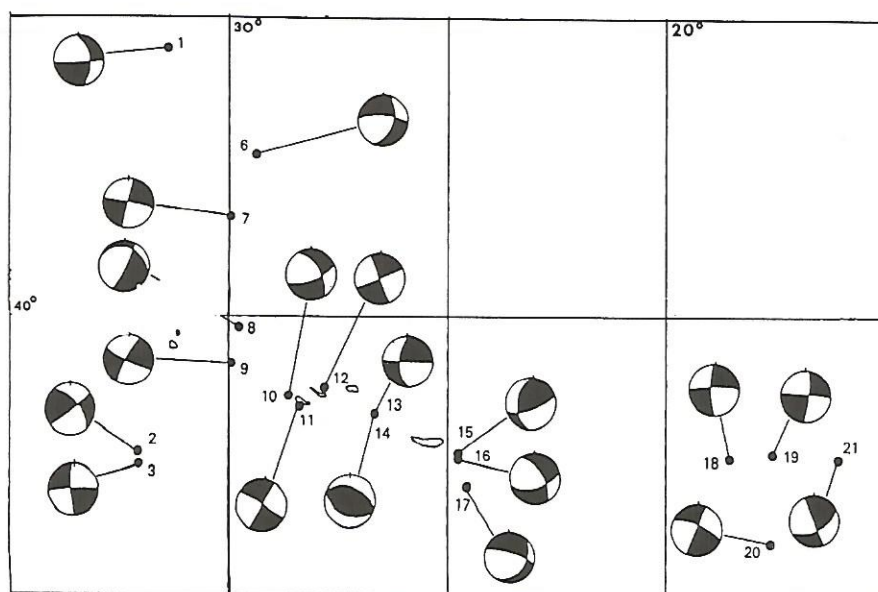


Fig. 3. Focal mechanism solutions for nineteen earthquakes at the Azores triple junction (simplified from Udias et al., 1986). Event 12 is the Jan 1, 1980 earthquake.

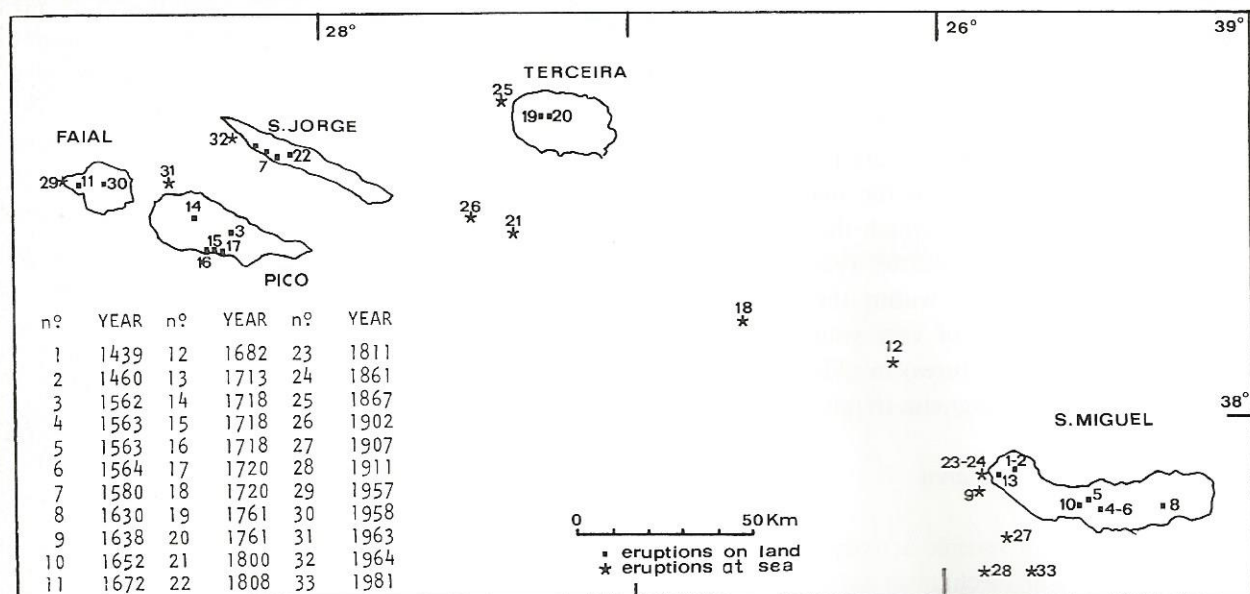


Fig. 4. Recorded volcanic eruptions in the Azores (modified from Weston, 1963/1964).

