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Del Mesozoic al Present

Treball fet per RAIMON PALLÀS i SERRA

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Geomorfología de la península del Cabo Shirreff. Isla Livingston. Shetland del Sur. Antártida

Geomorphology of Cape Shirreff. Livingston Island. South Shetland. Antartica

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ABSTRACT

The geomorphological exploration and mapping of Cape Shirreff area was carried out during the 1992/93 Spanish Antartic Expedition in Livingston Island. In this area two main systems of lanforms were recognized. A) Marine landforms mostly constituted by three groups of raised platforms and by five levels of raised beaches. B) Glacial landforms conformed by recent moraines related to the present ice-margin and by older glacial deposits located on the different marine levels. These landforms and the relathionship between them allow us to reconstruct the recent deglaciation of this uplift controlled area.

Key words: *erosion platforms, raised beaches, moraines, eustatism, uplift.*

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Introducción

Durante la primera fase de la Campaña Antártica 1992/93 se ha realizado la exploración y la cartografía geomorfológica del Cabo Shirreff, en la costa norte de la Isla Livingston. En esta nota se presentan los resultados de dicho trabajo que se concretan en el levantamiento del primer mapa geomorfológico de esta zona . Este trabajo se enmarca en un estudio regional de la Isla Livingston que se inició en la campaña 1989/90.

El Cabo Shirreff es una península rocosa, descubierta de hielo glaciar, formada por una serie de rocas volcánicas (lavas y brechas) y diques subvolcánicos similares a las formaciones que afloran en Península Byers (Smellie *et al*., 1984). Morfológicamente, cabe distinguir la presencia de superficies erosivas o plataformas en las que se han encajado unos pequeños valles en forma de corredores que las disectan. Estas vallonadas presentan unas laderas con fuertes pendientes y fondos cóncavos, casi planos. Una intensa dinámica crionival ha degradado fuertemente las formas y depósitos, y es la responsable de la existencia de una formación superficial sobre las plataformas y las laderas.

La línea de costa tiene una geometría enormemente recortada y configura una serie de salientes rocosos entre los que se han desarrollado calas de dimensiones variables. En ellas se conservan distintos niveles escalonados de playas.

En el istmo de la península del Cabo Shirreff se encuentra el margen del gran glaciar de plataforma con morfología dómica, que cubre la zona central de la Isla Livingston. Dicho margen se subdivide en dos lóbulos glaciares que llegan hasta el mar: al NE, el de la playa de Media Luna, y al NW, el de San Telmo.

Plataformas de erosión marina

Hobbs (1968) ya cita la existencia de una plataforma marina levantada en Cabo Shirreff (también descrita en Península Byers) con una elevación estimada entre 46.2 m y 53.3 m sobre el nivel del mar. También indica la presencia de otras plataformas inferiores (7.6 - 9.1 m y 12.2 - 15.2 m) en las que encuentra, esparcidos sobre su superfície, gravas y cantos rodados.

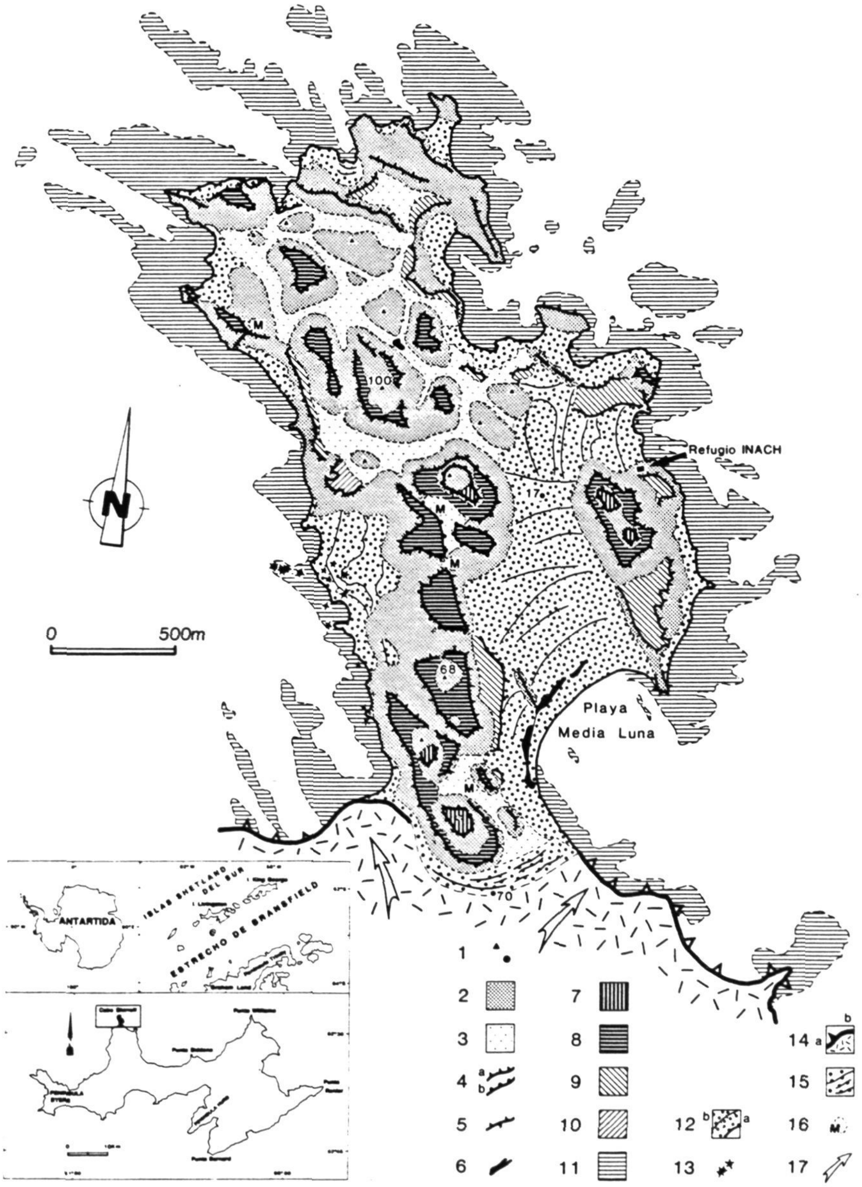
Plataformas altas: existen restos de una plataforma situada a una altura de 65 - 68 m sobre el nivel del mar. Estos retazos de superfície son de poca extensión y aparecen únicamente en la mitad sur de Cabo Shirreff. De este nivel sobresalen algunos relieves de orden decamétrico que podrían corresponder a paleoislotes pertenencientes a esta antigua plataforma marina. A cota 50 - 55 m existe otra plataforma que seguramente corresponde a la que cita Hobbs (1968). Los restos de esta antigua plataforma son muy abundantes y extensos en toda la península. Los límites de dicha plataforma coinciden, en la mayoría de los casos, con la presencia de un escarpe que destaca en el paisaje. Dicho escarpe corresponde al paleoacantilado de una antigua línea de costa. El trazado del escarpe presenta tramos rectilíneos de dirección NNW - SSE, coincidente con la orientación de la actual costa oeste del Cabo Shirreff. Dicha orientación viene condicionada por diques y fracturas.

Plataformas intermedias: por debajo de la gran plataforma superior hay varios niveles de terrazas marinas interpretados fundamentalmente como erosivos; la mayoría de ellos tienen recubrimiento de gravas rodadas. Tienen una extensión muy reducida y una disposición escalonada. Hay un único resto del nivel de 22 m en la costa oeste (San Telmo). Todos los demás niveles se encuentran a cota 11 - 15 m sobre el nivel del mar que podrían corresponder a retazos de rasas relacionables con algunas de las playas levantadas comentadas más adelante.

Plataforma actual: corresponde a la plataforma de abrasión marina cubierta por el mar y en bajamar emerge parcialmente. Ha sido interpretada y cartogra-

Fig.1.— Mapa geomorfológico del Cabo Shirreff

Fig.1.— Geomorphological map of Cape Shirreff



Leyenda:
1. Cima; 2. Pendientes fuertes; 3. Pendientes suaves; 4a. Escarpe abrupto; 4b. Escarpe suave; 5. Crestón; 6. Laguna; 7. Plataforma de abrasión marina (P.a.m.) de 65-68 m; 8. P.a.m. de 50-55 m; 9. P.a.m. de 22 m; 10. P.a.m. de 11-15 m; 11. P.a.m. actual; 12. Nivel de playa (a) elevado ,(b) actual; 13. Islote, "stack"; 14. Margen glaciar (a) con escarpe, (b) en rampa; 15. Morrena con núcleo de hielo y crestones; 16. Depósitos morrénicos; 17. Flujo glaciar.

Legend:
*1. Peak; 2. Steep slope; 3. Gentle slope; 4a. Scarp with break of slope; 4b. Scarp with smooth change of slope; 5. Crest; 6. Lagoon/lake; 7. Marine platform (M.p.) to 65-68 m; 8. M.p. to 50-55 m; 9. M.p. to 22 m; 10. M.p. to 11-15 m; 11. Present M.p.; 12a. Raised beach level; 12b. Present beach; 13. Stack; 14. Glacial margin (a) ice-cliff; (b) ice-ramp; 15. Ice-cored moraine and morainic ridges; 16. Morainic deposits (**M**); 17. Ice flow.*

fiada a partir de las fotografías aéreas del vuelo británico realizado en diciembre de 1956 y enero de 1957. Esta plataforma tiene un límite enormemente sinuoso y su anchura oscila entre 100 y 700 m.

Depósitos asociados: en todas las plataformas superiores (65 - 68 m y 50 - 55 m) se encuentran, diseminados en su superfície, gravas y cantos poligénicos rodados por la acción litoral. Localmente hay gran cantidad de cantos. La litología de dichos cantos y gravas corresponde, en parte, a rocas no aflorantes en Shirreff tales como granitoides. Estos clastos provinientes de áreas fuente alejadas de Shirreff , así como una buena parte de los locales,conservan, facetas y estrías, lo cual nos permite interpretar su orígen glaciar. Muchos de estos clastos prodrían proceder de morrenas degradadas por la acción marina que las retrabaja como playas.

Se han localizado tres acumulaciones de depósitos morrénicos encajados en la plataforma de 50 - 55 m (**M** en el mapa geomorfológico) retrabajados por acción marina y, posteriormente, por la dinámica crionival. La fracción fina de estas acumulaciones ha sido lavada y sólo se conservan los cantos y bloques cuyas dimensiones llegan a ser métricas, especialmente en los granitoides. Estos clastos tienen estrías, facetas planares y morfología en "punta de nariz" pero se aprecia un cierto grado de rodadura.

Niveles de playa

Tal como se ha descrito en otros lugares de las Shetland del Sur y muy especialmente en la Isla Livingston (Hobbs, 1968; John and Sugden, 1971; López *et al.*, 1992) se encuentran distintos niveles de playas elevadas escalonadas. En la zona del Cabo Shirreff están muy bien representados en la playa de la Media Luna, dónde aparece una secuencia con seis niveles de terraza situados a: 4.2 m; 6.0 m; 8.8 m; 15.8 m y 17.2 m. Los materiales que constituyen estas playas están formados por gravas muy rodadas con una matriz arenosa. La litología de los clastos es muy variada y no corresponde únicamente al sustrato volcánico de Shirreff, también aparecen granitoides, y rocas cuarcíticas. Muchos de estos clastos conservan aún indicios de su orígen glaciar (forma, estrías). Estas características son las mismas que se observan en aquellas playas actuales donde el frente glaciar se dispone en contacto con el mar.

El margen glaciar

El glaciar, subdividido en dos lóbulos, se ha instalado sobre la plataforma de abrasión subactual; el frente glaciar configura un escarpe de 10 a 15 m de altura, al pie del cual se dispone una pequeña franja de playa. En el istmo de la península del cabo Shirreff,entre los dos lóbulos antes citados, el glaciar se dispone sobre un alto del sustrato debido al cual la línea cartográfica del margen glaciar adquiere una geometría cóncava. En esta franja se encuentra una morrena cuya anchura supera los 100 m. Esta morrena posee un núcleo de hielo recubierto por un manto de depósitos que raramente llega al metro de espesor y que presenta varios crestones. El material morrénico está constituído por cantos de orígen subglaciar que han aflorado en superfície, muchos de ellos gelifractados. La matriz es lutítico-arenosa. Este material se encuentra en constante removilización, debido a la formación de movimentos en masa de tipo flujo.

Resultados y conclusiones

El estudio de la geomorfología del Cabo Shirreff pone de manifiesto dos hechos importantes: 1) la deglaciación de este sector; 2) el levantamiento reciente del área.

1) De la comparación de los márgenes glaciares observados en el terreno con los de la fotografía aérea británica de 1956 - 57, se desprende que ha habido un claro retroceso de los mismos durante, al menos, estos últimos 35 años. La retirada del glaciar ha sido especialmente importante en los lóbulos glaciares de Media Luna (sector E) y de San Telmo (sector W), donde el glaciar, en contacto con el mar, ha llegado a retroceder entre 100 y 150 m en algunos puntos. En la zona del istmo, el retroceso no se ha traducido en una desconexión entre le hielo y la morrena, sino en una notable disminución del espesor del glaciar en la zona marginal. El retroceso reciente de los glaciares de Livingston también ha sido observado en otros sectores de la isla (Calvet *et al.*, 1992; López *et al.*, 1992).

Del estudio de los dos lóbulos glaciares que se disponen en contacto con el mar, se desprende la siguiente secuencia de procesos:

a) el glaciar avanzó inicialmente sobre la plataforma de abrasión marina subactual, probablemente incorporando material de playa en su base.

b) posteriormente retrocedió hasta su posición actual. En este retroceso el glaciar abandona material de la morrena de fondo que es retrabajado por el mar y pasa a formar parte de las playas actuales.

