CENOZOIC TECTONIC EVOLUTION IN LIVINGSTON ISLAND (SOUTH SHETLAND, ANTARCTICA): MESOSTRUCTURAL AND GEOMORPHOLOGICAL APPROACH.

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ABSTRACT

Analysis of the meso fault data collected in Livingston Island (South Shetland, Antarctica) during the 1989/90 Spanish Expedition suggests subhorizontal post-Eocene maximum stress axes mostly oriented NW-SE and ENE-WSW; in addition, few axes plunge strongly. The first mentioned orientation is parallel to the movement of the Drake oceanic plate which has been subducting obliquely below South Shetland Islands arc. According to the deduced stresses, the Bransfield master fault must have originated, as a strike slip fault, and moved as such, before its extensional movement was initiated 2 Ma ago. A set of Quaternary raised beaches studied in Livingston Island could be consistent with an uplift rate of 4-5 mm/year during the last 50,000 years. Several hypotheses are suggested to explain this uplift, which could be related to ice cap melting or to tectonic processes. The latter could be, a) a shoulder effect of the Bransfield master extensional fault, b) oceanic ridge migration and c) mass transfer related to volcanism.

Key words: Geodynamics, Strike-slip faults, Recent Quaternary, Uplift, Antarctica.

RESUMEN

Los análisis de los datos de fallas obtenidos en la Isla Livingston (Shetland del Sur, Antártida) durante la campaña 1989/90 sugieren que, después del Eoceno, la mayoría de esfuerzos máximos locales eran subhorizontales y tenían una orientación NW-SE o ENE-WSW; además, también se deducen unos pocos esfuerzos máximos con disposición cercana a la vertical. La primera de las orientaciones mencionadas es paralela al movimiento de la placa oceánica de Drake la cual subduce oblicuamente bajo el arco de las islas Shetland del Sur. De acuerdo con los esfuezos deducidos, la falla principal de Bransfield debió de originarse como una falla direccional y moverse como tal antes de que actuase como extensional. Este último movimiento se inició hace tan solo 2 Ma. Un conjunto de playas cuaternarias levantadas permiten estimar que durante los últimos 50.000 años Livingston se ha levantado a razón de 4-5 mm/año. Se sugieren distintas hipótesis para explicar este levantamiento que podría estar relacionado con la fusión de parte del casquete glaciar que recubría la isla o con procesos tectónicos. Entre estos últimos se señalan: el efecto espalda de la falla extensional de Bransfield, la migración de la dorsal oceánica y la transferencia de masas relacionada con el vulcanismo.

Palabras clave: Geodinámica, Fallas direccionales, Cuaternario reciente, Levantamiento, Antártida.

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1. INTRODUCTION

The South Shetland Islands are located on the west side of the Antarctic Peninsula close to its northern tip. The islands are separated from the peninsula by the Bransfield Strait (Fig. 1).

Most of the Peninsula has been built along a convergent continental margin during Mesozoic and Ce-

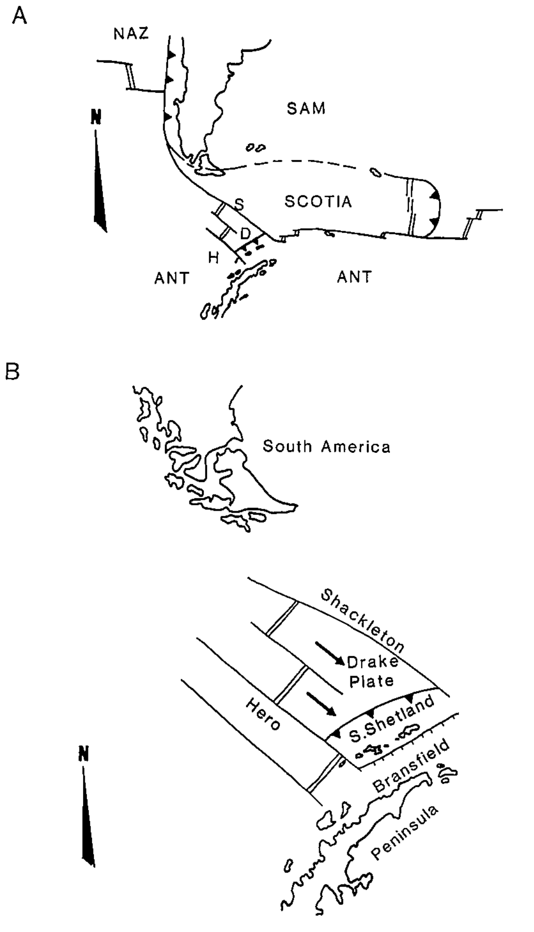

Fig. 1.-A) Lithospheric plates between South America and Antarctic Peninsula (After Barker, 1982). NAZ, Nazca plate; SAM, South America plate; ANT, Antarctic plate; D, Drake plate; S, Shackleton fracture zone; H, Hero fracture zone. B) Geodynamic of South Shetland Islands and Bransfield Sea (modified from Barker, 1982). Small arrows indicate motion of Drake oceanic plate.