The oldest ages yielded by the samples indicate emergence of Santa Maria during the Miocene and of S. Miguel and Formigas in the Pliocene, while all the other islands must have emerged during Quaternary times. A careful analysis of isotopic age determinations on Santa Maria (Serralheiro and Madeira, in prep.) has shown that in

many cases samples may not have been collected in the oldest formations or may have been assigned to incorrect units, so higher age values may yet be found. This age distribution is probably unrelated to the distance to the Mid-Atlantic Ridge because the islands of the central and eastern groups are clearly related to the eastern branch of

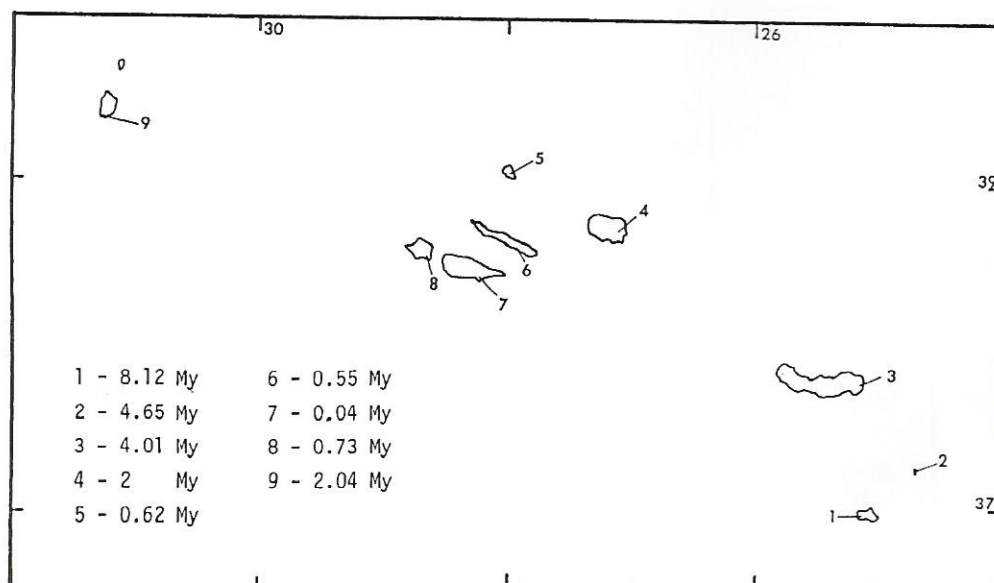


Fig. 5. Highest K-Ar ages determined from rocks from the Azores (data collected from Abdel-Monem et al., 1968, 1975; Féraud et al., 1980, 1984; Azevedo et al., 1986; Forjaz, 1988).

the triple junction. This may simply mean that the oblique structure has nucleated from Gloria Fault in the east-southeast and grew towards the west-northwest.

Geodynamic models for the Azores triple junction

Terceira Ridge model (Fig. 6)

Some authors consider a model in which the eastern branch of the junction is a normal rift boundary with a pure tensional regime (Udías, 1980; Udías et al., 1986; Bufo et al., 1988). In this model, focal mechanism solutions in the eastern branch should indicate normal faulting on planes striking N60W (the direction of the Terceira Ridge), or strike-slip faulting on transforms with a N30E trend; faults with the mentioned directions and movements have not been observed in the islands adjacent to this boundary.

Seafloor spreading in the Mid-Atlantic Rift and in the Terceira Rift would result in a northeastward motion of Eurasia with respect to Africa, inducing a transtensive regime on Gloria Fault.

