

Paleoseismology study of Pico do Carvão Fault in the Island of S. Jorge (Azores)

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Palavras-chave: S. Jorge; Açores; neotectónica; paleossismologia; Falha do Pico do Carvão;

Resumo: Efectuou-se o estudo paleossismológico de uma das falhas activas principais da ilha de S. Jorge, a Falha do Pico do Carvão, através da abertura de uma sanja transversal àquela estrutura. A análise geométrica, cinemática e a datação por radiocarbono dos depósitos expostos revelaram que 2 a 5 eventos com rotura superficial ocorreram nos últimos 750-700 anos. Aqueles eventos produziram uma separação normal acumulada de 3,5 m com abatimento do bloco norte. Estimou-se uma magnitude de momento sísmico superior a $M=6,3-6,6$ para o sismo máximo expectável, revelando que aquele acidente pode gerar sismos com magnitude moderada a alta. Discutem-se as consequências de um evento actual daquela magnitude.

Key-words: S. Jorge; Azores; neotectonics; paleoseismology; Pico do Carvão fault;

Abstract: To study the paleoseismicity of one of the main active faults of the island of S. Jorge, the Pico do Carvão fault, a trench was open across the fault scarp. Geometric and kinematic analyses and radiocarbon dating of the exposed deposits indicate that 2 to 5 seismic events with surface rupture occurred in the last 750-700 years. They produced 3.5 m of accumulated normal separation and the downthrow of the northern block. A moment magnitude $M \geq 6.3-6.6$ was estimated for the maximum expected earthquake, revealing that the structure can generate moderate to high magnitude seismic events. The consequences of such an event in present times are discussed.

INTRODUCTION: TECTONICS AND SEISMOTECTONICS OF S. JORGE

The island of S. Jorge is a 55 km long fissural active volcanic building, with maximum width of 6.7 km and reaching an altitude of 1053 m at Pico da Esperança. Two main dextral normal WNW-ESE fault zones dominate the western half of the island: the Picos fault zone (P) and the Pico do Carvão fault zone (PC) (Fig. 1). On the eastern half a set of faults with the same direction defines a graben structure; the most important tectonic accident in that region is the Urze-S. João fault (U-SJ) with a 10 km long continuous scarp. These two regions are separated by the sinistral normal NNW-SSE Ribeira Seca fault (RS), represented by a west facing degraded scarp. Three other NNW-SSE accidents are marked by alignments of scoria cones to the west of Ribeira Seca fault. The age of the oldest tectonically displaced volcanic materials, 600 ka, indicates that all faults in the island are active.

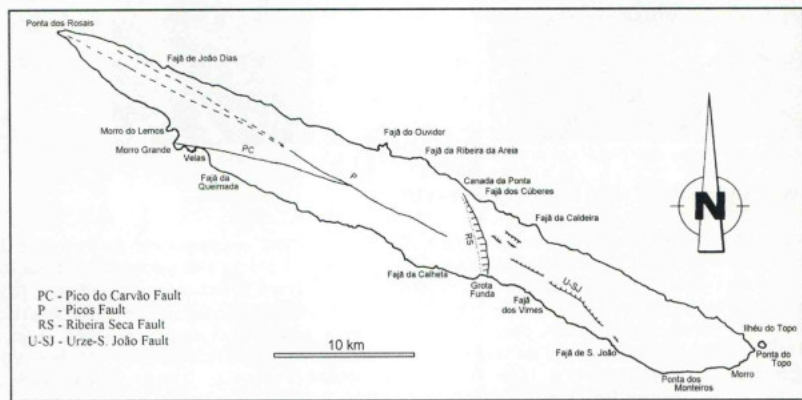


Fig. 1 – Simplified tectonic sketch of S. Jorge.

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Both fault families (WNE-ESE and NNW-SSE) are represented by structures dipping in the two opposite senses; the existence of four sets of faults indicate a three dimensional strain regime as demonstrated by Reches (1983) and Reches & Dieterich (1983). The oblique slip on these faults, with strike slip and normal components, characterize the tectonic regime in the area as transtensive. Present maximum horizontal compressive stress strikes NW-SE as indicated by the direction and kinematics of the two families of active faults (Ribeiro, 1982; Madeira & Ribeiro, 1990, 1992).

