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Trinity Peninsula Group (Permo-Triassic?) at Hope Bay, Antarctic Peninsula

ABSTRACT: The Trinity Peninsula Group (Permo-Triassic?) at Hope Bay, northern Antarctic Peninsula, is represented by the Hope Bay Formation, more than 1200 m thick. It is subdivided into three members: the Hut Cove Member (HBF_1), more than 500 m thick (base unknown), is a generally unfossiliferous marine turbidite unit formed under anaerobic to dysaerobic conditions, with trace fossils only in its upper part; the Seal Point Member (HBF_2), 170–200 m thick, is a marine turbidite unit formed under dysaerobic conditions, with trace fossils and allochthonous plant detritus; the Scar Hills Member (HBF_3), more than 550 m thick (top unknown), is a predominantly sandstone unit rich in plant detritus, probably formed under deltaic conditions. The supply of clastic material was from northeastern sources.

The Hope Bay Formation was folded prior to Middle Jurassic terrestrial plant-bearing beds (Mount Flora Formation), from which it is separated by angular unconformity. Acidic porphyritic dykes and sills cut through the Hope Bay Formation. They were probably feeders for terrestrial volcanics of the Kenney Glacier Formation (Lower Cretaceous) which unconformably covers the Mount Flora Formation. Andean-type diorite and gabbro plutons and dykes (Cretaceous) intrude the Hope Bay Formation, causing thermal alteration of its deposits in a zone up to several hundred metres thick. All the above units are displaced by two system of faults, an older longitudinal, and a younger transversal, of late Cretaceous or Tertiary age.

Key words: West Antarctica, Permo-Triassic (?), marine turbidites, structure, lithostratigraphy.

Introduction

Field studies on the Trinity Peninsula Group at Hope Bay, Antarctic Peninsula (Fig. 1), were carried out by the present author during the 3rd Polish Geodynamic Expedition to West Antarctica, 1987–88, led by