In a RRR junction there would be no reason for the WNW-ESE trending magnetic anomalies to be less clear than those generated in the Mid-Atlantic Rift.

In short, this model is not in agreement with the neotectonic, seismotectonic and palaeomagnetic data.

Azores microplate model (Fig. 7)

Another model (Forjaz, 1988) proposes a triangular microplate in the Azores area bounded by the Mid-Atlantic Rift to the west, the East Azores Fault Zone to the south, and a fault or set of faults passing through S. Miguel and Terceira to the northeast. The last two boundaries, acting as pure dextral strike-slip faults, would create space problems at the eastern corner of the microplate, inducing a transpressive regime (oblique compression) at Gloria Fault. Furthermore, this model would require oblique spreading in the Mid-Atlantic Rift north of the triple junction, and would not explain the irregular but strong WNW-ESE magnetic lineations. We believe that a micro-

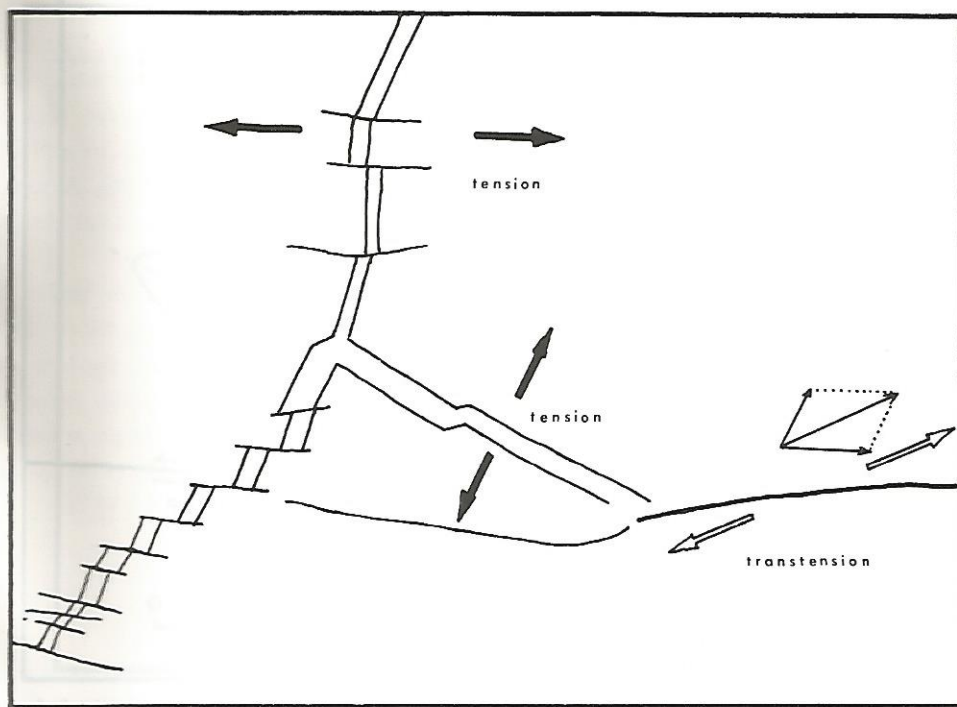


Fig. 6. Terceira Ridge model (modified from Bufo et al., 1988).

