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Mesozoic geology of Cape Shirreff , Livingston Island, South Shetland Islands, Antarctica

Geologia del Mesozoic del Cap de Shirreff , Illa de Livingston, Shetland del Sud,Antàrtida

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ABSTRACT

The stratigraphic succession at Cape Shirreff has a minimum thickness of 450 m and is mainly composed of lavas and a smaller amount of volcaniclastic breccias. Lavas are subalkaline olivine basalts and basaltic andesites which are locally well-bedded, but in most areas give a homogeneous, sometimes massive aspect to outcrops. Volcaniclastic massive breccias are found in the northern part of Cape Shirreff where they are interstratified with lavas in a few outcrops.

Breccias are indurated, heterometric, grain-supported and consist of angular to subangular volcanic rock fragments, 5 to 80 cm in diameter. Petrographic evidence of magma supercooling (skeletal microlites of plagioclase, thermal-shocked phenocrysts of olivine) enables a subaqueous environment for part of the lavas to be deposited and suggests a possible hyaloclastic origin for some interstratified volcanic breccias. The whole succession is cut by subvertical dykes (10 to 40 cm thick and a few meters to 400 m long), which show variable trends around a NW-SE maximum. These consist of commonly vesiculated basaltic and basaltic andesite porphyritic rocks, commonly indistinguishable from the lava bodies.

Lavas dip variably between 15 and 80º, more gently in the south than in the central and northern areas. Although significant variations in dipping attitude could be associated with depositional geometries, the general dipping pattern is clearly consistent with NW-SE-oriented large-scale folds showing a gentle dome and basin structure. In the southern area, the NW-SE folds are not so well developed and the structure seems to be consistent with an interference of N-S and E-W oriented folds. The large scale NW-SE folds are consistent with NE-SW shortening. This shortening direction is parallel to the direction of extension deducible from dykes and, hence, folds and dykes are not consistent with the same deformational event.

Keywords: South Shetland Islands. Livingston Island. Antarctic Peninsula Volcanic Group. Magmatic arc. Volcanic succession. Volcaniclastic rocks.

RESUM

Al Cap de Shirreff (Fig. 1) hi aflora una successió volcànica de com a mínim 450 m de potència, constituïda principalment per laves i, en menor proporció, bretxes vulcanoclàstiques (Fig. 2). Les laves són basalts olivínics subalcalins i andesites basàltiques, que generalment tenen un aspecte massiu. Tot i això, la successió volcànica localment forma una alternança decimètrica de nivells durs i tous, amb potències variables i presència local de discordances angulars i onlaps, que reflecteixen geometries deposicionals complexes. A la zona nord del Cap de Shirreff hi ha aflorament de bretxes vulcanoclàstiques d'aspecte massiu, que localment tenen intercalacions de laves.

Aquestes bretxes es troben ben consolidades, són heteromètriques, amb suport de fragments de roca angulosos a subangulosos d'entre 5 i 80 cm de diàmetre. La presència d'evidències petrogràfiques de sobrerefredament (supercooling) del magma (micròlits esquelètics de plagiòclasi i fenocristalls d'olivina que han estat sotmesos a xoc tèrmic) ens permet deduir un ambient subacuàtic per part dels cossos de lava i sospitar un caràcter hialoclàstic per les bretxes volcàniques que s'hi intercalen. El conjunt de la successió volcànica és tallat per dics porfírics de composició anàloga a les laves (basalts subalcalins i andesites basàltiques) i aspecte macroscòpic similar. Aquests dics mostren una disposició subvertical (Figs. 2 i 3), direccions variables al voltant d'un màxim NW-SE, gruixos de 10 a 40 cm i longituds en planta de fins a 400 m.

La successió volcànica té cabussaments variables entre 15 i 80º, amb tendència a ser més suaus en la zona sud que en les zones central i nord (Fig. 4). Aquests cabussaments permeten deduir una estructura en doms i cubetes d'escala hectomètrica amb plecs elongats segons una direcció NW-SE. A la zona sud, aquesta direcció de plegament principal no hi és tan ben desenvolupada, i l'estructura suggereix una interferència de plecs laxos amb direccions al voltant de N-S i E-W. Els plecs principals són compatibles amb un escurçament de direcció NE-SW, que coincideix amb la direcció d'extensió deduïble a partir de la disposició dels dics. Per tant, els plecs i els dics no són compatibles amb una única fase de deformació.

Paraules clau: Illes Shetland del Sud. Illa de Livingston. Grup Volcànic de la Península Antàrtica. Arc magmàtic. Successió volcànica. Roques vulcanoclàstiques.

INTRODUCTION

Cape Shirreff is a small (3 x 1.5 km) peninsula located between Byers Peninsula and Siddons Point, on the north-western coast of Livingston Island. It is mainly a low-relief area dominated by the existence of extensive flat surfaces at different heights above sea-level, which are interpreted as emerged marine platforms (Vilaplana et al., 1994). The highest hill on the peninsula is the 100 m high Cerro el Toqui. Prior to our visit in 1992-93, only a few observations had been made by Hobbs during 1958, which were later reported by Smellie et al. (1984). Part of our data, such as K-Ar and geochemical analyses, was published by Smellie et al. (1996). The aim of the present paper is to provide new preliminary data concerning the petrography, volcanology, stratigraphy and structure of this little-known peninsula.

