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Pre-caldera pyroclastic deposits of Deception Island (South Shetland Islands)

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Abstract: The youngest pre-caldera volcanism of Deception Island is represented by a thick sequence of subaerial pyroclastic deposits which has been grouped as the Yellow Tuff Formation. Most of these deposits were related to the explosive activity of a central vent which was destroyed during the formation of the caldera. Two members can be distinguished in this formation. The lower member is mainly composed of 1 to 12 m thick massive pyroclastic flow deposits with interbedded air-fall and surge deposits. The upper member is in stratigraphical continuity with the lower member and consists of base surge deposits with minor air-fall and thin pyroclastic flow deposits. The pre-caldera deposits have undergone a palagonitic alteration which produced crystallization of smectites, Fe-oxides, zeolites and calcite.

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Introduction

Deception Island is situated astride a Quaternary (<1.5 Ma) marginal basin spreading centre in Bransfield Strait (Smellie 1988, 1989), which separates the South Shetland Islands from the Antarctic Peninsula (Fig. 1). The spreading centre is best developed between Deception and Bridgeman islands and includes a line of submerged seamounts (Smellie 1989). Deception Island is a young (< 750 Ka, after Smellie 1988) stratovolcano 25 km in submerged basal diameter (Smellie 1988) which has been very active during its entire evolution, although different periods of activity can be distinguished. The last eruptions took place in 1967, 1969 and 1970.

Previous studies on the petrology and volcanology of the recent eruptions of Deception Island have been made by Hawkes (1961), González-Ferrán & Katsui (1970), Baker *et al.* (1975) and Smellie (1988, 1989). Nevertheless, the oldest volcanic rocks are still not well known.

During three field seasons between 1987 and 1989, an international expedition involving Spanish, Italian and Argentine working groups studied the volcanology, structure and unrest of Deception Island. This paper presents some results of this study and addresses the stratigraphy, sedimentology and volcanology of the old volcanic series, which have in the past been classified as pre-caldera rocks (e.g. Hawkes 1961, González-Ferrán & Katsui 1970, Baker *et al.* 1975, Smellie 1988). The hydrovolcanic character of these deposits was misinterpreted by some previous workers (Baker *et al.* 1975, Roobol 1982) and until recently has not been clearly identified (Smellie 1988, 1989, Martí & Baraldo 1989).

Geological background

The South Shetland Islands form an archipelago 550 km long parallel to the northern extreme of the west coast of the Antarctica Peninsula. Geophysical data (Ashcroft 1972, Barker & Griffiths 1972, Parra *et al.* 1984) suggest that these islands lie on a continental plate restricted to the east by the Bransfield Strait back-arc marginal basin, to the west by a well-defined trench zone and to the north and south by transform faults.

The edge of the Bransfield rift is defined by a spreading centre with which Deception, Penguin and Bridgeman islands

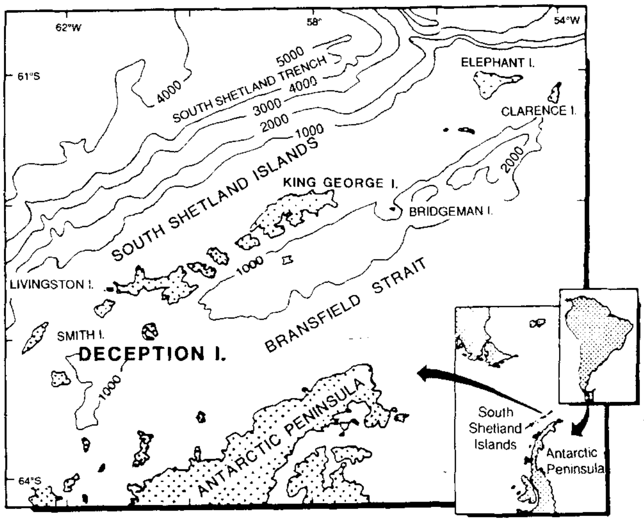

Fig. 1. Location map of Deception Island.

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and some submerged volcanic vents are associated. The geochemical character of volcanic rocks from these islands is transitional between calc-alkaline and MORB (Weaver *et al.* 1979). This fact appears to be consistent with a model of mantle diapirism and crustal fracturing during the first stages of back-arc spreading (Weaver *et al.* 1979, Tarney *et al.* 1982).