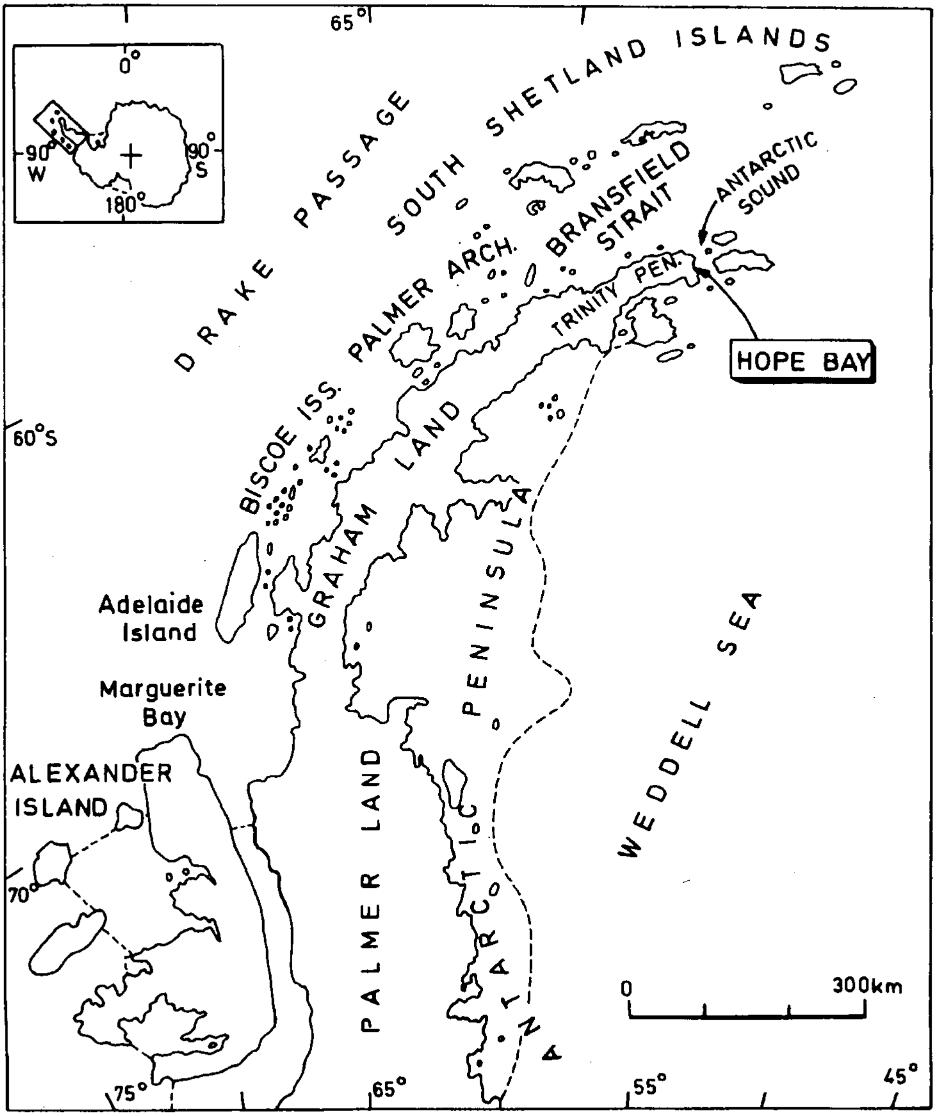

Fig. 1. Key map to show position of Hope Bay in Antarctic Peninsula and in Antarctica (inset)

Prof. A. Guterch (Birkenmajer 1988a). Their aim was to establish sedimentary character, sources of clastics, stratigraphy, thickness, relation to Jurassic terrestrial deposits (Mount Flora Formation) and Andean-type plutons, structure and age of the group. Geological maps to 1:25,000 and 1:10,000 scales were made as a basis for the above studies (Figs 2, 3).