Livingston is the second largest of the South Shetland Islands. The archipelago is separated from the Antarctic Peninsula by the Bransfield Strait (Fig. 1). Several of the main geological units of the Antarctic Peninsula region (such as forearc basin, magmatic arc and extension-related volcanics) crop out on Livingston Island (see Pallàs, 1996 for a review).

The early Triassic (?, Willan et al., 1994), 3 km-thick Miers Bluff Formation is the oldest unit in the South Shetland Islands and makes up most of Hurd Peninsula. It consists of a NW-dipping, open-folded and mostly overturned turbiditic sequence (Dalziel, 1969; Pallàs et al., 1992; Doktor et al., 1994; Smellie et al., 1995) of equivocal and not yet well understood tectonic setting (Smellie et al., 1995; Tokarski et al., 1997). The late Jurassic to early Cretaceous Byers Group crops out in Byers Peninsula and records deposition in a marine to continental forearc basin (Smellie et al., 1980; Crame et al., 1993). The amount of intercalated volcanic rocks increases upwards, indicating a gradual encroachment of the magmatic arc into the forearc basin (Hathway and Lomas, 1995). The sequence is little deformed and displays a dome and basin structure. The mesozoic to cenozoic magmatic arc is represented both by calcalkaline plutonic rocks (Antarctic Peninsula Batholith, Leat et al., 1995) and volcanics (Antarctic Peninsula Volcanic Group, Thomson, 1982). On Livingston Island, the batholith consists of late Cretaceous (Kamenov, 1995) tonalite plutons which cut through the Miers Bluff Formation in Hurd Peninsula, and Eocene tonalites thought to make up most of the Mount Friesland range (Smellie et al., 1995; 1996). Apart from Cape Shirreff, the

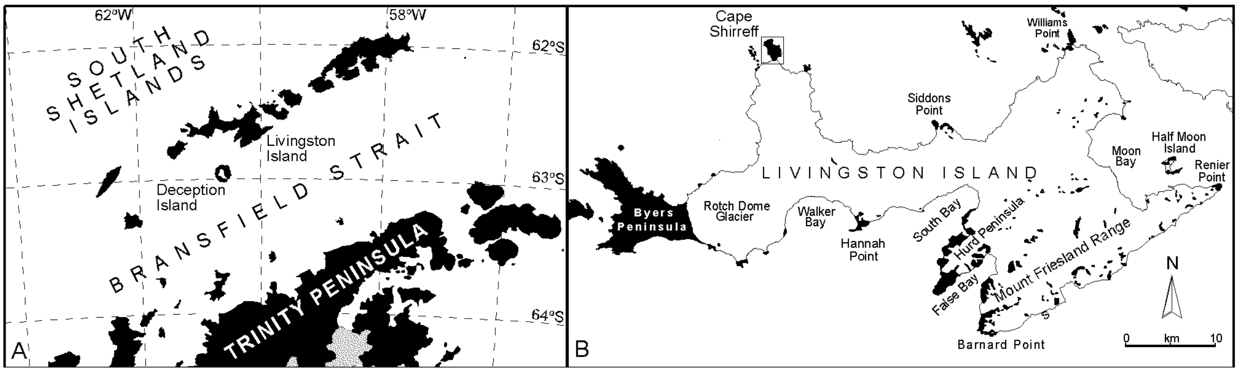

Figure 1.- Location of the area studied and place names referred to in text.

Figura 1.- Situació de l'àrea d'estudi i noms de les localitats citades en el text.

Antarctic Peninsula Volcanic Group and its hypabyssal counterparts crop out in Hannah Point (see Pallàs et al., this volume), Siddons Point, Williams Point and the eastern-central part of the island (Smellie et al., 1995; 1996; Xiangsheng, Z. et al., 1996). Quaternary lavas and volcaniclastic rocks of alkaline affinity crop out on the central areas of Livingston Island, north-west of the Mount Friesland range, and are interpreted as related to extension of the Bransfield Basin rift (Smellie et al., 1995; 1996).

According to Smellie et al. (1984), Hobbs reported the outcrop in Cape Shirreff of volcanic rocks showing strong structural dips towards the NE and the SW. K-Ar dating of a subalkaline olivine basalt sample from either a lava layer or a dyke gave an Upper Cretaceous age (90.2 ± 5.6 My, Smellie et al., 1996). This date is interpreted as the erupting age, which would be a minimum estimate for the lava succession if the sample corresponded to a dyke. Geochemical analyses (major, trace elements and isotopic data) show similar signatures to the volcanic rocks of the upper portion of the Byers Group, suggesting the two successions may be cogenetic (Smellie et al., 1996; Xiangshen et al., 1996).

BEDROCK GEOLOGY OF CAPE SHIRREFF

Volcanic succession

The volcanic succession of Cape Shirreff is at least 450 m thick, and is mainly composed of vesiculated and amygdaloidal lavas and a smaller amount of volcaniclastic breccias. The volcanic succession is cut by a swarm of dykes (Fig. 2).

The lavas typically crop out in successions of alternating soft and hard layers, 20 to several m thick, showing no columnar jointing. The soft layers locally show a greater amount of vesicles and the general aspect of the outcrop is similar to a trap succession. Depositional geometries are complex, showing irregular beds of variable thickness, angular unconformities and onlaps of local extent. Although layering is often shown by contrasts in resistance to weathering, lithology is very homogeneous and many outcrops are massive. Lavas consists of both subalkaline olivine basalts and basaltic andesites. A systematic petrographic study of 21 samples characterized the volcanics, complemented by major and trace element geochemistry and mineral chemistry studies on some selected samples (Smellie et al., 1996; Xiangshen et al., 1996). A geochemical study of the entire samples set is in progress.

