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A past giant lateral collapse and present-day flank instability of Fogo, Cape Verde Islands

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Abstract

Fogo island is a large and extremely steepsided oceanic island volcano in the Cape Verde archipelago. It has a large (ca. 9 km across) east facing summit collapse structure, the Monte Amarelo collapse, with a probable volume of at least 150–200 km^3. For most of its history the Monte Amarelo volcano had a small but productive central vent complex and radial rift zones fed by laterally propagating dykes. Shortly before the collapse the latter were replaced by north–south-trending arrays of en echelon, vertically propagating dykes. Since the Monte Amarelo collapse the scar has partly filled with a new volcano, the Cha das Caldeiras volcano. The summit cone of this volcano, the Pico do Fogo, is a very young feature but has been abandoned in the most recent phase of activity, from the 18th century onwards. The same period has also seen the abandonment of earlier radial rift zones with laterally propagating dykes and their replacement with en echelon arrays of vents fed by vertically propagating dykes. These form an N–S-trending array within the older collapse structure and are associated with seaward displacement of the eastern flank of the volcano within the old collapse structure. The most recent eruptions, those of 1951 and 1995, appear to be associated with episodes of flank instability manifested in N–S surface fissuring and east facing normal faults. These recent structural changes in the volcano parallel those which took place in the Monte Amarelo volcano prior to its collapse. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Fogo Island; flank instability; volcano

1. Geological setting of Fogo island

Fogo island is in the southwestern part of the Cape Verde archipelago, some 800 km off the coast of Africa (Fig. 1). All the islands are volcanic in origin, related to the well characterised Cape Verde mantle plume (Courtney and White, 1986; White, 1989). They are characterised by strongly alkaline magmas (Davies et al., 1989). All the islands of the archipelago rise 3–4 km above the ocean floor of the Cape Verde swell, the central part of which is itself elevated some 1500 m above the adjacent ocean basins. Low resolution mapping of the ocean floor by means of shallow seismic profiling (Jacobi and Hayes, 1982) indicates the presence of numerous and extensive turbidite and debris flow/debris avalanche deposits on the flanks of the swell: these are considered to originate from the steep slopes of the islands. The least-sedimented (and by inference, the youngest)

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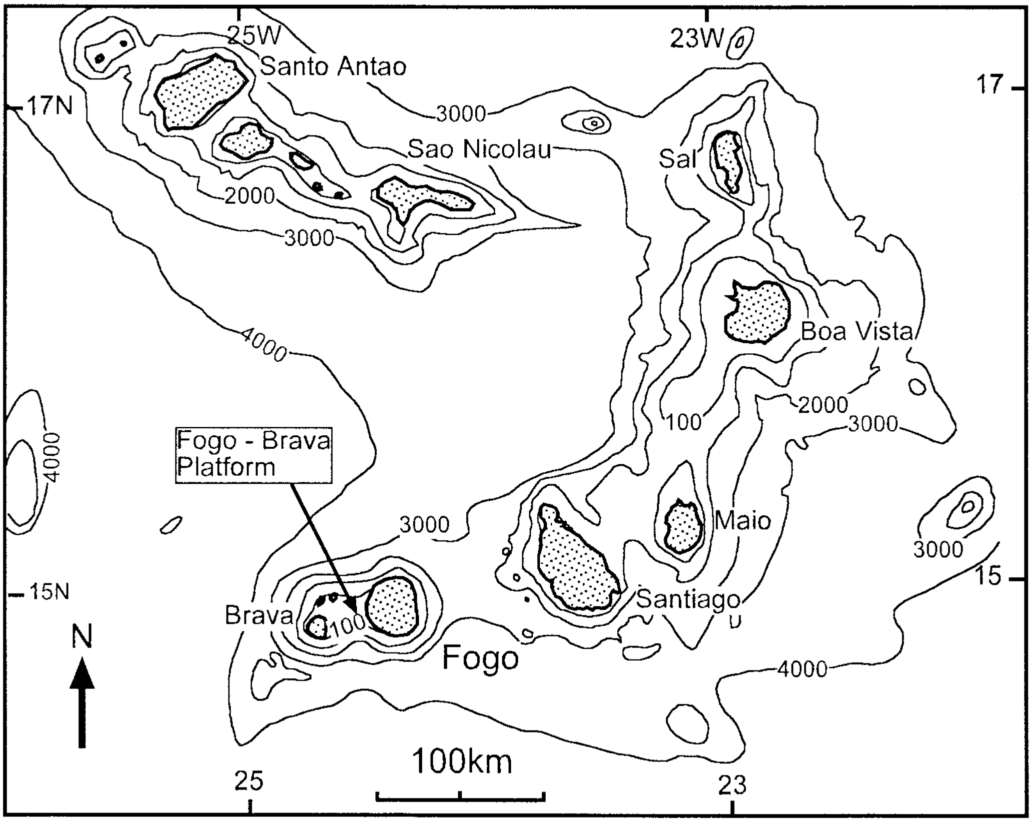

Fig. 1. Bathymetric map of the Cape Verde Islands.

of these deposits extend south of Fogo in a tongue some 300 km long and over 50 km wide.

Fogo and the adjacent island of Brava, which rest at either end of an elongate submarine pedestal with a flat top 200–500 m below present sea level, are the islands closest to the inferred position of the upwelling axis of the mantle plume (Courtney and White, 1986). The two islands are, consistent with the drifting hotspot model for the generation of such islands, the youngest and most seismically and volcanically active in the archipelago. All of the many historic eruptions in the archipelago have occurred on Fogo, although numerous morphologically young scoria cones and lava domes occur on Brava (Machado et al., 1968). Brava is also affected by numerous seismic swarms indicative of shallow intrusive activity and perhaps the presence of a persistent shallow magma body (Heleno da Silva and Fonseca, in press).

Although relatively small (sub-aerial area 476 km^2), Fogo has a maximum elevation above sea level of 2829 m, and numerous peaks above 2500 m. Amongst Atlantic ocean island volcanoes it is second only to Tenerife in the Canary Islands in height above the adjacent ocean floor (about 7 km; Fig. 1). The island is also remarkably steep, with average sub-aerial slope angles generally in excess of 15°. On the steep eastern flank of the island average sub-aerial slopes range from between 22 and 28° (Fig. 3, below). The combination of these steep slopes and the frequent volcanic activity on the island make it a likely candidate for flank instability and the development of giant lateral collapses both in the past and in the future.

The steep slopes of Fogo are comparable to, although actually rather greater than, those of volcanoes in the Canary islands where a number of giant lateral collapse structures have been identified (see, inter alia, Holcomb and Searle, 1991; Ancochea et al., 1994; Carracedo, 1994, 1996, 1999-this volume; Carracedo et al., 1999b-this volume). Fogo is, therefore, of particular interest as a test of whether the distinctive structural features of the steep sided volcanoes of the Canary islands (Carracedo et al., 1998; Carracedo, 1999-this volume) are to be found elsewhere.

Largely as a result of the remote location of the Cape Verdes, Fogo island has been studied much less intensively than the Hawaiian or even the Canarian volcanoes, particularly since the end of Portuguese rule in 1975. Thus very little geological work has been done there since the recognition of lateral collapses as an important volcanic process in the aftermath of the Mount St. Helens eruption of 1980 and the general acceptance of the Moore (1964) hypothesis of giant landslides in the Hawaiian islands (Moore et al., 1989, 1994; see McGuire, 1996 for a general review of the history of ideas concerning lateral collapse processes). The work described here largely results from two brief visits in December 1996/January 1997 and December 1997/January 1998. It should in some respects be regarded as a reconnaissance level study. However, the spectacular nature and excellent exposure (the latter as a consequence of the semiarid climate) of the geology of the island has nevertheless allowed significant conclusions to be drawn from these visits. A more detailed account of the geology of Fogo will be presented by Day (in prep.). In addition, the excellent review of accounts of historic period activity in the island by Ribeiro (1960) (see Day et al., in press for a reanalysis of these historical accounts in the light of geological observations) and seismic monitoring and other studies of the 1995 eruption on Fogo (IICT, 1997; Heleno da Silva et al., 1999-this volume) have contributed greatly to the following reinterpretation of the geology of Fogo.

2. Morphology and previous geological and geophysical studies of Fogo

The principal morphological elements of Fogo are readily apparent from Figs. 2 and 3. The basic shape of the island lies between that of an asymmetric truncated cone and an asymmetric truncated tetrahedron, with its corners in the NE, SE and west or southwest. The missing apex of the cone or pyramid is offset to the east: thus the steepest slopes are to be found on the eastern side of the island. The truncation takes the form of an eastward opening scar, some 9 km wide north to south, and bounded on its northern, western and southern sides by a continuous and extremely steep (slope angles 60–90°) cliff known locally as the Bordeira. At its highest, along the western side of the scar, this cliff is some 800–1000 m high. It forms a continuous curved rock face over 20 km long, cut only by minor gullies, except in a sector slightly north of the mid-point of the western wall where it is interrupted by a steep sided triangular spur, Monte Amarelo. At its northern and southern ends the Bordeira cliff drops to the level of the plain enclosed within it over a distance of 1–2 km and it cannot be traced directly towards the coast. The southern wall is however aligned with the steep E–W trending Espigao escarpment to its east.

Within the Bordeira escarpment is a remarkably flat plain, the Cha das Caldeiras (which translates as ‘‘plain of craters’’ in English) divided into two unequal parts by the lower end of the Monte Amarelo spur (partly buried by recent lava flows): the southern part is about 1750 m above sea level, the northern about 1650 m above sea level. The Cha das Caldeiras is partly isolated from the steep eastern flank of the island by a large and extremely steep sided volcanic cone, the Pico do Fogo, whose summit is presently the highest point on the island (2829 m), and by numerous scoria cones north and south of the Pico (Fig. 3).

The spectacular topography of the Bordeira cliffs is in strong contrast to the outer slopes of the island, which are in many places formed by well preserved lava flows and scoria cones. More deeply eroded regions occur high on the flanks of the island, above the 1500-m contour, and on the relatively humid northern side. These areas are characterised by the development of radial gully and canyon systems up to 300 m (but generally less than 100 m) deep: all scales of these are known locally as ribeiras. They represent an early stage of erosion of the edifice.

The island is bounded by steep coastal cliffs, up to 500 m high in places on its northern and eastern sides but generally less than 200 m. In places, however, the cliffs are themselves separated from the sea

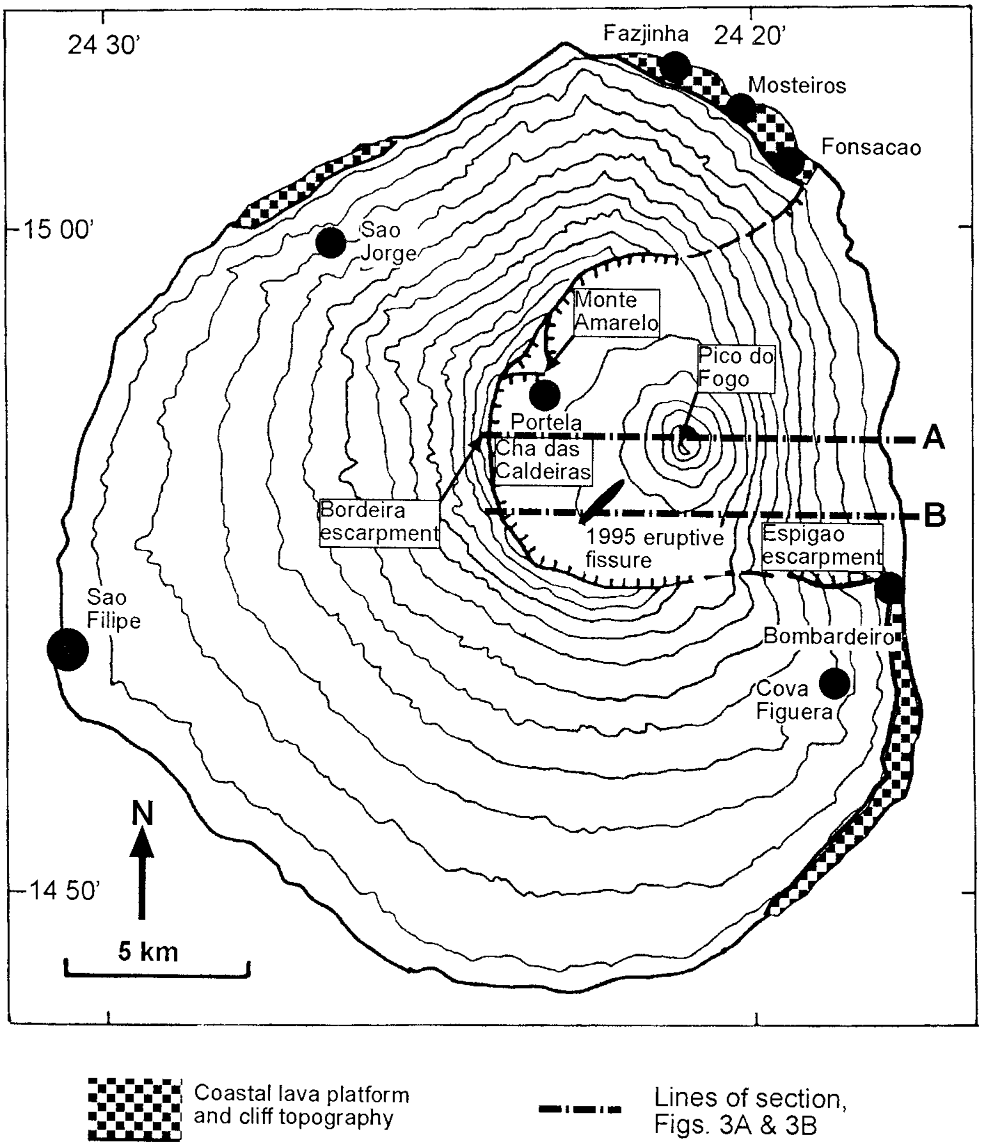

Fig. 2. Topographic map of Fogo with main morphological features and towns and villages indicated.