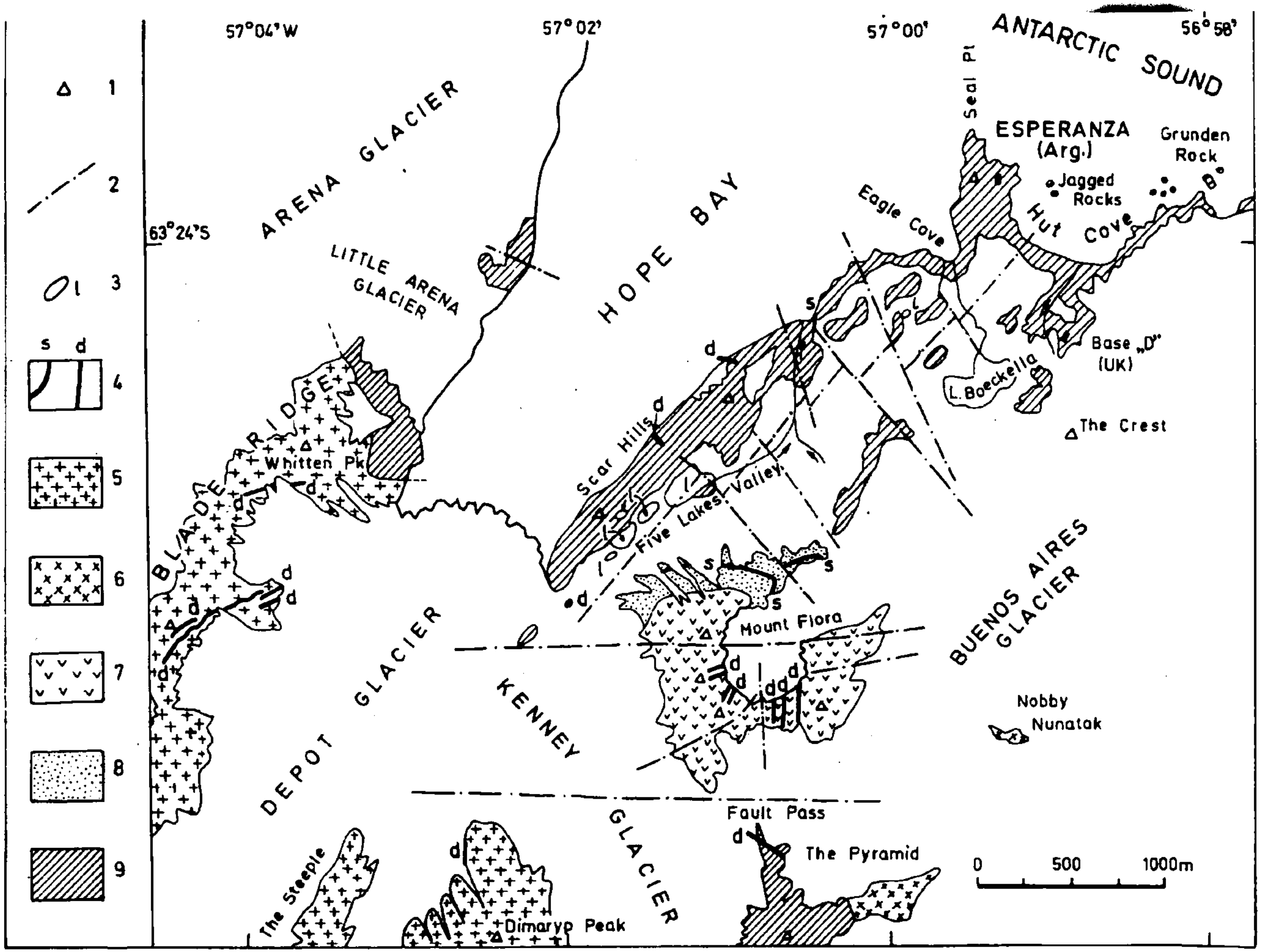

Fig. 2. Geological map of the Hope Bay area. 1 – peaks. 2 – faults. 3 – lakes. 4 – basic and acidic dykes (d) and sills (s). 5, 6 – Andean plutons (5 – diorite. 6 – gabbro). 7 – Kenney Glacier Formation (acidic lavas and pyroclastics). 8 – Mount Flora Formation. 9 – Hope Bay Formation (Trinity Peninsula Group). 5–7 – Cretaceous. 8 – Jurassic. 9 – Permo-Triassic (?)

Lithostratigraphy

The Trinity Peninsula Group at Hope Bay is represented by the Hope Bay Formation (Hyden and Tanner 1981; Smellie 1987, 1991) developed as a clastic sequence with turbidite characteristics (Birkenmajer 1988a). Three lithostratigraphic units of member rank gradually passing into one another have been distinguished: the Hut Cove Member (HBF_1), the Seal Point Member (HBF_2), and the Scar Hills Member (HBF_3).

(1) Hut Cove Member (HBF_1)

The Hut Cove Member (new unit) occurs in the eastern and central parts of Hut Cove and around the old British Base *D* (Fig. 3). Its type section is along the coast from Jagged Rocks to Grunden Rock. The rocks are locally strongly folded, hard, slightly metamorphic. The thickness of the member exceeds 500 m, its base is unknown (Fig. 4). There is a gradual transition to the overlying Seal Point Member: the first appearance of plant detritus is chosen as a marker for the bottom of the Seal Point Member.

The Hut Cove Member is a marine turbidite sequence of grey to greenish, usually homogenous, fine- to medium-grained sandstones, alternating with black shale. Intraformational shale-clast slump-breccias frequently occur as intercalations in the sandstones (see Fig. 8A, B). The sandstone beds are 0.2—3 m thick, the shales are usually 0.5—1 m thick. The sandstone to shale ratio is about 5:1 in the lower, changing to 2:1 and 1:1 in the upper parts of the member. Rhythmic repetitions (rhythmites) of thin shale and siltstone-sandstone units occur here and there. A variety of sedimentary structures prove turbidite character of the member (see description of Sites 371, 370, 369, 361, 404 and the section on sedimentary features).

(2) Seal Point Member (HBF_2)

The Seal Point Member (new unit) occurs in the western part of Hut Cove, at Seal Point, along the coast of Hope Bay from Seal Point to Eagle Cove and, further on, to the mouths of Five Lakes Valley, moreover in an area between Boeckella Lake and Five Lakes Valley, north-west of Mount Flora (Figs 3, 5). Its type locality is near Seal Point, around Argentinian Base *Esperanza*. The thickness of the unit is 170—200 m (Fig. 4), the bottom and top contacts are transitional, to the Hut Cove and Scar Hills members, respectively. The lower boundary is accepted at the first appearance of plant detritus, the upper one at the colour change: from grey-greenish (in the Seal Point Member) to rusty-weathered (in the Scar Hills Member). The rocks are strongly folded between Seal Point and Scar Hills, but become monoclinally dipping due west at the north-western slope of Mount Flora (Figs 3–5).

The Seal Point Member is a marine turbidite unit of greenish, usually homogenous, often amalgamated, fine- to medium-grained sandstones alternating with black silty shales. In the lower part of the sequence, the sandstones are from 2–3 to 5–6 m thick, the shales are from 3–5 to 5–10 m thick. There is a marked increase in the share of sandstones in the middle and upper parts of the unit, where the shales thin out to form intercalations from 20 cm down to 5–1 cm thick, while the sandstones simultaneously thicken to 3–5 m. Rhythmic repetition of thin sandstone-siltstone and shale beds (rhythmites) occurs only in the lower and middle parts of the member. Sedimentary features in the lower part of the Seal Point Member are similar to those of the upper part of the Hut Cove member. They gradually become impoverished in the middle and upper parts of the Seal Point Member whose typical feature is the presence of fine- to medium- and large-size land-plant detritus (*see* description of Sites 399, 396–7, 385, 364, 375, 390).