The preliminary data available enable us to classify all the samples as part of a subalkaline suite, with similar amounts of olivine basalts and basaltic andesite. The petrographic classification took into account the degree of porphyricity of the rock, the persistance of mineral paragenesis, the modal contribution of each mineral phase and, in some cases, the presence of secondary minerals. The mineral chemistry of the diagnostic mineral phases was checked by means of an electron microprobe. Despite the fact that sampling may be biased by the scarcity and inaccessibility of outcrops, the exclusive presence of basic or poorly differentiated rocks is remarkable.

The mineral paragenesis contains olivine, clinopyroxene, plagioclase and opaque minerals; the presence of ortopyroxene is suspected after pseudomorphic aggregates

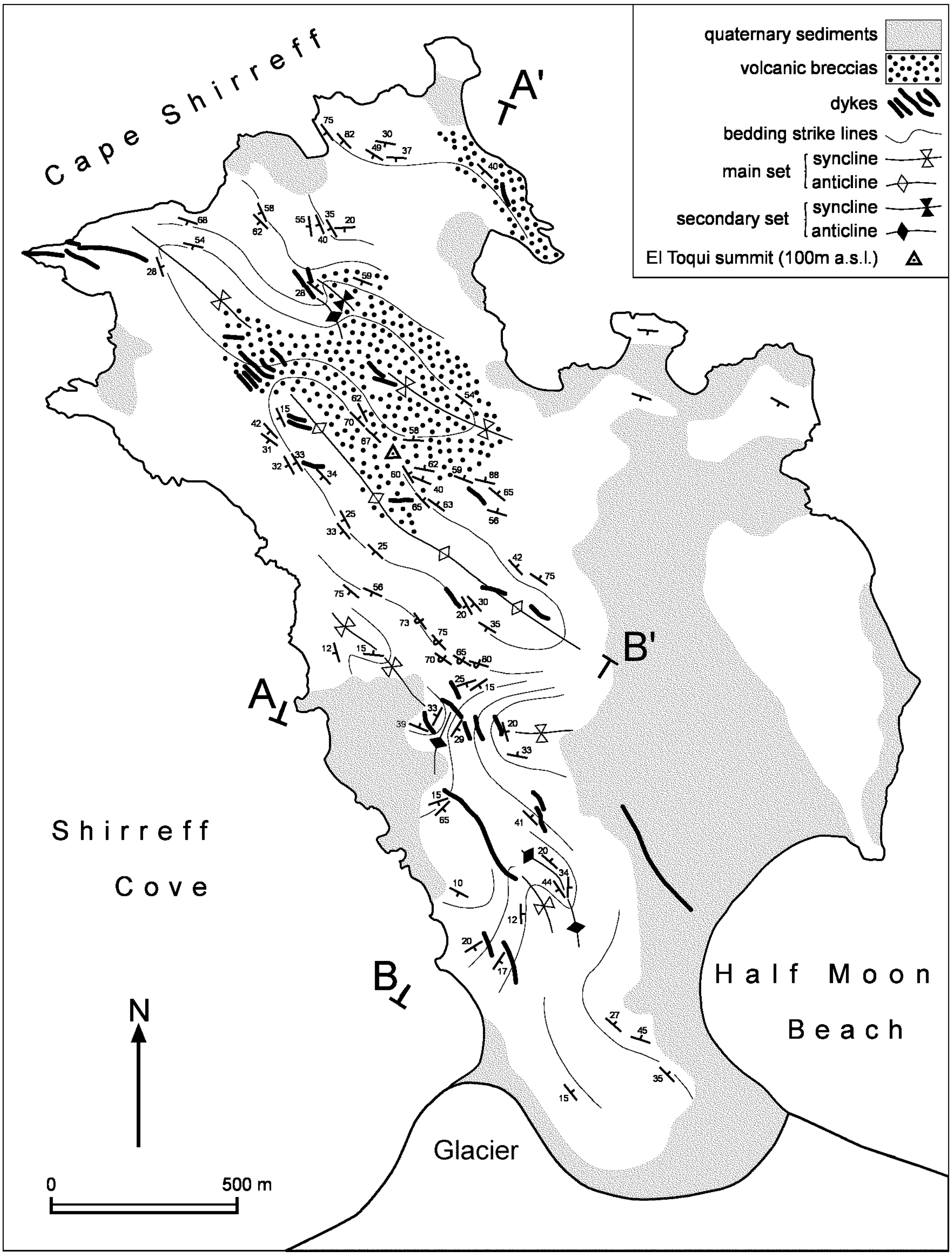

Figure 2.- Geological and bedding trace sketch map of Cape Shirreff. White areas indicate a predominance of lavas. Bedding strike lines do not consider the topographic effect and may slightly differ from geological boundaries. The area indicated by the volcanic breccias pattern also includes minor interstratified lavas.