According to Weaver *et al.* (1979) the composition of the Deception Island volcanic rocks ranges from olivine basalt to rhyodacite. However, the basic and intermediate rocks are the most abundant volcanic products on this island.

Previous workers have pointed out the existence of a caldera structure in the central part of the island which is thought to have formed by collapse of several pre-existing volcanic edifices (Hawkes 1961) or by the collapse of a central stratovolcano (González-Ferrán & Katsui 1970; Baker *et al.* 1975). Subsequent to this, the volcanic activity continued associated with the concentric faults around the edge of the caldera (Smellie 1988).

Stratigraphy of Deception Island

Volcanic rocks of Deception Island have been traditionally divided into pre- and post-caldera products (Hawkes 1961, González-Ferrán & Katsui 1970, Baker *et al.* 1975). A syn-caldera group has also been considered by some authors (Baker *et al.* 1975). Smellie (1988) proposed a detailed stratigraphy of Deception Island classifying the pre- and post-caldera rocks in different rock groups.

The results of our study are in agreement with the stratigraphy proposed by Smellie (1988), but suggest that a more detailed subdivision of the pre-caldera deposits can be made. Therefore, we stratigraphically divide the precaldera products into two formations: the Basaltic Shield Formation (BSF) and the Yellow Tuff Formation (YTF). The BSF includes basaltic lava flows and some scoria deposits and palagonitized tuffs. These rocks form the shield structure which represents the basement of the island. The volcanic episode represented by this formation was mainly submarine, but a sequence of