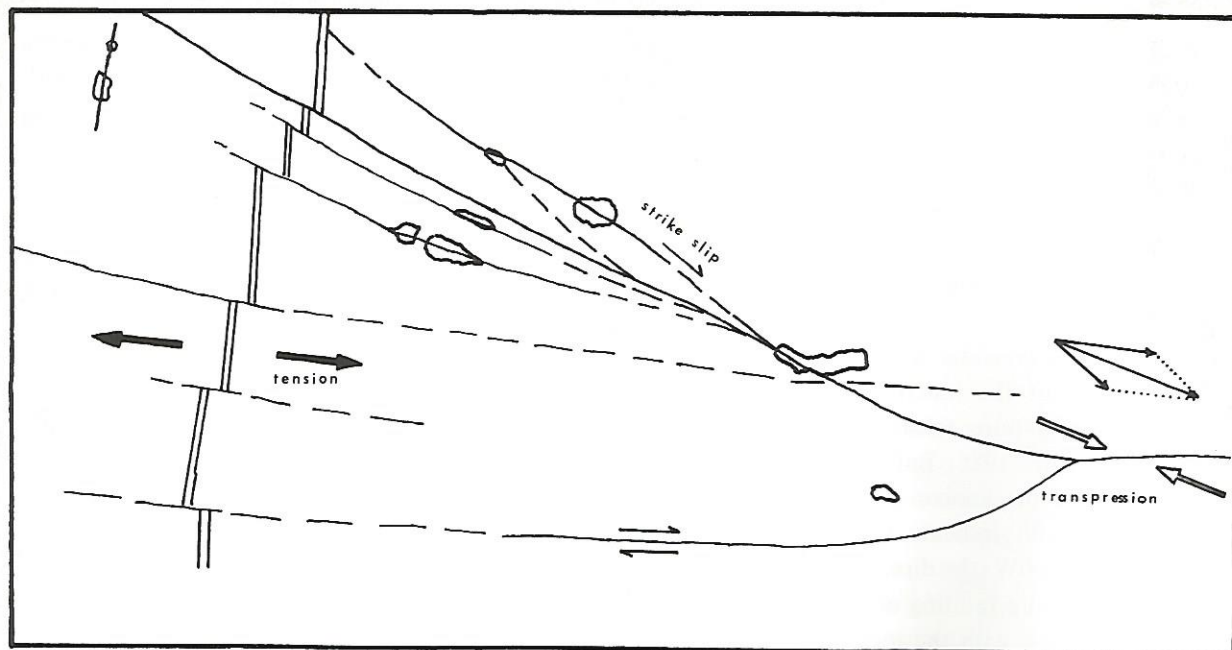


Fig. 7. Azores microplate model (after Forjaz, 1988).

plate existed in the area for a short period during the boundary jump from the East Azores Fault Zone, west of Santa Maria, to the oblique structure, when both fault zones should have been active.

The "leaky transform" model (Fig. 8)

In this model, which has been proposed by several authors (McKenzie, 1972; Laughton and Whitmarsh, 1974; Searle, 1980; Ribeiro, 1982), the

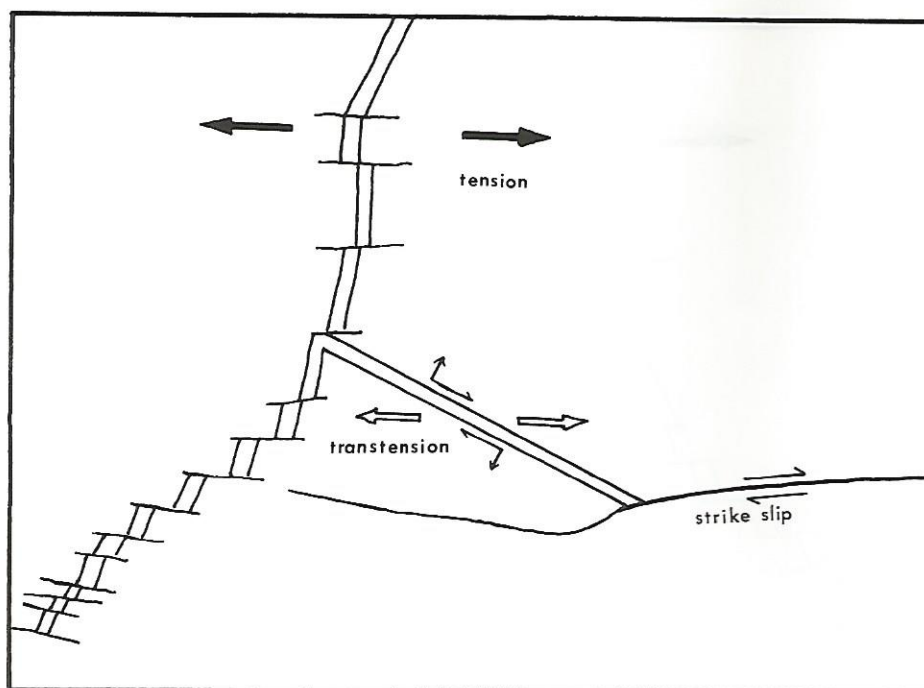


Fig. 8. Leaky transform model: Seafloor spreading in the Mid-Atlantic Ridge induces transtension in the leaky transform and strike-slip on Gloria Fault.