by narrow platforms formed by more recent lava flows. These flows have spread over the wave cut platforms at the foot of the cliffs and they are absent where this platform is not developed. The extent of the cliff-and-platform coastal morphology is shown in Fig. 2. It is especially well developed on the northern, eastern and southeastern sides of the island except in the sector directly east of the Bordeira cliffs. The abrupt termination of the southeastern lava platform at the intersection of the Espigao escarpment with the coast is especially noteworthy, but to the north a palaeocliff (partly buried by recent lavas) and platform topography can be traced as far south as Fonsacao, which lies ENE of the northern end of the Bordeira escarpment.

In all of the areas of cliff-and-platform topography indicated in Fig. 2 there is a single cliff, cut into thick sequences of sub-aerial lavas without develop-

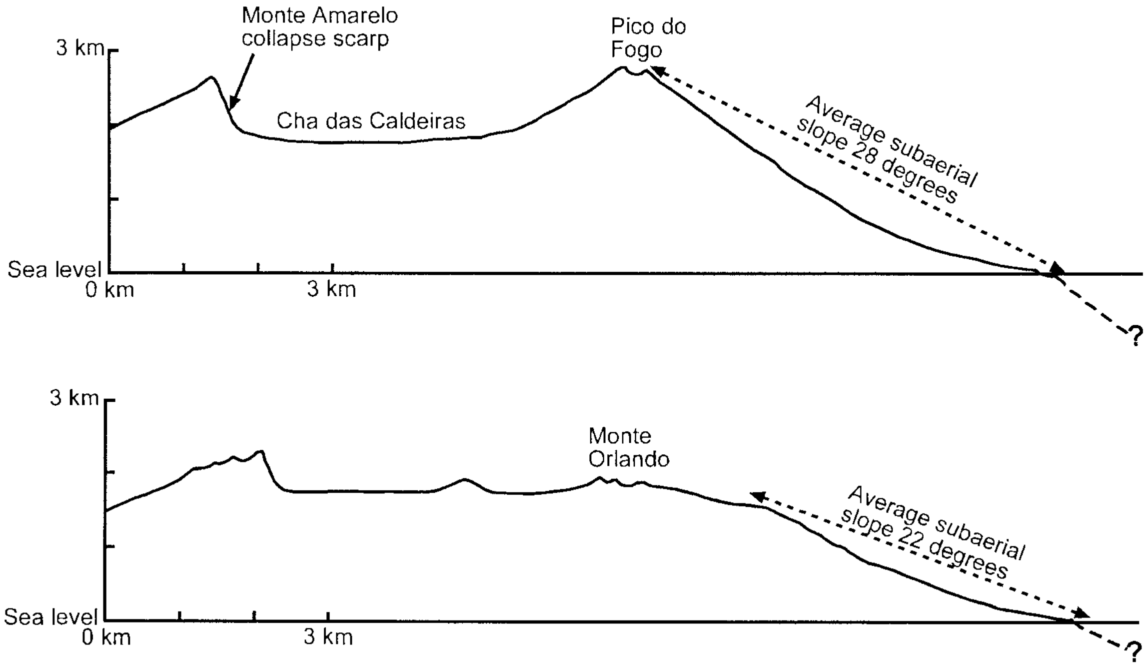

Fig. 3. East–west cross-sections of the island's eastern flank, through the Bordeira cliff. Note no vertical exaggeration.

ment of palaeocliffs within these sequences. There is also no evidence for the former proximity of the coast in the form of phreatomagmatic ash layers or tuff rings. Conversely, there is only a single lava platform preserved along these coastal sections (multiple lava platforms, where present in the islands of the Canaries discussed below, can be recognised by the presence of different platform levels separated by low or partly buried palaeocliffs). The consistent development of this pattern of very simple cliff-and-platform topography on several sides of the island suggests the development of an eruptive hiatus or period of intense erosion in much of the island, separating emplacement of the cliff forming sequences in one period of activity and of the platform forming sequences in a later period. This is discussed further below. The development of coastal cliff and platform topography in the youngest volcanic edifices on the islands of La Palma (Carracedo et al., 1997a, 1999a) and El Hierro (Carracedo et al., 1997b) in the Canary islands has been shown to have chronostratigraphic significance, with all radiometrically dated platform forming lavas in these edifices younger than all radiometrically dated cliff forming lavas.

The established interpretation of the Bordeira escarpment and other aspects of the geology of Fogo is due to Machado and co-workers (Machado, 1965a; Machado and Torre de Assuncao, 1965). Machado (1965a) proposed that the Bordeira represented the remaining part of the wall of a central subsidence caldera and drew a close analogy with the central intrusive ring dyke complexes of the British Tertiary Volcanic Provinces. He further proposed that the eastern side of the caldera wall had subsequently been removed by eastward downthrowing movement along a north–south regional fault passing through the island, or by erosion.

Recently, Brum da Silveira et al. (1995, 1997a, b) have proposed that this eastern sector was removed by a relatively small-scale lateral collapse but have retained and elaborated upon the hypothesis of initial central caldera subsidence, proposing that the Cha das Caldeiras is underlain by two distinct small calderas, respectively about 6 km and 3 km across, separated by the Monte Amarelo spur. These authors have also identified numerous faults forming N–S-, NNW–SSE- and NE–SW-trending systems transecting the island and inferred to be mainly of regional tectonic origin, but largely on the basis of postulated volcanic vent alignments. With the exception of a few structures with very small offsets these authors did not demonstrate clear offsets across their proposed faults.

Although no formal stratigraphy of Fogo has been constructed previous to the present work Machado and co-workers used the inferred caldera collapse to divide the island into two main units (in addition to a basement sequence formed by carbonatite and alkali basic intrusive rocks which are exposed only in gully floors in a very restricted area in the southwest of the island). The pre-collapse sequence was considered to form the bulk of the sub-aerial volcanic edifice. No subdivisions of this sequence have been proposed, except by Barmen et al. (1990) who suggested that the upper slopes of the pre-collapse volcanic edifice were formed by a scoria-dominated edifice built up upon a lava-dominated shield volcano with more gently inclined slopes. Post-collapse rocks were considered to be represented over most of the island by a thin discontinuous veneer of lava flows and scoria cones on the flanks of the older edifice, best developed on the southeastern and southwestern flanks. The bulk of the post-collapse rocks identified by these authors were considered to be within the old caldera, forming a thick fill sequence, and burying the eastern flank of the volcano in the area between Espigao and Fonsacao.

3. Stratigraphic subdivision of Fogo

Fig. 4 shows a provisional stratigraphic sequence based upon the fieldwork noted above: this is used here in the absence of an established stratigraphy for

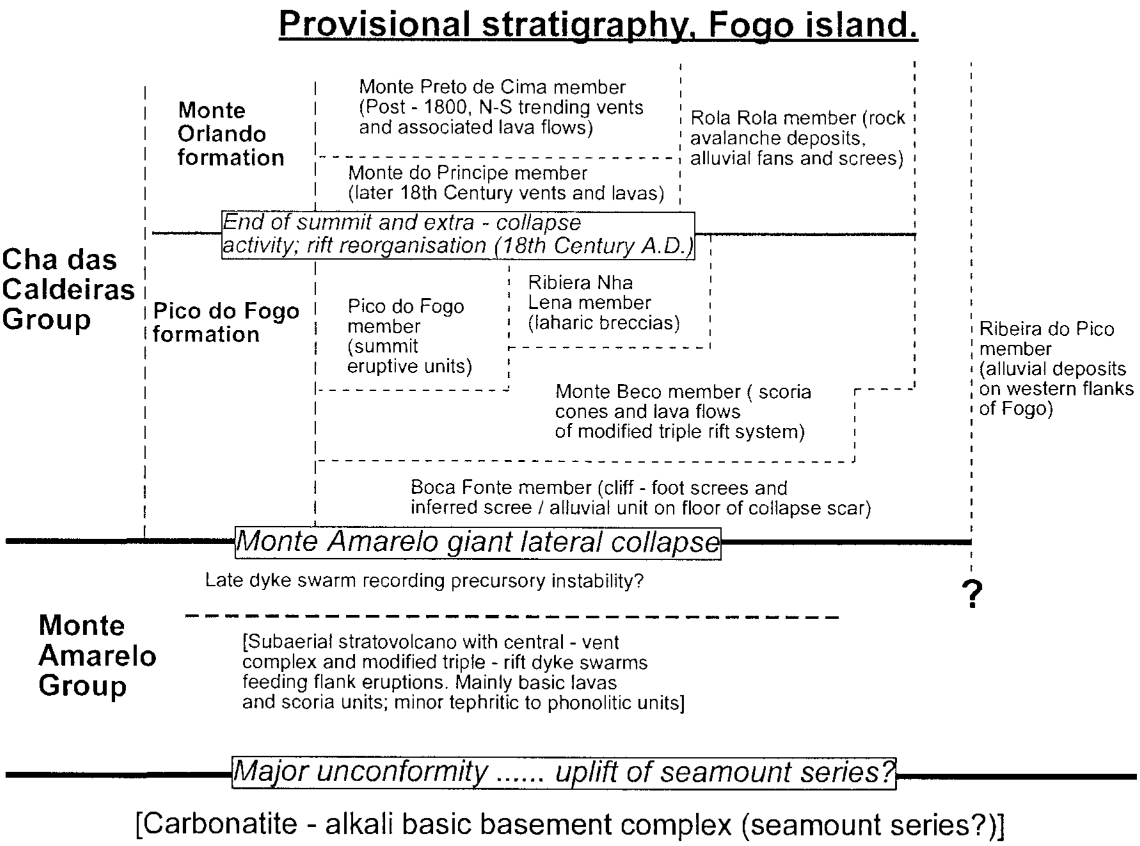

Fig. 4. Provisional stratigraphic correlation diagram for Fogo. Inferred structural events (in italics) are discussed in the text.

the island. The approximate distributions of the principal units are shown in Fig. 5. Certain of the unit boundaries — particularly that between the Pico do Fogo and Monte Orlando formations — are based in part upon structural criteria which are discussed in subsequent sections. However, it is appropriate to briefly consider the lithological characteristics, distribution and age relationships of the units shown in Figs. 4 and 5, since the definition of these units is an important step in the reconstruction of the history and structural evolution of the volcanoes making up Fogo island. More detailed descriptions of these stratigraphic units will be presented elsewhere (Day, in prep.). As noted previously, the sub-aerial volcanic units of the island appear to unconformably overlie a poorly exposed basal intrusive complex. This may be a counterpart of the seamount sequences of rocks which are the oldest components of other islands in the Cape Verdes (Stillman et al., 1982).