Estas consideraciones sobre la evolución reciente nos servirán para reconstruir los episodios más antiguos. Los clastos glaciares diseminados en las plataformas altas, así como las acumulaciones morrénicas (M) asociadas nos permiten interpretar la siguiente evolución:

a) Avance del glaciar hacia el mar (ocupando toda la zona del actual Cabo Shirreff) recubriendo una extensa plataforma de abrasión previa. El glaciar puede incorporar material litoral en su base.

b) Retroceso del frente glaciar dejando al descubierto todo el Cabo Shirreff. El mar retrabaja el material de la morrena de fondo abandonado sobre la plataforma. Las acumulaciones morrénicas (M) podrían significar algunas estabilizaciones del glaciar en su retroceso.

c) El levantamiento de toda el área produce la disección de las plataformas altas y posibilita la formación de terrazas marinas escalonadas a niveles inferiores (plataformas intermedias y playas). Los depósitos de las plataformas altas son degradados por procesos crionivales y, en gran parte, son retomados en los niveles inferiores.

2) El levantamiento de este sector ya fue apuntado por Hobbs (1968). Otros autores posteriores han realizado nuevas observaciones al respecto, especialmente en la Península de Hurd donde se estima un levantamiento de 3-5 mm/año (Sàbat *et al.*, 1992; López *et al.*, 1992). En Shirreff no se ha podido datar ninguno de los niveles ni de plataformas ni de playas. La única posibilidad de establecer una cronología absoluta, por el momento, sería la correlación con niveles datados en Byers (Hansom, 1979) y en King George (Clapperton, C.M. y Sugden D., 1988) o utilizar los valores de tasas de levantamiento propuesto por otros autores en otros sectores antes apuntados. En relación a los posibles mecanismos que originan dicho levantamiento únicamente podemos apuntar las dos hipótesis en las que se centra nuestro análisis: causas tectónicas, causas glacioisostáticas o una combinación de ambas. El desarrollo de este análisis se enmarca en un trabajo regional en curso que ultrapasa los objetivos de la presente nota.

Agradecimientos

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Pallàs,R., Vilaplana,J.M. & Sàbat,F. (1995): Geomorphology and Neotectonic features of Hurd Peninsula (Livingston Island, South Shetland Islands). *Antarctic Science*, 7, 395-406.

Aquest article busca indicis de la relació entre la geomorfologia i la tectònica a les Illes Shetland del Sud a partir d'una anàlisi detallada i local de la Península de Hurd. Es presenten els primers mapes geomorfològic i neotectònic del conjunt de la Península de Hurd. Es discuteix quin paper pot haver tingut el fallament en la distribució de les unitats del relleu i s'analitza quin és el potencial dels diferents elements geomorfològics (especialment els marins) per tal de detectar moviments tectònics recents en aquesta àrea. Es fa una revisió de l'edat dels diferents elements geomorfològics i s'intenta acotar l'edat de les deformacions que els afecten.

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Geomorphological and neotectonic features of Hurd Peninsula, Livingston Island, South Shetland Islands

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Abstract: On Hurd Peninsula (Livingston Island) neotectonic features, such as faults, affect the landforms and emerged marine levels. A detailed local study of these features provides information on the recent structural and geomorphological evolution of the area. We suggest that Hurd Peninsula is divided into several tectonic blocks separated by faults. Movement of the faults determines the relative altitude of these blocks and, in consequence, their susceptibility to glacial, periglacial or marine processes. Although some of the tectonic movements reflected in the landforms may have been inherited from former phases of deformation, some of the neotectonic faulting has a maximum lower Miocene age. A new method of correlation of emerged beach levels is suggested and the possibility of analysing the effects of neotectonic deformations from their analysis is discussed. The application of the methods tested here to other areas of the South Shetland archipelago could provide insights into the timing and mechanisms of recent tectonic evolution.

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Key words: neotectonics, geomorphology, emerged marine features, glacial deposits, Livingston Island

Introduction

The aim of the present study is to understand the interplay between tectonic and geomorphological processes in the South Shetland Islands through detailed local neotectonic analysis. On Hurd Peninsula, Livingston Island (Fig. 1) tectonic, glacial and marine elements are interrelated and show clear signs of neotectonic activity: on the one hand there are faults which affect the landforms and, on the other, there is a striking set of emerged marine levels. The approach used here can yield useful information on the recent tectonic and geomorphological evolution not only of Hurd Peninsula area but also of other areas in the archipelago.

The South Shetland Islands are a fragment of the Antarctic Peninsula Mesozoic to Cenozoic magmatic arc that lies above a continental basement (Smellie *et al.* 1984). The NE–SW trending South Shetland archipelago is separated from the Antarctic Peninsula by the 100 km-wide Bransfield Strait (Fig. 1). Its seismicity (Forsyth 1975, Pelayo & Wiens 1989, Vila *et al.* 1992) and its volcanism (e.g. Smellie 1987) are clear indications of present-day tectonic extensional activity. To the north-west, the South Shetland crustal block abuts the Drake microplate along the South Shetland trench (British Antarctic Survey 1985). Farther north-west, the Drake microplate is bordered by a segmented oceanic ridge (Aluk Ridge), whose extension determined the subduction of the Drake plate below the South Shetland Islands during the Tertiary. According to Barker (1982) accretion at the Aluk Ridge slowed or stopped *c.* 4 Ma ago. As Bransfield Strait extension seems to be active, slow subduction of oceanic lithosphere below the South Shetland block is probably still taking place (Barker 1982, Larter/GRAPE 1991).

The South Shetland Islands and Bransfield Strait constitute a part of the southern arm of the Scotia arc, an arcuate alignment of positive, mostly submerged high relief crustal fragments linking the southern South America continent, South Georgia, the South Sandwich and South Orkney

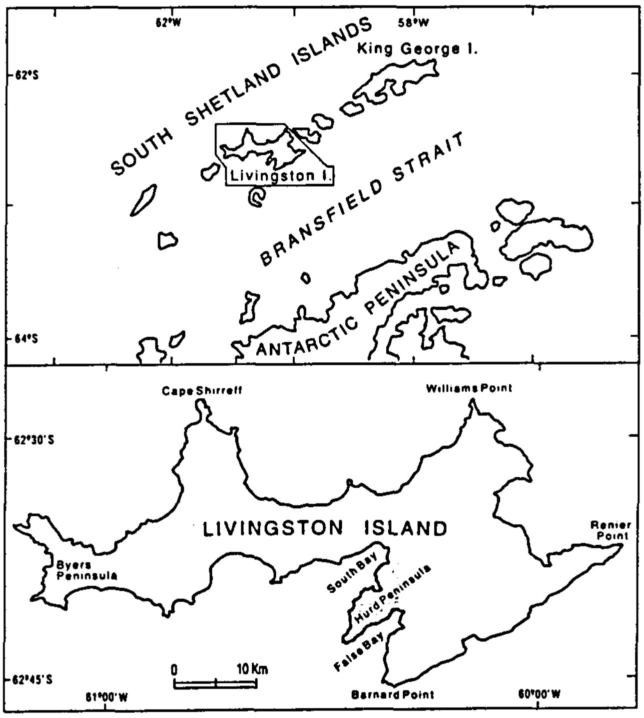

Fig 1. Maps to show the geographical setting of Hurd Peninsula.

Islands and the northern Antarctic Peninsula. The E–W trending southern arm of the arc has a sinistral strike-slip movement (Forsyth 1975, British Antarctic Survey 1985).

The relationships between the South Shetland trench, Bransfield Strait and the Scotia arc are still poorly understood. It seems that the inception of the Bransfield basin did not begin until immediately after the slowing or cessation of accretion at the Aluk Ridge. According to Barker (1982), the opening of the basin was probably due to the excess weight of the subducted slab and roll back of the hinge of the subduction. It has also been suggested that the origin of the basin could be due to a strike-slip motion determined by the push of spreading ridges surrounding the Antarctic plate (Tokarski 1991).

In the South Shetland Islands there is a record of brittle deformation, which can yield some insight into the tectonic history of the area (Tokarski 1991, Santanach *et al.* 1992, Willan 1992, 1994). Those authors point out that fracturing is polyphasic and mainly strike-slip in nature.

Hurd Peninsula (28 km^2) lies on the southern coast of Livingston Island between South Bay and False Bay (Fig. 1). Most of the peninsula is formed by the Miers Bluff Formation, an intensely folded and overturned *flysch*-like succession, which corresponds to the pre-magmatic arc basement (Hobbs 1968, Dalziel 1972, Pallàs *et al.* 1992, Muñoz *et al.* 1992). The top of Miers Bluff Formation is in either unconformable or tectonic contact with massive (?)Cretaceous volcanic breccias that crop out along the False Bay coast. In addition, there are some small outcrops of (?)Eocene plutonic rocks (Smellie *et al.* 1984).

Widespread brittle structures affect the bedrock (Willan 1992, 1994, Santanach *et al.* 1992, Doktor *et al.* 1994) and up to three phases of deformation have been deduced from the study of microfault data (Santanach *et al.* 1992, Pallàs 1993). There is poor agreement on the ages of these phases: Willan (1994) suggested a Cretaceous age for the main phase, whereas Santanach *et al.* (1992) and Pallàs (1993) pointed out that the bulk of the recorded brittle deformation may be either Eocene or younger in age.

Glacial history of the South Shetland Islands

The South Shetland Islands lie between latitudes 61°00' and 63° 30'S. The climate is dominated by depressions circulating clockwise around Antarctica, which generally track over the archipelago, bringing high precipitation to the area. The climatic and surrounding oceanographic conditions, and proximity to the Antarctic continent determine that the islands are mostly covered by extensive ice-caps.

A complex glacial record permits reconstruction of some of the Quaternary glacial fluctuations. From a study of selected areas of Livingston Island, Everett (1971) identified two main glacial phases. Similarly, John & Sugden (1971) studied the whole South Shetland archipelago and concluded that the islands have been affected by at least two Pleistocene glaciations. According to them, during the first recorded *Main Glaciation* (or glaciations) the whole archipelago and the continental platform to the north-west was covered by a single ice-cap, which was responsible for the bulk of glacial moulding and erosion. Rapid deglaciation led to an interglacial period followed by a *Local Glaciation* when each island had its own ice-cap covering most of the present-day ice-free areas. Although there was little erosion, most of the glacial drift on the islands was deposited during this local glaciation. John (1972) suggested a correlation of the South Shetland Islands glaciations with the two last Pleistocene glaciations of northern Europe. Sugden & John (1973) pointed out that the glacial phases were probably slightly out of phase with respect to global glacial cycles but considered that long-term fluctuations correlated well with world-wide climatic trends. According to them, the Main Glaciation(s) could thus correspond either to the penultimate glaciation (broadly equivalent to the North-European Saale) or to earlier glaciations, and be no younger than late Middle Pleistocene, whereas the Local Glaciation could correspond to the final glacial stage (broadly equivalent to the North-European Weichsel) of the last glaciation and so be late Pleistocene in age. After the Local Glaciation, later and minor advances of the ice are well recorded by fresh morainic material which, according to Clapperton & Sugden (1988), correspond to the late Holocene or neoglacial (post-5 ka B.P.) advances.

Geomorphology of Hurd Peninsula

Hurd Peninsula can be divided into three main geomorphological units (Fig 2):

a) platform area: on the coast of South Bay there is an essentially flat, subhorizontal and gently undulating surface at 90–160 m a.s.l; coastal cliffs separate this surface from the sea,

b) mountain area: at the southern end of the peninsula and discontinuously along the False Bay coast there is a mountain area with abrupt crests, steep slopes and summits at *c.* 400 m a.s.l.,

c) glacial dome: the central part of the peninsula is covered by an ice-cap with a maximum altitude of 330 m a.s.l; the ice of this dome-shaped glacier flows radially towards the sea, forming several ice-lobes which descend gently towards South Bay and more steeply towards False Bay.

Glacial record

The *platform area* on the South Bay side is cut by several steep glacial valleys, which are occupied by ice-lobes descending from the ice cap (Fig. 2). The ice-lobes of most of these valleys reach the sea and terminate in coastal ice-cliffs. Some valleys are partially free of ice and show, in