eastern branch of the junction is a WNW–ESE oblique transcurrent fault zone linking the Mid-Atlantic Rift to the E–W Gloria Fault. East–west spreading in the Mid-Atlantic Rift induces trans-tension in the oblique structure (leaky transform) and this movement is transferred to Gloria Fault as pure dextral strike-slip. The geometry and kinematics in this model create no space problems, agree with the plate motions and are supported by neotectonic, seismotectonic and palaeomagnetic data.

Neotectonic and seismotectonic evidence of trans-tension

In all the islands of the central and eastern groups a strong tensile component is evident (volcanic activity and important normal separation on faults); strike-slip is, however, also present, as shown by neotectonic and seismotectonic evidence.

The island of Faial (Fig. 9)

The fault geometry on Faial indicates a dextral transtensive regime. In the western part of the island a chain of very recent volcanic cones indicates the presence of a set of en échelon Riedel shears. In the central and eastern parts of the island, the main faults, which strike N60W, show push-up structures associated with restraining bends. On the sea cliffs, secondary fault planes associated with one of the main faults bear slickensides indicating pure strike-slip as well as pure normal slip; this is probably the result of decoupling of movement in the upper levels of the faults. A small earthquake on the northernmost fault has opened cracks on a bridge, these cracks showing normal dextral slip.

The island of S. Jorge (Fig. 10)

The most striking feature of S. Jorge is its shape: the island is 60 km long but only 7 km

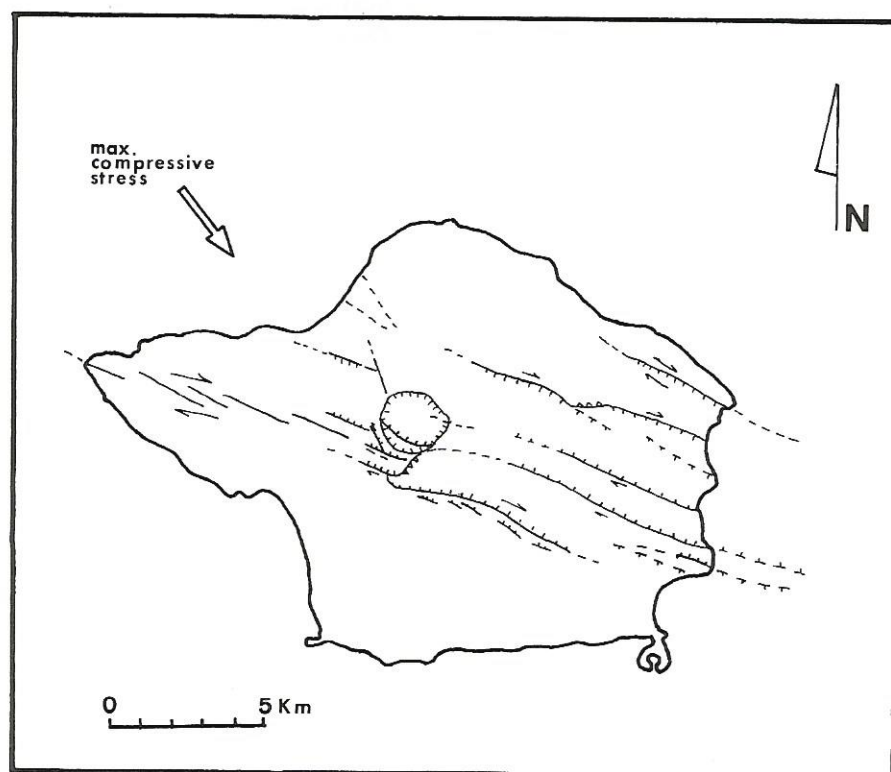


Fig. 9. Main tectonic structures on Faial: Most faults are dextral normal faults (dextral reverse on restraining segments); NNW–SSE structures are sinistral faults; circular structure is a caldera. Maximum compressive stress deduced from active faults is NW–SE.