3.1. Monte Amarelo Group

The Monte Amarelo Group is broadly equivalent to the ''pre-collapse'' sequence of earlier workers. It consists of the sequence exposed in the Bordeira cliffs, which is at its greatest thickness at the Monte Amarelo spur noted above, and its lateral equivalents discussed below. Apart from numerous dykes and some other minor intrusions (discussed in Section 4), the Monte Amarelo Group consists entirely of volcanic and epiclastic rocks. The sequence in the Bordeira cliff dips broadly outwards, but with a significant cliff-parallel component of dip in the southern and northern segments of the cliff such that the oldest rocks of the sequence are exposed around Monte Amarelo. Dips in this region are up to 40°, but decline to lower values (20–30°) higher in the sequence. There is no evidence of a downward transition to more lava-dominated units at the base of the Monte Amarelo cliff, although the rocks in this area

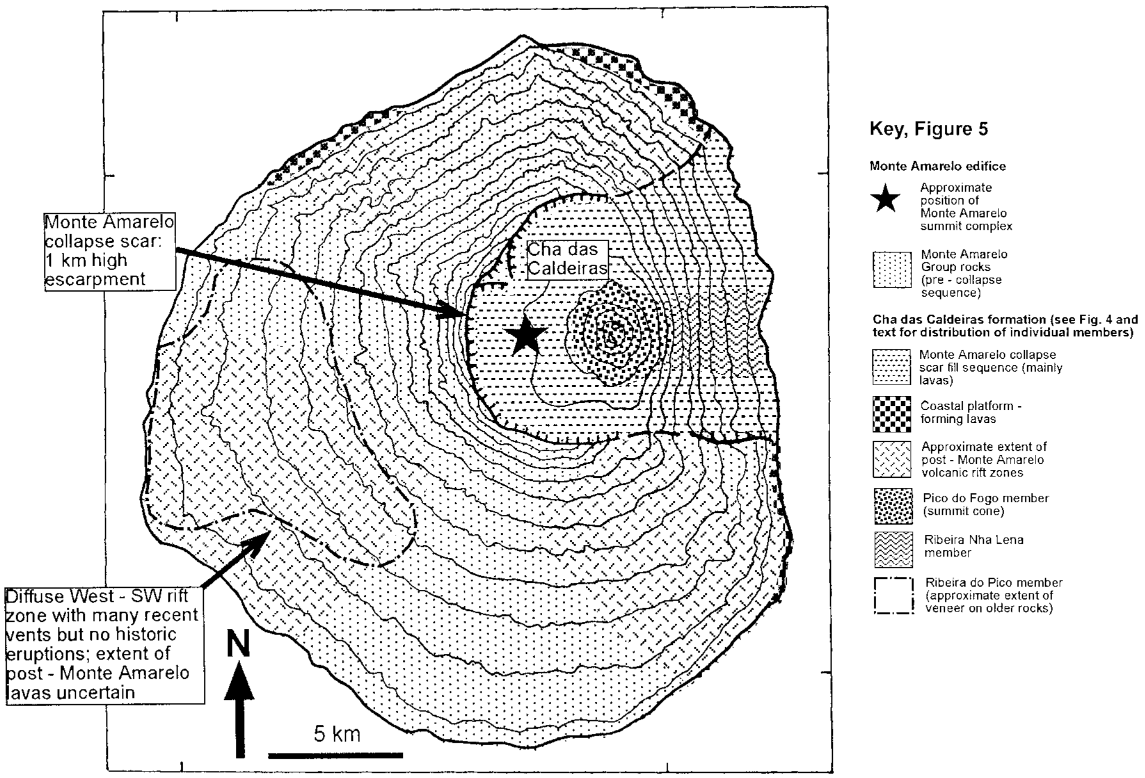

Fig. 5. Simplified sketch geological map showing main stratigraphic units (see Fig. 12 for post-18th century stratigraphic units).

are positioned structurally below the top of the sequence on the lower slopes of the volcano. The division of the ''pre-collapse'' volcano into upper and lower units proposed by Barmen et al. (1990) is therefore invalid and their observations are better explained by a lateral facies variation (Section 4).

Dips all along the cliff are directed radially outwards from a single centre whose inferred position is about 1–2 km south of the eastern end of the Monte Amarelo spur (see Fig. 7, below). The eruptive sequence consists mainly of highly alkaline basic to intermediate (Torre de Assuncao et al., 1967) lavas; numerous scoriaceous (including discrete scoria and spatter cones), lapilli and epiclastic breccia units; and very rare felsic units. The latter include a single prominent unit in the SW sector of the Bordeira cliff, up to 10 m thick but extending laterally for only 2–3 km, of welded ignimbrite. There are no large volume felsic pyroclastic units, at the top of the sequence or elsewhere. The numerous dykes cutting the Monte Amarelo Group rocks in the Bordeira cliff are discussed in Section 4.

The rocks of the Monte Amarelo Group can be traced continuously down to the coast in certain areas, most especially in the north and northeast of the island where younger rocks are largely restricted to gully- and canyon-filling lava flows. In these areas Monte Amarelo Group rocks form the coastal cliffs, with a marked erosional break both at the coast and at the top of the cliffs between continuous sequences of Monte Amarelo Group rocks (mainly conformable sequences of lavas, with some scoria cones and dykes in certain sections of the coast as discussed in Section 4) and the younger rocks, the latter including the coastal lava platform forming flows where present.

Similar field relationships are developed between the lava-dominated sequences forming the Espigao escarpment and the coastal cliffs to the south, and younger rocks in the SE of the island. This consistent relationship implies that the Espigao sequence is also part of the Monte Amarelo Group although it is separated from the Bordeira cliff exposures by a tract of young lavas and scoria cones 2–3 km wide (Fig. 5). No rocks of the Monte Amarelo Group occur in the sector of the eastern flank between Espigao and Fonsacao where the coastal cliffs, although up to 100 m high in places, expose continuous sequences of lavas and breccias of the Monte Beco and Ribeira Nha Lena members (see below) up to recent and historic flows at the top of the cliffs. There is also no evidence of a coastal abrasion platform offshore from the coast in this area, in the form of lava platforms. This implies that it lacks the extended period of past marine erosion recorded to north and south.

These relationships suggest a significant erosional hiatus between eruption of the Monte Amarelo sequence and younger activity in the N, NE and SE of the island. The situation in the south and west is less clear because although there are many fairly young lava flows and scoria cones in this area there are no discrete cliff forming and platform forming sequences. It is possible that there is a continuous sequence in this area ranging in age from Monte Amarelo Group rocks, best exposed in gullied regions high on the western flank of the volcano which extend up to the incised crest of the Bordeira cliffs, to sub historic flows.

No laterally extensive unconformities or lithological changes exist within the Monte Amarelo Group and subdivision of the Group therefore awaits more detailed mapping, petrological and perhaps geochemical studies.

3.2. Cha das Caldeiras Group

The Cha das Caldeiras Group is largely equivalent to the ''post-collapse'' sequence of previous workers. It is composed primarily of the thick sequence forming Cha das Caldeiras, the Pico do Fogo itself and the slope to the east. This is the region largely enclosed by the Bordeira cliffs but the Group also includes thin, discontinuous sequences of recent rocks on the northern, western and southern flanks of Fogo. As discussed above, the boundary between the Monte Amarelo and Cha das Caldeiras Group is not easily defined on the western slopes of the island.

The Cha das Caldeiras Group is subdivided into two components in Fig. 4, the Pico do Fogo and Monte Orlando formations. These are highly unequal in volume as the division between the two is defined by the end of major activity at the summit of the Pico do Fogo cone. As discussed in subsequent sections, these changes largely took place during the 18th century A.D. and assignation of individual eruptive and other units to the two formations is thus based in part on historical evidence. Brief comments on the distribution and lithological characteristics of individual members of the two formations follow; structural aspects are discussed in Section 5.

3.2.1. Ribeira do Pico member

This consists of widespread gully filling and alluvial fan deposits on the western side of Fogo, forming a partial cover on top of (although locally interbedded with the uppermost flows of) the sequences of lava flows and scoria cones in that area. This suggests that the level of volcanic activity on the western flank of Fogo may have been declining for some time. Fig. 4 is drafted to recognise the possibility that this decline may have occurred as long ago as the latter part of Monte Amarelo Group activity: although this seems unlikely, radiometric and cosmic ray exposure dating (presently in progress) is required to test this hypothesis.

3.2.2. Boca Fonte member

This consists of screes and alluvial fan deposits at the foot of the Bordeira cliffs. As discussed below there is a possibility that this unit may have been more extensive in the early stages of deposition of the Cha das Caldeiras Group. The screes and other deposits are locally interbedded with lapilli beds and scoria and spatter units, most probably deposited from buried vents of the Monte Beco member.

3.2.3. Monte Beco member

The bulk of the basic (mostly basanitic according to Torre de Assuncao et al., 1967) lava flows exposed in Cha das Caldeiras, on the slope to the east and in the coastal cliffs between Espigao and Fonsacao, together with their eruptive vents and associated lapilli units, are assigned to the Monte Beco member. For reasons discussed below, few of these lava flows appear to have been erupted from the summit or upper flanks of the Pico do Fogo, at least in the most recent stages of its history. Equivalent lava flows erupted from vents outside the Cha das Caldeiras (Section 5), together with flows from Cha das Caldeiras which have spilled onto the outer flanks of Fogo via routes to the east of the two ends of the Bordeira cliff, are also assigned to the Monte Beco member.

3.2.4. Pico do Fogo member

This unit, which forms the cone of Pico do Fogo itself, is dominated by thick sheets of welded spatter and clastogenic lava, scoria beds, thin lapilli units and laminated yellow to grey ash beds of probable phreatomagmatic origin. Normal lava flows do not occur, at least in the upper parts of the member which have been exposed by erosion. This has incised to depths of up to a few hundred metres on the eastern flank of the cone in particular. It does not seem likely that many normal lava flows have been generated from the summit or upper flanks of the cone for much of its history.

The occurrence of such lava flows beneath the thin Ribeira Nha Lena member (see below) in the coastal cliffs downslope of the cone to the east therefore suggests that until the later stages of the growth of the Cha das Caldeiras volcano the site of the Pico do Fogo cone was occupied by a relatively subdued central vent erupting lava flows similar to those erupted from vents further to the north and south. This may have been comparable to the Bory–Dolomieu complex at the summit of Piton de la Fournaise, Reunion (Duffield et al., 1982; Lenat and Labazuy, 1990); alternatively there may have been no discrete summit edifice at all.

Further evidence for the rapid growth of the Pico do Fogo comes from a comparison of early historical accounts (Ribeiro, 1960) with the sequence of discrete eruptive units exposed in gullies on the flanks of the Pico do Fogo. As discussed by Day et al. (in press) the sequence of these units, which together form a sequence more than 50 m thick, corresponds to changes in activity of the Pico do Fogo recorded from 1664 to 1725: assuming a constant volumetric eruption rate leads to the conclusion that the Pico could have largely formed within a period of 3–5 centuries.

3.2.5. Ribeira Nha Lena member

The Ribeira Nha Lena forms a thin (10–20 m thick in gully and cliff exposures at and near the coast) but laterally extensive sheet composed of lensoid breccia bodies. These are interpreted (Day, in prep.) as mudflow and hyperconcentrated streamflow deposits produced by reworking from the steep eastern flank of the Pico do Fogo at the time that it was actively growing. The unit is restricted to the area directly downslope of the Pico do Fogo and is laterally equivalent to, and locally interbedded with, lava flows close to and at the top of the sequences to north and south.

3.2.6. Rola Rola member

This consists of unconsolidated, matrix poor polymict lithic breccias and mixed lapilli and lithic deposits produced by rockfalls, rock avalanches and wet season floods which have reworked material from the Pico do Fogo (including lapilli from recent eruptions deposited on it) since the end of its activity in the 18th century.