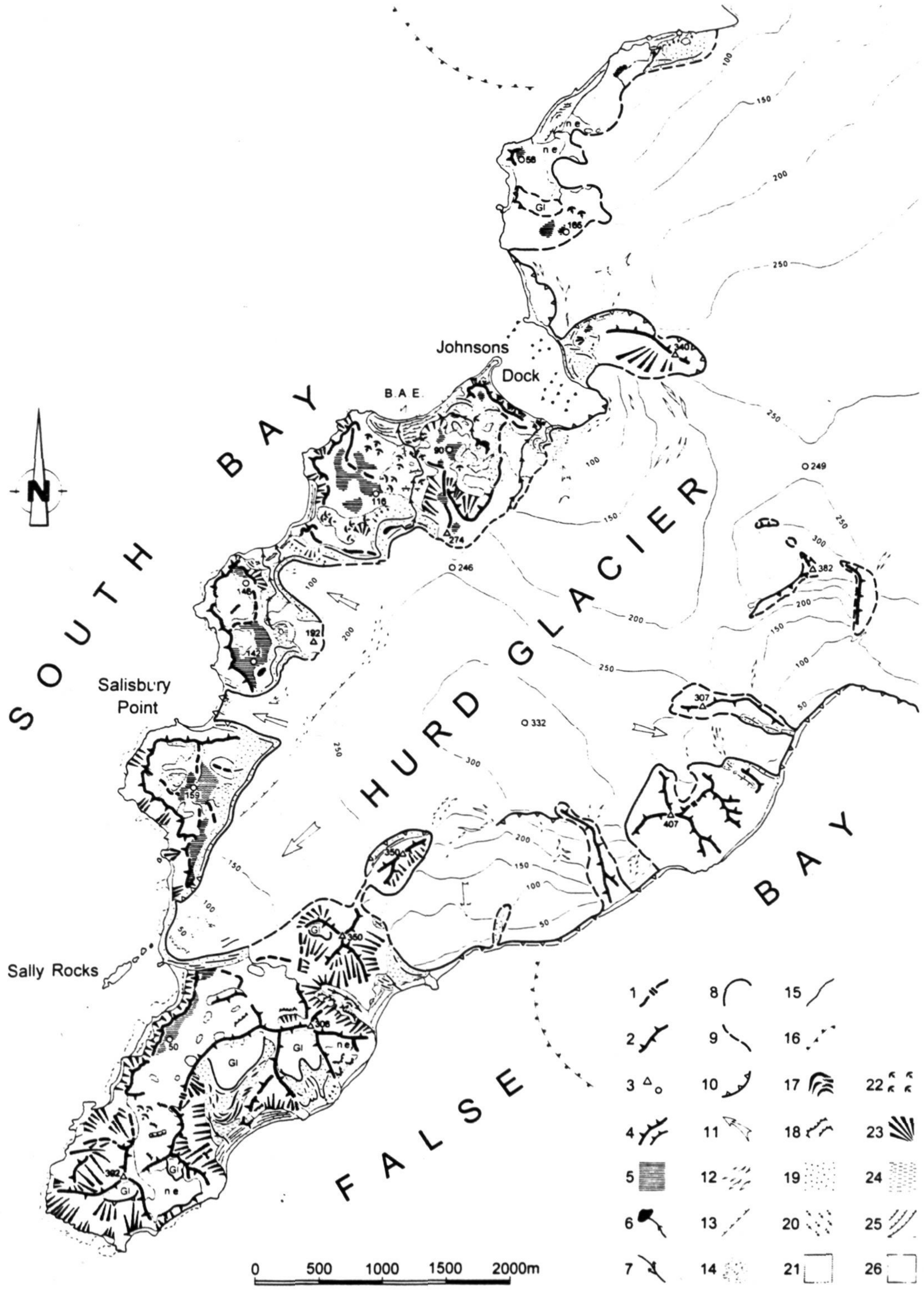

Fig 2. Geomorphological map of Hurd Peninsula. 1 = divide and col, 2 = ridge, 3 = summit, height above sea level, 4 = cliff, 5 = erosive platform undisturbed remnants, 6 = lake and stream, 7 = fluvio-glacial fan, 8 = ramp-like glacial margin, 9 = glacial margin, 10 = ice cliff, 11 = glacial flow direction, 12 = crevasses, 13 = slope change in glacier surface, 14 = interstratified ash layers outcropping on the glacier surface, 15 = morainic arc/ridge, 16 = submerged morainic arc, 17 = rock glacier morainic ridges, 18 = protalus rampart, 19 = morainic deposit, 20 = mass flow in morainic deposits, 21 = periglacial soil, 22 = gelifluction lobes, 23 = scree, 24 = infilled depression, 25 = emerged beach and scarp, 26 = bedrock, Gl. = glacier, n.e. = not mapped because of perennial snow cover. B.A.E. (Base Antártica Española) indicates the location of the Spanish Antarctic Station.

addition to the inner ice-cored moraine, at least three different groups of little-weathered morainic arcs beyond the glacial front. Bathymetric charts (Instituto Hidrográfico de la Marina 1989, 1991) reveal several submerged ridges that are interpreted here as end moraines. In both South and False bays there are single arcuate ridges at a maximum depth of *c.* 70 m, whereas in Johnsons Dock a series of at least six much smaller submerged ridges occur at depths no greater than 10 m (Fig. 2).

The undulating surface of the platform area is covered by extensive periglacial deposits. An outcrop at the top of Salisbury Point coastal cliff shows that the periglacial soil overlies and is the weathering product of a compacted till. Its sandy-silty matrix with sparse, striated, polymictic, flat-iron shaped clasts suggests that this till was subglacial in origin. Although only exposed at Salisbury Point, it probably overlies most of the 90–160 m high platform area.

Marine record

Although no marine sediments have been found on the extensive 90–160 m high platform area, its marine origin is suggested by its large extent, coastal location and regularity in shape. The possibilities that the platform could either be conditioned by an original horizontal bedding attitude or be due to differential erosion caused by lithological variations, are ruled out because the strata dip at about 45–65° NW and there are no major lithological contrasts between this area and, for example, the *mountain area* at the southern end of Hurd Peninsula (Pallàs *et al.* 1992). In addition, the widespread presence of erosive marine platforms all around the South Shetland archipelago (Hobbs 1968, John & Sugden 1971, Curl 1980, Vilaplana *et al.* 1993) also gives support to our interpretation.

Coves along the Hurd Peninsula coastline are caused by

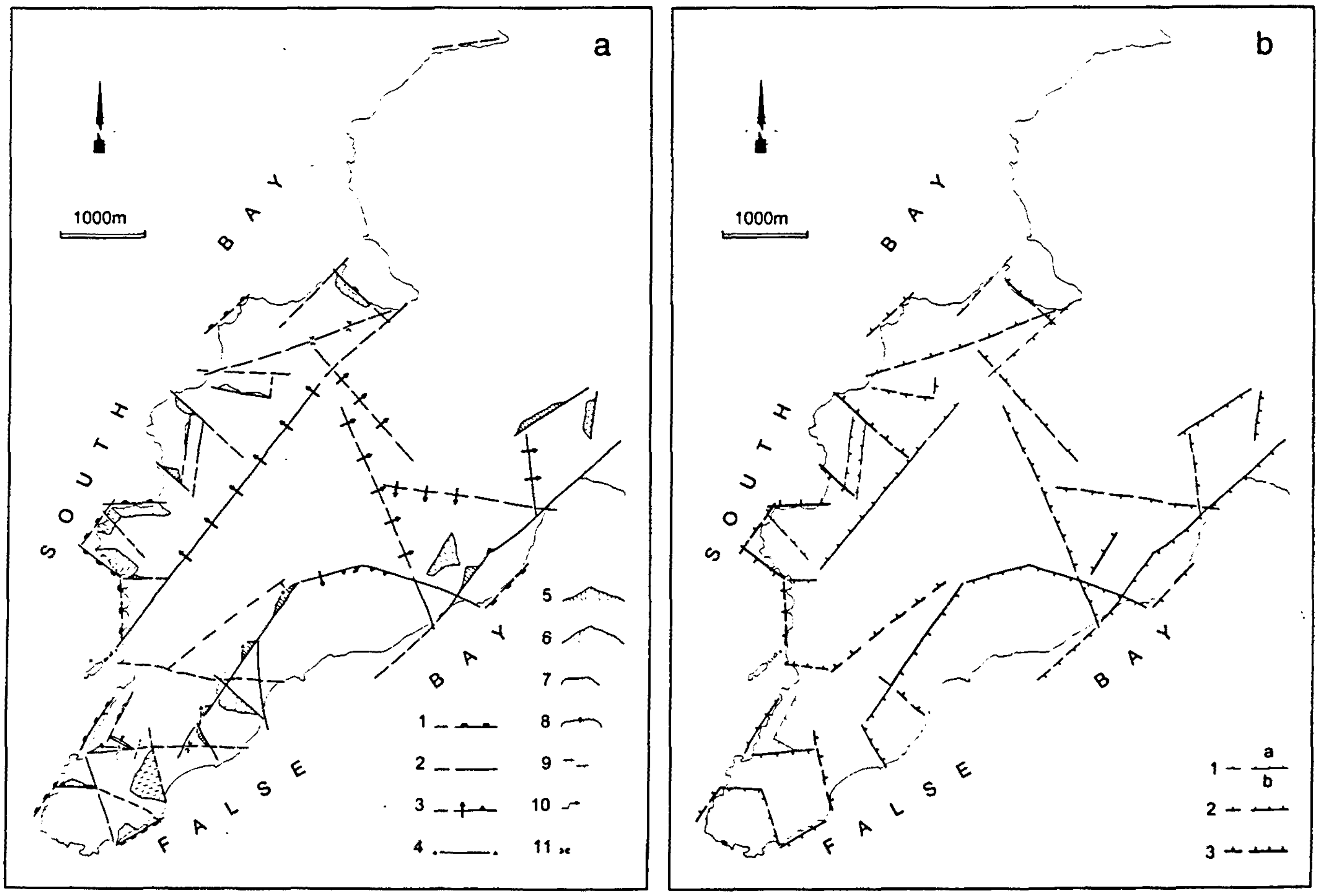

Fig 3. **a.** Scheme of lineations and morphoneotectonic features. 1 = lineation of rocky coastline, 2 = lineation on bedrock or Quaternary deposits, 3 = lineation by slope change/slope break on the ice, 4 = alignment of peaks, 5 = slightly degraded planar steep rocky slope, parallel lines indicate direction of maximum slope, 6 = strongly degraded planar steep rocky slope, parallel lines indicate direction of maximum slope, 7 = gentle slope rupture on Quaternary deposits, 8 = reverse slope, 9 = ridge offset, 10 = break in *talveg* direction. **b.** Neotectonic faults scheme. a = upfaulted block, b = downfaulted block, 1 = faults with less than 50 m estimated dip-slip, 2 = faults with an estimated dip-slip between 50 and 100 m, 3 = faults with more than 100 m estimated dip-slip. Normal-fault symbol is used only to distinguish between upfaulted and downfaulted blocks and does not give any information on either the spatial fault-plane attitude or on the kind of movement experienced.

submergence of the lower part of the glacial valleys. Where free of glacial ice, these valley outlets show a series of emerged stepped beaches (Fig. 2) which reach a maximum altitude of 22 m a.s.l. The coarse shingle and blocks of these beaches are derived mainly from morainic debris reworked by coastal processes and extensively colonized by lichen and moss. Only the lower part of the beaches is constituted by fresh shingle, locally devoid of vegetation up to a maximum height of 4.5 m a.s.l. The freshness and proximity to the high water mark indicates the present-day active beach. The boundary between the active and colonized parts of the beach is sharp.

Neotectonics of Hurd Peninsula

The usual definition of neotectonics (e.g. Fairbridge 1981) implies that the tectonic deformation has taken place during an arbitrarily restricted period ranging either from the Neogene or the Quaternary onwards. In this study we consider neotectonics as referring to tectonic deformations whose direct effects are detectable in present-day landforms. This is a less restrictive, more descriptive approach and appears to be very useful for the analysis of certain areas, such as the South Shetland Islands, where the age of the geomorphological and tectonic processes is still poorly constrained.

Methodology used in the neotectonic faulting analysis

The most recent tectonic deformation of Hurd Peninsula was studied first by deducing the location of neotectonic faults and describing how they are morphologically represented in the landscape (neotectonic faulting analysis). Secondly, the age and mode of deformation is discussed by assessing the effect of deformation on marine features, such as emerged shore platforms and beaches. To highlight important points of this study it is worth describing some methodological aspects.

The neotectonic faulting analysis of Hurd Peninsula is based upon the stepped method suggested by Panizza *et al.* (1987). It started with a detailed study of vertical aerial photographs (Falkland Islands Dependencies Aerial Survey Expedition, FIDASE February–December 1956) at *c.* 1:27 000 scale, and developed through three main steps.

a) All the available aerial photographs of Hurd Peninsula were analysed for lineations. In conjunction with this, other morphological elements which might support the neotectonic nature of these lineations (morphoneotectonic features of Panizza *et al.* 1987) were located and studied. These observations led to the compilation of the scheme of lineations and morphoneotectonic features (Fig. 3a), in which different lineations were classified into characteristic types. It should be noted that no genetic interpretative meaning is given to the term lineation.

b) Once all the morphologic elements had been mapped, the lineations were interpreted. We consider that lineations are probably due to neotectonic movements if (1) they are straight and continuous, (2) they separate two topographically different areas (in morphology and/or altitude), (3) they are associated with morphoneotectonic features, and (4) they cannot be explained by processes other than tectonic, such as coincidence with stratification, lateral glacial valley erosion, etc. The deduced faults are represented in the neotectonic faults scheme (Fig. 3b) which distinguishes between the up- and down-faulted blocks and shows the magnitude of dip slip, which can be broadly inferred from the topography by measuring the unevenness between upper and lower parts of the facets.

c) The neotectonic map of Hurd Peninsula (Fig. 4) is a combination of the information taken from the neotectonic faults scheme, with some elements of the lineations and morphoneotectonic features scheme and the geomorphological map. In addition to faults and morphoneotectonic features, the neotectonic map includes areas of some recent deposits and landforms, such as morainic ridges and emerged beaches, that may have been affected by the neotectonic movements.

Neotectonic faulting of Hurd Peninsula

The neotectonic map (Fig. 4) shows that Hurd Peninsula is divided into a set of several tectonic blocks bounded by faults. It should be noted that, because the morphological analysis highlights only vertical displacements, no information is available on whether the faults are mainly normal, reverse or strike-slip. Although the usual normal-fault symbol is used in the neotectonic map, the only meaning of the symbol is to distinguish the relative vertical movement between blocks. From field work it is not possible to ascribe a given neotectonic fault to a specific type. As deformation is polyphasic any fault plane could have moved several times in different directions and the net displacement only determined from external markers. Lack of geometric relationships between markers and faults in Hurd Peninsula preclude any conclusive results.

The neotectonic faults have widely variable trends but, if they are plotted proportionally to their length, there is a well-developed maximum between N030° and N050°. This main direction of faulting is coincident with the general trend of Hurd Peninsula.

The calculated dip-slip downthrows of the neotectonic faults generally range between a few tens of metres and 150 m. The higher values are calculated from facets corresponding either to coastal cliffs or to slopes abutting on glaciers. It should be noted that, in these situations, the effect of erosion probably tends to enlarge the height of the facets and consequently only an approximate evaluation of the downthrows can be made.