(3) Scar Hills Member (HBF_3)

The Scar Hills Member (new unit) occurs along the coast of Hope Bay between the mouths of Five Lakes Valley and the Depot Glacier front (Fig. 3): this is the type locality of the unit. The thickness of the member exceeds 550 m (Fig. 4). Its lower boundary is accepted at rock colour change from greenish (Seal Point Member) to rusty-weathered (Scar Hills Member), the top boundary is unknown. The rocks are gently folded at Scar Hills where they dip 30–35° due west (Figs 3–5).

The Scar Hills Member is a predominantly grey, rusty-weathered quartzitic sandstone unit rich in plant detritus, often of large size, with subordinate black shale intercalations. Sedimentary structures include small-scale cross--lamination and asymmetric ripplemarks as the most common ones (see description of Sites 389, 365, 366, 368, 388). The deposits were probably laid down under deltaic conditions, shallow-marine rather than fresh-water.

Age

The age of the Hope Bay Formation, as well as of the whole Trinity Peninsula Group, is still under debate. According to Grikurov and Dibner (1968), based on sporomorphs obtained from shale intercalations at Hope Bay, it corresponds to Early and Middle Carboniferous. This view was criticized by Schopf (1973), as the spores were poorly preserved and not illustrated by these authors.

The present author took many samples for palynological investigations throughout the whole section of the Hope Bay Formation at Hope Bay, particularly from the Hut Cove and Seal Point members. The samples were taken wherever shale intercalations were soft enough and looked promising for that type of investigation. However, despite careful laboratory examination, all proved to be barren of determinable sporomorphs. Thus, Schopf's criticism seems fully substantiated.

Mega-plant remains were collected at several sites, mainly in the upper part of the Hope Bay Formation at Scar Hills (Scar Hills Member). All represent allochthonous land-plant material supplied to the basin from the coast by currents. Some plant fragments resemble those illustrated but not determined by Schopf (1973) from the Miers Bluff Formation on Livingston Island. There are also lanceolate leaf fragments resembling *Glossopteris*.

Miller *et al.* (1987) studied detrital zircons from the Trinity Peninsula Group (TPG). Euhedral zircons of granitoid origin recovered from metasandstones at Hurd Peninsula, Livingston Island, South Shetland Islands (TPG: Miers Bluff Formation), and at Gandara Island, Base O'Higgins area, Antarctic Peninsula (TPG: Legoupil Formation), yielded U-Pb ages between 350 and 520 Ma. The authors conclude that nearly all euhedral zircons from these localities are of Early Carboniferous age. It may be thus concluded that the deposits of the Trinity Peninsula Group rocks of both areas occupy a stratigraphical position between Early Carboniferous and Middle Jurassic.

A Rb-Sr analysis of two samples from a deformed shale bed in the Hope Bay Formation (close location not given) yielded „a Permian ‚apparent age' (242 m yr) probably reflecting diagenesis and/or deformation" (Dalziel 1972, p. 53). New Rb-Sr data presented by Pankhurst (1983) refer to green, red and purple shales and siltstones from Scar Hills (=Scar Hills Member). They give a reasonably precise errorchron age estimate of 281 ±16 Ma believed to represent „diagenetic homogenisation of Sr-isotopes during latest Carboniferous or earliest Permian" (Pankhurst 1983, p. 368).

Lack of indicators of glacial control of sedimentation during the time of deposition of the Hope Bay Formation, e.g. in the form of iceberg-rafted dropstones, should exclude at least a part of the Late Carboniferous to Early Permian times as a possible age of the formation. During that time Antarctic Peninsula, being part of Gondwana supercontinent, was located close to the centre of southern glaciation (e.g., González-Bonorino 1992), in any case within the zone influenced by glacial climate.

Appearance of abundant land-plant detritus in the middle and particularly upper parts of the Hope Bay Formation (Seal Point and Scar Hills members – see above), and in the Miers Bluff Formation (Schopf 1973), indicates non-glacial, rich vegetation-favourable climate that reminds of Permian coal-bearing formations of the Transantarctic Mountains.