3.2.7. Monte do Principe member

A small number of vents and lava flows fed by them exist on the slopes of the Pico do Fogo which postdate the end of summit activity (the Pico do Fogo member noted above) and overlie at least some Rola Rola member rockfall breccias but retain the same vent orientations as the earlier eruptive units of the Monte Beco member. The structural significance of this is discussed further below but it is to be noted that field observations show that, wherever the lava flows and pyroclastic units of this member are in contact with Monte Preto de Cima member rocks they are demonstrably older. Available historical data (Ribeiro, 1960) discussed further below indicates that the principal eruptions which produced the Monte do Principe member were in 1769, 1785 and possibly 1799.

3.2.8. Monte Preto de Cima member

This consists of lava flows and scoria cones formed in eruptions since the end of the 18th century. The distinction between this unit and the Monte Beco and Monte do Principe members is made to reflect the change in distribution and orientation of volcanic vents since that time (Section 6).

4. The growth and structural evolution of the Monte Amarelo volcano, and the Monte Amarelo giant lateral collapse

4.1. The structure of the Monte Amarelo volcano

The steep, outward directed dips of the Monte Amarelo Group rocks in the Bordeira cliffs and the downslope facies variation discussed in Section 3.1 imply that the Monte Amarelo volcano was dominated by a summit eruption centre positioned just to the south of the Monte Amarelo spur. The eruptive rocks and some dykes of the Monte Amarelo spur

Fig. 6. Photomosaic of the Monte Amarelo cliff section, viewed from the inferred location of the Monte Amarelo summit complex to the southeast. Overlapping and undisturbed lava flows in the cliff exclude the possibility of NW-trending faults in this cliff section. Height of central section of cliff ca. 900 m.

and adjacent sections of the Bordeira cliff do not show evidence of faulting or crater wall unconformities (Fig. 6), implying that the summit crater and conduit systems were of relatively small dimensions, probably less than 2 km across. The widespread occurrences of dykes in the Bordeira cliffs and the distribution of dykes and eruptive vents on the outer flanks of the volcano must therefore be interpreted in terms of numerous flank eruptions.

Although dykes are distributed all along the Bordeira cliffs they are concentrated in specific sectors within which particular trends are developed, as shown in Fig. 7. Four major swarms can be distinguished on the basis of visual observations of the cliffs: SE- to south-trending dykes (bearings 140–180) along the SE sector of the Bordeira; WSW-trending dykes (approximate bearing 240) which occur from the SW corner of the Bordeira to the southern side of the Monte Amarelo spur; WNW-trending dykes (approximate bearing 300) in a swarm extending from about 1 km south of Monte Amarelo to the north side of Monte Amarelo; and north- to

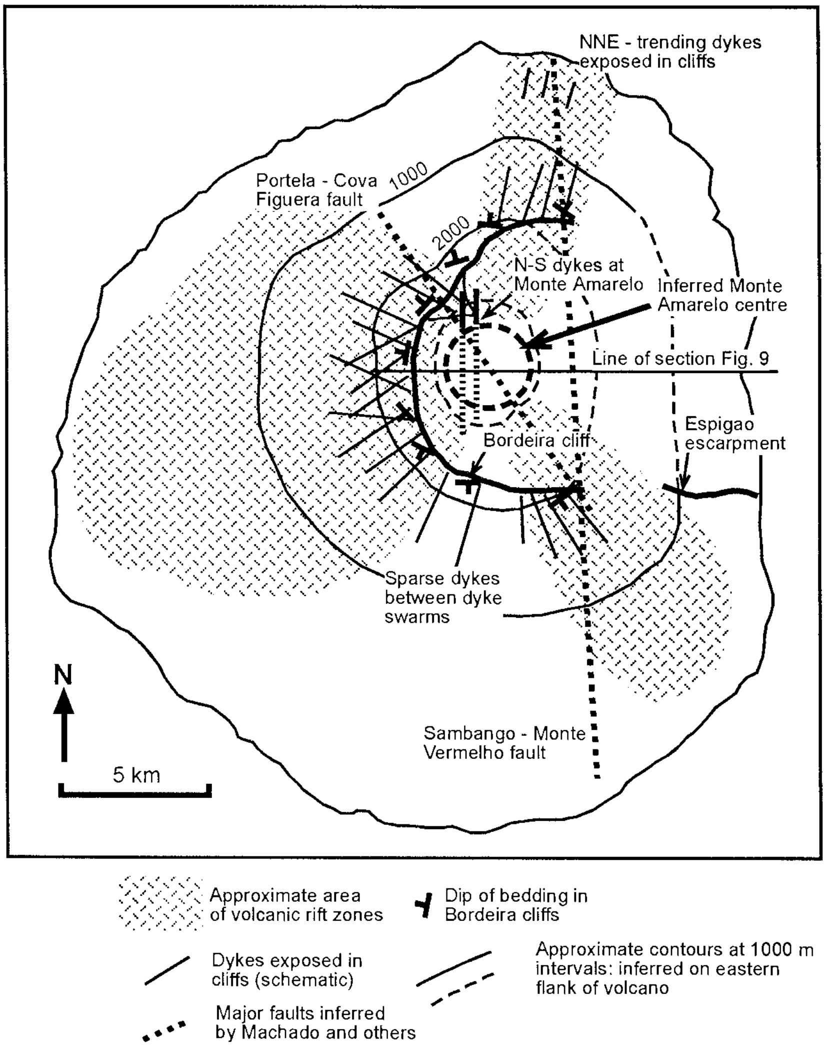

Fig. 7. Structural features of the Monte Amarelo volcano, observed and inferred. Major faults inferred by Machado, Brum da Silveira and others, but rejected here are shown as dotted lines.

NNE-trending dykes (approximate bearings 000–020) in the northeastern part of the cliff. The 240- and 300-bearing swarms overlap on the south side of Monte Amarelo, and show many dyke intersections. There is no systematic age pattern in this area, with dykes of both swarms cutting and cut by dykes of the other.

Most of the dykes in these swarms are near vertical although inclined sheets with dips as low as 55° are present. Many of the dykes can be traced up the cliffs for distances of several hundred metres and consist of a number of segments, although without any consistent pattern of stepping. The appearance of this segmentation in the near vertical cliffs implies that the segments are elongated in horizontal or gently inclined directions. Although it was not possible to reach these segments during fieldwork, the systematic relationship between segments and other magma flow indicators observed in comparable ''fingered'' and segmented dyke swarms (Pollard et al., 1975; Smith, 1987), together with the simple geometric constraint that magma cannot have flowed from segment to segment in a vertical direction unless and until they linked up, implies mainly lateral propagation and magma flow in these dykes. Their overall radial geometry further implies that this lateral propagation took place from high in the central conduit region of the volcano.

A small number of dykes exposed in the Monte Amarelo spur show a distinctive geometry. These dykes trend N to NNE overall but show well developed en echelon segmentation, with vertical segment tip lines (Fig. 8) implying vertical propagation from depth. They cannot have been fed from the source region of the older, laterally propagating dykes in the upper levels of the central conduit. These dykes consistently cut 300-trending dykes in the same outcrops and are petrographically fresh, in contrast to the variably hydrothermally altered volcanic and earlier dyke rocks which they cut. They appear to have been emplaced very late in the history of the Monte Amarelo volcano, or possibly later still as discussed below.

The inferred lateral propagation of the bulk of the dykes exposed in the Bordeira cliffs implies that they should have fed vents on the flanks of the Monte Amarelo volcano. This appears to be the case, as large numbers of weathered and often partially eroded

Fig. 8. N–S en echelon dykes at the extreme eastern end of the Monte Amarelo spur, viewed from the north. View is oblique to dyke segments: true sense of segment offset is right-stepping.

scoria cones occur on the flanks of the volcano in three discrete zones bearing NNE, SSE and WSW to WNW from the inferred centre of the Monte Amarelo volcano (Fig. 7). The diffuse western zone corresponds to both the WSW and WNW dyke swarms in the Bordeira. In a number of cases the older scoria cones higher on the slopes of Fogo are surrounded by lavas which descend outwards from the rim of the Bordeira and lack visible sources: this implies that the lavas and hence the scoria cones predate the event which formed the Bordeira cliffs. Furthermore, the NNE rift zone extends to the coast in the section of coastline near Mosteiros (Fig. 7): in this area the cliff forming sequence includes numerous scoria cones and some vertically-segmented dykes, the latter trending 000–020. The other rift zones are not observed in the coastal cliffs and appear to terminate higher up the slopes of the volcano.

The development of a summit vent complex, coupled with flank vents fed by laterally propagating dykes, accounts for the downslope variation in the lithologies of the Monte Amarelo volcano, from the relatively scoria- and breccia-rich sequences in the Bordeira cliffs (although even these are generally dominated by lavas) to the coastal sequences which are almost entirely composed of lavas. This lateral facies variation appears, as noted above, to have been misinterpreted by Barmen et al. (1990) as a vertical variation reflecting a change in the activity of the volcano with time.

The Monte Amarelo volcano can therefore be inferred to have had a single, relatively small central vent complex and three (or four, depending on whether the overlapping 240- and 300-trending dyke swarms are considered to represent separate rift zones) volcanic rift zones. The three rift zones are at approximately 120° to one another in plan view. The structure of the Monte Amarelo edifice therefore resembles the ''Mercedes Star'' pattern proposed by Carracedo (1994, 1999-this volume) as being typical of oceanic island volcanoes in the absence of disturbing influences such as the buttressing effect of older edifices or regional structures (Walker, 1999-this volume). The diffuse or bifurcated western zone of the Monte Amarelo edifice may be due to such a disturbing influence, in this case the carbonatite–alkali basic intrusive basement complex of the Brava–Fogo platform (Fig. 1), exposed in the southwest of Fogo. Although this platform is largely below sea level, it should be noted that the other sides of Fogo descend steeply to the ocean floor at a depth more than one and a half times the height of the island above sea level: the platform may therefore have had a substantial buttressing effect upon the Monte Amarelo edifice.

Minor faults, with displacements of at most a few metres, occur close to the margins of many of the dykes. They may be emplacement related, analogous to the faults inferred to have been active during the 1995 eruption (Heleno da Silva et al., 1999-this volume). However, the larger faults inferred by previous workers (Machado and Torre de Assuncao, 1965; Brum da Silveira et al., 1995, 1997a,b) are not visible in locations where they should be well exposed. In particular, there is no evidence for offsets along the proposed Sambango–Monte Vermelho fault where this would displace rocks of the Monte Amarelo Group (Fig. 7), although this is inferred by these workers as an explanation for the missing eastern flank of the Monte Amarelo volcano; nor along the proposed Portela–Cova Figuera fault, also indicated in Fig. 7, where this would cut the cliff face shown in Fig. 6. Overall, the remaining parts of the Monte Amarelo edifice show no evidence for large scale deformation.

This observation excludes the possibility that the missing section of the eastern flank of the Monte Amarelo volcano could have been removed by movement on regional scale faults transecting the island as proposed by Machado (1965a). The remaining alternatives are central or caldera collapse followed by erosion and/or a small volume lateral collapse as proposed by Brum da Silveira et al. (1995, 1997a); or a large volume lateral collapse removing the entire missing sector.

4.2. Origin of the Bordeira and Espigao escarpments: caldera collapse or giant lateral collapse?

Large calderas, of the order of 5–10 km across, in oceanic island volcanoes are of two types: felsic and mafic. The former, typified by the calderas of the Las Canadas edifice on Tenerife (Ridley, 1971; Marti et al., 1994) are associated with large volume pyroclastic eruptive units including ignimbrites. No such units occur in the Monte Amarelo edifice, and especially not at the top of the sequence. Pyroclastic eruptive units with emplaced volumes of the order 20–60 km^3, the size required to explain even the smaller calderas proposed by Brum da Silveira et al. (1997a), would blanket much of the island with deposits tens of metres thick. The latter type of caldera, typified by the large calderas of the Galapagos islands (Walker, 1984, 1993) are associated with concentric fracture systems surrounding the caldera and interpreted by Walker as being the surface expression of cone sheet swarms. The latter are also not observed in the Bordeira cliffs, even in sections such as the sides of the Monte Amarelo spur (Fig. 6) which are approximately perpendicular to the predicted strike of any cone sheet swarms. The other features identified as being typical of Galapagos-type calderas by Walker, circumcaldera plateaux and concentric fracture systems, are also not present on

Fogo. Quental (1994) proposed that certain locally cliff parallel sheets exposed on the lower southern side of Monte Amarelo might be ring dykes: however, these WSW-trending sheets can be traced continuously up into the cliffs to the southwest, where they continue up the cliff with the same WSW trend and can be seen to be part of one of the radial dyke swarms.