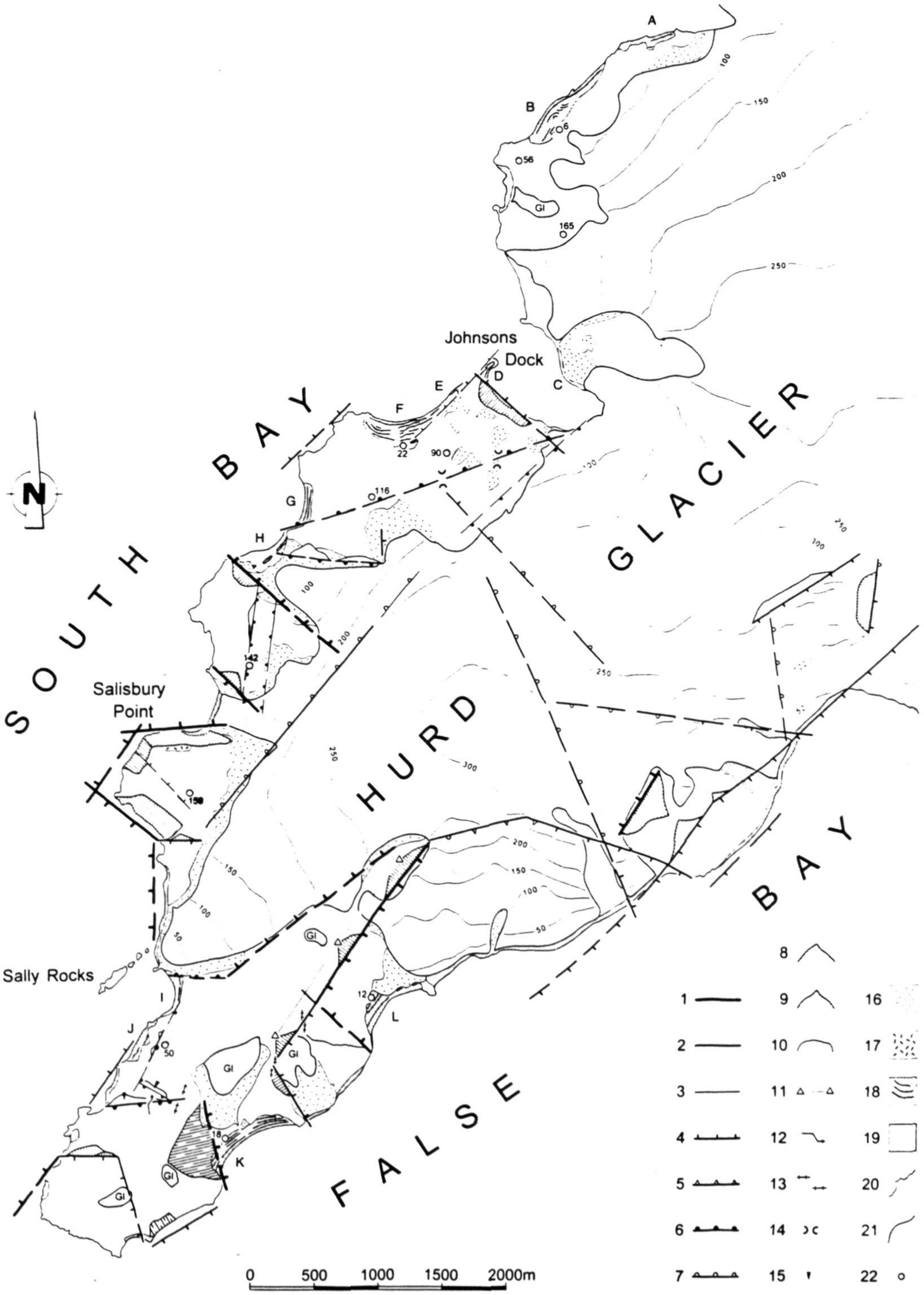

Fig 4. Neotectonic map of Hurd Peninsula. For design reasons some of the faults are represented superimposed on the pattern of Quaternary sediments (moraines and beaches) although none of the faults has been observed cutting them. 1 = fault with more than 100 m estimated dip-slip, 2 = fault with estimated dip-slip between 50 and 100 m, 3 = fault with less than 50 m estimated dip-slip, 4 = fault determining a slope break on bedrock, 5 = fault determining a slope break on an area covered by glacier, 6= fault determining a gentle change of slope on an area covered by quaternary deposits, 7 = fault determining a gentle change of slope on an area covered by glacier, 8 = slightly degraded facet, parallel lines indicate direction of maximum slope, 9 = strongly degraded facet, parallel lines indicate direction of maximum slope, 10 = gentle change of slope on area covered by Quaternary deposits, 1 1= alignment of peaks, 12 = *talveg* direction rupture, 13 = ridge offset, 14 = col, 15 = reverse slope, 16 = Holocene moraine/till, 17 = pre-Holocene till, 18 = emerged beach and scarp, 19 = undisturbed remnants of the 160 to 90 m a.s.l. erosive platform, 20 = coastline, 21 = glacial margin, 22 = spot height. A to L indicate the location of beach profiles represented in Fig. 5.

Discussion

Age of the emerged beaches

Radiocarbon analyses of datable material obtained mainly from beaches on King George and Livingston islands by Sugden & John (1973), Hansom (1979), Curl (1980) and Barsch & Mausbacher (1986) were revised by Clapperton & Sugden (1988, table 2) using updated corrections for the reservoir effect. Clapperton & Sugden (1988) gave ages of 106–360 years B.P. for the 3 m beach, 510–802 years B.P. for the 6 m beach, 1680 years B.P. for the 7.6 m beach, 1973–2271 years B.P. for the 10 m beach and 5710–5800 years B.P. for the 18 m beach. Although no precise correlation by height is possible between different areas, these data indicate that even the highest and oldest beach levels in Hurd Peninsula cannot be older than Holocene, and suggest that the 22 m beach at the cove west of Johnsons Dock probably has an age of about 6000 years B.P.

Age of the glacial deposits

The innermost of the morainic ridges present in the valleys which dissect the 90–160 m high shore platform is an ice-cored moraine indicating the position of the ice front around 1956 AD (recorded on the FIDASE aerial photographs). Farther from the present-day glacial ice front, the valleys have prominent moraines which, by their location and freshness, probably correspond to the late Holocene (neoglacial) readvances. In addition, lower in some of the valleys, there are moraines that are slightly more altered and affected by solifluction processes, and which might correspond either to older neoglacial or to Pleistocene readvances of the ice. This is indicated by the fact that south-west of Johnsons Dock (B.A.E. in Fig.2) the outermost moraine is reworked by the highest (22 m) beach indicating that the moraine has a minimum age of *c.* 6000 years B.P. Thus, we conclude that the oldest recorded morainic ridges on Hurd Peninsula (including the Johnsons Dock submerged moraines) are either Holocene or Pleistocene and that the valleys were completely occupied by ice during the Last Glacial maximum. No discussion on the age of the submerged moraines of South and False bays is given here because they correspond to glacial systems that are not included in the present study.

The degree of weathering, the much higher altitude, and distance of the Salisbury Point to the present-day position of the glacial front contrast sharply with the fresher, late Pleistocene or younger morainic ridges present in the valleys. Thus, the Salisbury Point till records an advanced position of the glaciers, is older than the glacial deposits in the valleys and, in consequence, has an age no younger than late Pleistocene. This conclusion agrees with John & Sugden (1971), who reported erratics as well as patches of till with faceted and striated pebbles set in a clayey matrix on many platforms throughout the South Shetland Islands. Regional criteria led these authors to consider these widespread deposits as evidence of the Local Glaciation. Deposits corresponding to young glacial phases are less likely to be subjected to erosion, and are more likely to be preserved than deposits of older glacial cycles.

Age of the 90–160 m high platform of South Bay

The erosive 90–160 m high platform of South Bay is partially covered by the till at Salisbury Point. Because the till corresponds to the last glaciation or earlier phases of glaciation, it suggests that the cutting of the marine platform dates at least from the late Pleistocene.

The maximum age of the platform cannot be inferred from relationships present at Hurd Peninsula. However, at Lions Rump (King George Island) the relationships between marine platforms and the stratigraphical record allow us to draw some conclusions on their age. A fossiliferous level (the *Pecten Conglomerate*) is interstratified in a sedimentary and volcanic sequence which, at the top, is cut by a marine platform 150–180 m a.s.l. Taking into account its foraminiferal fauna and similarity with a deposit on Cockburn Island (north-eastern Antarctic Peninsula) this pectinid-bearing conglomerate was dated as Pliocene (Barton 1965), and consequently John & Sugden (1971) considered the platform could be no older than Pliocene. Birkenmajer (1980, 1982) included this succession within his Polonez Cove Formation which, through palaeontological studies and K-Ar analyses of the lavas, was dated by Birkenmajer & Gazdzicki (1986) as middle Oligocene. The age of this formation is still open to discussion due to new Ar-Ar dates (J.L. Smellie, personal communication 1995) which suggest it could be early Miocene. Whatever its age, the succession is cut by a large dyke that, both from K-Ar and Ar-Ar analyses, yielded the same age of *c.* 22 Ma (Birkenmajer *et al.* 1986, J.L. Smellie, personal communication 1995). As the dyke is also out by the 150–180 m platform at Lions Rump, the maximum age of this marine surface is early Miocene. At Cape Melville (King George Island) the 150 m platform cuts across lower Miocene sedimentary rocks and dykes that range in age between 19.9 and 23 Ma (Birkenmajer *et al.* 1985 Birkenmajer & Łuczowska 1987). Thus, the maximum age of the Cape Melville platform is also lower Miocene.

So far, these are the only constraints on the maximum age for the formation of the extensive South Shetland marine platforms. The 90–160 m a.s.l. platform of Hurd Peninsula is at a comparable height with the marine platforms of Lions Rump and Cape Melville so that, broadly speaking, a maximum lower Miocene age can be assigned to it.

Influence of the neotectonic faulting on the landscape

The comparison between the geomorphological and neotectonic maps (Figs 2 & 4 respectively) shows that the boundaries of the major geomorphological units largely coincide with the neotectonic faults. The coincidence suggests that the distribution of geomorphological elements, such as orientation of glacial valley walls, coastline and topographical altitudes, are largely controlled by neotectonic faulting.

Significance of emerged marine features

Emerged shore platforms and emerged beaches in the South Shetland Islands are the result of relative sea-level (RSL) changes of very different ranges in magnitude and age, and thus might be the result of different processes. Whereas shore platforms on Hurd Peninsula could be as old as Tertiary, record RSL variations > 150 m in range and are erosive, the beaches are no older than Holocene, show maximum RSL changes of only *c.* 20 m in range and are accumulative. RSL changes may be related to fault bounded block movements, isostasy, eustatic oscillations or to a combination of these. The relative importance of tectonic processes (including isostasy) in determining changes of RSL of a given area may be established by subtracting the eustatic effect. In the South Shetland Islands, the unknown age of the older marine levels (platforms) prevents the possibility of drawing a detailed local RSL curve. In spite of the differences in age and magnitude ranges, and although no detailed RSL curve is available, the emerged platforms and the emerged beaches of the South Shetland Islands as a whole have generally been interpreted as being largely the result of tectonic uplift and/or glacio-isostatic rebound (John & Sugden 1971, Curl 1980, Sàbat *et al.* 1992). This is supported by the following:

1) the remarkable altitude of some of these marine levels (up to 275 m of a residual beach deposit and platform on King George Island, John & Sugden, 1971) does not coincide with any recorded high eustatic level,
2) the apparent synchronism between Holocene deglaciation and emergence of beaches suggests that uplift is due to glacio-isostatic rebound,
3) the archipelago is located on the footwall block of the Bransfield Basin marginal faults (Jeffers *et al.* 1991), which may have undergone uplift by unloading of the hanging-wall block.

Nevertheless, because of the complexity of the processes affecting the South Shetland Islands area, it is difficult to identify how much RSL changes indicated by the marine features are influenced by tectonic, glacio or hydro-isostatic processes, and how much by eustatic processes. It has to be taken into account that,

1) the archipelago is located close to the Antarctic Peninsula and could be affected by the "forebulge" effect during glacial cycles (Sugden & John 1973), and
2) that it represents a small area surrounded by relatively shallow waters to the north and a deep basin to the south where it is difficult to evaluate the interplay between glacio-isostasy and hydro-isostasy during a whole glacial cycle (e.g. Clark *et al.* 1978).

Although emerged marine features on the South Shetland Islands cannot give, at present, any information on the vertical movements experienced by the archipelago as a whole, some local information on the age and mode of relative neotectonic movements between different areas may, in principle, be obtained.

Effects of the neotectonic faulting on the 90–160 m high shore platform

The emerged shore platform of South Bay is affected by neotectonic faulting as shown by the neotectonic map of Hurd Peninsula (Fig. 4). In a few cases, faults separate adjacent areas of the same platform. The clearest example is adjacent to spot height 142 m, north of Salisbury Point, where two NNE-trending faults, with downthrows of no more than 15 m, cut the gently undulated platform and delineate a small graben-like structure *c.* 160 m wide (Fig. 4). Another example is the fault next to spot height 159 near Salisbury Point, which produces a vertical displacement of *c.* 40 m of the coastal cliff slope break. Nevertheless, the most prominent faults separate the shore platform either from the sea or from the valleys occupied by glacier outlets, glacial sediments and beaches. Faults of this kind (with probably a minimum dip-slip between *c.* 160 and 100 m) determine the orientation of the coastline in the Salisbury Point area and the glacial valley walls in the area immediately to the north (Fig. 4). Although these faults do not show the displacement between adjacent parts of the same surface, the contrasts in altitude between about 160, 140 and 100 m a.s.l of the different portions of the platform (from south to north) are interpreted as being due to their movement. Thus, faulting dissects the South Bay platform dividing it into blocks that range in area from <1 km^2 to several km^2.

Effects of neotectonic faulting on emerged beaches

None of the beaches of Hurd Peninsula seem to be cut by neotectonic faults, because no unevenness attributable to faulting has been observed at any site. Note that for design reasons, in the neotectonic map some of the faults are represented as superimposed on the pattern of Quaternary sediments but none has been observed cutting through quaternary deposits. Nevertheless, the neotectonic map (Fig. 4) shows that beach localities lie within several tectonic blocks and this suggests the possibility that there may be some unevenness between equivalent beach levels of different sites.

Theoretically, if some variation in altitude between equivalent beaches of distinct localities were detected, this would indicate that differential vertical movement between blocks had taken place since the sedimentation of the beaches (e.g. Lecolle *et al.* 1990, Suggate 1992). By contrast, if no variations in altitude were present, this would indicate either that, since the deposition of the beaches, vertical tectonic movements had not taken place or that they were small. To ascertain these potential differences a correlation must be first established between beach altitudes. In the South Shetland Islands this is not a straightforward task (John & Sugden 1971, Curl 1980, López-Martínez *et al.* 1991, 1992a, 1992b, Sàbat *et al.* 1992). John & Sugden (1971) suggested that it is better to correlate beaches from their morphology rather than their altitude.