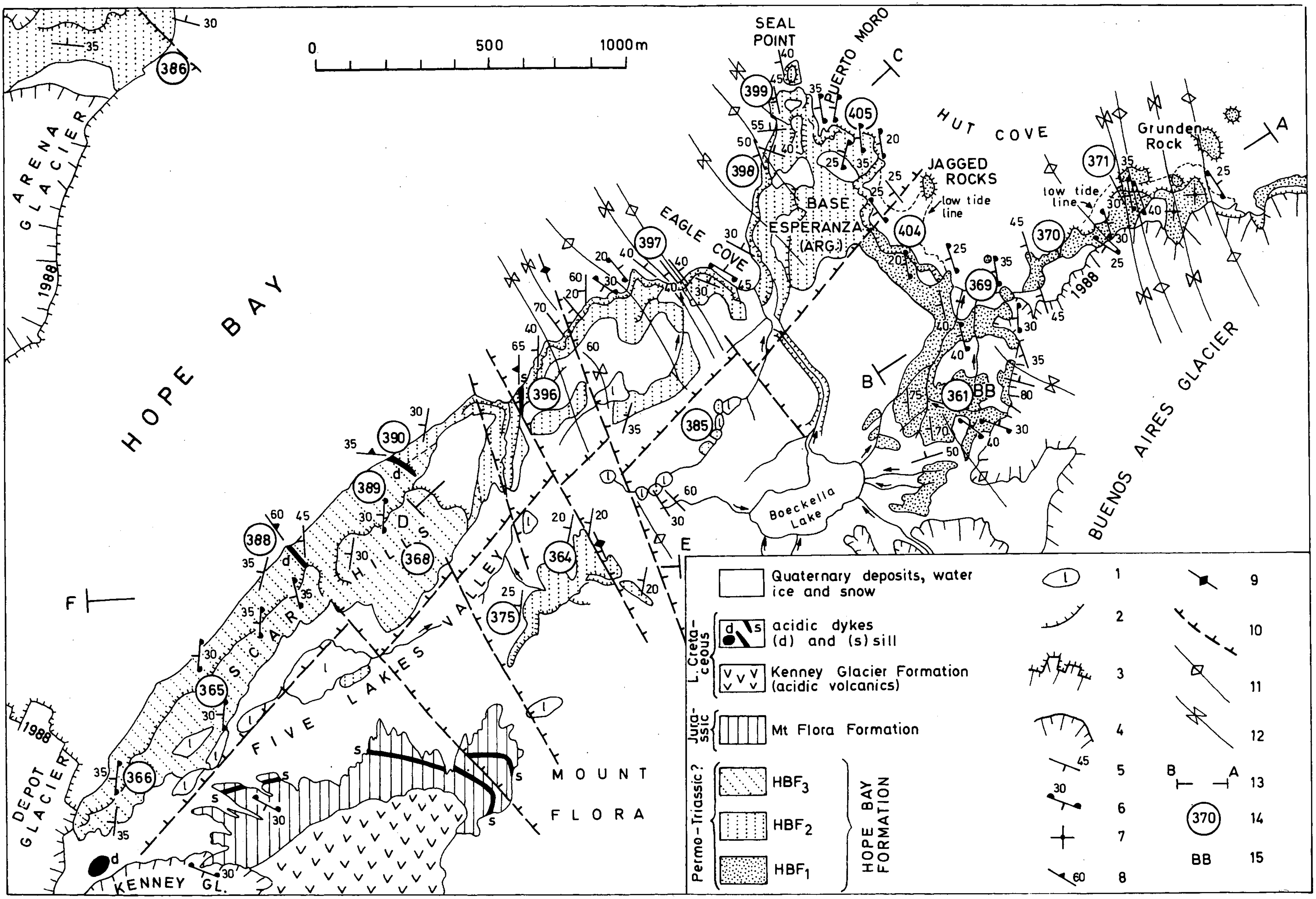

Fig. 3. Geological map of the Hope Bay Formation at Hope Bay. 1 — lake. 2 — scarps, cliffs. 3 — ice cliff. 4 — glacier margin. 5 — dip of strata. 6 — normal dip of strata (based on sedimentary features). 7 — horizontal strata. 8 — dip of dykes. 9 — vertical dip of fault. 10 — faults recognized and supposed (barbed downthrow); 11 — anticlinal axis. 12 — synclinal axis. 13 — geological cross-section. 14 — sites described in the text. 15 — old British Base *D*

Marine bivalves ?*Myalinella* sp., *Bakevellia (Bakevelloides)* aff. *hekiensis* (Kobayashi et Ishikawa), ?*Hoernesia* sp. and *Neoschizodus halperni* sp. nov. Thomson, were determined by Thomson (1975a, b, 1977) from the Legoupil Formation (previously considered to be Lower Cretaceous by Halpern 1964, 1965). Despite poor preservation and doubtful taxonomic position of these bivalves, and a new species of *Schizodus*, Thomson considers this faunule to be indicative of a Triassic age of the Legoupil Formation. The bivalve-bearing intercalations in this formation are exceptional in the whole Trinity Peninsula Group of West Antarctica. Whether Triassic or older (?Permian), they need careful re-examination of field relations, and new fossil sampling in the Base O'Higgins area.