The preferred interpretation of the Bordeira cliffs and the associated feature of the Espigao escarpment is therefore that these are parts of a large volume lateral collapse structure, here named the Monte Amarelo collapse structure. The gap between the Bordeira cliffs and the Espigao escarpment coincides with the younger SSE volcanic rift zone, which is interpreted as having buried this part of the cliff. The largely buried northern sidewall is inferred to run from the northeastern limit of the Bordeira cliffs to the southern limit of coastal palaeocliff and lava platform topography at Fonsacao (Fig. 2; see also Fig. 10). The occurrence of a large volume collapse of this type is supported by the evidence of early seismic profile mapping (Jacobi and Hayes, 1982). As noted in Section 1, this indicates the presence of large areas of recent debris avalanche deposit on the ocean floor south of Fogo.

The determination of the age of the collapse awaits the results of radiometric and cosmic ray exposure dating presently in progress: however, some inferences can be made from the morphology of the island. The state of preservation of the Bordeira cliffs, which as noted in Section 2 are near vertical and have been subjected to very little gully development in comparison to other recent collapse structures in broadly similar climates, such as the ca. 560-ka old Cumbre Nueva collapse structure in La Palma, Canary Islands (Carracedo et al., 1999a, 1999b-this volume) and the ca. 130-ka old El Golfo collapse structure in El Hierro, Canary Islands (Carracedo et al., 1997b), suggests that the collapse is at most some tens of thousands of years old. The age relationship of the collapse and the end of Monte Amarelo Group activity to the development of the coastal cliff and platform morphology does however suggest that, by analogy with the timing of the development of similar coastal morphologies in La Palma (Carracedo et al., 1999a), the collapse occurred before or during the main period of the postglacial rise in sea level. If this analogy holds true, then the collapse must be at least 10 ka old. Nevertheless, these age brackets would suggest that the lateral collapse of the Monte Amarelo volcano is one of the most recent in the Atlantic ocean basin. The ocean floor debris avalanche deposits inferred from the seismic profiles should therefore be exceptionally well exposed and susceptible both to sidescan sonar mapping and dredge sampling.

It is difficult to infer the depth of the collapse scar and thus the precise volume of the collapse from the available surface data. However, the observation that, except at the Monte Amarelo spur, the Bordeira cliffs are near vertical throughout their height, and with no evidence of curving into a basal detachment surface above the present level of the Cha das Caldeiras, suggests that they extend downwards below the surface of the Cha das Caldeiras for some hundreds of metres before linking into more gently inclined surfaces. The same argument applies to the Espigao escarpment. Furthermore, the lack of development of a coastal lava platform along the coast within the collapse scar and the inferred rapid erosion of the cliffs in this sector, in contrast to the coastal morphology to the north and south, imply very steep submarine topography offshore. This would not exist if a gently inclined collapse scar floor were present close to sea level. It therefore appears likely that the collapse scar fill sequence is several hundreds of metres thick throughout the region of the collapse scar with the sole exception of the region of the Monte Amarelo spur (Figs. 7 and 11). A sketch cross-section through the structure is presented in Fig. 9. This implies a collapse volume of the order of 200–300 km^3, or more if the collapse structure extended further down the submarine slope of the volcano. This is comparable to the volumes of collapses in the Canary Islands (Carracedo, 1994, 1996; Watts and Masson, 1995; Carracedo et al., 1999b-this volume).

Fig. 7 shows the projected position of the N–S trending en echelon dykes exposed on the Monte Amarelo spur. These dykes, if they extended to the south of Monte Amarelo, would have passed west of the summit region of the volcano. The development of the en echelon segmentation of these dykes indicates rotation of the extension direction from about 110 (the extension direction of the NNE rift zone) at

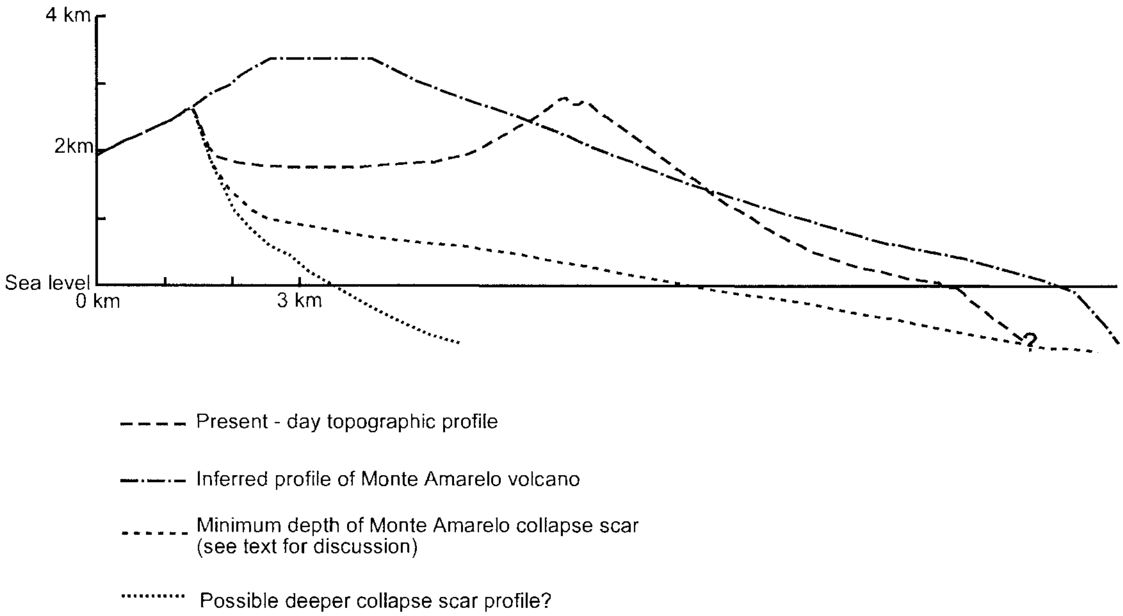

Fig. 9. Scaled cross-section showing the inferred pre-collapse profile of the Monte Amarelo volcano and the minimum cross-sectional extent of the Monte Amarelo collapse structure.

depth to E–W as these dykes propagated toward the surface. Their orientation and age relationships (discussed in Section 4.1) therefore indicate east–west dilation of the near surface region and most probably eastward movement of the summit region, immediately before or after the collapse. While the development of these dykes could have occurred as a result of piecemeal instability and failure of the initial collapse headwall (in the manner of recent dykes in the headwall of the Valle del Bove, Etna (McGuire and Pullen, 1989; McGuire et al., 1991), the inferred hiatus in activity after the collapse (Section 3, above) makes this less likely than the alternative. This is that these dykes record precursory instability of the Monte Amarelo edifice, prior to the collapse. This hypothesis will be further tested by the radiometric dating in progress.

5. Early growth of the Cha das Caldeiras volcano: a typical triple rift volcano

As noted in Section 3, most activity since the formation of the Monte Amarelo lateral collapse has occurred within the collapse scar, producing the Cha das Caldeiras volcano. Activity outside the collapse structure has virtually ceased at levels above that of the Cha das Caldeiras plain. However, it has persisted at lower altitudes in areas corresponding to the older volcanic rift zones, producing a thin veneer of young lava flows on the lower slopes of the volcano and the recent lava platforms at the seaward ends of these zones. Erosion during this post-collapse period has been limited and insufficient to expose feeder dykes. However, the preservation of the scoria and spatter cones built up around the vents is generally excellent and elongation directions of these, where apparent, can be used to deduce the alignment of the underlying feeder dykes according to the criteria proposed by Tibaldi (1995). Fig. 10 shows the general structural features of the Cha das Caldeiras volcano. A more detailed map of the vents within Cha das Caldeiras is presented below (Fig. 11). As in the previous period, only the NNE rift zone appears to extend to the coast and beyond: a Surtseyan tuff ring occurs on the coastal platform at Sambango, and a number of vents occur at the foot of the palaeocliff, including at least one formed in the eruption of 1785

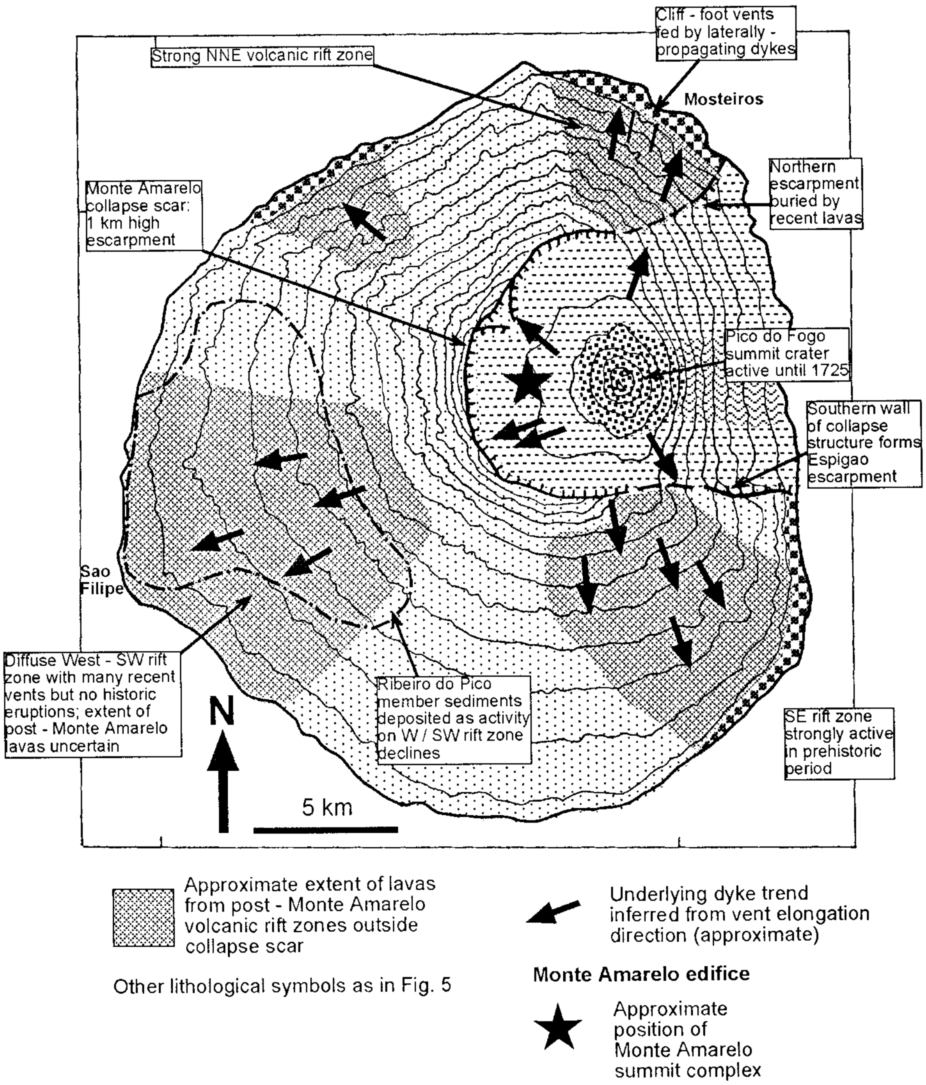

Fig. 10. Structural features of the Cha das Caldeiras volcano before the 18th century structural reorganisation of the volcano.

(Feijo, 1786; see also Ribeiro, 1960; Day, in prep.). This concentration of vents at the foot of the cliffs strongly suggests that the vents are fed by laterally propagating dykes.