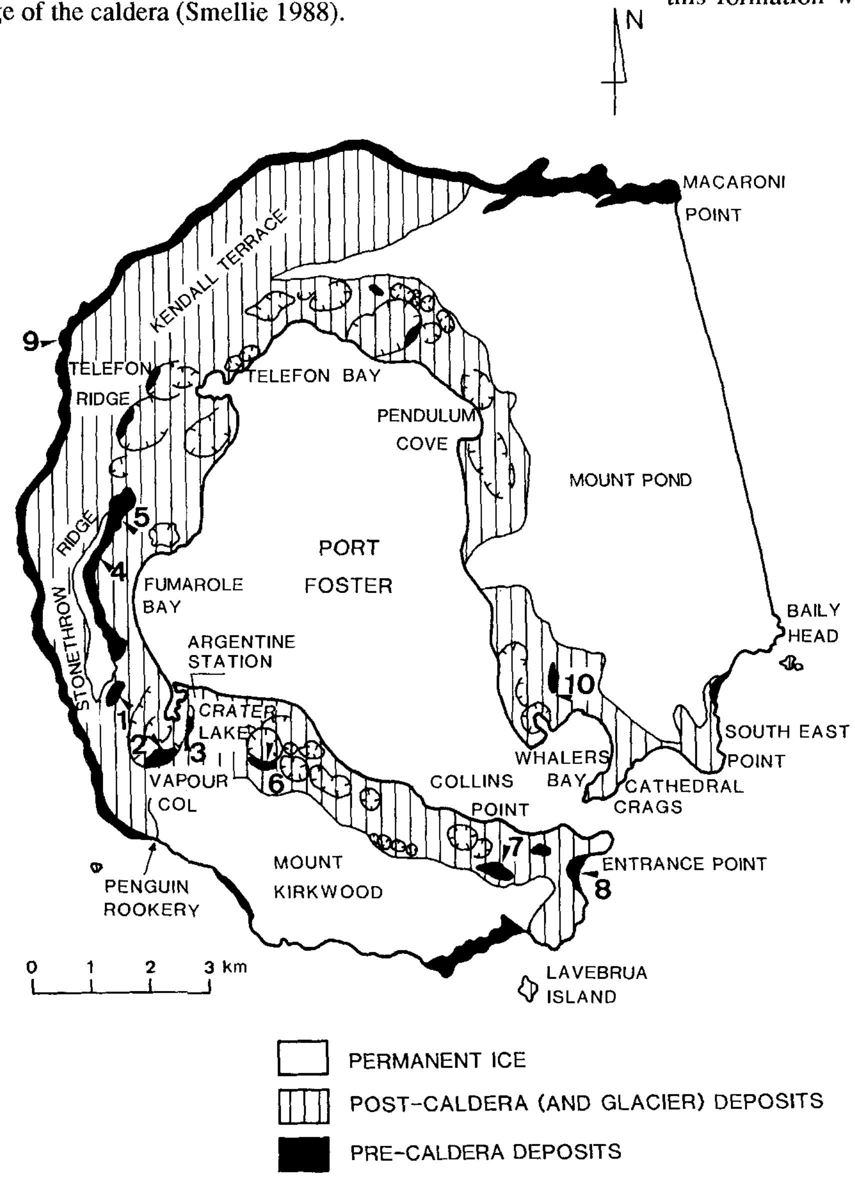

Fig. 2. Simplified geological map of Deception Island, showing the distribution of the pre- and post-caldera volcanic deposits. Numbered localities correspond to the stratigraphic sections shown in Fig. 3.

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subaerial brecciated and pahoehoe lava flows and strombolian deposits is exposed in Stonethrow Ridge. The YTF represents the youngest of the pre-caldera deposits and consists of palagonitized subaerial tuffs. This formation is divided into two members, a lower member with massive deposits and minor interbedded laminated beds, and an upper member which consists of finely-laminated deposits. For the most part the lower member corresponds to the Outer Coast Tuff of Hawkes (1961). The lower member crops out forming an interrupted exposure from Macaroni Point to the south of Entrance Point (see Fig. 2). In contrast, the upper member only appears forming discontinuous outcrops and is better exposed in the interior of the island. The products of post-caldera volcanism are not discussed in this paper.

Pre-caldera volcanism

Fig. 2 shows a schematic representation of the geology of Deception Island. The location of the studied outcrops are also shown and Fig. 3 shows stratigraphic sections of the YTF observed at some of these outcrops.

Discrimination between pre- and post-caldera rocks is not always easy due to lack of radiometric dates, disturbance of the earliest structure by contemporaneous faults, and because part of the island is covered by permanent ice which has been coated by basaltic ash from the latest eruptions. Nevertheless, identification of the main part of the pre-caldera rocks has been made using criteria such as geometric relationships, correlations between similar stratigraphic series, coincidence of alteration processes and similar distribution with respect to the tectonic structure. The presence of pre-caldera basaltic rocks (BSF), which constitute the unexposed basement of the island, has mainly been inferred from the study of the lithic fragments in the YTF rocks and by the presence of basaltic rocks at the base of the YTF at Stonethrow Ridge and Macaroni Point. The characteristics of these earliest pre-caldera rocks are not presented in this work.

Many of the YFT outcrops shown on Fig. 2 have already been attributed to the pre-caldera volcanism (Hawkes 1961, González Ferrán & Katsui 1970, Baker *et al.* 1975, Smellie 1988, 1989). However, different interpretations are made here for some of them. The Entrance Point and Cathedral Crags rocks, which were attributed to the pre-caldera volcanism by González-Ferrán & Katsui (1970) and to a syn-caldera episode by Baker *et al.* (1975), are identified as post-caldera volcanism, in accordance with Smellie (1988, 1989). Nevertheless, as was indicated by Smellie, the presence of undifferentiated pre-caldera rocks can be noted not only at Entrance Point, but also between the South East Point and Baily Head. The Vapour Col zone represents a large post-caldera vent (Baker *et al.* 1975, Smellie 1989). Here the post-caldera deposits rest unconformably on a sequence of pre-caldera YTF deposits (see Figs. 4 & 5), a feature which was not identified by previous workers. The same sequence also crops out at the north-west of Vapour Col along the penguin rookery track (1 in Fig. 2) and can be partially correlated with those appearing at the outer coast. Other pre-caldera outcrops have been identified at Crater Lake, Telefon Ridge, Whalers Bay, Collins Point and the eastern side of Telefon Bay (Figs. 2 & 3)