Terrestrial plant-bearing beds of the Mount Flora Formation rest with an angular unconformity upon folded and eroded Hope Bay Formation (Adie 1964; Bibby 1966; Birkenmajer 1988a). This is well evident on different strike-and-dip patterns in both formations (see Figs 2, 3). However their contact is nowhere exposed well enough for detailed studies. The age of the Mount Flora Formation, as based on well preserved plant megafossils, was originally determined to be Middle Jurassic (Andersson 1906; Halle 1913), subsequently changed to Late Jurassic or Early Cretaceous (Stipanicic and Bonetti 1970 – *fide* Thomson 1977, pp. 888–889; Thomson and Pankhurst 1983), and recently re-evaluated as Middle-Late Jurassic (Rees 1988).

The folding and erosion which preceded deposition of the Mount Flora Formation correlates with the diastrophism during the Late Triassic to Early Jurassic time span (Gondwanian Orogeny – Smellie 1981; Peninsula Orogeny – Smellie 1991). The age of the Hope Bay Formation thus probably falls within the Permian (?Late Permian) to Triassic time-span, however without any closer determination at the present stage of investigation.

Structure

The Hope Bay Formation at Hope Bay is folded and faulted, with the oldest beds occurring in the east, near Tabarin Peninsula, younging towards the west, in the direction of Scar Hills (Figs 3, 4). The strongest folding is observable between Hut Cove and the mouths of Five Lakes Valley. The folds are straight to sub-isoclinal, with fold axes running NW-SE between the mouths of Five Lakes Valley and Seal Point, and near the British Base *D*, turning NNW-SSE in the eastern part of Hut Cove close to Grunden Rock. Axial surfaces of the folds are either vertical or inclined at high angles towards SW (WSW) or NE (ENE). The fold axes are transversal to the elongation of Antarctic Peninsula (which is SW-NE), contrary to the statement by Dalziel (1984, p. 23) that the folds in the Trinity Peninsula Group at Hope Bay have „hinge lines sub-parallel to the Antarctic Peninsula and axial surfaces dipping

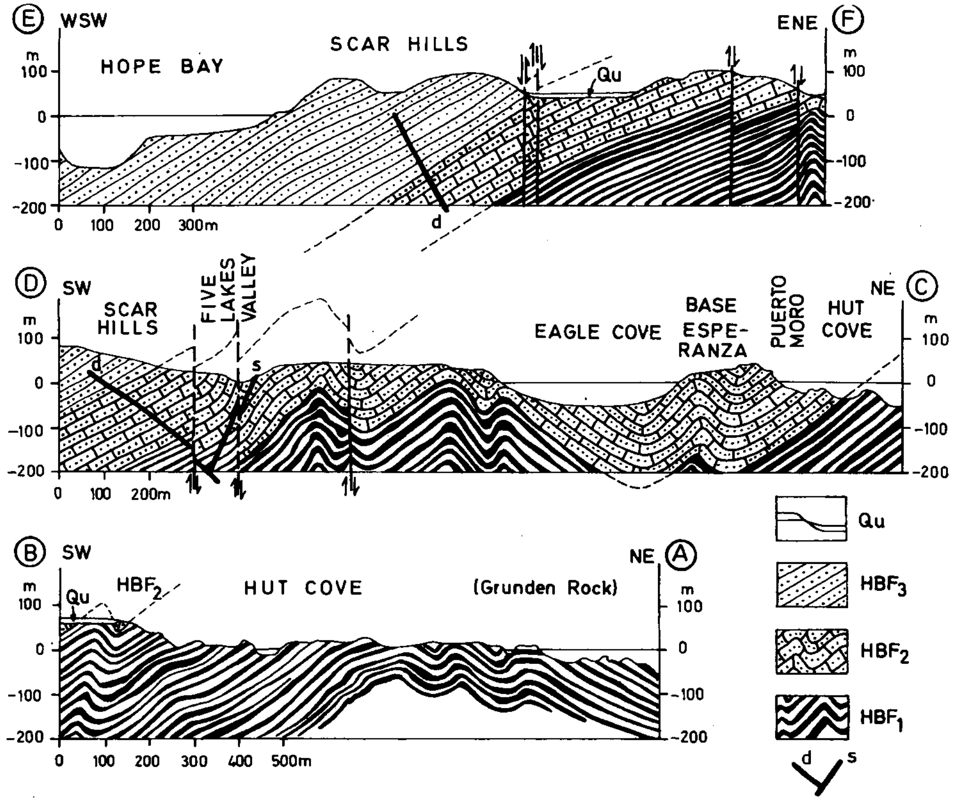

Fig. 4. Geological cross-sections across the Hope Bay Formation at Hope Bay (for location *see* Fig. 3). Qu — Quaternary cover.
d — dykes s — sills

Pacificward". Along the coast of Hope Bay, between the mouths of Five Lakes Valley and the Depot Glacier front, and at Scar Hills, the Hope Bay Formation (Scar Hills Member) monoclinally dips due west at steady angles of 30—45° (Figs 3, 4).