On Hurd Peninsula, the upper limit of the active beach at a given locality is markedly variable in altitude. Its height is even more variable when the different beach profiles are referred to the high water mark (Fig. 5a). This suggests that the position of the upper limit is highly sensitive to hydrodynamic conditions which can be affected by local-scale factors such as coastal profile, submerged beach bathymetry, coastal topography, exposure to the main wave directions, and sediment supply. Thus, in an area affected by neotectonics, two main factors may influence the variation in altitude between beach levels of different sites: (1) the geomorphological conditions, and (2) the differential neotectonic vertical movements. Evaluating the relative effect of the geomorphological and neotectonic components in the variability of the beaches of different sites is discussed below.

Because neotectonic movements are cumulative through time, the vertical offsets of lower beaches would be much smaller than the vertical offset of the higher (older) beaches. Hence, the older the beach level, the more easily any neotectonic component could be detected. Moreover, present-day dynamics would tend to erase any effect of neotectonic movements on the present-day beaches.

The geomorphological variability between different sites may be accommodated by standardizing the height of the upper limit of the active beach. This provides for a better altitudinal correlation of the different sites in which morphologically similar beaches tend to be grouped together into a few altitudinal intervals (Fig. 5b). Nevertheless, this method cannot counteract the effects of the intrinsic geomorphological variability of the beach levels. This intrinsic variability is responsible for the fact that, at a single site, a given RSL is not recorded by only one beach level, but rather by several beach levels included within an altitudinal range. On Hurd Peninsula this is clearly shown by the occurrence of several active beach levels at altitudes of up to 4.5 m above high water mark.

Hence, the neotectonic component affecting the unevenness of equivalent beach levels at different localities could only be discerned if it was larger than the component due to their intrinsic geomorphological variability. Thus, in principle, differential neotectonic vertical movements of at least 5 m would be required to be detected by the analysis of the emerged beaches of Hurd Peninsula.

However, the neotectonic component cannot be discerned from differences in beach levels unless two additional conditions have been met:

1) the spacing between groups of beach levels (each group corresponding to a single RSL) has to be at least of similar magnitude than their intrinsic geomorphological variability. Otherwise, any neotectonic component would remain undetected, because beach levels corresponding to different RSL may be mixed, and there is no way to discern whether a given level is either a beach displaced by vertical neotectonic component or a level of the neighbouring group of beaches.
2) the higher beach levels must be well represented in a spatial sense.

The different groups of beaches in Hurd Peninsula are too close to each other and the higher beach groups are too poorly represented to enable the separation of any neotectonic component. Thus, we conclude that, although relative vertical neotectonic displacements between different blocks may have taken place during the late Holocene, they cannot be detected by the study of the beaches of Hurd Peninsula.

Age of Hurd Peninsula neotectonic faulting

The faults that cut the 90–160 m shore platform of South Bay have a maximum lower Miocene age. The amount of vertical displacement deduced from these faults is small (no more than a few tens of metres) in comparison with the vertical displacement (>100 m) deduced from the larger faults detected on Hurd Peninsula. This suggests that the amount of deformation since the cutting of the platform may have been much smaller than the deformation shown by other faults on Hurd Peninsula which could record the accumulated effects of deformation through a larger period of time.

Thus, neotectonic faulting of Hurd Peninsula can be seen as part of the South Shetland Islands brittle deformation history, which might have taken place since Cretaceous (Tokarski 1991, Willan 1992, 1994) or the Eocene (Santanach 1992, Pallàs 1993). The area studied has been covered by ice during several glaciations which would tend to erode fault scarps formed during earlier phases of deformation. However, some good examples of landform survival beneath ice caps have been documented elsewhere (e.g. Kleman 1994), and it is possible that a large part of the displacement of the major faults observable on the landforms is inherited from Mesozoic and/or Cenozoic deformation.

Conclusions

Morainic ridges located in the valleys cutting the 90–160 m high shore platform of South Bay are Holocene and ?late Pleistocene in age. Intensely altered till cropping out at Salisbury Point has a minimum age of late Pleistocene. An age between lower Miocene and late Pleistocene can be

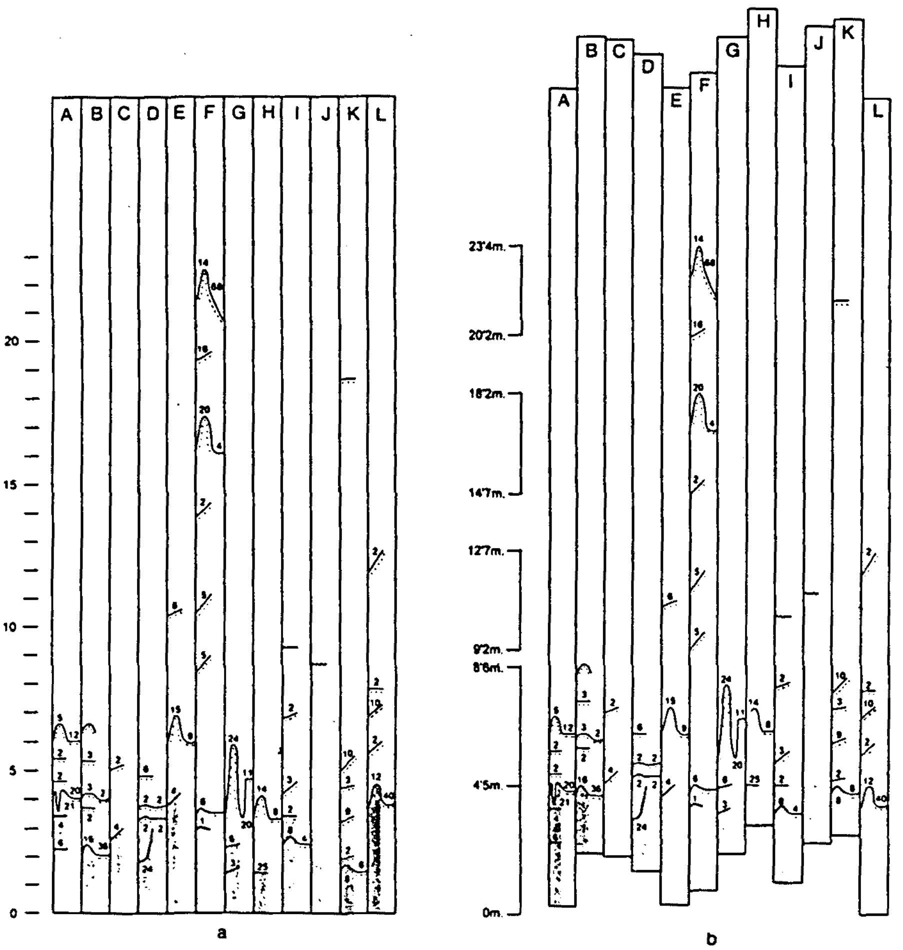

Fig 5. a. Juxtaposition of the synthesis of 12 emerged beach transverse profiles of Hurd Peninsula (capital letters A to L). Each column represents a single locality (see Fig. 4) and shows the altitude of the beaches with respect to the high water mark (scale in m on the left). Beaches dipping to the sea and berms are represented at the left side of each column and backberm troughs (when present) are represented at the right side. Small numbers show the width in metres of all these features. Shaded areas represent the fresh, non-colonized and present-day active portion of the beach. Note that the upper limit of the active beach on different localities has a very variable altitude which is, at least partly, due to the strong differences in hydrodynamic conditions between localities. No simple correlation between localities arise. **b.** In order to counteract the local variability of the hydrodynamic conditions between beach localities, we put at the same level all the active beach upper limits. It can clearly be seen that a much better altitudinal correlation arise so that different altitudinal intervals (0 to 4.5, 4.5 to 8.6, 9.2 to 12.7, 14.7 to 18.2, 20.2 to 23.4 m) can be distinguished. This kind of correlation is supported by the fact that beach levels shown at the same altitude are morphologically similar.

broadly assigned to the 90–160 m high shore platform of South Bay, whereas the emerged beaches present on Hurd Peninsula are no older than late Holocene.

The emergence of platforms and beaches in the South Sheltand Islands is interpreted as largely the result of tectonic and/or isostatic processes. However, uncertainty of the age of some geomorphological and structural elements, as well as the complexity of the processes affecting the archipelago, prevent us from determining the relative extent to which the RSL changes indicated by the emerged marine features are influenced by fault-bounded block movements, glacioisostasy, hydroisostasy and eustasy.

Hurd Peninsula is divided into several tectonic blocks bounded by faults. Due to the complexity of the structural history of the area, the method applied in the analysis of the neotectonic faulting does not permit detailed discussion of the kind of movement these faults have undergone but it does give some insights the large-scale brittle deformation of Hurd Peninsula. Although the observed faults have variable trends there is a well-developed maximum, parallel to the general NE–SW trend of the peninsula. The approximate dip-slip downthrows of the faults range from about few tens of metres to 150 m. Faulting determines the height of the different Hurd Peninsula tectonic blocks, the distribution of the geomorphological elements such as glaciers and coastline and, by consequence, determines the susceptibility of the different areas to modification by marine, glacial or periglacial processes.

Part of the neotectonic faulting of Hurd Peninsula could be inherited from the Mesozoic or Cenozoic brittle deformation and there are clear signs of landforms being affected by faulting from the lower Miocene onwards. Although vertical neotectonic movements between blocks may have taken place during the late Holocene, they could not be distinguished by the analysis of the raised beaches.

Marine platforms on Hurd Peninsula are disturbed by faulting and so altitudinal correlation between platform levels in the South Shetland Islands should be undertaken with caution.

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Pallàs,R., James,T.S., Sàbat,F. & Vilaplana,J.M., Grant,D.R. (submitted): Holocene uplift in the South Shetland Islands: evaluation of tectonics and glacio-isostasy. *In: Proceedings of the VII International Symposium on Antarctic Earth Sciences, 10-15 September 1995, Siena* (Italy).

En aquest article s'intenta quantificar per primer cop el paper de la tectònica i el de la glàcio-isostàsia en l'emersió de l'arxipèlag de les Illes Shetland del Sud. L'anàlisi de les plataformes d'erosió marina indica que els índexs d'aixecament tectònic han de ser sensiblement inferiors als que havien estat proposats anteriorment. L'anàlisi de les platges holocenes a través de la informació aportada a partir d'un model geofísic de deformació glàcio-hidro-isostàtica permet d'acotar l'amplitud de l'aixecament glàcio-isostàtic holocè. Es discuteix la validesa del model geofísic utilitzat i es proposen modificacions que caldria introduir-hi.

Holocene uplift in the South Shetland Islands: evaluation of tectonics and glacio-isostasy

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ABSTRACT

Analysis of the Miocene-Pleistocene emerged marine platforms present in the South Shetland Islands indicates a maximum tectonic uplift rate of 0.4 m/ka. This explains 16% or less of the observed emergence since 6.4 ka BP and, as a consequence, indicates that most of the observed Holocene uplift of the islands is due to glacio-isostasy. The relative-sea-level (RSL) variations predicted by the ICE-3G model of glacio-hydro-isostatic deformation suggest that the South Shetland Islands are not only affected by variations in local ice-loads but also by variations in the Antarctic Peninsula ice-loads. The comparison of the ICE-3G relative-sea-level predictions with the available geological data from the South Shetland Islands (dated beaches) suggests that the maximum Holocene inundation in the South Shetland Islands would have been 30 m (or lower), instead of the more than 54 m previously suggested. Disagreement between the observed rates of Holocene emergence and the ones predicted by ICE-3G may be explained by the anomalous rheological parameters of the lithosphere and mantle underlying Bransfield Strait as well as by the grid size and inaccuracies in ice-thickness of the deglaciation model.

INTRODUCTION

The South Shetland Islands are separated from the Antarctic Peninsula by the 100 km wide Bransfield Strait. Volcanism and seismicity indicate that the Bransfield Basin is an active rift system (Pelayo & Wiens, 1989; Smellie, 1990). The Bransfield Basin is underlain by thinned crust with respect to the 40 km thick continental crust of the South Shetland Islands and Antarctic Peninsula magmatic arc (Ashcroft, 1972, Grad et al., 1993). The South Shetland Islands and the Antarctic Peninsula are extensively glaciated at present and show clear evidence of glacial retreat since about 10 ka BP (Hjört et al., 1992).

John & Sugden (1971) reported beach remnants in the South Shetland Islands ranging up to 275 m in height. The lower beaches (up to about 18-22m) are widespread and morphologically well preserved, in clear contrast to the much less common and more strongly altered higher remnants. Through criteria of geomorphological similarities, John & Sugden (1971) correlated beaches at around 18 m a.s.l. of King George Island with the ones at around 20 m in Livingston Island. The degree of preservation and freshness decreases sharply upwards, but beach morphology is partly preserved up to 54 m. This led John & Sugden (1971) to suggest a Holocene age at least for the beaches up to this height. Nevertheless, the Holocene age has only been proven for beaches at 18 m and below (e.g. Clapperton & Sugden, 1988) and no reliable dateable material has yet been recovered from higher levels. In addition, in the South Shetland Islands there are extensive emerged platforms of unconstrained age (lower Miocene to late Pleistocene, Pallàs et al., in press) which are considered to have a marine origin up to at least 120 m (John & Sugden, 1971).

As no fall of "eustatic" sea level has taken place during post-glacial times, uplift of the South Shetland Islands is required to explain emergence of the Holocene beaches. The mechanism that has generally been accepted for the Holocene uplift of the archipelago is postglacial glacio-isostatic rebound due to the ice unloading of the local ice-caps. The possible effect of the Antarctic Peninsula ice-loads on the South Shetland Islands uplift has never been evaluated. In principle, the archipelago may also be affected by neotectonics; the islands are located next to the active Bransfield Basin rift and by consequence, they are possibly affected by uplift due to a shoulder effect (Sàbat et al., 1992).

The aim of the present paper is to explore the possible effects of glacio-isostasy and neotectonics in the Antarctic Peninsula - South Shetland Islands region. To achieve this we examined predicted relative sea-level (RSL) variations due to the ICE-3G glacial rebound model of Tushingham & Peltier (1991, 1992). A comparison between predictions of the model and the observed geological data (dated beaches) permits (1) a discussion of the validity of the model in this region, (2) to suggest how the model should be changed to fit the available RSL and ice-thickness data and (3) to infer the timing and amplitude of the maximum Holocene inundation in the South Shetland Islands. From the analysis of emerged marine platforms, we infer the maximum expected role of tectonics in the Holocene uplift of the archipelago.