Fig. 1.-A) Placas litosféricas entre Sudamérica y la Península Antártida (según Barker, 1982). B) Geodinámica de las islas Shetland del Sur y del mar de Bransfield (a partir de Barker, 1982). Las flechas indican el movimiento de la placa oceánica de Drake.

nozoic times with the proto-Pacific oceanic plate subducting beneath the Antarctic continent. Basement rocks correspond also to an arc-trench system Late Paleozoic and Early Mesozoic in age (Smellie, 1981). Older rocks are scarce and restricted to the East side of the Peninsula (Storey and Garret, 1985).

The purpose of this paper is to analyze the relationships between the present tectonic situation of the South Shetland Islands, the brittle deformation of Mesozoic and Cenozoic rocks of Livingston Island and the recent uplift of those islands.

2. TECTONIC SETTINGT

The South Shetland and the South Orkney Islands constitute the southern arm of the Scotia Arc which links the South American Andes with the Antarctic Peninsula Ranges (Fig. 1A). Almost all the area enclosed within the arc belongs to the Scotia Plate which is surrounded by the South American plate to the North and by the Antarctic plate to the South (Barker, 1982). Actually, the picture is more complex because between the Scotia and the Antarctic plates there exists a micro-plate, the Drake plate, which is a remnant of the oceanic plate subducted beneath the Antarctic Peninsula during Mesozoic and Cenozoic times (Fig. 1B).

The bathymetric map of the area (Davey, 1972) clearly reflects the main tectonic features. Following a section from NW to SE (Fig. 2), first we find the abyssal plain and the South Shetland Trench which corresponds to the subduction of the Drake plate beneath the South Shetland Islands. The islands themselves constitute a topographic platform corresponding, together with the Antarctic Peninsula, to the calcoalcaline volcanic arc related to Mesozoic and Cenozoic subduction. The Bransfield Strait is a linear basin located between the South Shetland Islands and the Antarctic Peninsula; its bottom is tilted towards the islands. The boundary between the islands and the Bransfield Strait is a

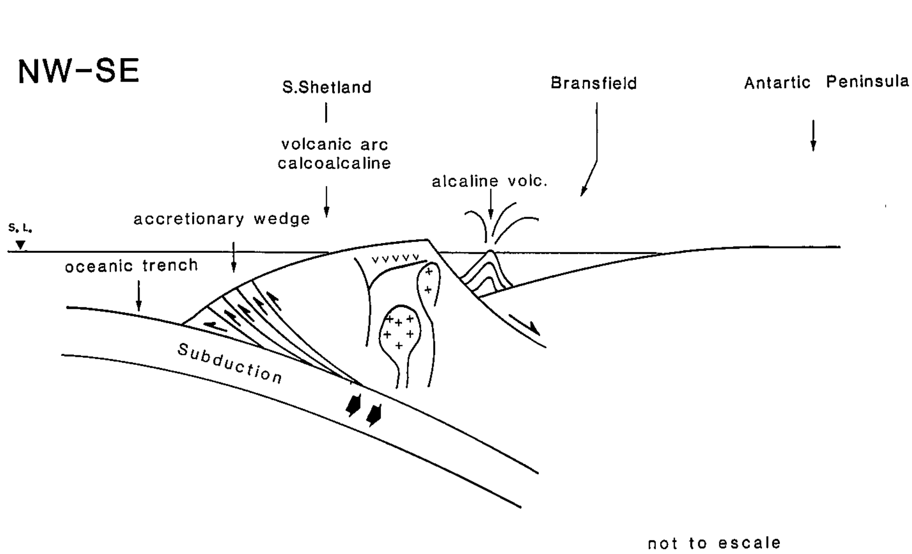

Fig. 2.-Cross section showing the tectonic setting of South Shetland Islands and Bransfield sea.

Fig. 2.-Perfil indicativo del contexto tectónico de las islas Shetland del Sur y del mar de Bransfield.