Basal conglomerates of the Mount Flora Formation (Middle Jurassic) are separated from the Hope Bay Formation by an angular unconformity (Adie 1964; Bibby 1966; Hyden and Tanner 1981; Birkenmajer 1988a). The Mount Flora Formation dips about 30° due SW (Fig. 3) and shows tectonic pattern different from that of the Hope Bay Formation.

There are two sets of faults: the older set (longitudinal) runs SW-NE, the younger one (transversal) runs NW-SE, displacing the former one. The throws of both systems are small (Fig. 4), of the order of up to several tens of metres. Both systems could be strike-slip faults. However, due to the lack of suitable exposures of fault surfaces available for closer examination, the problem has not been solved.

The older set of faults displaces only the Hope Bay Formation, the younger one – both the Hope Bay, the Mount Flora and the Kenney Glacier formations. Thus the age of the younger set is late Cretaceous or Tertiary.

Site description

The description of sites follows lithostratigraphic order, with the oldest rocks in the east and the youngest rocks in the west (Fig. 3).

Site 371 (HPF_1). Gentle anticline built of grey sandstones 20–50 cm thick, alternating with black shales and grey siltstones, slightly displaced by small radial joints (Fig. 8C). The sandstones show sharp contacts with underlying shales and transition to shales at the top. Graded bedding with coarser grains at the bottom and fining upward is visible in some layers. Load casts are visible at some sandstone soles, often being accentuated by radial jointing. Single, isolated current ripples flattened at the top, with load-casted bases (Fig. 7E) occur within rhythmite intervals (alternating shale and siltstone). No directional structures were observed either on the top or bottom surfaces of sandstone layers which are firmly attached to intervening shales. The rocks become horizontal near Grunden Rock and dip 25° due SE further east.

Site 370 (HBF_1). There occur predominantly homogenous, medium to fine-grained amalgamated sandstones with intercalations of shale-clast breccias, moreover normally graded sandstones (Figs 8A, B). There are two types of breccias: coarse and fine. The coarse breccias form layers up to 2 m thick. They consist of shale clasts (50–80 volume per cent) supported by medium-grained sandy matrix. The shale clasts are up to 10–20 cm in size, there occur also large fragments of rhythmites more than 50 cm across. The majority of clasts lie parallel to bedding. The fine breccias consist entirely of shale clasts up to 1 cm in size. The breccias have sharp bottom contacts and sharp or transitional top contacts with respect to the sandstones. Shale clasts may also occur at the base of graded sandstones, being coarsest at the sole and fining upward (Fig. 8A). The sandstones are usually structureless (homogenous), and only in case they alternate with finer breccias, they show internal disturbance due to slumping.

Site 369 (HBF_1). There occur green jointed homogenous sandstones fine- to medium-grained, in layers 1–3 m thick, alternating with black silty shale 0.5–1 m thick. The sandstone to shale ratio is 5:1. The thicker sandstone layers are often amalgamated ones. Discontinuous zones of shale clasts appear at 0.5–1 m intervals marking tops of individual sedimentary units in homogenous sandstones which usually do not show grading (Figs 6A, B). Graded beds with *Ta* (graded sandstone) and *Tb* (top laminae 1–2 cm thick each) Bouma units may sometimes be observed in the sandstones. Intercalations 0.5–5 m thick of black to dark-grey laminated sandstones with slump structures (Fig. 6C) appear sometimes between sets of homogenous amalgamated sandstones. Finely-laminated sandstone intercalations with deformed ripples and small-scale cross-lamination occur in thicker shale intercalations; they help define way-up of the sequence which is normal, dipping at 30—35° due west.

Site 361 (HBF_1). Greenish, fine- to coarse-grained sandstones, in beds 1—3 m thick, alternating with black shale-siltstone beds 0.2—0.5 m thick. The rocks are slightly metamorphosed, very hard, tectonized, crossed by thin quartz veins. Relics of sedimentary structures include shale-flakes at top surfaces of the sandstones and parallel lamination; they help define the way-up of the sequence which is normal, with dips 30—40° due NE in the eastern part, and 70—75° due west in the western part, thus marking an aticline with axis directed NNW-SSE. Poor exposures continue towards Boeckella Lake, where the rocks dip 50° due N and are highly jointed.