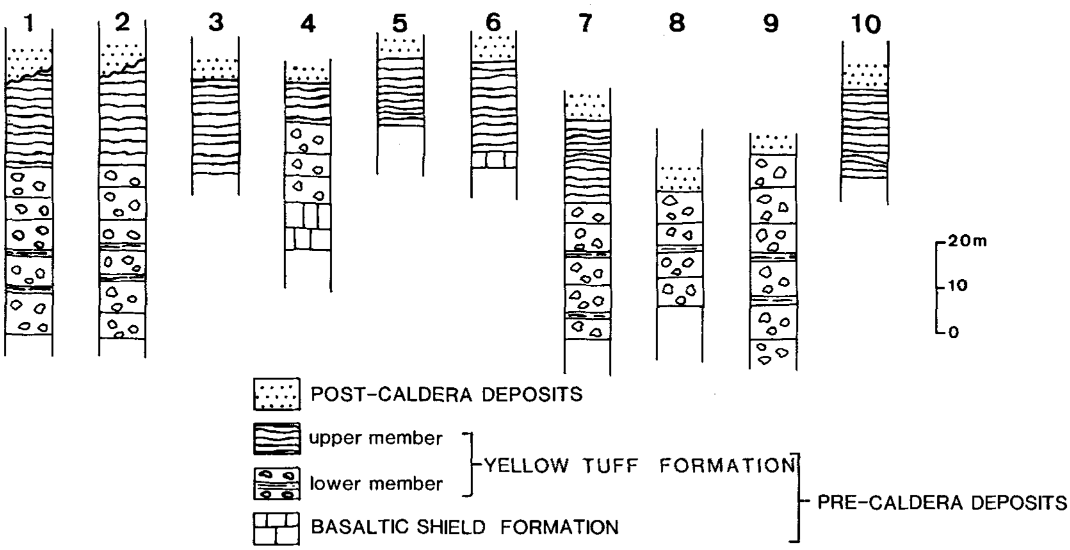

Fig. 3. Stratigraphic sections of the Yellow Tuff Formation. The Basaltic Shield Formation is mainly formed of basaltic lava flows. The Yellow Tuff Formation lower member is mainly composed of thick pyroclastic flow deposits and the upper member consists of well-stratified base surge deposits. 1, 2 and 3, Vapour Col; 4 and 5, Stonethrow Ridge; 6, Crater Lake; 7, Collins Point; 8, Entrance Point; 9, Kendall Terrace; 10, Whalers Bay.

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The Yellow Tuff Formation

Lower member

The YTF lower member is formed of several units of massive yellow tuff 1 to 12 m thick (Fig. 6). The main morphological characteristics of these massive deposits are the lack of internal stratification, flat bases, and the existence of an incipiently developed columnar jointing (Smellie 1988, 1989). These deposits are poorly sorted and contain abundant lithic clasts (15-30%) of basalt and basaltic-andesite, together with vesiculated juvenile pyroclasts of andesitic composition. Juvenile fragments are sometimes flattened. Lithic clasts may attain 0.5 m in diameter and show normal or reverse grading. The groundmass of these pyroclastic deposits comprises small pumice clasts with tachylitic textures and glass shards with blocky morphology. The glass shards and pumice fragments are angular, suggesting little or no abrasion during transport. Some deposits have a finely laminated basal layer.

No major discontinuities have been observed in the lower member. Nevertheless, some well-stratified fine-grained deposits appear interbedded and in stratigraphic continuity with the pyroclastic flow deposits (Fig. 6). These fine grained deposits include air fall and base surge deposits, but the high degree of alteration locally makes them difficult to interpret. Nevertheless, the absence of discontinuities suggest that all these deposits originated during the same eruption episode. The lower member corresponds to the Outer Coast Tuff defined by Hawkes (1961; cf. Smellie 1988, 1989) and forms a nearly continuous outcrop which extends from Macaroni Point to the south of Entrance Point. The lower member also crops out in some exposures in the interior of the island (Figs. 2 & 3). Hawkes suggested that the Outer Coast Tuff deposits were on top of the pre-caldera rocks at Stonethrow Ridge. However, Baker *et al.* (1975) suggested that the pre-caldera deposits at the outer coast and Stonethrow Ridge were stratigraphically equivalent. In fact, the Outer Coast Tuff and lower part of the Stonethrow Ridge pyroclastic sequence are interpreted here as lower member (cf. Smellie 1988, 1989) similar to those which form the lower part of the Vapour Col outcrops (1 & 2 in Fig. 2).