ICE-3G MODEL OF GLACIO-HYDRO-ISOSTATIC DEFORMATION

The ICE-3G model simulates ice-unloading in glaciated areas and consequent water loading through gravitationally self-consistent filling of the ocean basins as deglaciation proceeds. Elastic and viscoelastic (Maxwell) deformation of the Earth occurs due to changing surface loads. To achieve this, the model includes (1) a rheological model of the Earth and (2) a deglaciation history from 18 ka B.P to the Present of both Northern and Southern hemisphere ice-sheets.

The ICE-3G rheological model of the earth considers a lithosphere with a constant effective thickness of 120 km, an upper mantle viscosity of 10^{21} Pa s, and a lower mantle viscosity of 2×10^{21} Pa s These values deliver good agreement to observed RSL variations in the northern hemisphere, especially near the former centres of glaciation (Tushingham & Peltier, 1991, 1992).

The ICE-3G deglaciation model was constructed according to geological data (ice extent and relative sea-level variations). Where few data were available (such as Antarctica) a plausible deglaciation history was inferred through indirect criteria. The model simulates deglaciation considering a series of ice and ocean-water disks of varying thickness through time. RSL predictions for the ICE-3G model can be computed for any point on the Earth's surface between 18 ka B.P to the Present.

ICE-3G RELATIVE SEA-LEVEL PREDICTIONS

We examined about 250 ICE-3G-predicted RSL curves corresponding to the area of the Antarctic Peninsula and the South Shetland Islands between latitudes 60°00'S to 73°00'S and longitudes 53°00'W to 70°00'W. These predictions indicate a marked gradual variation in the RSL signature from the strongly glaciated areas of the southern Antarctic Peninsula to the oceanic areas located to the N (Fig. 1). Before 10-9 ka BP the whole area analysed is characterised by submergence. In contrast, from 10-9 ka to present most of the area region is subjected to emergence, the amplitude of which decreases gradually northwards. From 73°00'S to 60°00'S the predicted total amount of emergence after 10 ka BP ranges from about 250 m to nil.

In the model no significant ice unloading in Antarctica is considered to take place from 18 to 10 ka BP. This determines that the whole area is affected by submergence due to melting of the Northern Hemisphere ice-sheets. In contrast, after 10 ka BP deglaciation of the Antarctic Peninsula ice-sheets, and the subsequent glacio-isostatic rebound, determine emergence. The amplitude of this emergence is larger in the more intensely deglaciated areas to the south of the Peninsula and decreases gradually northwards.

Predictions for the South Shetland archipelago show important differences in the RSL history. Amplitude of emergence decreases from about 65 m in Byers Peninsula (Livingston Island) to about 25 m in North Foreland (King George Island) (Fig 2).

COMPARISON BETWEEN ICE-3G PREDICTIONS AND GEOLOGICAL OBSERVATIONS

To construct a reliable RSL history we made a revision of the radiocarbon data available from beaches in the South Shetland Islands. As suggested by Björk et al. (1991) and Gordon & Harkness (1992) we applied the minimum correction of 1 ka for the reservoir effect to the whole radiocarbon data set available from the South Shetland Islands beaches. Once corrected, dates were calibrated by the automated intersection method of Stuiver & Reimer (1993). As shown in Table I, the new dates are sensibly older than the ones suggested by Clapperton & Sugden (1988).

In a time/height diagram beaches about 500 years old plot from 3 to 6 m above present mean sea-level (Fig. 3). This is consistent with the dynamics of the present-day active beaches in Hurd Peninsula (SE Livingston Island). Pallàs et al. (in press) show that beach berms are formed between 1.5 and 4.5 m above sea level at high tide. If we consider that tidal oscillations in this area have an amplitude of about 3 m, this means that beach sediments as well as dateable material can be deposited at about 3 to 6 m above mean sea-level. According to this, in the time/height diagram, the range of expected RSL curves lies from 3 to 6 m below all the dated beaches. When these expected RSL curves are drawn, they indicate much less emergence than the one suggested by the ICE-3G predictions (Fig. 3). In Maxwell Bay and Byers Peninsula the model overpredicts emergence by 160-200 % and 120- 210 % respectively.

The ICE-3G model predicts quite strong variations in the RSL behaviour along the South Shetland Islands. A consequence of this would be that correlative beaches would have quite different heights when considering distant localities. This would be in clear conflict with the plausible, almost altitudinal, correlation of beaches suggested by John & Sugden (1971). Thus, ICE-3G may also overpredict the lateral variation in RSL amplitudes.

DISCUSSION

Excessive emergence and the probably too strong lateral variation in the ICE-3G predictions may both be due to limitations of the model. The main drawbacks are: a) The model does not consider tectonic movements. b) In this region the ICE-3G model is under-constrained due to scarcity in source data related to deglaciation history. This scarcity concerns both ice thickness and timing of deglaciation. c) The model does not take into account lateral variations in mantle viscosity or lateral variations in lithospheric thickness such as the transition between normal and thinned (?)continental crust present in Bransfield Strait Basin.

Tectonic component

In the South Shetland Islands there are sets of extensive marine platforms emerged to heights of at least 120 m (John & Sugden, 1971). They are covered by tills corresponding to the last glaciation or earlier glaciations and have a poorly constrained age of lower Miocene to late Pleistocene (Pallàs et al., in press). Platforms in the South Shetland Islands could only have been cut during interglaciations or nonglacial periods, when substrate is locally free of ice and susceptible to marine modelling.

We consider that the height of a marine platform's inner limit corresponds to the position of sea-level when the platforms was cut. The oxygen isotope record indicates that "eustatic" sea-level during the last interglacial stages (stages 11, 9 and 5e) was close to the one at present (Holocene, stage 1). Thus, in the case the platforms had been cut during these interglaciations, they would record no eustatic oscillations but the tectonic uplift of the islands. According to the oxygen isotope record, stage 7 "eustatic" level seems to have been lower (to an unknown amount) than sea level of stages 11, 9, 5e and 1 (see Shackleton, 1987 for a review). In consequence, in an area subjected to tectonic uplift, the platform of stage 7 could be either (1) above the platform of stage 5e, (2) lower than the one of stage 5e or (3) lower than the present sea level (Shackleton & Opdyke, 1973). Taking into account these three possibilities, to get a first approximation about the magnitude of tectonic uplift rates we tentatively applied the ages of the last several interglaciations to the platforms of the localities in the South Shetland Islands where a set of 3 or more of them occur (Fig. 4). The result of this analysis is that the maximum uplift rate expected in the archipelago is of about 0.4 m/ka. It has to be borne in mind that this is an extreme maximum figure because the platforms could even be Tertiary, instead of Pleistocene (Pallàs et al., in press). Thus, tectonic uplift has to be considered as a secondary component in the short period in which the assemblage of raised beaches is formed; only 2.5 m (or possibly less) of the 18 m emergence since 6.4 ka BP may be explained by tectonics.

In any case, the extensive emerged marine platforms (up to 120 m a.s.l. or higher) indicate that long term tectonic movement in the South Shetland Islands is the one of uplift rather than subsidence. This is also consistent with the expected shoulder effect close to the Bransfield Basin rift. It seems clear that tectonic deformations, because they are slow and determine uplift instead of subsidence, cannot explain the differences between the observed Holocene RSL and the predictions of the glacial rebound model.

Effect of inaccuracies in deglaciation timing

If beginning of deglaciation in the Antarctic Peninsula region took place prior to what is considered in the model, this could explain the differences between model predictions and the observed emergence.

Hjort et al. (1992) made a review of the available deglaciation data from the Antarctic Peninsula region. These authors consider that deglaciation in the South Shetland Islands and the northern tip of the Peninsula began at about 10 ka, that there was a glacial readvance (locally of more than 20 km) at around 7 ka which lasted for 500 years and that there was a general retraction of ice at around 6-5 ka. On the other hand, ICE-3G considers that deglaciation began at about 10-9 ka and that there was a gradual decrease in ice thickness until 4 ka. Thus, beginning of deglaciation considered in ICE-3G is broadly in agreement with Hjort et al. (1992), while expansion of ice at 7 ka is not taken into account in the model. Nevertheless variation of ice thickness related to the 7 ka expansion is not known, and by consequence, variation of ice-thickness considered in the model may still be consistent with Hjort et al. (1992). In the case the 7 ka expansion was accompanied by a significant ice thickening, the timing of deglaciation in ICE-3G would be a bit advanced with respect to observations rather than delayed. This indicates that (1) the differences between observations and predictions in the model cannot properly be explained by inaccuracies in the deglaciation timing and that (2) the predicted time of the maximum inundation is either correct or a bit too old.

Effect of inaccuracies in ice-load

Obviously, ICE-3G predictions could also be wrong because in the area analized the deglaciation model is poorly constrained by ice-thickness and ice-extent data.

From bathymetric data and height of the trimline, we estimate that the fjord of False Bay (Livingston Island) had a maximum ice-thickness of about 500 m and that ice was locally grounded at more than 400 m below present sea-level. This is quite in agreement with the 440 m considered in the model for the ice-disk centered to the NW, but it disagrees with the disk centered to the E of the archipelago (Fig 1). This indicates that ice-thickness considered in the model may be plausible in some localities, while could be wrong in others. As a general rule, in the Antarctic Peninsula region the ice-thickness considered in the model is largely underconstrained.

Some of the ice-disks used in the ICE-3G model to simulate deglaciation seem to be too large and may, in consequence, contribute to the overestimation in the predicted Holocene emergence of the South Shetland Islands. As shown in Figure 1, important portions of several ice-disks are located in oceanic areas which are too deep to support grounded ice-sheets (depths greater than 500 m, which is the aproximate depth of the shelf edge). These inaccuracies in the ice-load grid-size used in the model may explain part of the overprediction in the amount of emergence.

Most of the strong contrast in the predicted RSL behaviour between the western and the eastern part of the South Shetland Islands seem to be strongly influenced by the distribution of ice-disks and the large differences in ice unloading considered in the model (Fig. 1). If the correlation of beaches suggested by John & Sugden (1971) is accepted, only small differences in ice-load between different parts of the archipelago can be envisaged. The small tilting of the 18-20 m beach observed by John & Sugden (1971) may be due to slight differences in ice-unloading along the archipelago, but also to the closer position of Livingston Island with respect to the strongly glaciated areas of the Antarctic Peninsula.

Effect of the Earth model

The ICE-3G model considers a lithosphere of constant thickness. However, this is not realistic because crust in Bransfield strait is faulted and thinned with respect to normal crust of Antarctic Peninsula and the South Shetland Islands blocks (Ashcroft, 1972, Grad et al. 1993). Transmission of deformation due to ice-load in the Antarctic Peninsula should be less effective than the one considered in the model. Thus, inaccuracies in lithosphere thickness may account for part of the overpredictions of the glacial rebound model.

ICE-3G viscosity structure may not be particularly appropriate because the underlying mantle in Bransfield Strait is probably warmer than usual. A relatively warm upper mantle would imply a lower viscosity and a faster response to varying loads so that, over a given amount of time, there would be more rebound experienced with respect to what is considered in the model. Thus, if a lower viscosity was used, difference between the observed and predicted emergence would be larger. This suggests even more strongly that the values of ice-load and/or lithospheric thickness in the model are too large.

Holocene marine limit in the South Shetland Islands

The highest dated beach in the South Shetland Islands is the one at 18 m in Maxwell Bay and has an age of 6.4 ka (Tab 1). This is not far in time from the maximum inundation time predicted by the model for this site (9 ka) and is quite close to the inflection point (7 ka) between the convex part and the concave part of the RSL curve (Fig. 5). This suggests that maximum Holocene inundation may not have been much higher than the 18 m beach. To have a first estimate we can consider that at 9 ka the predicted curve could also be 200 % to 160 % in excess with respect to the real RSL curve. Thus, applying this correction, the predicted maximum inundation (40 m) is reduced to 20-25 m (Fig. 5). This expected maximum Holocene inundation would allow beach deposition at a maximum height of only 26 to 31 m. These may be maximum figures, because time of maximum inundation may be a bit younger than the one considered in the model (Hjört et al., 1992). The sharp contrast between the widespread and better preserved beaches located below 20 m and the much less common and more strongly altered higher remnants suggests that the Holocene marine limit may have been closer to 20 m than to 30 m a.s.l.

CONCLUSIONS

In the light of the information given by the ICE-3G model and from what is presently known about Holocene deglaciation history in the Antarctic Peninsula region we suggest that:

a) Maximum index of tectonic uplift in the South Shetland Islands is not higher than 0.4 m/ka and is possibly much lower. This may explain 16 % (or less) of the observed emergence since 6.4 ka.

b) The South Shetland Islands are not only affected by variations in local ice-loads but also by the Antarctic Peninsula ice-loads.

c) Glacio-hydro-isostatic processes alone can properly explain the observed emergence of the Holocene beaches.

d) If the assumed timing of deglaciation at around 10 ka is correct (Hjört et al, 1992) the maximum Holocene submergence in the northern Antarctic Peninsula area took place around 10-9 ka or later.

e) In the South Shetland Islands beaches above 30 m should not be considered to be Holocene; they probably correspond to older interglaciations. The Holocene marine limit is likely closer to 20 m than to 30 m a.s.l.

Disagreement in emergence rates between the observed and the ICE-3G predicted Holocene RSL variations in the South Shetland Islands can probably be explained by:

a) Thinned lithosphere in Bransfield Strait transmits deformation less effectively than the lithosphere of constant thickness used in the model.

b) Inaccuracies due to the grid size and inaccuracies in the ice thickness of the model.

Future modelling will enable us to see how ICE-3G or the Earth model needs to be changed to fit all the glaciological and RSL data in this region. While it is clear that the maximum extent of grounded ice has to correspond to the position of the continental shelf break, ice thickness estimations are still scarce. To construct a realistic model it would be extremely useful to include additional estimations of ice thickness and, if possible, RSL data from this region. Some of the inherent limitations of ICE-3G, such as the large grid size, may be addressed in Peltier's (1994) more recent ICE-4G model.