The island of S. Jorge was affected by two high magnitude earthquakes: the July 9th, 1757, with an estimated magnitude $M=7.4$ (Machado, 1949) and the January 1st, 1980, $M=7.1$ event (Hirn *et al.*, 1980). The 1980 earthquake, with epicenter between S. Jorge, Terceira and Graciosa, produced strong destruction on the eastern half of the island and some tens of deaths. The 1757 historic event was even more destructive: all the eastern region of S. Jorge, from the village of Calheta to Ponta do Topo, was completely destroyed, killing 1000 people from a total population of 5000. This earthquake has been related to a fault rupture in S. Jorge Channel near the island south coast (Machado, 1949), the Pico do Carvão fault surface rupture (Ribeiro, 1982), or to a fault rupture close to the island north coast (Madeira, 1998).

GEOMETRY, KINEMATICS AND GEOMORPHIC EXPRESSION OF PICO DO CARVÃO FAULT

Pico do Carvão fault zone, composed of three parallel branches, crosses the island of S. Jorge in the N75W direction. It extends for 12 km, from Pico do Carvão cinder cone to Morro Grande (Velas) surtseyan cone; to the east it merges with Picos fault zone and to the west it probably extends to the site of the 1964 submarine eruption, adding, at least, 5 km more to its length. *En échelon* secondary scarps and a displaced crater indicate that the fault is an oblique, dextral normal, structure.

Holocene volcanism (Manadas Volcanic Complex) occurred along this structure and materials of this age are locally displaced by the fault. As a result, Pico do Carvão fault zone exhibits a well developed and continuous geomorphic expression, represented by alignments of volcanic cones and craters and a fault scarp at the eastern sector; the north facing scarp is 1750 m long and 2.5 to 10 m high (Fig 2).



Fig. 2 – Oblique aerial photograph of Pico do Carvão fault scarp



Fig. 3 – Pico do Carvão fault scarp and trench

PALEOSEISMOLOGY OF PICO DO CARVÃO FAULT

To study the paleoseismology of Pico do Carvão fault an 11.5 m long trench was open across the fault scarp (Fig. 3, 4). It revealed a sequence of basalt lapilli fall deposits (levels 1, 2, 3, 4 and 9) with paleosols developed on top, colluvial deposits from the erosion of the fault scarp (levels 4a, 5, 6 and 7) and carbonaceous clay sediments (level 8), containing wood fragments, peat layers and a thin basaltic ash layer, representing a sag pond (tectonic lake) deposit. The lapilli layers display southward dips, parallel to the slope, while the colluvium deposits present a wedge shape inclined to the north in the dependence of the fault scarp. These deposits were dated by radiocarbon (Madeira *et al.*, this volume): level 2 - 3740 ± 50 BP; level 3 - 1530 ± 90 BP; level 4 - 700 ± 70 BP; level 4a - 750 ± 45 BP; level 5 - 510 ± 100 BP; level 8 - 380 ± 40 to 150 ± 40 BP; level 9 - 1808 AD.

The fault plane strikes N63-81W, dips 75°-85° NNE and presents an anastomosed geometry. No striated surfaces were observed. The fault produces a 3.5 m normal displacement in levels 2 to 4, indicating surface rupture about 750-700 years ago (the age of levels 4 and 4a). Since that rupture the fault scarp receded about 1.8 m but maintains a steep inclination, supported by fast growing vegetation.

The propagation of the fault plane to the level 7 colluvium, prior to 380 ± 40 years BP, produced millimetric displacements, and indicates the occurrence of other seismic event(s) in the 700-380 BP time interval.

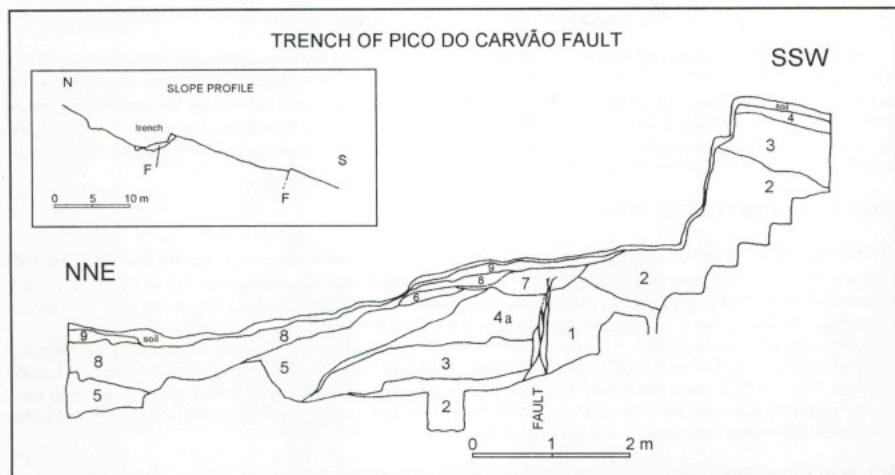


Fig. 4 – Simplified cartography of the eastern wall of the Pico do Carvão trench. The exposed sequence is composed of pyroclast fall deposits (1, 2, 3, 4 and 9), colluvium (4a, 5, 6 and 7) and sag pond sediments (8). The fault produces a 3.5 m normal separation of levels 2 to 4.