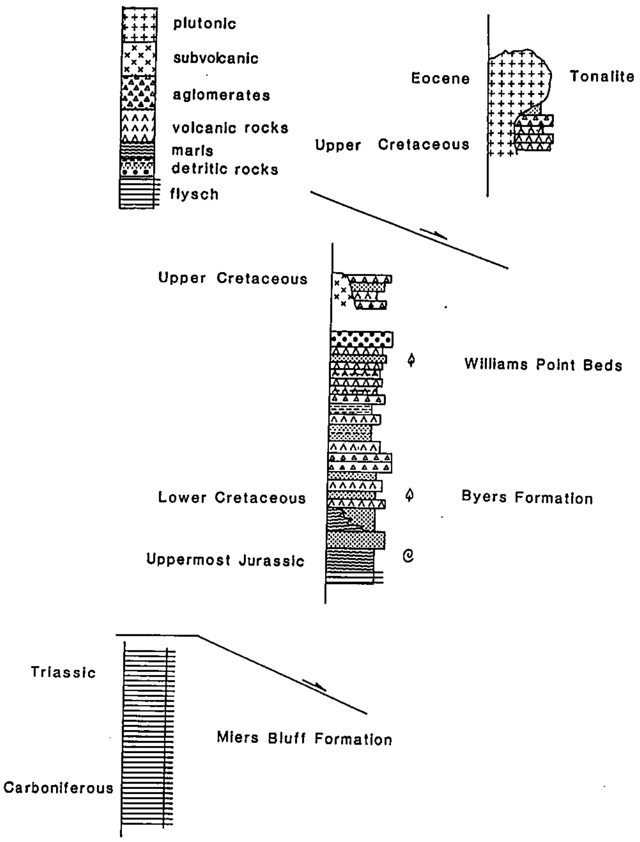

Fig. 3.-Stratigraphy of Livingston Island (after Smellie *et al.*, 1984). Partial columns correspond to different areas in Livingston Island, which are separated by faults.

Fig. 3.-Estratigrafía de la Isla Livingston (según Smellie *et al.*, 1984). Las columnas parciales están levantadas en areas distintas de la isla que están relacionadas entre si por fallas.

very steep and linear slope corresponding to the extensional NE-SW master fault of the Bransfield semi-graben. Along the master fault there are recent alkaline volcanoes (Deception, Pingouin, Bridgeman and several submarine cones). The oceanic ridge is cut by several transversal transform faults striking NW-SE (Shackleton, Bridgeman, Hero, Anvers,...) (Fig. 1).

The main calcoalkaline volcanic activity in the arc shifted from SW to NE with time, it is Late Jurassic-Cretaceous in the SW (Livingston island) and Late Cretaceous - Early Cenozoic in the NE (King George island) (Smellie *et al.*, 1984). During the Cenozoic, the oceanic ridge bounding the Drake plate to the West was subducted beneath the Antarctic Peninsula (Fig. 1B); this process also progressed from SW to NE as the calcoalkaline vulcanism did but the ridge has not yet reached the South Shetland Islands (Tarney *et al.*, 1982); thus, the subduction beneath the South Shetland could still be active. According to several authors the Bransfield Strait seems to be only 2 Ma old (e.g. Barker, 1982), if so it could be difficult to relate it to the major event of arc build up.

3. GEOLOGY OF LIVINGSTON ISLAND

According to Smellie *et al.* (1984) several rock assemblages can be distinguished (Fig. 3). The Miers Bluff Formation is a sequence of shales and greywackes (turbiditic deposits) with no diagnostic fossils. Folds are abundant and have been interpreted as second order folds in an overturned limb of an ESE facing mega-fold (Dalziel, 1969, 1972). A Late Carboniferous - Triassic age has tentatively been assigned to this formation by comparison with similar sequences on the Antarctic Peninsula.

Byers Formation consists of calcoalcaline volcanogenic rocks interlayered with marine and continental sedimentary rocks. Intrusions are common and consist of plugs displaying columnar jointing and pipes of brecciated basaltic and sedimentary rocks. No tight fold has