Lithological and sedimentological characteristics of the YTF lower member deposits suggest that they originated from high-density flows. The presence of abundant vitroclastic groundmass in these deposits and the existence of flattened juvenile pumices indicate that the flows had a primary pyroclastic origin. The small size of pumice fragments the presence of blocky morphologies of ash fragments, the abundance of small size lithic clasts and the palagonitic alteration, suggest a hydrovolcanic origin. Nevertheless, the presence of columnar jointing and flattened pumices suggest a relative high emplacement temperature for some of them. The homogeneous distribution of the YTF lower member deposits suggests that they originated from a central vent.

Upper member

The upper member only appears in small exposures (Fig. 3) where it is seen to be well stratified with planar, dune and antidune high-energy bedforms (Figs 7 & 8). These deposits are also lithic-rich and locally contain cored and accretionary lapilli. Bomb sag structures are common in these deposits (Fig. 7). The grain size and composition is similar to the groundmass of the pyroclastic flow deposits of the lower member. Glass shards have a blocky morphology and some have adhering dust. In most of the upper member horizons, the glass shards are moderately rounded, probably due to abrasion during transport.

The deposits of the upper member are interpreted as being of base surge origin. Some interbedded air-fall and thin pyroclastic flow deposits are also present in the upper member. In the various outcrops, the interpretation of the directional indicators, such as bedforms and bomb sags, shows an irregular distribution. This suggests that the upper member deposits originated not only from the central vent but also from some parasitic cones. However, the lower and upper members are in stratigraphic continuity, without any erosion or paleosol surfaces between them. This can be observed in the Vapour Col outcrops where post-caldera deposits unconformably overlie the upper member (Figs 4 & 5). In contrast with the lower member, the upper member only appears in some of the inner outcrops and, in the outer coast, at the top of the lower member in the north-east sector of Kendall Terrace. This indicates that the upper member could have been mostly eroded off at more distal localities prior to the post-caldera volcanism. However, an irregular and proximal distribution of the upper member deposits, which was probably the result of activity of different vents, is also suggested.

The base surge deposits of the upper member had a hydrovolcanic origin. The presence of accretionary and cored lapilli in some deposits indicates an alternation of wet and dry base surge deposits. The deposition of some sequences was characterized by an increase in the energy of the flow towards the upper levels, as is indicated by the presence of high-energy plane beds and antidunes and an increase in the degree of fragmentation of pyroclasts. Similar eruptive phases have been described in surtseyan eruptions, when the volcanic edifice is high enough to avoid the massive entrance of water in the volcanic conduit, favouring the efficiency of the magma/water interaction (Kokelaar 1983, Wohletz & Sheridan 1983).

Alteration

All the YTF deposits suffered a palagonitic alteration which produced their characteristic yellowish colour. This alteration particularly affected the vitric fragments whereas the phenocrysts were unaltered. The palagonitization is more intense in the pyroclastic flow deposits than in the base surge

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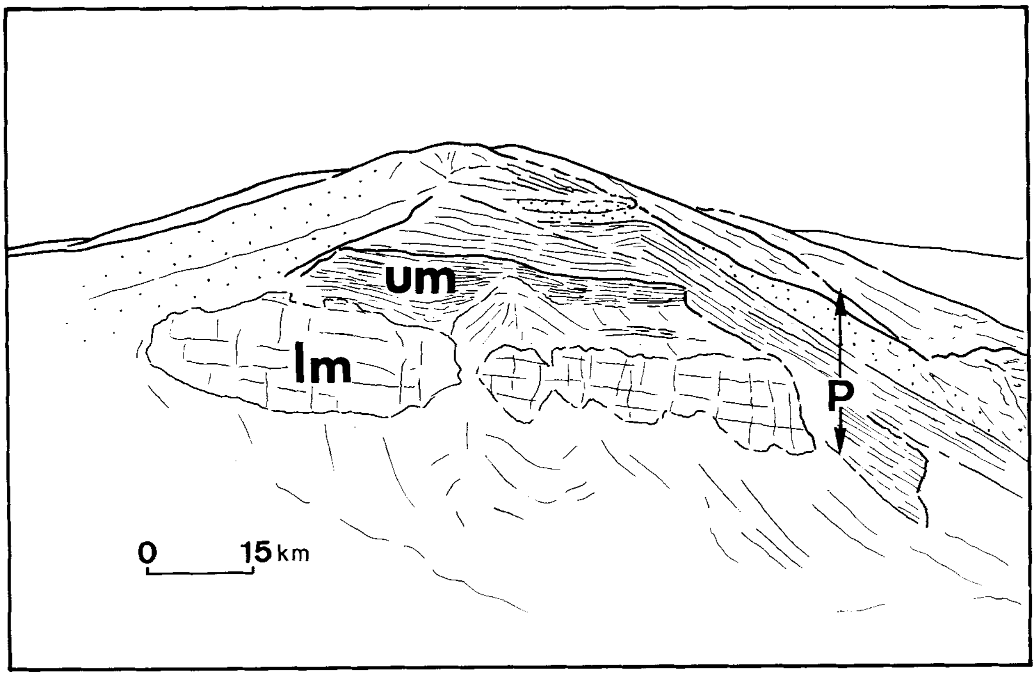