Figura 2.- Esquema cartogràfic i de traces de l'estratificació del Cap de Shirreff. En blanc es marca l'aflorament majoritari de laves. Les traces de l'estratificació no tenen en compte l'efecte del relleu que, a causa de la topografia majoritàriament planar d'aquesta localitat, no és gaire important. En l'àrea marcada amb aflorament de bretxes vulcanoclàstiques hi ha inclusió de laves interestratificades.

of hydrated ferromagnesian minerals. Generally, plagioclase is in the labradorite-bytownite compositional range, the opaque rock is ulvospinel, olivine is mainly in the chrysolite range and clinopyroxene is a relatively Ca-poor augite. This paragenetic assemblage is characteristic of basic to basic-intermediate rocks, and the presence of olivine indicates more basic rocks. The modal occurrence of these minerals, the MgO and trace element contents and the mineral chemistry of the analyzed samples are coherent with a non-pristine, relatively evolved set of basic rocks. Olivine phenocrysts are idiomorphic with a lantern-like shape or, more exceptionally, have more elongated morphologies suggesting accelerated crystalline growth. When present, they constitute around 5% of the rock volume and are distinctive of basaltic rocks. Basaltic andesites (and probably andesites) in holocrystalline rocks have over 70 % of plagioclase crystals, with predominance of elongate laths in the rock mesostase, over phenocrysts. Phenocrysts frequently show glomeroporphyritic textures, sometimes including clinopyroxene phenocrysts.

The mineral chemistry of clinopyroxene is a well contrasted indication of the geochemical character of a volcanic suite (Nisbet and Pearce, 1977; Leterrier et al., 1982). In the Cape Shirreff case clinopyroxene chemistry corresponds to a subalkaline suite; which is supported by the presence of pseudomorphs after orthopyroxene phenocrysts. In spite of this, the absence of pigeonite is remarkable.

All rocks studied show holocrystalline to hypohialine character, but in some poorly porphyritic rocks the secondary chloritic microcrystalline mesostase may reflect an originary mesocrystalline to hypocrystalline character. Vesicular and amygdaloidal texture are more frequent but not exclusive of lava flows and we must interpret this as evidence of shallow intrusion in the case of the dykes.

Most samples show inequigranular texture, mainly porphyritic or glomeroporphyritic, with fine to medium-grained intergranular texture in the mesostase that is mainly constituted of tabular plagioclase laths and a minor amount of hypidiomorphic to anhedral pyroxene and fine-grained idiomorphic to hypidiomorphic iron ores. Plagioclase is always the dominant phenocryst, showing sometimes sieve texture and more sodic overgrowths, but in general desequilibria or zoned textures are not prominent. Some of the more fine-grained rocks show trachytic pilotaxitic textures and clear evidence of magmatic flow around phenocrysts, and exceptionally inequigranular porphyritic textures with micro- to cryptocrystalline mesostase with no plagioclase laths.

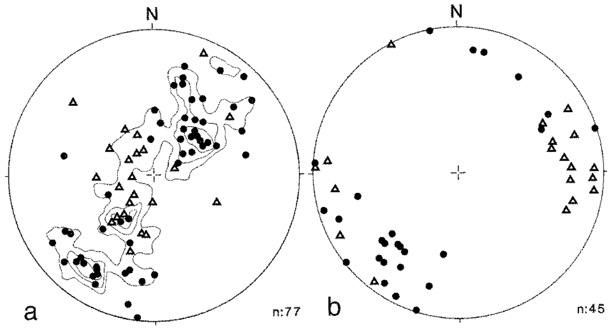

Figure 3.- Lower hemisphere stereographic plots showing the attitude of bedding and dykes measured at Cape Shirreff. a) bedding, b) dykes. Data from the northern and central areas of the peninsula are represented by black dots while those from the southern area are represented by triangles. Contours correspond to 1.9, 3.9, 5.8 and 7.8% per 1% of the area.

Figura 3.- Estereogrames de la disposició de l'estratificació i dels dics al cap de Shirreff. a) estratificació, b) dics. Els punts negres corresponen a l'àrea nord i central de la península mentre que els triangles corresponen a l'extrem sud. Els contorns corresponen a les concentracions de punts de 1.9, 3.9, 5.8 i 7.8% per cada 1% de superfície.

The described textures do not enable intrusive and extrusive lava bodies to be distinguished. On the one hand, dykes are vesiculated indicating a shallow intrusive character. On the other, lava flows show inequigranular porphyritic textures with trachytic pilotaxitic character, which range to intergranular mesostases. These textures of the lavas indicate a transition between relatively quick and slow cooling conditions, suggesting crystallization in thick (several meters) lava flows. Nevertheless, we can note that some rocks are remarkably less crystalline and, in some cases, show clear evidence of supercooling of the magma (skeletal laths of plagioclase, curved-shaped fractures in olivine phenocrysts originated by thermal shock *sensu* Gimeno, 1994; see Plate 1, photos 3 and 4), which should be interpreted as extrusion of magma within a subaqueous environment.