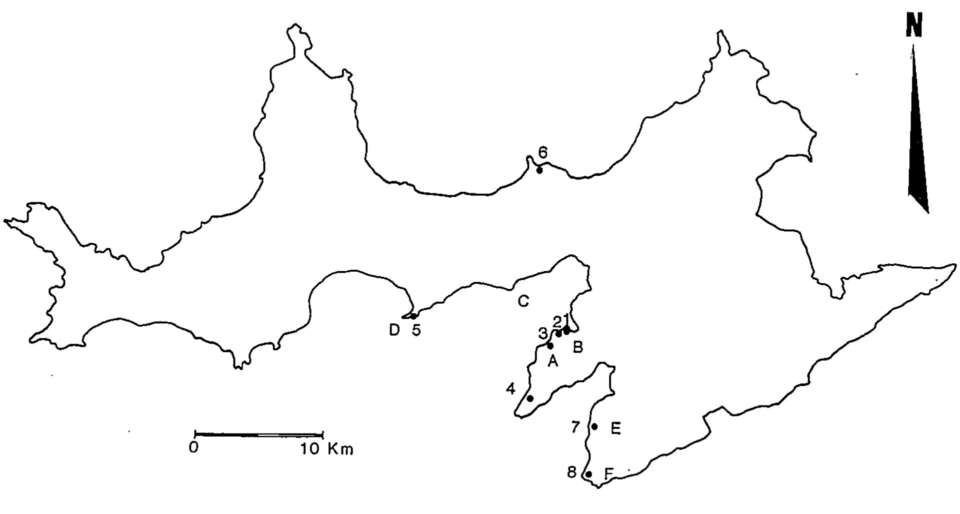

Fig. 4.-Location of fault sites (numbers) and raised beaches sections (letters) in Livingston Island. 1, Johsons Dock; 2 and B, Spanish Station; 3 and A, Caleta Argentina; 4, Miers Bluff; C, Ereby Point; 5 and D, Hannah Point; 6, Siddons Point; 7 and E, Est side of False Bay; 8 and F, Barnard Point.

Fig. 4.-Situación de las localidades de fallas (números) y perfiles de playas levantadas (letras) en la Isla Livingston. 1, Johsons Dock; 2 y B, Base española; 3 y A, Caleta Argentina; 4, Miers Bluff; C, Ereby Point; 5 y D, Hannah Point; 6, Siddons Point; 7 y E, localidad al este de False Bay; 8 y F, Barnard Point.

been observed and bedding is usually gently dipping. The ammonites from the lower part of the sequence are Late Jurassic and Early Cretaceous in age (Tavera, 1970; Covacevich, 1976). Radiometric ages from lava flows interlayered in the lower part of the sequence are Early Cretaceous and those from volcanic plugs Late Cretaceous (Pankhurst *et al.*, 1979).

Williams Point Beds are detritic and volcanogenic rocks yielding fossil flora Cretaceous (Albo-Cenomanian) in age (Rees and Smellie, 1989). They were previously assigned to Late Triassic.

Tonalites intrude in Miers Bluff and Cretaceous volcanic rocks. According to radiometric analyses, the tonalites are Late Eocene in age (Dalziel *et al.*, 1973). Dykes, intermediate in composition, are widespread in Livingston Island and are thought to be Early Cenozoic in age (Caminos *et al.*, 1973; Smellie, 1983).

4. MESO-FAULTS

Data from 8 sites, where different rock formations crop out, have been studied (Fig. 4). Rocks from four of these sites (Johsons Dock, Spanish Station, Caleta Argentina, Miers Bluff) are Late Carboniferous-Triassic in age (Miers Bluff Formation). Cretaceous volcanic rocks crop out at two sites (Hannah Point, Siddons Point) while the other two sites (East site of False Bay, Barnard Point) correspond to Eocene plutonic rocks.

Several methods have been described to deduce the deformation or stress axes from a population of mesofaults (Arthaud, 1969; Arthaud and Choukroune, 1972; Angelier and Mechler, 1977; Armijo, 1977; Etchecopar *et al.*, 1981). The structural elements needed to apply any of these methods are the strike and dip of the fault, the pitch of the slickenside striae and the relative movement of walls. The criteria to deduce the relative movement are well known for carbonate rocks (Arthaud and Mattauer, 1969) and have also been described for silicic rocks (Petit, 1987).

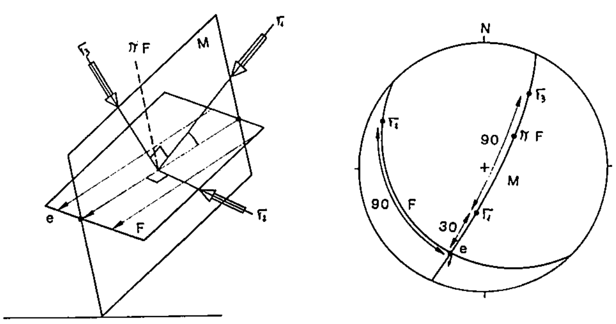

Fig. 5.-Sketch and stereographic plot illustrating the Optimal Stress Method. F, fault plane; M, motion plane; e, estriae-slickenside; Pi F, fault plane pole; sigma 1, 2 and 3, maximum, intermediate and minimum principal stress axes respectivelly.