Fig. 4. Sketch of the southern side of Vapour Col showing the relationships between pre and post-caldera deposits. Pre-caldera deposits are represented by the Yellow Tuff Formation lower (lm) and upper (um) members, and are unconformably overlain by post-caldera (P) base surge and strombolian deposits.

Fig. 5. Angular unconformity between pre- and post-caldera base surge deposits east of Vapour Col (south of the Argentine Station).

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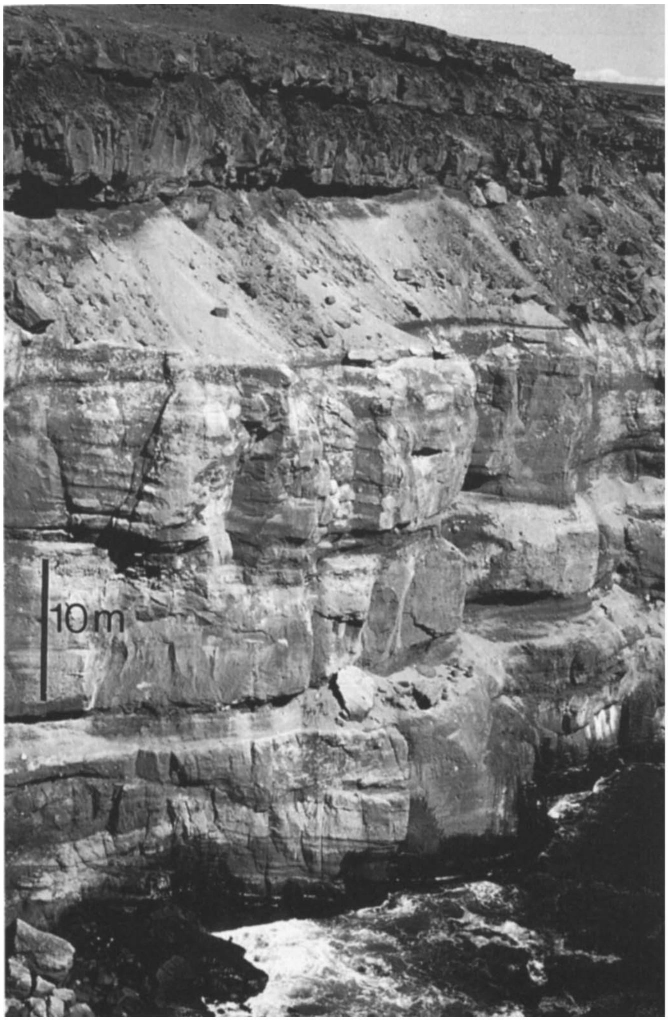

Fig. 6. View of the Yellow Tuff Formation lower member in the outer coast (Kendall Terrace). Note the existence of three massive pyroclastic flow units separated by finely laminated pyroclastic deposits, and the presence of post-caldera lavas at the top of this sequence. The thickness of each massive unit is approximately 10 m.