SLIP RATE, RECURRENCE INTERVAL AND EXPECTED MAXIMUM MAGNITUDE

There are two possible interpretations for recent tectonic activity on the fault. One is that only one major surface rupture occurred 750-700 years ago, producing the 3.5 m displacement observed on stratigraphic references from levels 2, 3 and 4. This was followed by a much smaller seismic event producing millimetric surface displacement after the deposition of level 7 colluvium.

Another interpretation is that the 3.5 m separation is the sum of displacements produced by five events with surface rupture in the period between 700 ± 70 BP to 380 ± 40 BP, each event represented by a colluvial deposit. However, since there isn't a direct geometric relation between the fault plane and the colluvial sediments of levels 5 and 6 (part of those deposits was eroded before the deposition of the overlying level), there is no way of verifying if those deposits are displaced by different amounts of normal separation as they are only present in the downthrown block. The propagation of the fault plane to colluvium 7 is the only indirect evidence that the colluvial sediments of levels 5 and 6 are tectonically displaced.

These two hypothesis lead to different estimates of the recurrence interval between seismic events producing surface displacement. The first interpretation is that one major earthquake occurred 750-700 years ago, after a time interval of 3000 years or more without surface rupture events; this is deduced from the fact that levels 2, 3 and 4 show the same amount of normal separation. The second interpretation is that, after 3000 years without surface rupture, five events occurred in a 300 to 400 year interval, producing a sum of 3.5 m separation. This would indicate the occurrence of short periods of seismic clustering, with average recurrence intervals of 60 to 80 years, separated by longer periods without surface rupture.

The slip rate of the Pico do Carvão fault, for events with surface rupture, shouldn't be calculated from the simple division of 3.5 m displacement by 750-700 years, but from the duration of the recurrence interval between single events (producing displacements of 3.5m) or between clusters of events (producing an accumulated displacement of the same order), that is about 3000 years or more. This allows an estimation of a slip rate, for events with surface rupture, of the order of 0,1cm/year for the normal component of the fault.

Assuming the case of a single event producing 3.5 m of normal displacement, a moment magnitude of $M=7.1$ is obtained using the correlation $[M=6.69+0.74\log(MD)]$ between maximum displacement (MD) and moment magnitude (M) of Wells & Coppersmith (1994). This value is not compatible with the moment magnitude, $M=5.4$, deduced from a surface rupture length (SRL) of 1.75 km using the Wells & Coppersmith (1994) regression equation $M=5.08+1.16\log(SRL)$.

If the correlation between rupture area (RA) and moment magnitude (M) is used $[M=4.07+0.98\log(RA)]$, with a minimum fault length of 17 km for the Pico do Carvão fault zone and assuming rupture of the total length of the fault and a seismogenic thickness of 10 km (Hirn *et al.*, 1980), a minimum value of $M=6.3$ for the maximum expected moment magnitude is obtained. This value is in better agreement with a moment magnitude of $M=6.6$, estimated from the maximum displacement/moment magnitude correlation, if only 0.7 m of average surface displacement in a single event is used (3.5 m of displacement divided by five events).

DISCUSSION AND CONCLUSIONS

The island of S. Jorge was affected by two highly destructive earthquakes since its settlement (ca. 1450). Both the 1980 and the 1757 event sources were located at sea close to the island. Paleoseismology studies revealed that onshore structures are also capable of producing earthquakes of moderate to high magnitude; Pico do Carvão fault, for example, can produce surface rupture from moment magnitude $M=5.4$ to $M=6.6$ events.

Such earthquakes could produce huge destruction and an enormous death toll, not only as a result of the magnitude but also because the fault runs through the southern slope of S. Jorge above the most densely populated area (Manadas, Terreiros, Urzelina, Queimada and Velas). The airport (in Queimada), port facilities (at Velas) and the south road could become inoperative, leaving the affected area completely isolated. Important slope failure must also be expected adding to the direct destruction from ground shaking and surface rupture.

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