Volcaniclastic breccias are more abundant than lavas in two areas in the northern half of Cape Shirreff (Fig. 2). The most extensive outcrop of volcaniclastic breccias is Cerro el Toqui, while the second largest outcrop is located north-east of it. They are lithified clast-supported breccias, angular to subangular rock fragments of 5 to 80 cm in diametre. The outcrops are massive and only locally,

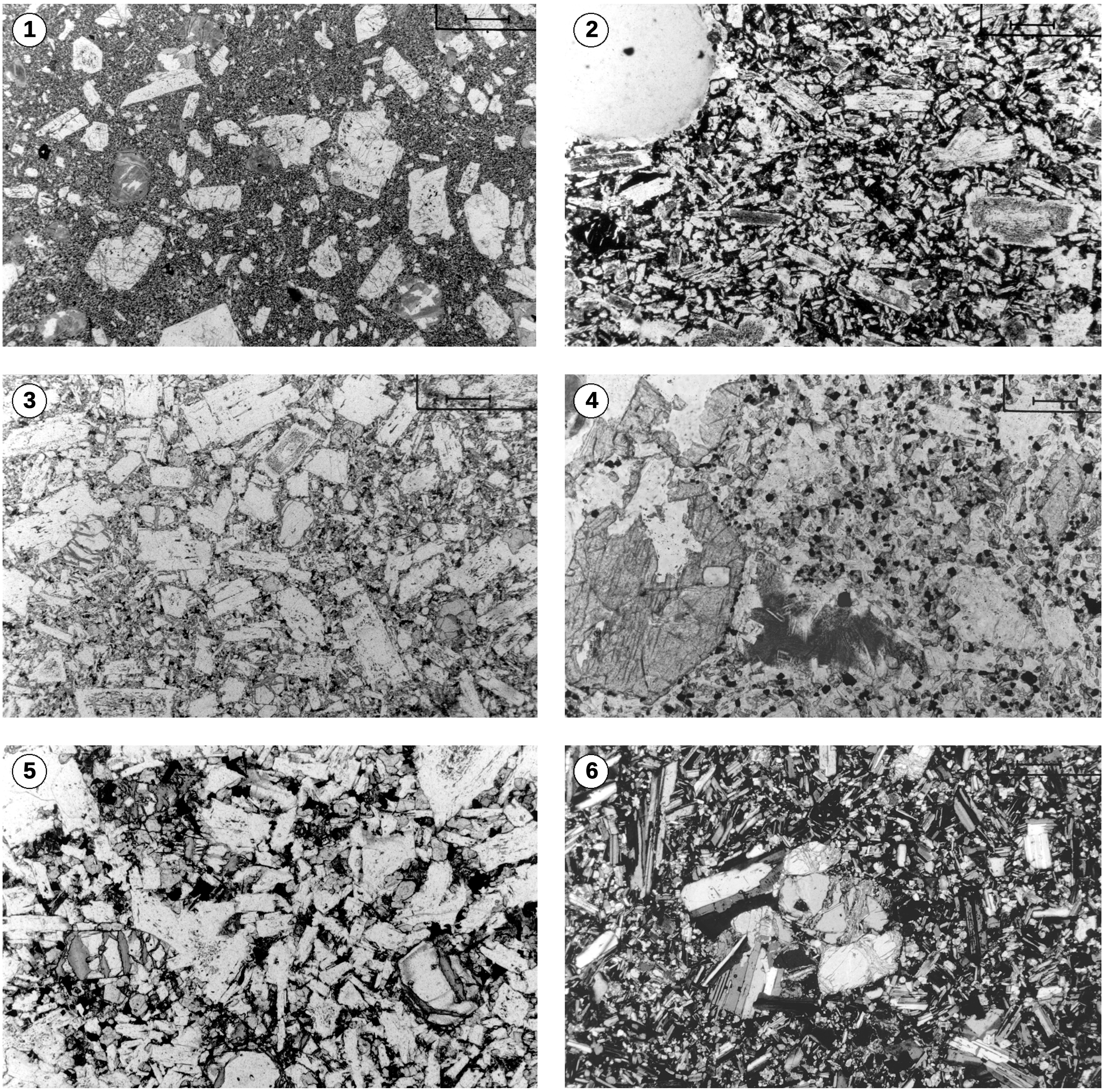

Plate 1.- Photo 1. Inequigranular porphyritic olivine basalt with microcrystalline mesostase. Phenocrysts are plagioclase (white), clinopyroxene (white-light grey with prominent exfoliation) and olivine (deep grey, affected by curved-shaped fractures, altered and frequently lacking the center of crystals (white) due to the thin-section polishing). Also note some microphenocrysts of opaque iron minerals (black) sparse in the mesostase. Scale bar is 0.32 mm. Plane parallel light (PPL). Sample 311S. Photo 2. Hypohialine inequigranular vesicular basalt, locally with trachytic texture marked by plagioclase laths and phenocrysts (white and dirty grey, note the differential alteration following concentric growth bands of contrasting composition). Upper left is a hollow vesicle. Scale bar is 0.32 mm. Plane parallel light (PPL). Sample 318S. Photo 3. Holocrystalline inequigranular porphyritic olivine basalt with microcrystalline to intergranular mesostase. Phenocrysts as in photo 1: note in the upper centre sector an unaltered olivine phenocryst that has undergone thermal shock as shown by curved jig-saw fractures.Scale bar is 0.32 mm. Plane parallel light (PPL). Sample 307S. Photo 4. Hypohialine inequigranular porphyritic olivinic basalt with intergranular to microcrystalline mesostase. Note the presence of a triangle-shaped sector with brown (dark grey in the photo) glass with skeletal hollow sections of plagioclase that are evidence of supercooling, lying at the right of the large clinopyroxene phenocryst. Mesostase consists of medium-sized idio- to hypidiomorphic plagioclase laths

where interstratified lavas occur, can the bedding attitude of the succession be inferred.