The young volcanic rift zones converge upon an area in the centre of the Cha das Caldeiras, close to the inferred Monte Amarelo volcanic centre but possibly displaced to the east of it by up to 2 km. This zone of convergence now lies beneath the western flank of the Pico do Fogo, the summit of which is displaced further still to the east. As noted in Section 3 the Pico do Fogo may be a very recent overgrowth upon the top of the Cha das Caldeiras volcano: if so, the centre of activity may have moved eastwards with time. In addition to its summit vent, the Pico has a number of fissure vents exposed on its flanks. These are concentrated on its northern and southern flanks, with broadly N–S trends (Fig. 11, below). A north–south alignment of fumaroles on the northern side of the Pico and within the summit crater is also present. The Pico do Fogo cone also shows a slight overall north–south elongation (Fig. 11), perhaps

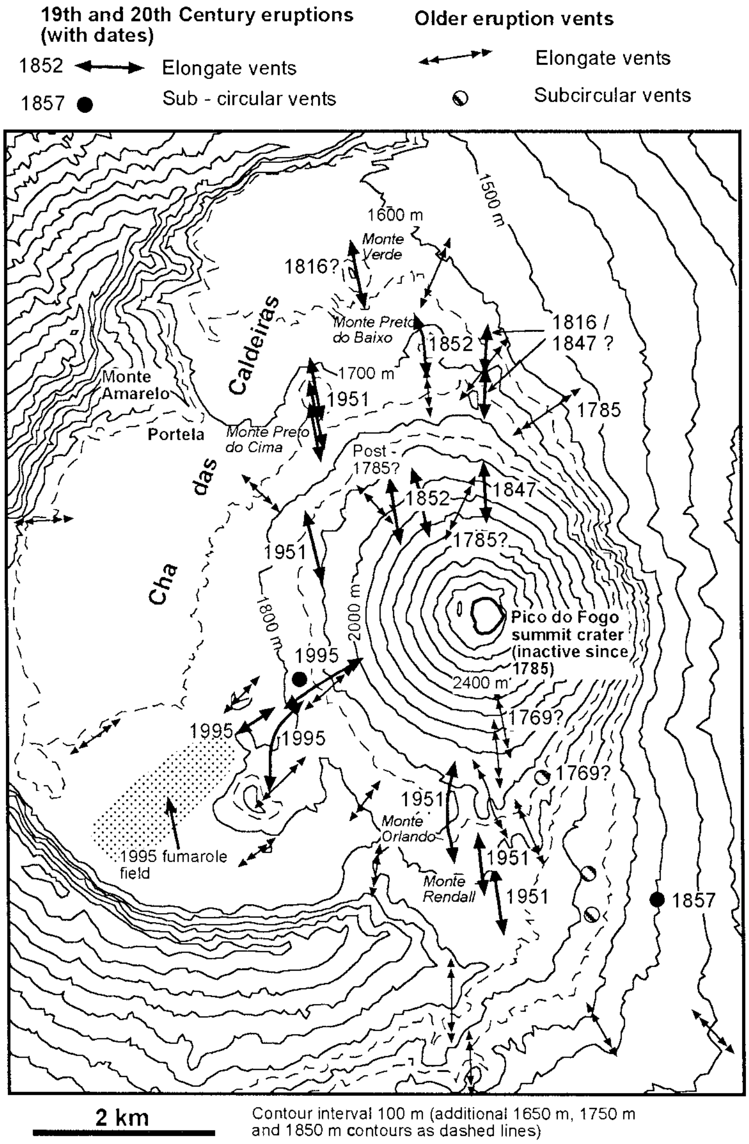

Fig. 11. Vents and vent elongation directions within Cha das Caldeiras — pre- and post-1800 vents separated, name 1951 eruptive vents.

due in part to the activity of these fissure vents since the summit crater itself is almost perfectly circular. The development of this north–south trend may be a precursor of the more widespread north–south fissure alignment trend developed in the post-18th century period (Section 6, below).

The growth of the Pico do Fogo, coupled with eruptions from the upper parts of the NNE and SSE rift zones themselves, may explain why any morphological expression of the rift zones is obscured within the Monte Amarelo collapse structure. Lava flows erupted from these rift zones and flowing westwards are trapped within the Cha das Caldeiras and tend to pond there resulting in the development of almost flat enclosed plains. The western rift zone(s) in particular are only defined by partially buried vents (Fig. 11). The ponded lavas have also, in many parts of Cha das Caldeiras, buried screes of the Boca

Fonte member. Many cuspate rockfall scars exist in the Bordeira cliffs suggesting that the Boca Fonte breccias may be more extensive at depth. Comparison with less completely filled or more deeply incised collapse structures in the Canary Islands (Carracedo et al., 1997b, 1999a) also suggests that post-collapse rockfall and alluvial breccias covered much of the floor of the collapse structure in the immediate post-collapse period.

The lack of expression of the western rift zone(s) within Cha das Caldeiras may in part be an expression of a decline in activity through time. Outside Cha das Caldeiras the same decline may be manifested in the development of the Ribeira do Pico member (Section 3.1). If, as seems likely, deposition of the Ribeira do Pico member began after the Monte Amarelo collapse, this may represent the first stage in the recent structural reconfiguration of the Cha das Caldeiras volcano discussed in Section 6. A second stage may be represented by the concentration of activity which produced the Pico do Fogo. The 1995 eruption, the only known historic eruption to have occurred with a westerly (actually 240) fissure alignment, is therefore something of an anomaly.

A comparison may be drawn between the activity on Fogo during this period and the distribution of recent activity on Piton de la Fournaise volcano, Reunion island, which also sits largely within an older collapse structure (Duffield et al., 1982; Lenat and Labazuy, 1990; Steiltjes, 1990): the two rift zones which flank the collapse structure and face out to sea have been active on a number of occasions within the historic period whilst the third, diffuse rift zone has only one recorded eruption.

6. Structural reconfiguration of the Cha das Caldeiras volcano during the past 3 centuries

Historical accounts of eruptive activity on Fogo are summarised and analysed by Ribeiro (1960): further discussions and correlations with geological evidence are to be found in the work of Day et al. (in press). Accounts dating from the 16th century to around 1725 indicate very frequent (although not continuous as argued by, inter alia, Machado, 1965b) and intense strombolian eruptions (with some episodes of vulcanian activity) at the summit of the Pico do Fogo, accompanied in some cases by flank eruptions on the eastern side of the island. No eruptions occurred on the southwest side of the island where the town of Sao Filipe (Fig. 2) has been occupied continuously since the end of the 15th century. The actual locations of the flank eruptions are poorly known because the eastern side of the island was not settled in an organised manner until later in the 18th century.

The last intense activity at the summit of the volcano occurred in about 1725 and thereafter, apart from brief, possibly phreatic or phreatomagmatic, explosions in the well documented eruption of 1785 (Feijo, 1786; see discussion in Ribeiro, 1960; Day et al., in press), the summit crater of Pico do Fogo has been inactive. The 1785 eruption, which took place at a number of vents aligned along the NNE rift zone including two on the northeastern coast (Figs. 10 and 12), was also the last to involve vents outside the region enclosed by the Monte Amarelo collapse structure and thus the last occasion on which near surface dykes are known to have propagated outside that structure.

With one or possibly two exceptions all post-1785 eruptions have occurred on a distinctive N–S structural trend, which is illustrated in Fig. 11. Detailed evidence for the location of these vents, which differ in a few cases from those proposed by Torres et al. (1997a), is presented by Day et al. (in press) and Day (in prep.). The exceptions are the 1995 eruption, as noted above, and possibly the poorly located 1799 eruption, which has been correlated by Torres et al. (1997a) with a rather anomalous, NE-trending group of fissures on the steep eastern flank of the island ENE of Pico do Fogo and thus at the extreme southern edge of the NNE rift zone. Apart from these two all the eruptions in this period have occurred on N–S-trending fissures.

The data on vent orientations and their changes through the 18th century, as summarised in Fig. 11, indicate that the 18th century was a period of rapid change in the style and distribution of volcanic activity on Fogo. Up until the end of the first quarter of the century the most spectacular activity was that at the summit of the Pico do Fogo. The rest of the century was marked by flank eruptions, but along established trends in the in the existing rift zones: these produced the Monte do Principe member,

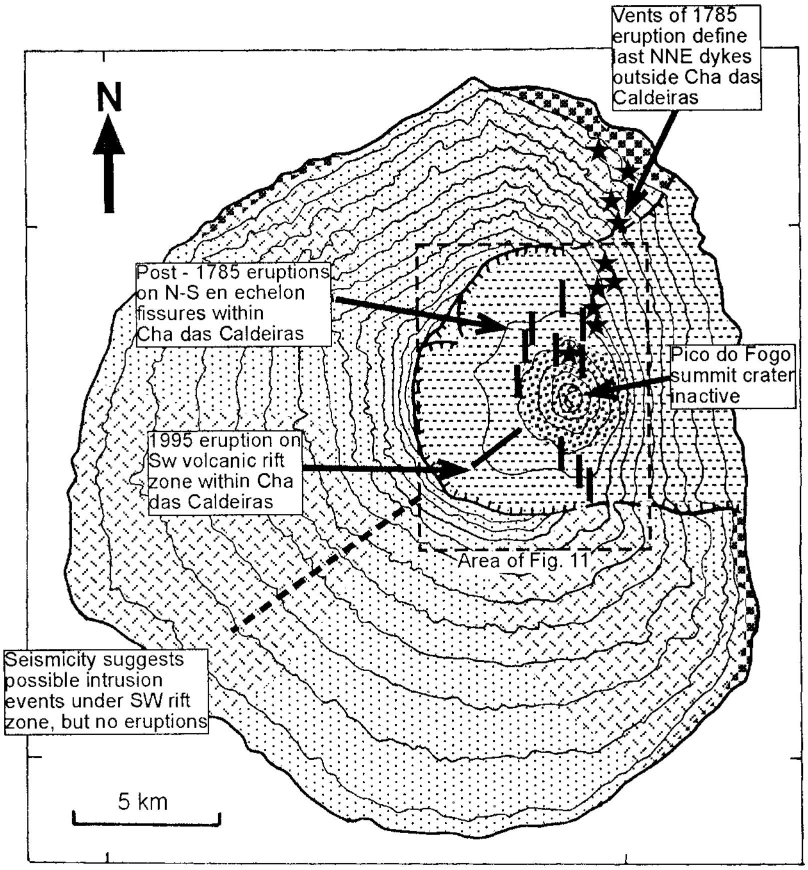

Fig. 12. Summary map of differences between pre- and post-1800 activity.

named after a vent of the 1785 eruption. The N–S-trending swarm of fissure eruptions, which arguably forms a new rift zone although it is a very young feature, defines the Monte Preto de Cima member. This fundamental change in the style and distribution of activity is the justification for the separation of the Pico do Fogo and Monte Orlando formations (Fig. 4).

At least two of these eruptions, those of 1852 and 1951, have involved eruptions from en echelon arrays of fissures. Ribeiro (1960) provides a detailed account of the 1951 eruption, and Day et al. (in press) and Day (in prep.) consider the detailed evidence for the 1852 and 1951 vent locations. In the case of the 1852 eruption, which occurred north of the Pico do Fogo, these en echelon fissures are aligned along an NNE trend. In the 1951 eruption, two groups of right stepping fissures developed along N and NNE trends, respectively NW and NNW of Pico do Fogo, and a third group of left stepping fissures developed along an SSE trend south of the Pico.

The systematic development of en echelon segmentation in these fissure sets is significant. The overall trends of the groups of fissures are interpreted as indicating the orientations of the feeder dykes at depth, while the orientations of individual eruptive segments are interpreted as indicating the orientations of the feeder dykes in the immediate subsurface (see Carracedo et al., 1999b-this volume; Day et al., 1999-this volume for a more detailed discussion). The patterns developed in the 1852 and 1951 eruptions imply that they were fed by dykes emplaced along the old NNE and SSE trends at depth, but which subsequently propagated upwards into an east–west extensional stress field nearer the surface.

This implies at least partial decoupling of the stress field associated with triple rift development at depth (Carracedo, 1994) from the near surface stress field. The near surface stress field is aligned with its minimum (least compressive) principal stress parallel to the top of the east facing slope on the east side of Cha das Caldeiras, a geometry consistent with the near surface stress field being controlled by the gravitational-topographic stresses associated with that slope (McGuire and Pullen, 1989). This stress field geometry is similar to that documented by McGuire and Pullen (1989) and McGuire et al. (1991) for dykes emplaced across the headwall of the Valle del Bove, Etna. Furthermore, the distribution of young N–S aligned fissures across the width of the Cha das Caldeiras in an N–S zone, up to the sidewalls of the Monte Amarelo collapse structure, indicates the development of east–west extension within this structure, but not outside it. The extension must therefore have been accommodated by deformation in zones coinciding, at least at the surface, with the sidewalls of the Monte Amarelo collapse structure. It may be significant that the largest felt earthquakes during eruptions in the last two centuries, including one in 1847 (Ribeiro, 1960) which caused severe damage and one death in the village of Bombardeiro (Fig. 2), have been felt most intensely in the vicinity of the Espigao escarpment, suggesting seismogenic movements along the southern sidewall of the Monte Amarelo collapse structure.