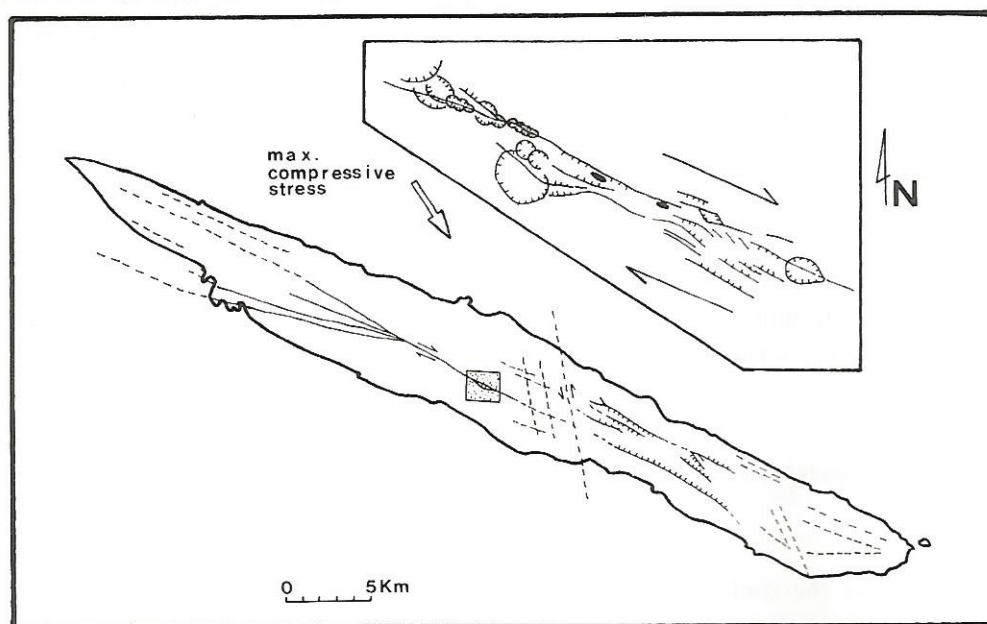


Fig. 10. Main tectonic features on S. Jorge: WNW-ESE structures are dextral normal faults (dotted where recent activity is not evident); sinistral faults are NNW-SSE and less prominent). Inset is a magnification of the stippled box and shows the typical geometry of the main fault zone (circular structures are volcanic craters and dark areas are sag ponds). Maximum compressive stress deduced from active faults is NW-SE.

wide, and reaches an altitude of 1000 m. This shape is the result of fissure volcanism on a set of faults with a mean WNW-ESE trend. Its geometry at the surface is typical of strike-slip faults: dextral en échelon Riedel shears, anastomosing segments, sag ponds and even a very small pull-

apart basin. Some fault segments show important vertical separation.

The earthquake of January 1st, 1980, which had an estimated average magnitude of 7, occurred on a fault located between the islands of S. Jorge, Graciosa and Terceira (Fig. 11). The focal mechanism solution and the epicentral location of aftershocks indicated left-lateral slip on a fault striking NNW-SSE, changing to a N-S direction to the north (Hirn et al., 1980). A small tsunami was also recorded, indicating a vertical component of movement.

Although as a result of its higher density of population Terceira suffered more damage than the other islands, a surface rupture on a small fault of the same family was observed at the southeastern point of S. Jorge, where the earthquake was felt with an intensity of IX-X, confirming left-lateral slip (Ribeiro, 1982).