Hypabyssal rocks

Dykes cutting through the volcanic succession are very similar to lavas, both in the field and through thin section. The distinction between lavas and dykes is sometimes difficult due to the often massive structure of the outcrops and the similarities in composition between the two . When dykes show distinctive zonation on both walls originated by magmatic flow or the bedding plane of the lava flows is clear, they are revealed as cutting the volcanic pile at high angles. They show slightly variable trends around a NW-SE maximum, strong dips (Fig. 3), are 40 cm to 10 m thick and a few metres to 400 m alongstrike.

The lavas and dykes show a variable degree of alteration. Olivine phenocrysts show frequent iddingsite or limonite alteration developed following curved fractures; the alteration in some samples is pervasive and affects virtually the entire volume of the phenocrysts. Plagioclase is moderately altered to sericite and more rarely to calcite, and sometimes is replaced by zeolite. Chlorite is widespread in the mesostase of half the studied samples, and also occurs replacing ferromagnesian minerals. Exceptionally, some samples show pervasive carbonate replacing of the mesostase and, less commonly, the phenocrysts, suggesting alteration under subaerial weathering by bicarbonated waters. Amygdales are commonly filled with chlorite, and more sporadically also with zeolite and calcite

Structure

Lavas dip variably between 15º and 80º. Smaller dips are found in the southern third of the peninsula while strong dips are more common in the central and northern areas (Figs. 2 and 3). Small angular unconformities indi-

and tablets (white) with small idiomorphic opaque iron minerals (black) and hypidio- to xenomorphic clinopyroxene (grey) placed in between the plagioclase framework. Scale bar is 0.08 mm. Plane parallel light (PPL). Sample 378A. Photo 5. Holocrystalline inequigranular olivine basalt with medium-sized intergranular mesostase. Note the presence of large hypidiomorphic olivine crystals (white) with iddingsitized fractures (grey), large idio- to hypidiomorphic plagioclase crystals (white) with altered Ca-rich cores (dirty grey sectors in white crystals) and medium to fine sized opaque ore (black) and clinopyroxene (dark grey). Field represented is approx. 2 mm wide. Plane parallel light (PPL). Sample 325c3bis. Photo 6. Holocrystalline inequigranular glomeroporphyritic olivine basalt with intergranular mesostase. Note polysynthetic twins of plagioclase (left part of the glomerula, isolated phenocrysts and laths in the mesostase) and altered mafic phenocrysts (right of the glomerula and in between the framework of plagioclase laths in the mesostase). Scale bar is 0.32 mm. Crossed polars (CP). Sample 325c3.

Planxa 1.- Foto 1. Basalt olivínic amb textura inequigranular porfírica i mesòstasi microcristal·lina. Els fenocristalls que apareixen són plagiòclasi (blanc), clinopiroxè (blanc-gris pàlid amb exfoliacions marcades) i olivina (gris fosc amb fractures corbes, alterat i sovint incomplet al centre del cristall per pèrdua mecànica de part del cristall durant el procés d'elaboració de la làmina prima. L'escala gràfica fa 0,32 mm. Llum paral·lela (LlP). Mostra 311S. Foto 2. Basalt amb textura hipohialina inequigranular, localment amb textura traquítica marcada per fenocristalls i petites tabletes de plagiòclasi (cristalls blancs i de color gris brut, noteu l'alteració diferencial que segueix les bandes de creixement amb composició diferent). El sector esfèric de la part superior esquerra és una vesícula. L'escala gràfica fa 0,32 mm. Llum paral·lela (LlP). Mostra 318S. Foto 3. Basalt olivínic amb textura holocristal·lina inequigranular porfírica i matriu variable entre microcristal·lina i intergranular. Els fenocristalls es poden identificar com s'ha indicat a la foto 1, noteu en el sector central superior un cristall fresc d'olivina que ha experimentat xoc tèrmic com queda palès per la seva fracturació corba en trencaclosques. L'escala gràfica fa 0,32 mm. Llum paral·lela (LlP). Mostra 307S. Foto 4. Basalt olivínic amb textura hipohialina inequigranular porfírica amb matriu que varia d'intergranular a microcristal·lina. Noteu a la dreta d'un gran fenocristall de clinopiroxè la presència d'un sector amb forma de triangle reblert de vidre marró (gris fosc a la foto) amb seccions de plagiòclasi esquelètica (cristalls buits) que registren un procés de sobrerefredament (supercooling). La matriu consta de tabletes de plagiòclasi de mida mitja i hàbit idiomòrfic o hipidiomòrfic (blanc) amb petits cristalls idiomòrfics de minerals opacs (negre) i clinopiroxè hipidiomòrfics o xenomòrfics (gris) situats entre la carcassa de cristalls de plagiòclasi. L'escala gràfica fa 0,08 mm. Llum paral·lela (LlP). Mostra 378A. Foto 5. Basalt olivínic amb textura holocristal·lina inequigranular i matriu intergranular de gra mig. Noteu la presència de cristalls grans hipidiomòrfics d'olivina (blanc) amb fractures iddingsititzades (gris), cristalls grans de plagiòclasi idiomòrfics o hipidiomòrfics (blanc) amb nuclis rics en Ca alterats (colors gris brut en sectors centrals de cristalls blancs) i minerals de mida de gra fi, tant opacs (negres) com de clinopiroxè (gris fosc). El camp representat a la foto té una amplada de 2 mm aprox. Llum paral·lela (LlP) Mostra 325c3bis. Foto 6. Basalt olivínic holocristal·lí amb textura inequigranular glomeroporfírica amb matriu intergranular. Noteu les macles polisintètiques de la plagiòclasi (part esquerra del glomèrul, fenocristalls aïllats i tabletes a la matriu) i els fenocristalls màfics (part dreta del glomèrul i dins la matriu). L'escala gràfica fa 0,32 mm. Nícols creuats (NC). Mostra 325c3.