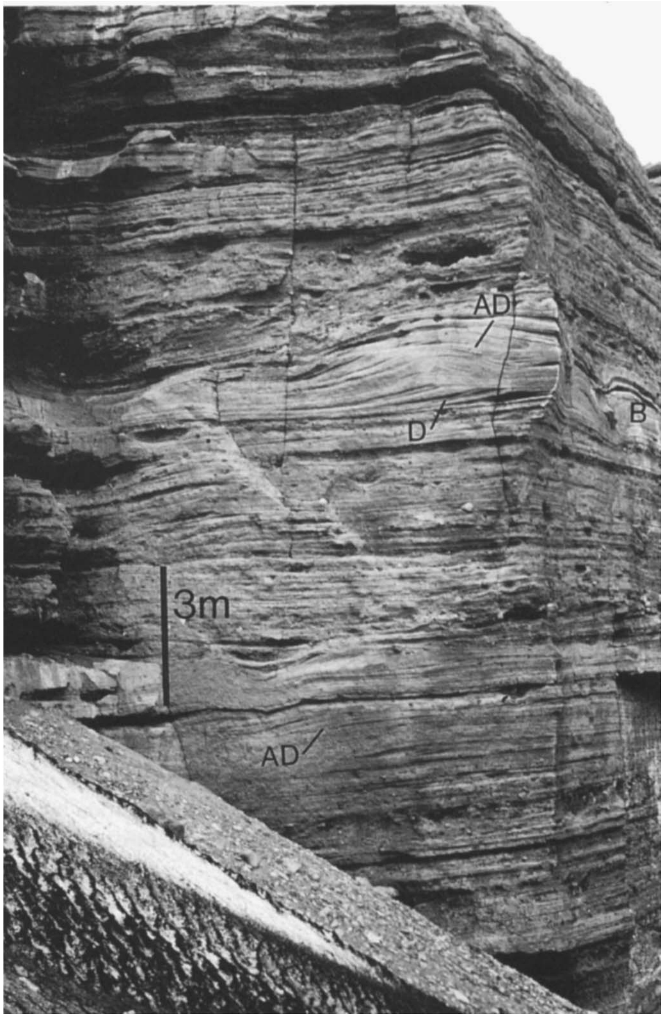

Fig. 7. Close view of the Yellow Tuff Formation upper member base surge deposits east of Vapour Col (south of the Argentine Station). Note the presence of high-energy dunes (D) and antidunes (AD) and the existence of bomb sag structures (B). The flow direction is from right to left.

deposits, but no vertical or lateral zonation has been detected. The main alteration products are smectites, Fe-oxides, zeolites and calcite. Smectites and Fe-oxides appear as the earliest secondary crystalline phase and mainly replace vesicle walls. Chabazite is the most abundant zeolite in the YTF deposits and represents the first phase of cement, which produced a significant reduction in rock porosity. The presence of different chabazite morphologies suggests different conditions during the precipitation of this cement phase.

Analcime appears as a second generation of cement and is always subordinate to chabazite. Other zeolite minerals which have been identified in lesser abundance are phillipsite and faujazite. A third generation of cement appears as calcite in some samples.

The subaerial character of the YTF deposits implies that meteoric alteration in a submarine environment would be unlikely. This is also in accordance with the fact that many of the post-caldera hydrovolcanic deposits, even the most recent and superficial, show a similar sequence of alteration products. In the same way, the lack of vertical zonation in the distribution of the altered products is not in accordance with a subaerial meteoric alteration.

These alteration products, however, can be interpreted as the reaction between a pore-fluid and volcanic glass. This pore-fluid mainly came from water-vapour incorporated into the system when the erupting magma interacted with sea-water, as is suggested by the composition and the order of appearance of the secondary minerals. The increase in intensity of alteration in the pyroclastic flows with respect to the base surge deposits suggests that this palagonitization process was not only dependent on temperature and glass composition, but also on water content.