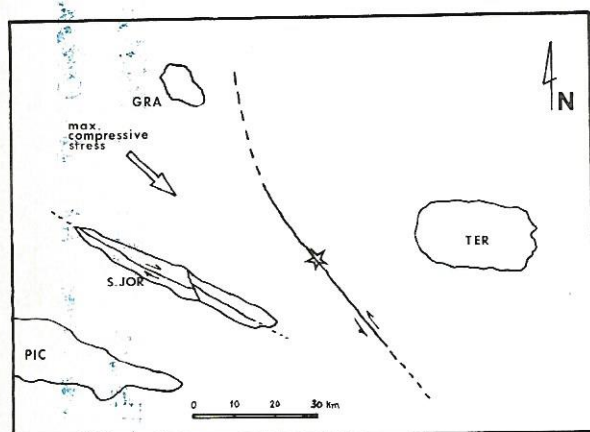


Fig. 11. Location of the fault responsible for the Jan 1, 1980 earthquake (inferred from distribution of aftershocks (star indicates main shock)). Aftershocks indicate rotation of fault to a more N-S direction to the north, so maximum compressive stress must rotate accordingly (modified from Hirn et al., 1980). In S. Jorge surface rupture occurred on a small-scale fault in the east-southeastern extremity of the island.

The island of Santa Maria

On Santa Maria neotectonic activity is represented by NNW-SSE dextral strike-slip faults and N-S normal faults (Fig. 12) (Madeira, 1986). These

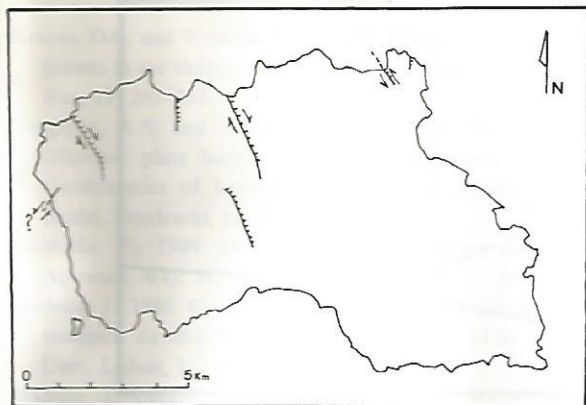


Fig. 12. Active faults on Santa Maria: Mainly NNW-SSE dextral normal faults with N-S normal terminations. These faults displace Quaternary wave-cut platforms in the western half of the island. Maximum compressive stress indicated by active faulting is N-S.

faults displace extensive wave cut platforms of Quaternary age. A probable left lateral fault strikes NNE-SSW but does not affect the abrasion platform. Active faulting together with the younger dyke swarm indicates a horizontal N-S compression and an E-W tension in Santa Maria area.

Discussion

We favour the leaky transform model because it is the only one that fits the magnetic, seismotectonic and neotectonic evidence.

The magnetic lineations parallel to the trend of the Azores may result from young intrusions in the older crust along fractures parallel to the oblique boundary, as has already been suggested by Searle (1980). In this case a rift may not be contemplated.

The fault geometry and kinematics on the islands indicate a transtensive regime, as would be expected in a fault zone oblique to the rift.

Irregularities in fault direction account for all types of focal mechanism solutions: dextral or sinistral strike-slip events on conjugate second-order faults, normal faulting on releasing bends, and reverse faulting on restraining bends.

Thus, we believe that the tensile regime near the Mid-Atlantic Ridge is disturbed by the dextral WNW-ESE leaky transform (Fig. 13). Permutations of stress axes occur, allowing a change to a transtensive regime, with maximum compressive