cate that dips may be partially associated to depositional geometries. Nevertheless, opposing dips and a general NW-SE bedding trend clearly suggest that the area is affected by tectonic deformation. The bedding strike map (Fig. 2) reveals hectometric folds which determine an elongated dome and basin structure. At the central and northern areas this structure is dominated by a NW-SE oriented open anticline and syncline (Fig. 4). At the southern area the NW-SE trend is not so well defined and the bedding trace map suggests interference between N-S and E-W trending folds. As no polarity criteria are available, the few overturned bedding symbols in Figure 2 are shown to maintain consistency with bedding trace lines. These apparently overturned beds can probably be explained as the combined effect of both the primary structures and tectonic deformation.

Dykes have variable trends but show a clear NW-SE maximum (Figs. 2 and 3) and subvertical dips.

DISCUSSION

Geochronological and geochemical data suggest that the successions cropping out at Cape Shirreff and eastern Byers Peninsula are correlative and that they may correspond to the same stratigraphic unit (Smellie et al., 1996). Nevertheless, the succession at Byers Peninsula is dominated by sedimentary rocks, whereas the succession at Cape Shirreff is dominated by volcanic rocks. While the Byers Group is interpreted as the result of deposition in a forearc setting (Smellie et al., 1980; Crame et al., 1993), the succession at Cape Shirreff should be seen as part of the volcanic arc and, hence, needs to be included in the Antarctic Peninsula Volcanic Group.

Both Cape Shirreff and Byers Peninsula display folding in dome and basin, and are similar in deformation style. The succession of Byers Peninsula has maximum dips of 50º. According to Valenzuela and Hervé (1972) its structure consists of slight NW-SE folds whereas Smellie et al. (1980) reported no preferred folding trend. In any case, stronger dips indicate that deformation in Cape Shirreff may be slightly stronger than in Byers Peninsula, showing a variation in deformation intensity between these two areas, which are 20 km apart.

Dykes at Cape Shirreff are generally vesiculated and petrographically indistinguishable from the lavas. In principle, this suggests that dykes might have been emplaced at shallow depths in close association with eruption of the volcanic pile, which would imply ages coeval

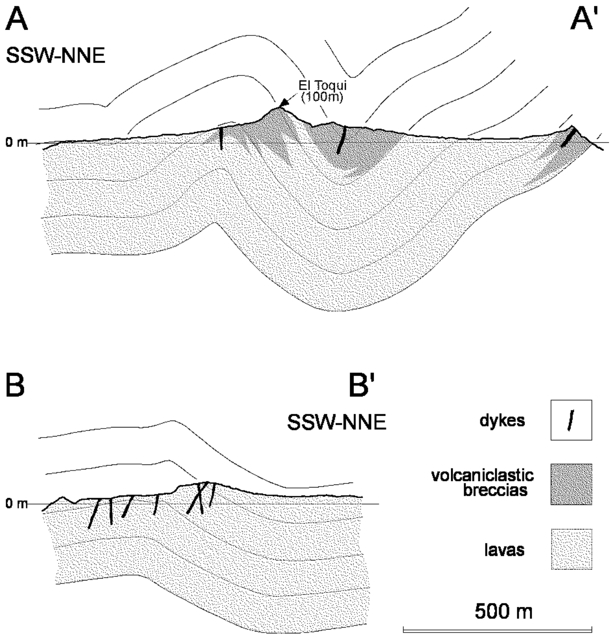

Figure 4.- Geological cross-sections of Cape Shirreff (see Fig. 2 for location). Both angular unconformities of depositional origin and variations in bedding thickness have been omitted. Lateral variation from breccias to lavas is tentatively suggested here, but a more complex geometric relationship cannot be ruled out.

Figura 4.- Talls geològics del Cap de Shirreff (vegeu-ne la situació a la Fig. 2). Aquests talls no tenen en compte les discordances angulars d'origen deposicional que afecten a la successió de les laves, ni les probables variacions de gruix de les capes. Els passos laterals entre les bretxes vulcanoclàstiques i la resta de la successsió són suggerits de forma temptativa, i no es poden descartar relacions geomètriques més complexes.

with those of the lavas. Nevertheless, dykes are largely subvertical, unaffected by the hectometric scale folds. In addition, the NE-SW shortening direction, which can be inferred from the main folding axis, coincides with the extension direction deducible from dyke trends. According to this, dyke emplacement clearly postdates both the volcanic succession and its deformation. To test this hypothesis, a detailed geochemical and geochronological study would be needed, which is beyond the scope of the present paper.

Appendix

The mineral chemistry of selected phases was determinated at the Serveis Científico-Tècnics of the Universitat de Barcelona with a CAMECA electron microprobe with 4 spectrometers, calibrated with natural mineral international standards and under 15 Kv and 20nA operating conditions. The following crystals were used to determine elements: LIF (Fe), TAP (Si, Al, Na, Mg), PET (Ba, K, Ca, Mn). The raw data were processed with a ZAF program.