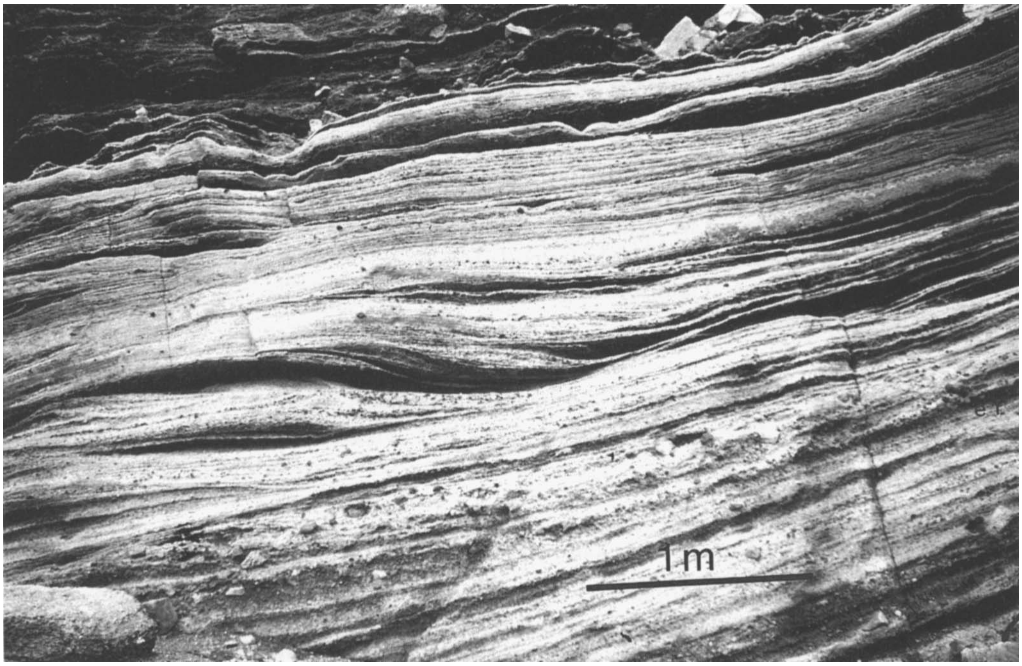

Fig. 8. Antidune bedforms in dry base surge deposits of the Yellow Tuff Formation upper member east of the Vapour Col (south of the Argentine Station). Flow direction from right to left.

Discussion and conclusions

The characteristics of the lower and upper member deposits suggest a subaerial origin. The presence of abundant juvenile pyroclasts with tachylitic textures indicates a progressive cooling of the deposit. This is interpreted as evidence for subaerial emplacement (see e.g. Fisher & Schmincke 1984). This is also suggested by the paragenesis of secondary minerals. The subaerial character of the youngest pre-caldera deposits contradicts hypotheses of Baker *et al.* (1975) and Roobol (1982) where reworking under submarine conditions was proposed to explain the origin of the upper member deposits. There is no evidence for an isostatic uplift of the island as significant as would be required if the deposits were altered in the sea.

Many of the youngest pre-caldera deposits had a hydrovolcanic origin. The palagonitic alteration has masked the possible presence of paleosols. Nevertheless, stratigraphical reconstruction has not revealed the existence of any kind of discontinuity to suggest an interruption of the eruptive activity during the deposition of the YTF. This eruptive episode followed a period of submarine basaltic volcanism. The pyroclastic flow deposits of the lower member may have resulted from immediate collapse of high density eruption columns, as is indicated by the lithological and sedimentological characteristics of these deposits and the absence of interbedded plinian fall deposits. Rapid widening of the vent, a high mass discharge rate and the entrance of sea-water in the volcanic conduit could have been the main cause of generation of these low non-convective eruption columns. Some blast phases may have preceded the eruption of the main units, as is suggested by the presence of pyroclastic surge deposits interbedded with the massive deposits. The high density of the pyroclastic flows caused low degrees of fluidization, preventing the escape of vapour formed by the interaction of magma with sea-water. This would explain the higher degree of palagonitic alteration in the lower member deposits, although the base surge deposits may have incorporated a higher volume of water.

A reduction of the mass discharge rate of magma and probably a change in the magma/water ratio, caused by the construction of the subaerial volcanic edifice, produced new eruption conditions which favoured the formation of base surge deposits of the upper member. These deposits were emplaced from high energy, low density turbulent currents which allowed the escape of high volumes of vapour before condensation.

In summary, the reconstruction of the eruption conditions for the Yellow Tuff Formation, as well as the stratigraphical correlation between the studied outcrops, produce a unique model for the pre-caldera volcanism of Deception Island. After a period of submarine fissure volcanism, mainly involving eruption of basaltic magmas, an episode of subaerial explosive volcanism took place. This new episode of volcanic activity was characterized by the eruption of slightly more differentiated magmas and by hydrovolcanic phenomena. Most of the pre-caldera volcanic activity seems to have been located on a central vent which produced a radial distribution of the lower member deposits, as well as some of the upper member deposits. The formation of the caldera, not discussed in this paper, could be explained as a consequence of this main episode of explosive volcanic activity (cf. Smellie 1988).

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