Fig. 5.-Esquema y proyección estereográfica que ilustran el método de los esfuerzos óptimos. F, plano de falla; M, plano de movimiento; e, estria de falla; Pi F, polo del plano de falla; sigma 1, 2 y 3, esfuerzo principal máximo, intermedio y mínimo respectivamente.

We have used the Optimal Stress Method (Etchecopard, 1984) based on the Anderson (1951) fault concept. Accounting for friction, the maximum principal stress axis (sigma 1) lies on the motion plane at 30° from the fault plane (the motion plane is the plane perpendicular to the fault plane and containing the slickenside striae) (Fig. 5). The main advantage of this method is its simplicity. Limitations arise because the Anderson fault concept only accounts for plane strain and not for the general situation (Bott, 1959; Oertel, 1965); in addition, the considered fault plane should not be a previous fracture acting as a fault.

As a whole, sites 1 to 4 from Late Carboniferous-Triassic rocks provide numerous useful observations (Table 1). A large scatter of sigma 1 deduced from these sites is evident (Fig. 6A); scattering probably results from the above mentioned limitations of the Optimal Stress Method. Nevertheless, the steroplot shows two maxima corresponding to gently inclined maximum stress axes; thus, they are coherent with strike-slip tectonic regimes. The main maximum is oriented NW-SE and the other ENE-WSW (Fig. 6A). Several other deduced axes plunge strongly and are coherent with an extensional regime. Preservation of slickenside striae is very poor in Cretaceous volcanic rocks (sites 5 and 6), thus few stress axes can be deduced, the obtained sigma 1 axes are NW-SE oriented (Fig. 6B). In addition we used joints tentatively from Hannah Point in a qualitative way, but this procedure is not useful at Siddons Point where subvolcanic rocks display contractional columnar jointing (Table 1). Plutonic Eocene rocks (sites 7 and 8) provide scarce but good data, again two sets of sigma 1 orientations are inferred which are close to those from older rocks (Fig. 6C). Similar stress axis orientations deduced from faults in rocks ranging from Upper Carboniferous to Eocene suggest that the related stress tensors acted later than Eocene. Moreover, the pitch of striae in only 55 from a total of 156 faults (35%) is larger than 35° (Table 1) clearly suggesting that post-Eocene stress tensors mostly correspond to wrench tectonic regimes (maximum and minimum stress axes close to horizontal).

5. RAISED BEACHES

Well exposed raised beaches demostrate that the South Shetland Islands are rising above sea level (John and Sugden, 1971). We studied 15 sections perpendicular to the present coast line in order to establish how many beach levels exist and their altitude above sea level. The raised beaches complex at the Spanish Station in Livingston is described in detail by López *et al.* (1991). The observed beaches have been correlated with those quoted in previous works (John and Sugden, 1971). Only six of the 15 studied sections are presented in Fig. 7. At least 8 different old superposed beaches (in addition to the present one) can be differentiated, the uppermost one being the oldest and the lowermost one the youngest. The former has been recorded in only one

a site	b name	c age	d bedding dip	e faults	f pitch>35º	g shear criteria	h σ_1 mean orientation	i Joints	j σ_1 orientat.
1	Johsons Dock	P_z^+ - Tr	35 - 310 overturned	27	12	13	140	-----	-----
2	Spanish St.	P_z^+ - Tr	40 - 298 overturned	37	5	27	1ª)080; 2ª) 145	-----	-----
3	Caleta Argentina	P_z^+ - Tr	80-110;70-270 overt.	30	5	13	a) 040; b) 130	-----	-----
4	Miers Bluff	P_z^+ - Tr	30 - 285 overturned	14	6	6	120	-----	-----
5	Hannah P.	K	20 - 350	--	-------	------	--------	13	WNW-ESE
6	Siddons P.	K^+	---------	8	1	4	NW - SE	20	?
7	East side False B.	K^+ - Pg	---------	47	11	18	110		
8	Barnard P	E_o	---------	23	15	9	a) 060; b) 110	52	W-E

Table 1.- Surveyed fault sites. a) Site number; b) site name; c) age of outcroping rocks, d) bedding disposition (dip and trend of maximum dip), e) number of faults measured, f) number of faults with a striae pitch larger than 35°, g) number of observed shear criteria, h) mean orientation of maximum stress axis after faults, i) number of joints measured, j) maximum stress axis orientation after joints.

Tabla 1.- Localidades de fallas estudiadas. a) número de la localidad; b) nombre; c) edad de la roca; d) disposición de la estratificación (buzamiento y dirección del máximo buzamiento; e) número de fallas medidas; f) número de fallas con *"pitch"* mayor de 35°; g) número de criterios de cizalla; h) orientación media del eje de máximo esfuerzo a partir de las fallas; i) número de diaclasas medidas; j) orientación del eje de máximo esfuerzo a partir de las diaclasas.