The changes in the pattern of eruptive activity of the Cha das Caldeiras volcano since the 18th century, summarised in Fig. 12, therefore suggest an incipient stage of reactivation of the Monte Amarelo collapse structure. This interpretation is discussed further in Section 8 in the light of evidence for surface deformation and seismicity during and after the 1951 and 1995 eruptions.

7. Deformation during the 1951 and 1995 eruptions: precursors to lateral collapse?

The 1951 and 1995 eruptions of the Cha das Caldeiras volcano are the only eruptions of Fogo to have been observed and described in detail by geologists and geophysicists. Detailed descriptions of the eruptions are presented, respectively, in Ribeiro (1960) and in IICT (1997). Although the locations of the two eruptions differ markedly, with the 1951 eruption taking place on the N–S eruptive fissure zone and the 1995 eruption on the WSW component of the broad western rift zone (Fig. 11), both are associated with ground deformation extending outside the immediate vicinity of the eruptive fissures. This is in contrast to the earlier historical eruptions, in which at most minor fracturing of scoria and/or spatter cones in the immediate vicinity of the vents (and thus perhaps due to magma drainback and subsidence in the immediate vicinity of the vents) is preserved. Brum da Silveira et al. (1995; 1997a; b) describe minor faults cutting lapilli beds exposed in the walls of one of the 1995 eruptive fissures which indicate earlier ground deformation: however, such faults must be rare since large tracts of undisturbed sediment and pahoehoe lavas exist within the Cha das Caldeiras. It is also possible that these faults formed in 1951, since they extend to the pre-1995 surface and lie within the region of the proposed 1951 fracture system, discussed below.

The 1951 eruption was observed by geologists (principally Ribeiro himself) but was not seismically monitored, although felt seismicity was recorded by colonial officials: thus the record of deformation is largely that of surface fissuring. In contrast, a number of separate seismic networks were deployed at various stages of the 1995 eruption (Brum da Silveira et al., 1995; Heleno da Silva and Fonseca, in press; Heleno da Silva et al., 1997, 1999-this volume; Pereira and Burton, 1997), although no geodetic networks were deployed.

7.1. Surface fissuring associated with the 1951 eruption

This fissuring is developed around the northernmost vents of the eruption, at Monte Preto de Cima, and the southern group of vents (Monte Orlando and Monte Rendall), shown in Figs. 11 and 14. The middle group of vents was only active in the first few days of the eruption and does not appear to have any surface fissuring associated with it, although it should be noted that this area has been partially

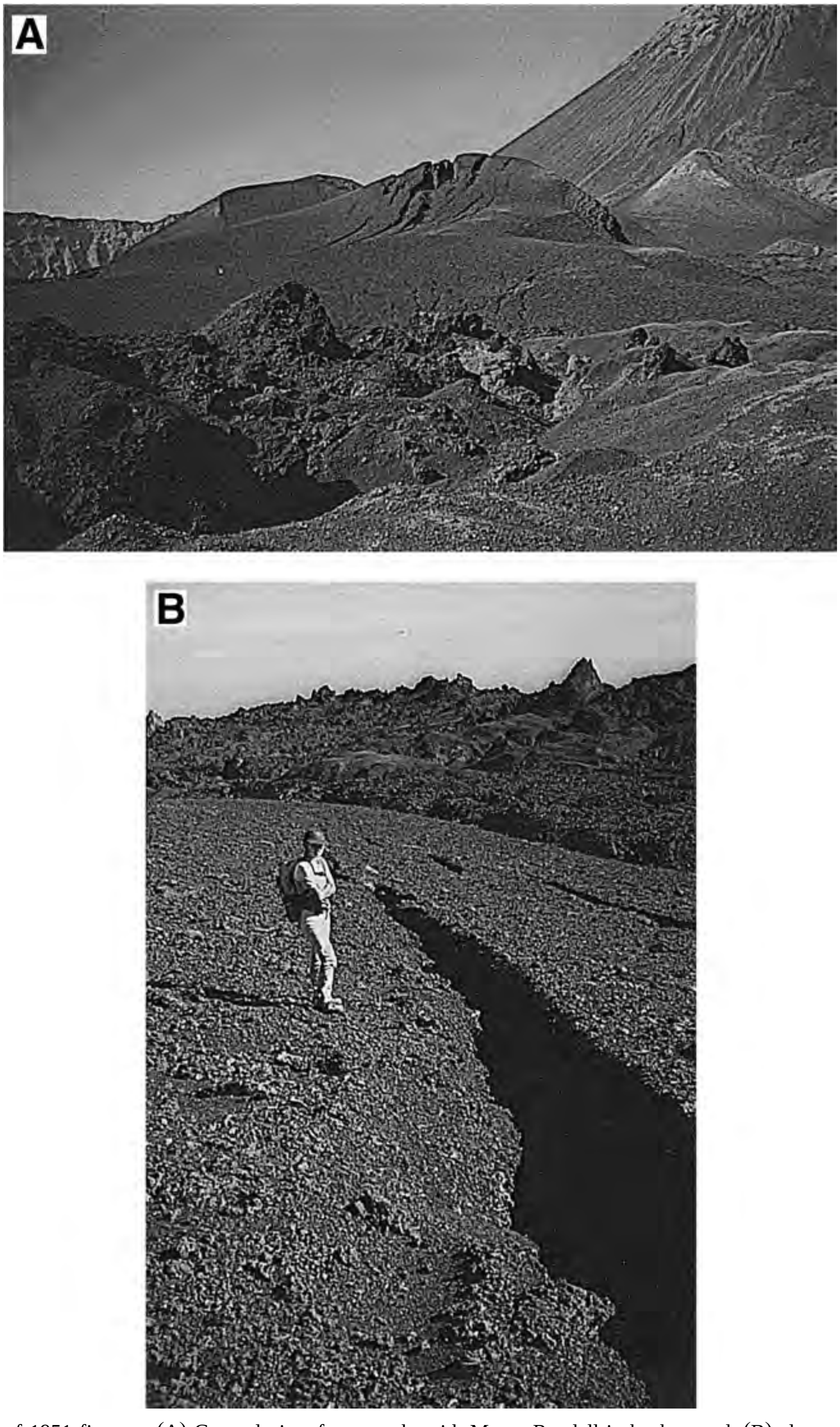

Fig. 13. Field photos of 1951 fissures. (A) General view from south, with Monte Rendall in background; (B) close-up of fissures, SINHS (1.7 m tall) for scale.

covered by lapilli from the 1995 eruption and thus any small scale fissuring may have been obscured.

The fissures are best developed around the southern group of vents: their appearance in this area is shown in Fig. 13. Most fissures are aligned N–S within en echelon sets up to 300 m long, but arcuate fissures linking the sets and trending NW–SE are also present. Widths of individual fissures range up to up to 2 m wide in the flat ground away from the vents: those at the summit of Monte Rendall (in the background of Fig. 13A) are substantially wider but may have been accentuated by subsidence and partial collapse of this scoria cone. There is however no evidence of vertical movements across individual fissures and no overall subsidence within or across the fissure zone, again except at the summit of Monte Rendall. The fissures appear to be purely dilational.

The timing of opening of the fissures in 1951 can be constrained by the observation that they are not filled by erupted lapilli and scoria, even when they are close to vents such as Monte Preto de Cima and Monte Orlando whose activity continued to the end of the eruption in early August 1951 (Ribeiro, 1960). They were also not observed by Ribeiro when he visited these vents in the middle of the eruption, in late June and early to mid July of 1951, but were fully developed by the time that he revisited the island in 1952. A further clue to the timing of their formation comes from the record of felt seismicity kept by the island administrator, L. Rendall, which includes a swarm of earthquakes from August 12 to August 18, 1951 that were not accompanied by any eruptive or phreatic explosive activity. This was at about the time of, or just after, the end of eruptive activity at the last vent to remain active (Monte Orlando) but if the fissuring were related simply to magma drainback in a subsurface dyke it would be expected to be dominated by subsidence rather than being dilational in character.

An alternative explanation of the 1951 dilational fissures is that they are the surface expression of eastward movement of the eastern flank and central region of the Cha das Caldeiras volcano. This hypothesis is illustrated in Fig. 14. One of the unknowns in this interpretation is the geometry of structures linking the central group of 1951 fissures at Monte Mendes with those in the south, since much

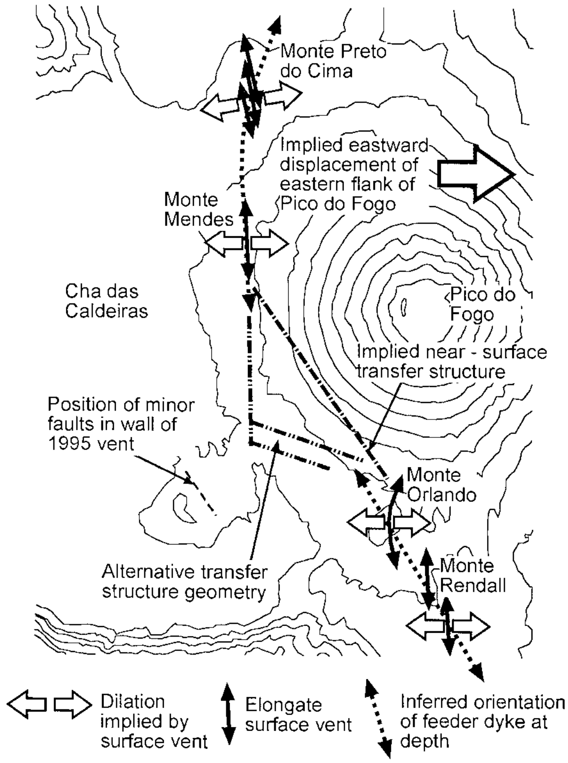

Fig. 14. The 1951 eruption structural sketch map.

of the intervening area has been covered by the products of the 1951 eruption. One of the alternatives shown in Fig. 14 links the two sets of structures along a transfer structure parallel to the minor NW–SE trending faulting observed by Brum da Silveira et al. (1995, 1997a) in the wall of one of the 1995 vents. Although the main fault observed by Brum da Silveira et al. had a net downthrow to the SW, the exposure was extremely limited and other faults may have been present.

7.2. Fissuring and seismicity associated with the 1995 eruption

A more detailed account of the seismicity associated with this eruption is to be found in the work of Heleno da Silva et al. (this volume). Here, we emphasise the structural implications of their results and also those of geological observations (Brum da Silveira et al., 1995, 1997b; Torres et al., 1997b) made during the eruption.

Much of the activity recorded by Heleno da Silva and co-workers can be related to movement on

WSW-trending faults, associated with inflation and deflation of the WSW-trending main dyke of the 1995 eruption, and to magma and hydrothermal fluid movement, expansion and degassing. However, groups of high frequency events (interpreted as fault movements), mainly during the magma drainback and post-eruptive phases of activity, occur to the north of the eruptive fissure as well as a fissure-parallel trend along the fissure and extending to the east under the Pico do Fogo. Amongst these events are groups with joint focal plane solutions indicating subhorizontal extension across steep, NNW- and NNE-striking fault surfaces. These events can be interpreted as indicating easterly, seaward movement of the eastern flank of the Cha das Caldeiras volcano.

As noted previously, the main eruptive fissure of the 1995 eruption is aligned along the WSW trend of the western rift zone, with an overall bearing of 240. However, to the south of this main trend an arcuate fissure curving southwards from an NE–SW to an N–S trend was active on the first day of the eruption (April 3, 1995) and again on April 9 and April 10, 1995 (Torres et al., 1997b). The position of this fissure is indicated in Fig. 11 and in Fig. 15, below. It produced a very small volume of erupted magma in comparison with the main fissure but can be traced for a distance of some hundreds of metres, in places as a vertical walled fracture 3–4 m across. Its development implies an east–west dilation. The very small amount of magma erupted from it suggests that this dilation was not primarily driven by a high magma overpressure in the fracture. Rather, dilation of this fracture system may have resulted from eastward movement of the eastern side of the fracture.