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Illustrations

Fig. 1 - Map of northern Antarctic Peninsula and the South Shetland Islands to show the area analysed. The approximate position of the continental margin is shown by the 1000 m bathymetric contour (thin, dashed line). Shadings indicate the areal extent of the different RSL histories predicted by the ICE-3G model, which have been classified according to the relative amount of submergence and emergence. The curves at the right correspond to the localities labelled A to F on the map and indicate the predicted relative sea-level variations with respect to present sea-level (0 m) from 18 ka to present. Ellipses indicate the distribution, extent and maximum thickness (m) of ice-disks considered in the deglaciation model included in ICE-3G (ellipticity is due to deformation in the Mercator projection). The model considers a gradual decrease in ice-thickness from 9 ka to 4 ka.

Fig. 2 - Relative sea-level variations predicted by the ICE-3G model for several localities in the South Shetland Islands. Note the strong differences in the predicted amplitude of Holocene marine limit between widely separated localities.

Fig. 3 - Time/height diagrams of the data available from Maxwell Bay and Byers Peninsula for the last 7 ka. Dated beaches are shown by black dots (calibrated ages), thin vertical bars (one sigma error intervals) and horizontal bars (two sigma error intervals). The expected RSL curves lie 3 to 6 m below all the dated beaches. Note that, in both localities, the emergence predicted by the ICE-3G model is larger than the expected one.

Fig. 4 - Time/height diagrams to show the determination of the expected maximum tectonic uplift rate for the South Shetland Islands. The age of the most recent interglaciations has been tentatively applied to the increasingly higher platforms of the localities where there are at least 3 emerged levels. Three different hypotheses have been considered to take into account that eustatic sea-level during stage 7 was lower than during stages 11, 9, 5e and 1 (or Holocene). The deduced maximum tectonic uplift rate is 0.4 m/ka.

Fig. 5 - Time/height diagram for the last 10 ka to show the RSL curve resulting from scaling the ICE-3G prediction to agree with the 18 m, 6 Ka observation at Maxwell Bay (King George Island). If the correlation of beaches suggested by John & Sugden (1971) is accepted, the expected maximum inundation level in the whole South Shetland Islands archipelago would be about 25 m or lower. This would be able to explain beach deposition at a maximum height of only about 30 m.

Tab. 1 - Review of the radiocarbon data available from the South Shetland Islands beaches. Fildes Peninsula, Nelson Island and Barton Peninsula are all labelled as *Maxwell Bay* in this paper. Information available prior to this paper is summarized to the left of the vertical double line. To the right there is the information relating to the new corrections and calibrations. Note that new ages are significantly older than the ones suggested in Clapperton & Sugden (1988). Calibrations have been calculated according to the automated intersection method of Stuiver & Reimer (1993). Ages in brackets correspond to calibrated ages and are located between error dates. As some radiocarbon ages intersect the calibration curve in more than one point, several calibrated ages are possible for a single date. 1955* denotes the *bomb effect* influence.

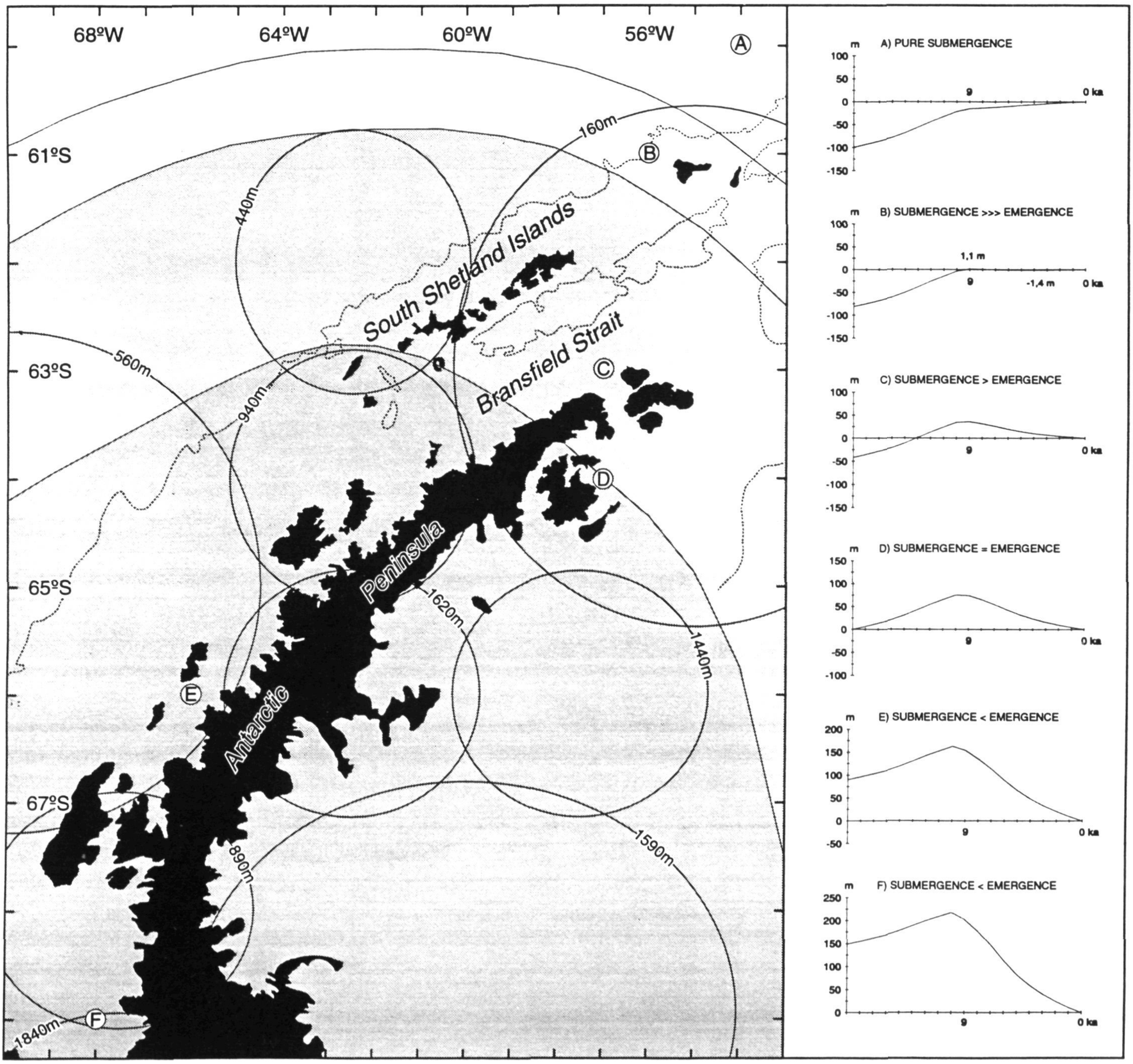

68ºW
64ºW
60ºW
56ºW
61ºS
63ºS
65ºS
67ºS
Ⓐ
Ⓑ
Ⓒ
Ⓓ
Ⓔ
Ⓕ
160m
440m
560m
940m
1620m
1440m
890m
1590m
1840m
South Shetland Islands
Bransfield Strait
Peninsula
Antarctic
m
A) PURE SUBMERGENCE
100
50
0
-50
-100
-150
9
0 ka
B) SUBMERGENCE >>> EMERGENCE
1,1 m
-1,4 m
C) SUBMERGENCE > EMERGENCE
D) SUBMERGENCE = EMERGENCE
150
E) SUBMERGENCE < EMERGENCE
200
F) SUBMERGENCE < EMERGENCE
250

Fig. 1

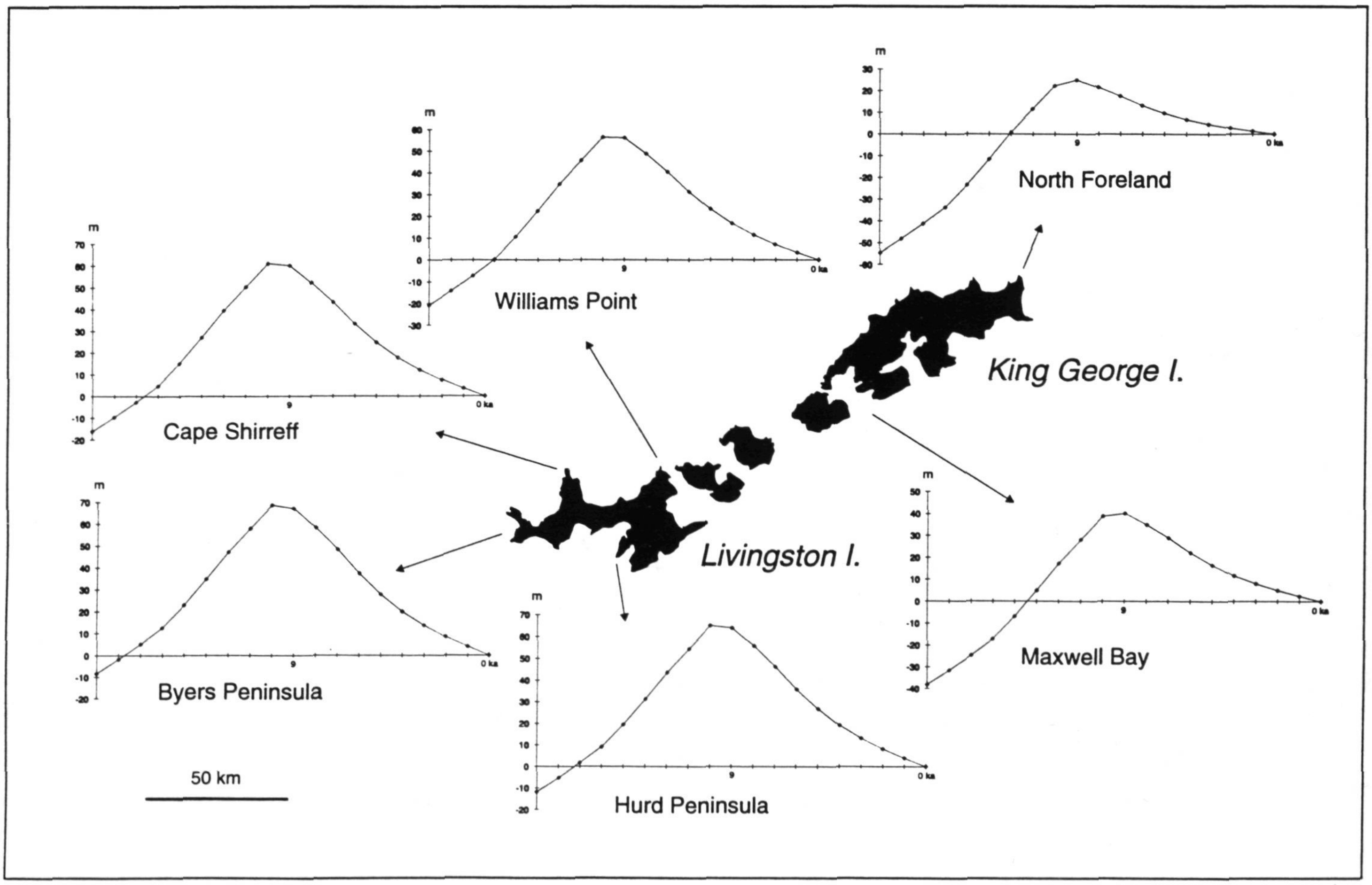

North Foreland
Williams Point
Cape Shirreff
Byers Peninsula
Hurd Peninsula
Maxwell Bay
King George I.
Livingston I.
50 km
m
9
0 ka