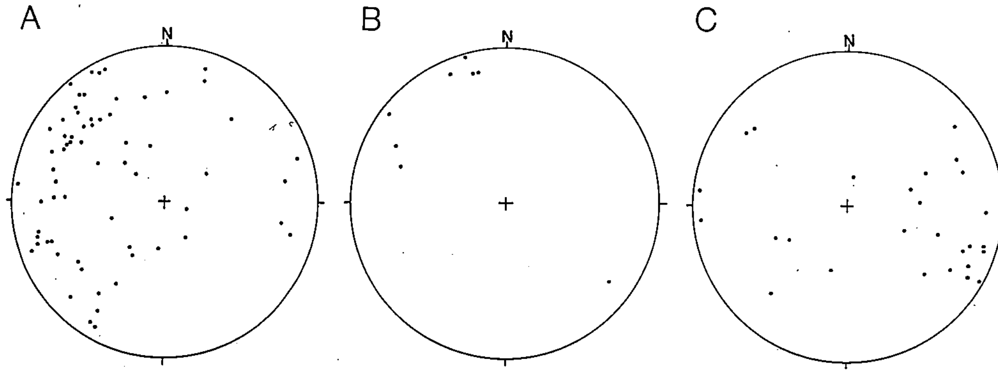

Fig. 6.-Estereoplot (lower hemisphery) of maximum stress axes deduced with Optimal Stress Method from faults in Livingston Island. A, sites 1, 2, 3 and 4 (Upper Carboniferous - Triassic sedimentary rocks); B, site 6 (Upper Cretaceous sub-volcanic rocks); C, sites 7 and 8 (Upper Cretaceous - Eocene plutonic rocks).

Fig.6.- Proyección estereográfica (hemisferio inferior) del eje de esfuerzo máximo de las fallas de Isla Livingston deducido a partir del método de esfuerzos óptimos. A, localidades 1, 2, 3 y 4 (Carbonífero superior - Triásico, rocas sedimentarias); B, localidad 6 (Cretácico superior, rocas subvolcánicas); C, localidades 7 y 8 (Cretácico superior - Eoceno, rocas plutónicas).

section (False Bay) whereas the latter is present in all studied sections (Fig. 7G), this is because shore sediments that are not lithified are easily eroded.

Radiocarbon analyses of buried organic remmants yield ages corresponding to several different levels in Byers Peninsula (Livingston Island) (Hansom, 1979) and other South Shetland localities (Sugden and John, 1973) (Fig. 7G). After correlation between dated levels and those presented in this paper, uplift rates for Livingston Island have been deduced. Obtained values are not linear but a mean uplift rate of 4 or 5 mm/year can be considered during the last 2000 years. If we consider the deduced mean uplift rate is valid for longer periods, then the oldest studied beach deposit located 70 m above sea level in False Bay should have an estimated age of 15,500 years. Moreover, at different localities as in Byers Peninsula (John and Sugden, 1971) and Hurd Peninsula, poorly preserved marine erosion levels occur up to 250 m above sea level suggesting uplift was probably active during the last 50,000 years. Unfortunately shore deposits are very scarce on those erosion levels and it is not possible to get any radiocarbon ages.

6. DISCUSSION

The deduced stress tensor from meso-fault analysis of three different rock associations has one maximum principal axis oriented NW-SE (N 130 E as a mean) and is considered to have acted during post Eocene times. This direction is parallel to the transform faults of the Drake plate, thus stress recorded in Livingston rocks could be, at least partially, linked to displacement of oceanic lithosphere towards SE (Fig. 1B). Moreover, convergence at the South Shetland continental margin is oblique and we propose that this oblique motion is divided into two components (Fitch, 1972; Walcott, 1978; Beck, 1983; Mount and Suppe, 1987). One of these components being perpendicular to the subduction strike (and acting on the accretionary prism)