These observations therefore suggest that, although the 1995 eruption occurred on the western (or WSW) rift zone of the Cha das Caldeiras volcano, it nevertheless triggered some eastward movement of the summit and eastern flank of the volcano. A possible geometry of deformation associated with the 1995 eruption is shown in Fig. 15. It will be noted that the inferred fracture systems of the 1951 eruption (Fig. 14) lie in directions of predicted high shear stress (Pollard, 1987) with respect to the postulated position of the tip of the 1995 dyke. Reactivation of these structures with a strike slip sense of displacement to accommodate emplacement of the dyke may have further complicated the pattern of seismicity in 1995.

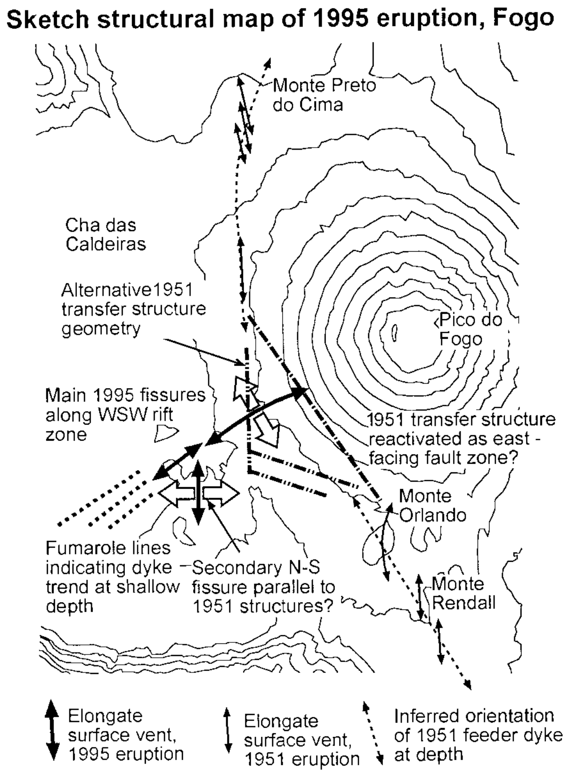

Fig. 15. The 1995 eruption structural sketch map.

8. Is the recent structural evolution of the Cha das Caldeiras volcano a precursor to a future lateral collapse?

The several stages of the recent structural evolution of the Cha das Caldeiras volcano can be summarised as follows, starting from the modified triple rift structure discussed in Section 5:

- Decline of activity on the WNW and WSW trends of the western rift zone, especially outside the Monte Amarelo collapse scar, and accumulation of the Ribeira do Pico alluvial deposits; continuing activity on the NNE and SSE rift zones involving laterally propagating dykes feeding multiple vents inside and outside the Monte Amarelo collapse structure.
- Development of the N–S-elongated Pico do Fogo summit cone at or slightly to the east of the rift

zone intersection, accompanied by reworking of epiclastic breccias onto the eastern flank of the volcano to produce the Ribeira Nha Lena member; period of intense summit activity lasting into the early historic period and ending about 1725.

- Cessation of summit activity and, after the eruptions of the Monte do Principe member over the remaining decades of the 18th century, the end of lateral propagation of dykes in the rift zones; subsequent (post-18th century) eruptions of the Monte Orlando formation confined to the Cha das Caldeiras and involving eruptions from N–S trending eruptive fissures.
- Development of en echelon arrays of N–S eruptive fissures in the eruptions of 1852 and 1951, indicating vertical propagation of feeder dyke arrays, from NNE- and SSE-trending dykes at depth, through a near surface region of E–W extension, possibly controlled by topographic-gravitational stresses, and bounded to north and south by the sidewalls of the old Monte Amarelo collapse structure.
- E–W extension developed on faults and surface rupturing dilational fissures during and immediately after the most recent eruptions of 1951 and 1995.

Although the numbers of eruptions involved in the later phases are small these events are suggestive of the development of an increasing instability of the eastern flank of the Cha das Caldeiras volcano during the recent period. In particular, the transition from laterally propagating dykes to vertically propagating en echelon arrays of dykes parallels the change from lateral to vertical propagation seen in the youngest dykes of the Monte Amarelo edifice (Section 4), prior to the Monte Amarelo collapse. The abandonment of the shallow central magma conduit of the Monte Amarelo volcano implied by the development of dykes propagating vertically from depth may also find a counterpart in the end of summit activity at the Pico do Fogo. The WSW-trending main fissure of the 1995 eruption is an anomaly in this pattern. However, the distribution of seismicity in 1994 (Heleno da Silva and Fonseca, in press; Heleno da Silva et al., 1997), suggests that the 1995 eruption may be related as much to activity beneath Brava as to the magma feeder system beneath Fogo.

The restriction of recent eruptive activity to within the Monte Amarelo collapse structure and the inference that the sidewalls of this collapse structure may have been reactivated as faults suggests that the older collapse structure may have some influence on the development of the volcano. This may be through the presence of weak deposits lining the collapse structure, such as remnant debris avalanche deposits, collapse fill breccias produced by piecemeal collapse and erosion of the collapse scar walls (buried equivalents of the Boca Fonte member screes and alluvial deposits seen at the surface (Section 3)), and hyaloclastites and phreatomagmatic deposits. An additional factor may be the absence of the structural reinforcement provided by the Monte Amarelo dyke swarms in the intact parts of the edifice. A schematic view of the inferred subsurface structure of the volcano at the present stage of its evolution is shown in Fig. 16. The volume of the inferred incipiently unstable region is less than that of the earlier Monte Amarelo collapse but is nevertheless of the order of several 10s to more than 100 km^3.

If the Cha das Caldeiras volcano is approaching an unstable condition, there is some evidence to indicate that the instability is at present only slight. The lack of net vertical offset or graben subsidence on the 1951 surface fissures indicates that the motion is accommodated primarily by the dilation of subsurface fissures rather than downslope sliding on a fault system; and that it is driven more by the presence of magma in the system and the dissipation of the resulting magmatic and pore fluid overpressures (Elsworth and Day, 1999-this volume) than by the release of gravitational energy associated with downslope movement. Although relevant data are limited, the lack of seismic activity beneath eastern Fogo in 1994 (Heleno da Silva and Fonseca, in press) and the absence of felt seismicity in intereruptive periods suggests that deformation of the eastern flank of the Cha das Caldeiras only occurs when the additional stresses associated with eruptions are operative.

Thus, although the geometry of the deformation is strongly influenced by gravitational-topographic stresses, it appears that actual deformation requires the addition of these stresses. Eruption related stresses would include direct magma overpressure, mechanical pore fluid pressurisation, seismic acceleration and thermal pore fluid pressurisation (Elsworth and Voight, 1995, 1996; Day, 1996; Iverson, 1996). Elsworth and Day (1999-this volume) consider the

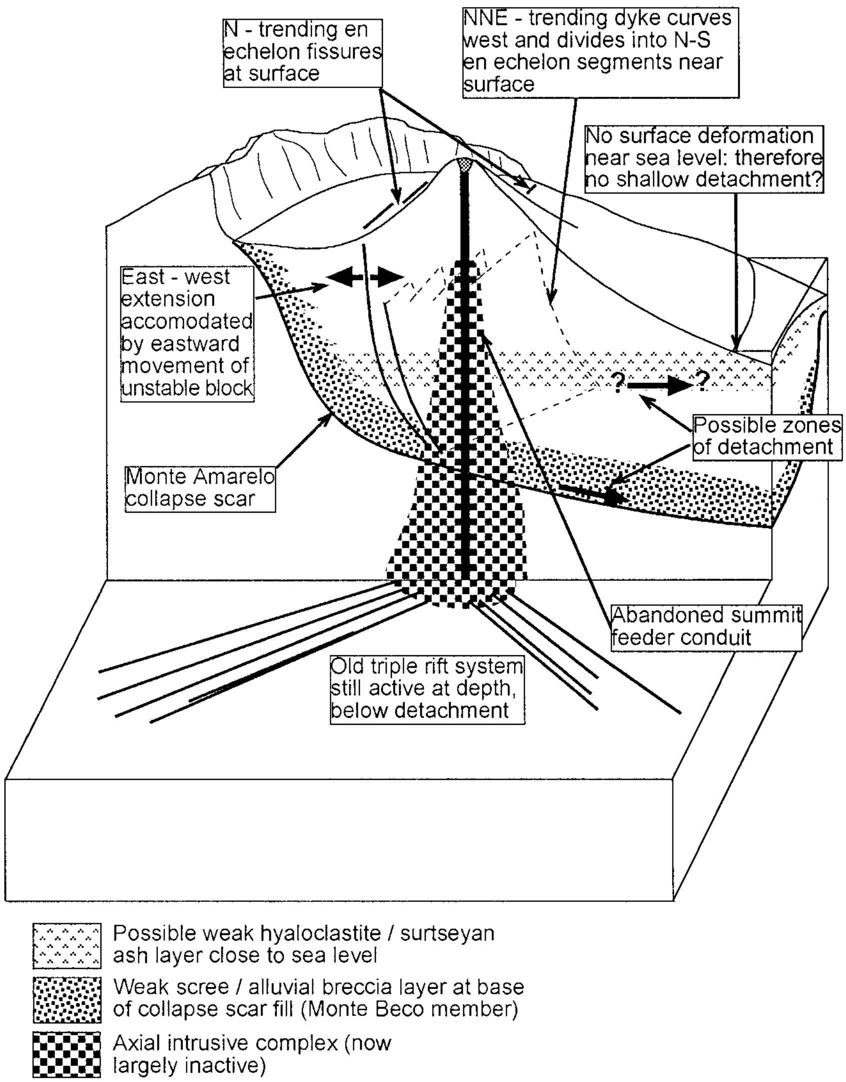

Fig. 16. Oblique sketch of the likely configuration of instability of the east flank, viewed from south, with rotation of dykes shown.

likely relative magnitudes of these stresses in steep sided volcanic edifices such as the Cha das Caldeiras and the timing of their operation relative to the start of eruptive activity, and conclude that the occurrence of dilational fissuring at the end of the 1951 eruption and of the post-eruptive, east directed faulting in 1995 suggest that thermal pore fluid pressurisation may be the most important force driving the incipient slope instability.

The lack of intereruptive deformation is in strong contrast with the near continuous seismic activity beneath the flank of the archetypal unstable volcano flank, that of Kilauea (Swanson et al., 1976; Moore et al., 1989). However, the slope angles of the flanks of Fogo, except in the west, are a factor of 3–4 greater than those at Kilauea and therefore significantly less stable (Elsworth and Day, 1999-this volume). Fogo may therefore be more closely comparable to the islands of the Canarian archipelago, where large scale slope failure may occur with little precursory activity (Day et al., 1997; Carracedo et al., 1999b-this volume). A comparison of the recent structural evolution of the Cha das Caldeiras volcano with that of the Cumbre Vieja volcano, La Palma (Carracedo et al., 1999b-this volume; Day et al., 1999-this volume) may be particularly instructive: both volcanoes have undergone a reconfiguration of their rift zones in the geologically very recent past, now have eruptive fissure trends indicative of control by gravitational-topographic stresses, and have experienced flank fissuring and faulting during recent eruptions.

Although the work described here is largely at the level of a reconnaissance, it nevertheless demonstrates the occurrence of a giant lateral collapse in the recent geological past of Fogo, the Monte Amarelo collapse, and indicates that the post-collapse volcano, the Cha das Caldeiras volcano, has undergone recent structural evolution which is best interpreted as indicating the onset of incipient instability. Permanent geodetic and geophysical monitoring of the island is presently being implemented (Fonseca et al., 1998) and the networks of seismometers and geodetic monuments have been specifically designed to facilitate detection and monitoring of any future movements of the eastern flank of the Cha das Caldeiras volcano. A future collapse of the volcano, especially in view of the very steep submarine topography and consequent likely high velocity of any debris avalanche, could cause a major tsunami hazard. Further studies of the Monte Amarelo volcano and collapse structure including dating of the collapse (presently in progress, through radiometric and cosmic ray exposure dating of pre- and post-collapse rocks) and surveying of any associated debris avalanche deposits offshore would be of value in quantifying the likely level of hazard.

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