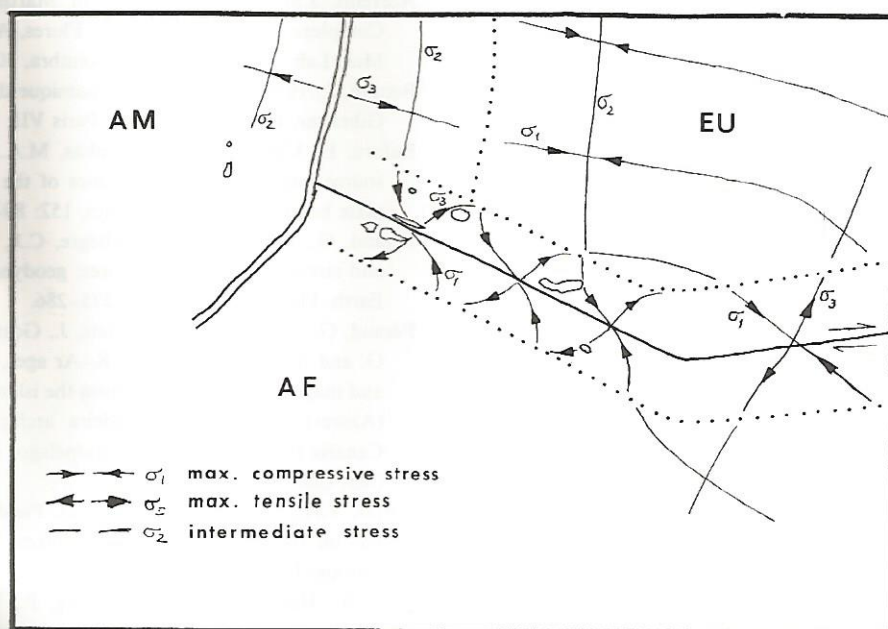


Fig. 13. Hypothetical stress trajectories in the Azores region as deduced from active faults (modified from Madeira et al., 1988). Dotted lines separate areas with different stress regimes.

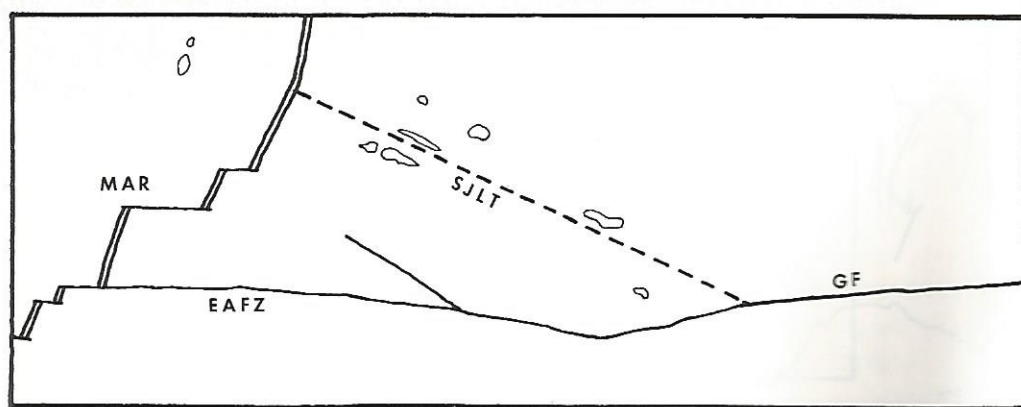


Fig. 14. Proposed location of S. Jorge Leaky Transform. MAR = Mid-Atlantic Rift; SJLT = S. Jorge Leaky Transform; EAFZ = East Azores Fault Zone; GF = Gloria Fault.

stress σ_1 horizontally rotating from a N–S direction away from the boundary to NW–SE near the boundary; σ_3 , the maximum tensional stress, is also horizontal.

In response to stress deviation, conjugate sets of second-order faults develop, with dextral faults changing from NNW–SSE to WNW–ESE and sinistral faults rotating from NNE–SSW to NNW–SSE as the leaky transform boundary is approached.

In the islands studied, dextral faults, which are synthetic with the plate boundary, are always more important than sinistral faults—they are more frequent, longer, and more active.

The leaky transform boundary must be located in the axis of the area with the disturbed stress trajectories; volcanic activity, seismicity and magnetic anomalies all suggest the same location for this fault zone, so it probably passes between the islands of S. Jorge and Pico, near the south coast of S. Miguel, and joins Gloria Fault east of Santa Maria (Fig. 14). We propose the name “S. Jorge Leaky Transform” for this plate boundary.

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