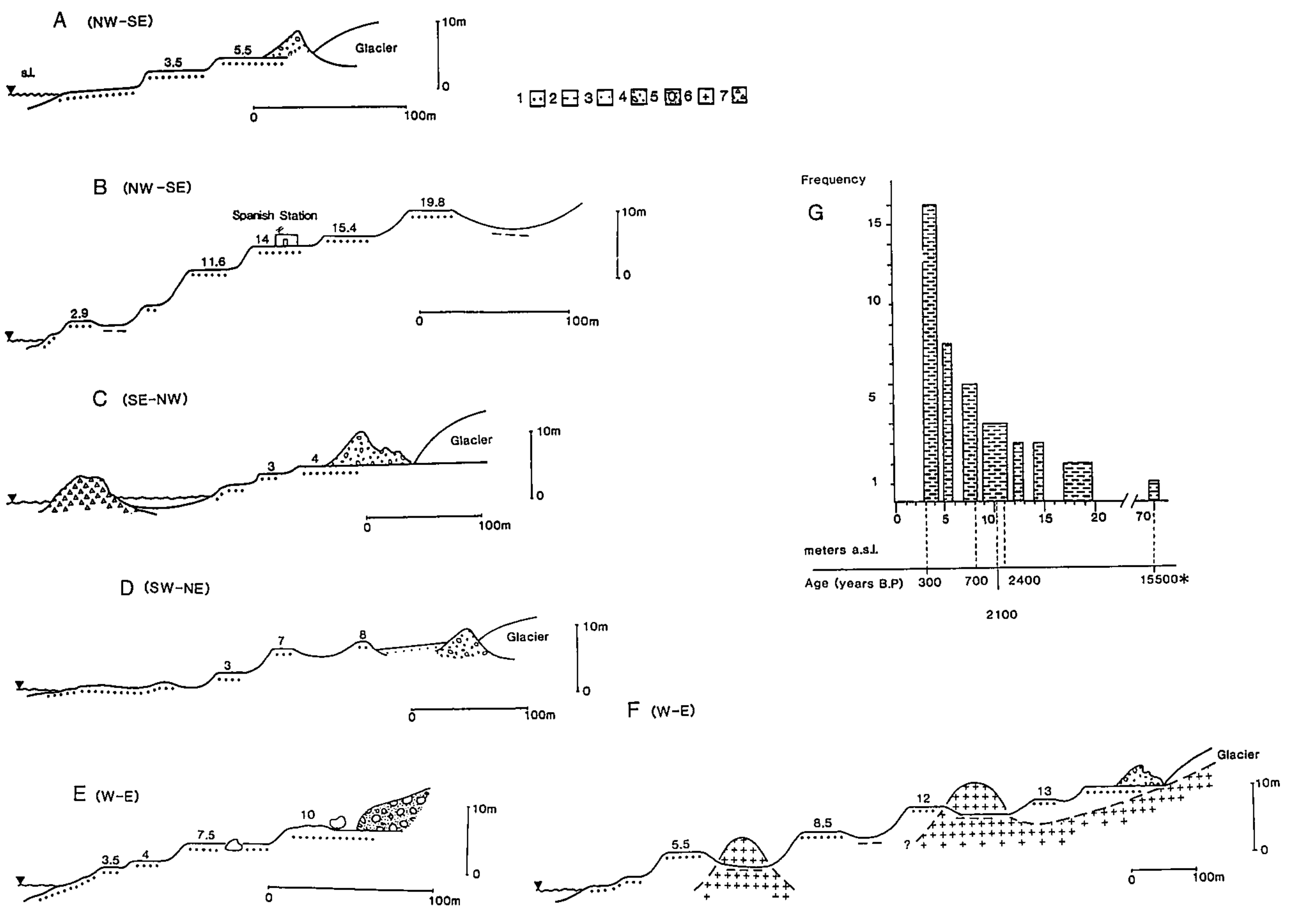

Fig. 7.-A, B, C, D, E and F, raised beaches sections of Livingston Island (location in Fig. 4). 1, gravel beaches; 2, lagoon deposits; 3, proglacial sands; 4, moraine; 5, debris flow; 6, tonalite bedrock; 7, Upper Cretaceous aglomerate. Numbers in the sections refer to meters above sea level. G, frequency histogram of observed old beaches. The age scale derives from correlation with equivalent levels in Byers Peninsula (Livingston Island) after Hansom (1979), the one marked with the star being an inferred value (explanation in the text).

Fig. 7.-A, B,C, D, E y F, perfiles de playas levantadas de Isla Livingston (situación en la Fig. 4). Los números en los perfiles hacen referencia a la altura en metros sobre el nivel del mar. G, histograma de frecuencias de los diferentes niveles de playa observados. La escala de edades se ha realizado a partir de la correlación con los niveles equivalentes de Península Byers (Isla Livingston) según Hansom (1979), la edad del nivel marcado con asterisco es estimada (explicación en el texto).

and the other parallel to the subduction strike and transferred to the magmatic arc where it would produce a transtensional regime. After having deduced the maximum stress axis and the position and orientation of the Bransfield trough master fault, this should act both as a right lateral fault and as an extensional fault. The former movement is widely suggested by the large amount of strike slip faults present in Livingston Island (Table 1) and the latter is supported by the existence of the trough itself. If 2 Ma is a reliable age for the generation of the Bransfield trough, the extensional movement should correspond to the youngest one, and the generation of the Bransfield master fault and most of its evolution has to have been produced in strike-slip regimes which are dominant in the region.