Fig. 2

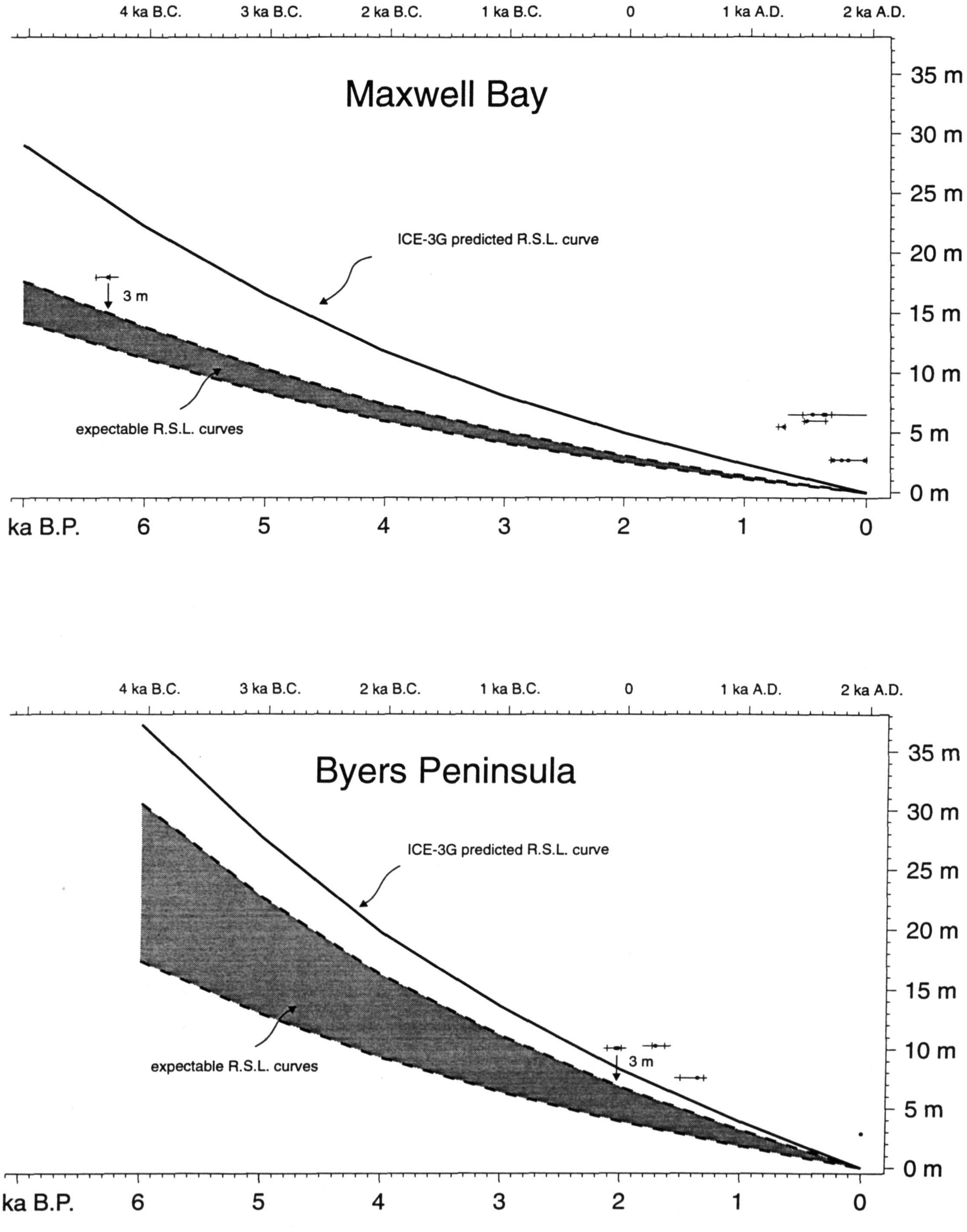
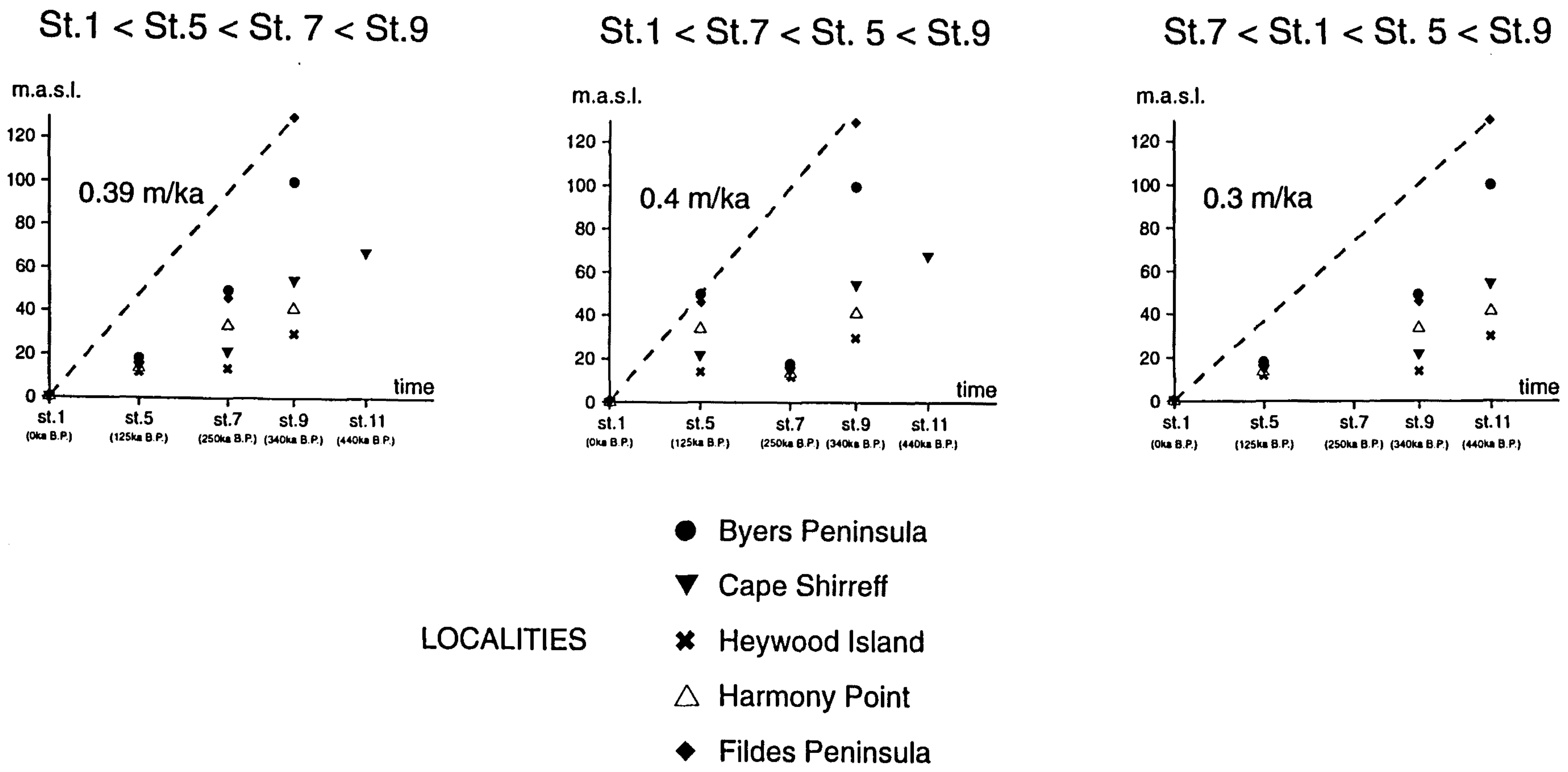

4 ka B.C.
3 ka B.C.
2 ka B.C.
1 ka B.C.
0
1 ka A.D.
2 ka A.D.
Maxwell Bay
35 m
30 m
25 m
20 m
15 m
10 m
5 m
0 m
ICE-3G predicted R.S.L. curve
3 m
expectable R.S.L. curves
ka B.P.
6
5
4
3
2
1
0
4 ka B.C.
3 ka B.C.
2 ka B.C.
1 ka B.C.
0
1 ka A.D.
2 ka A.D.
Byers Peninsula
35 m
30 m
25 m
20 m
15 m
10 m
5 m
0 m
ICE-3G predicted R.S.L. curve
3 m
expectable R.S.L. curves
ka B.P.
6
5
4
3
2
1
0

Fig. 3

MAXIMUM TECTONIC UPLIFT RATE DEDUCED FROM EMERGED MARINE PLATFORMS



St.1 < St.5 < St. 7 < St.9

St.1 < St.7 < St. 5 < St.9

St.7 < St.1 < St. 5 < St.9

Fig. 4

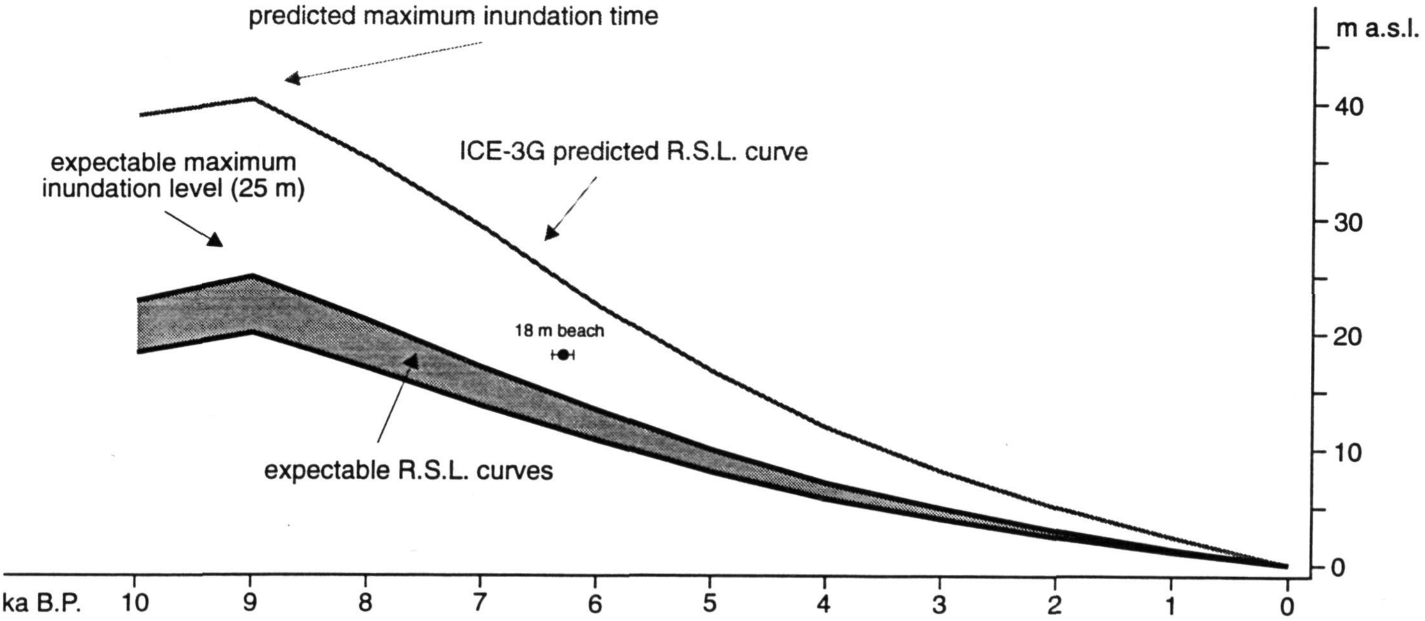

predicted maximum inundation time
ICE-3G predicted R.S.L. curve
expectable maximum inundation level (25 m)
18 m beach
expectable R.S.L. curves
m a.s.l.
40
30
20
10
0
ka B.P.
10
9
8
7
6
5
4
3
2
1
0

Fig. 5

Beach height (m)	site	dated material	sample number	radio-carbon age	reference	corrected age for the radio-carbon reservoir effect according to Clapperton & Sugden (1988)	corrected age for the minimum radiocarbon reservoir effect (-1000 years) (Gordon & Harkness 1992)	correction for the S hemisphere effect (-30 years)	calibrated age according to the two sigma error (95.4% probability)	calibrated age according to the one sigma error (68.3% probability)	calibrated age according to the one sigma error (68.3% probability) calendar BP
18	Fildes Peninsula	penguin bone	HD9425-9100	BP 6650±90	Barsh & Mausbacher (1986)	BP 5800±90	BP 5650±90	BP 5620±90	cal B.C. 4687 (cal B.C. 4460) cal B.C. 4266	cal B.C. 4536 (cal B.C. 4460) cal B.C. 4354	cal BP 6486 (cal BP 6410) cal BP 6304
18	Fildes Peninsula	penguin bone	HD8426-9106	BP 6560±55	Barsh & Mausbacher (1986)	BP 5710±55	BP 5560±55	BP 5530±55	cal B.C. 4463 (cal B.C. 4354) cal B.C. 4261	cal B.C. 4451 (cal B.C. 4354) cal B.C. 4339	cal BP 6401 (cal BP 6304) cal BP 6289
10.3	Byers Peninsula	penguin bone	SRR-1086	BP 2823±40	Hansom (1979)	BP 1973±40	BP 1823±40	BP 1793±40	cal AD 132 (cal AD 243) cal AD 374	cal AD 218 (cal AD 243) cal AD 323	cal BP 1732 (cal BP 1707) cal BP 1627
10.1	Byers Peninsula	penguin bone	SRR-1087	BP 3121±35	Hansom (1979)	BP 2271±35	BP 2121±35	BP 2091±35	cal B.C. 191 (cal B.C. 91, 83, 68) cal B.C. 1	cal B.C. 163 (cal B.C. 91, 83, 68) cal B.C. 43	cal BP 2113 cal BP 1993
7.6	Byers Peninsula	whale bone	I-7870	BP 2530±85	Curl (1980)	BP 1680±85	BP 1530±85	BP 1500±85	cal AD 404 (cal AD 596) cal AD 677	cal AD 448 (cal AD 596) cal AD 650	cal BP 1502 (cal BP 1354) cal BP 1300
6-5	Nelson Island	tree trunk	Birm-14	BP 802±43	Sugden & John (1973)	cal AD 1215 cal AD 1260		BP 772±43	cal AD 1213 (cal AD 1277) cal AD 1297	cal AD 1232 (cal AD 1277) cal AD 1287	cal BP 718 (cal BP 673) cal BP 663
6-7	Barton Peninsula	whale bone	Birm-224	BP 1390±140	Sugden & John (1973)	cal AD 1280 cal AD 1465	BP 390±140	BP 360±140	cal AD 1307 (cal AD 1511, 1600, 1616) cal AD 1955*	cal AD 1430 (cal AD 1511, 1600, 1616) cal AD 1666	cal BP 520 cal BP 284
6	Maxwell Bay	whale bone	Dic-373	BP 1440±55	Curl (1980)	cal AD 1295 cal AD 1410	BP 440±55	BP 410±55	cal AD 1419 (cal AD 1462) cal AD 1641	cal AD 1439 (cal AD 1462) cal AD 1619	cal BP 511 (cal BP 488) cal BP 331
6	Maxwell Bay	whale bone	Dic-371	BP 1360±165	Curl (1980)	cal AD 1285 cal AD 1510	BP 360±165	BP 330±165	cal AD 1302 (cal AD 1525, 1558, 1631) cal AD 1955*	cal AD 1432 (cal AD 1525, 1558, 1631) cal AD 1954	cal BP 518 present
3	Byers Peninsula	whale bone	Birm-50	BP 1056±130	Sugden & John (1973)	cal AD 1520 cal AD 180	BP 56±130	BP 26±130	present	present	present
2.5-3	Maxwell Bay	whale bone	Dic-368	BP 1200±110	Curl (1980)	cal AD 1440 cal AD 1660	BP 200±110	BP 170±110	cal AD 1477 (cal AD 1680, 1753, 1804, 1937, 1954) cal AD 1955*	cal AD 1647 (cal AD 1680, 1753, 1804, 1937, 1954) cal AD 1955*	cal BP 303 present
2.5-3	Maxwell Bay	whale bone	Dic-369	BP 1210±55	Curl (1980)	cal AD 1450 cal AD 1540	BP 210±55	BP 180±55	cal AD 1644 (cal AD 1678, 1772, 1801, 1941, 1954) cal AD 1955*	cal AD 1661 (cal AD 1678, 1772, 1801, 1941, 1954) cal AD 1954	cal BP 289 present

Table 1