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REFERENCES

Crame, J.A., Pirrie, D., Crampton, J.S., Duane, A.M., 1993. Stratigraphy and regional significance of the Upper Jurassic-Lower Cretaceous Byers Group, Livingston Island, Antarctica. Journal of the Geological Society of London, 150, 1075-1087.

Dalziel, I.D., 1969. Structural Studies in the Scotia Arc: Livingston Island. Antarctic Journal of the United States, 4, 137.

Doktor, M., Swierczewska, A., Tokarski, A., 1994. Lithostratigraphy and tectonics of the Miers Bluff Formation at Hurd Peninsula, Livingston Island (West Antarctica). Studia Geologica Polonica, 104, 41-104.

Gimeno, D., 1994. Genesis of crystal-rich epiclastic rocks from subaqueous silicic lava domes: role of thermal shock on quartz phenocrysts. Sedimentary Geology, 90, 33-47.

Hathway, B., Lomas, S., 1995. Jurassic-Cretaceous Arc-Forearc sedimentation, Byers Peninsula, Livingston Island, South Shetland Islands. In: VII International Symposium on Antarctic Earth Sciences, 10-15 September 1995, Siena, 187.

Kamenov, B.K., 1995. Geochemistry and Petrography of the Hesperides Point Pluton, Hurd Peninsula, Livingston Island. In: VII International Symposium on Antarctic Earth Sciences, 10-15 September 1995, Siena, 221.

Leat, P.T., Scarrow, J.H., Millar, I.L., 1995. On the Antarctic Peninsula batholith. Geological Magazine, 132, 399-412.

Leterrier, J., Maury, R.C., Thonon, P., Girard, D., Marchal, M., 1982. Clinopyroxene composition as a method of identification of the magmatic affinities of paleo-volcanic series. Earth Planetary Science Letters, 59, 139-154.

Nisbet, E.G., Pearce, J.A., 1977. Clinopyroxene composition in mafic lavas from different tectonic settings. Contributions of Mineralogy and Petrolology, 63, 149-160.

Pallàs, R., 1996. Geologia de l'Illa de Livingston (Shetland del Sud, Antàrtida): Del Mesozoic al Present. Tesis doctoral, Universitat de Barcelona. 265 pp.

Pallàs, R., Muñoz, J.A., Sàbat, F., 1992. Estratigrafía de la Formación Miers Bluff, Isla Livingston, Islas Shetland del Sur. In. J. López-Martínez (ed.). Geologia de la Antártida Occidental, Simposios T3, III Congreso Latinoamericano de Geología. Salamanca, España. 1992. 105-115.

Smellie, J.L., Davies, R.E.S., Thomson, M.R.A., 1980. Geology of a mesozoic intra-arc sequence on Byers Peninsula, Livingston Island, South Shetland Islands. British Antarctic Survey Bulletin, 50, 55-76.

Smellie, J.L., Pankhurst, R.J., Thomson, M.R.A., Davies, R.E.S., 1984. The geology of the South Shetland Islands: VI. Stratigraphy, Geochemistry and Evolution. British Antarctic Survey Scientific Reports, 87, 85 pp.

Smellie, J.L., Liesa, M., Muñoz, J.A., Sàbat, F., Pallàs, R., Willan, R.C.R., 1995. Lithostratigraphy of volcanic and sedimentary sequences in central Livingston Island, South Shetland Islands. Antarctic Science. 7, 99-113.

Smellie, J.L., Pallàs, R., Sàbat, F., Zheng, X., 1996. Age and correlation of volcanism in central Livingston Island, South Shetland Islands: K-Ar and geochemical constraints. Journal of South American Earth Sciences, 9 (3/4), 265-272.

Thomson, M.R.A., 1982. Mesozoic paleogeography of West Antarctica. In C. Craddock. (ed.). Antarctic Geoscience, 331-337. University of Wisconsin Press, Madison.

Tokarski, A.K., Swierczewska, A., Doktor, M., 1997. Miers Bluff Formation, Livingston Island (South Shetland Islands): Diagenesis/Metamorphism and Early Stage of Structural Development. In C.A. Ricci (ed.). The Antarctic Region: Geological Evolution and Processes, Siena, 409-416.

Valenzuela, E., Hervé, F., 1972. Geology of Byers Peninsula, Livingston Island, South Shetland Islands. In R.J. Adie (ed.). Antarctic Geology and Geophysics. Universitetforslaget, Oslo, 83-89.

Vilaplana, J.M., Pallàs, R., Calvet, J., 1994. Geomorfología de la Península del Cabo Shirreff, Isla Livingston, Shetland del Sur, Antártida. Geogaceta, 14, 52-54.

Willan, R.C.R., Pankhurst, R.J., Hervé, F., 1994. A probably Early Triassic age for the Miers Bluff Formation, Livingston Island, South Shetland Islands. Antarctic Science, 6, 401-408.

Xiangshen, Z., Sàbat, F., Smellie, J.L., 1996. Mesozoic-Cenozoic Volcanism on Livingston Island, South Shetland Islands, Antarctica: Geochemical Evidences for Multiple Magma Generation Processes. Korean Journal of Polar Research, 7 (1/2), 35-45.