The South Shetland recent uplift demostrated by raised beaches must be related to the dynamics of this area. A question arises on the relationships between the raised beaches and the dynamic processes that have affected the island. Are these processes related to vertical movements due to ice melting or are they properly related to the tectonic evolution of the island?.

Recent raised beaches can be explained by isostatic uplift due to ice cap reduction during the regional deglaciation initiated later than 18,000 years ago (John and Sugden, 1973) and dated of 8,000 years B.P. from radiocarbon analysis in King George Island (Maüsbachen *et al.*, 1989) (Fig. 8A), which is associated with an opposite effect corresponding to relative island foundering due to the rise of the sea level by global ice melting (Fig. 8B). The latter effect is probably equivalent to isostatic uplift in those areas where ice caps were small and thin, like it was in South Shetland. Moreover, if uplift in Livingston has been going on at least for 50,000 years it can not be linked to deglaciation which was iniciated later.

The uplift could also be related with the shoulder effect associated with the recent extensional movement of the nearby Bransfield master fault following the model of Weissel and Karner (1989) (Fig. 8C) or with oceanic ridge migration towards SE because younger and younger oceanic lithosphere is being subducted (Fig.

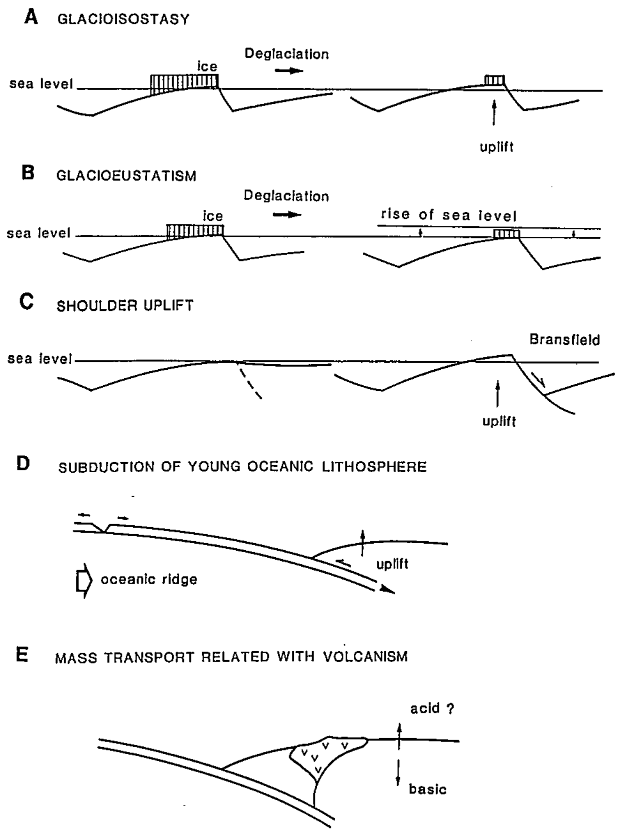

Fig. 8.-Several hypotheses to explain the vertical movement of South Shetland Islands (hypothesis C is favoured).

Fig.8.- Hipótesis para explicar el movimiento vertical de las islas Shetland del Sur (la hipótesis C es la más probable).

8D). Uplift related to this latter mechanism is described in the New-Hebrides Arc by Lecolle *et al.* (1990). To discriminate between these two hypotheses some additional data and calculations are needed; it is necessary to know when the uplift started and whether or not the uplift took place in other areas of the Antarctic Peninsula. The age of the uplift must correlate with the age of the calculated effect of causal phenomena. Moreover, uplift related with young oceanic lithosphere should be migrating northwards because subduction of the oceanic ridge progressed from SW to NE and should be long acting (around 30 Ma). With the present knowledge, our suggestion is to relate most of the uplift to the shoulder effect of the Bransfield master fault, because it is recorded by recent raised beaches and no available data suggest long acting uplift directly linked to subduction.

Uplift could also be associated with other geodynamic phenomena such as, for instance, the mass transfer related with vulcanism (Fig. 8E), but calcoalcaline vulcanism is too old to be linked with recent uplift and basaltic alcaline vulcanism should produce, if any, the oppossite effect (foundering). Further data and calculations are necessary to know the contribution of each mentioned mechanism to the total uplift.

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