Site 404 (HBF_1). There occur greenish fine-grained sandstones in bands 0.5—1 m thick, alternating with black banded siltstone-shale 0.5—1 m thick. The sandstone to siltstone-shale ratio is 1:1, 2:1. The complex dips uniformly 25° due SW. Flat black shale clasts 1—10 cm in diameter are common in generally homogenous sandstone bands which belong mainly to the *Ta* and, more seldom, to *Tab* and *Tac* Bouma units. Amalgamation of individual turbidite units may sometimes be traced.

An example of turbidite sequence illustrated in Fig. 7F shows the presence of *Tac* Bouma unit. It includes: 1 — homogenous, fine-grained sandstone; 2 — medium-grained trough cross-laminated sandstone; 3 — fine-grained trough cross-laminated sandstone; 4 — fine-grained slumped sandstone; 5 — shale; 6 — fine-grained ripple-laminated sandstone with shale clasts at tops of the ripples; 7 — shale; 8 — fine-grained slumped sandstone.

There is a variety of current ripples, often with load-casted bases, within the siltstone-shale rhythmites (Fig. 6D). These, together with current crescentic ripples present at tops of the sandstone units, help define directions of traction currents (see Figs 10, 11).

Convolutions formed by incipient slumping observed in some sandstones often result in short subparallel ridges resembling small clastic dykes (Fig. 9A). They may pass into irregular polygonal network (Fig. 9B). Normals to subparallel ridges were used to indicate direction of bottom inclination (see Fig. 11).

Short vertical pipes 2—3 cm long and 1—2 cm in diameter occur sometimes in deformed current-ripple sets (Fig. 9C); they represent either water- or gas-escape structures formed in soft sediment, or were produced by *Skolithos*-type burrowing organisms. The latter possibility is suggested by concave shapes of upper openings of the pipes which are filled by black shale.

Spheroidal bodies up to 0.5 m in diameter appear here and there in thicker sandstone bands. They are lighter-coloured than the enclosing sandstone and might be an effect of late-diagenetic dissolution of cement.

Site 405 (HBF$_2$). There occur amalgamated sandstone bands in sets 5 – 6 m thick, with amalgamation surfaces indistinctly marked every 1 – 2 m by black shale clasts. The whole unit is fine-grained, more seldom medium-grained. Internal lamination by darker minerals is often visible, marking large concave (trough-shaped) low-angle sets. Black siltstone-shale rhythmites which appear between amalgamated sandstone sets show the presence of crescentic current-ripples and carbonized plant twigs up to 10 cm in length and 3 cm in diameter. Burrows produced by mudeaters are sometimes present at top surfaces of sandstones in rhythmite sets; the trails are 1 – 1.5 cm wide, forming curved depressions 0.5 – 0.7 cm deep filled with black shale (Fig. 9D).

Site 399 (HBF$_2$). The sandstones form bands 2 – 3 m thick with changing dip direction, crossed by thin quartz veins. They alternate with hard black shales up to 2 m thick,. In the northernmost part of Seal Point, the sandstones are green, medium- to fine-grained, homogenous, in bands 3 – 5 m thick. They alternate with black silty shales 2 – 3 m thick. In the eastern part of Seal Point (Puerto Moro), rather regular sandstone bands 2 – 5 m thick alternate with black silty shale up to 5 – 10 m thick. The shales are often banded with thin interlayers of rippled siltstone-sandstone that helps define the way up in the rhythmite, being normal (dip 35° due W). Convoluted laminations with truncated (eroded) tops may appear in thin sandstone intercalations within the rhythmites (Fig. 7D).

Site 398 (HBF$_2$). Between Eagle Cove and Seal Point (Site 399), there occur poorly exposed jointed green massive sandstones in bands 3 – 5 m thick, with black shale-siltstone interbeddings 10 – 20 cm thick. The sandstones are fine- to medium-grained, homogenous, probably amalgamated.

Sites 396 – 397 (HBF$_2$). Between the mouths of Five Lakes Valley (Site 396) and Eagle Cove (Site 397), there occurs a faulted zone with several small synclines and anticlines in the sedimentary complex which consists mainly of strongly cleaved thick sandstone bands. The sandstones are green, fine- to medium-grained, 1 – 2 to 5 m thick, amalgamated, with indistinct bottom and top surfaces, and indistinct graded bedding. Silty shale intercalations 5 – 20 cm thick occur here and there. No slumping or shale-flake breccias have been found. Slightly east of Site 397, at Eagle Cove, occurs a syncline marked in black shale bands 1 – 1.5 m thick, which alternate with grey sandstone in layers 0.5 – 1 m thick; it is followed by an anticline. At the mouths of Five Lakes Valley, jointed, greenish, fine- to medium-grained sandstones are concordantly intruded by a porphyritic sill 2 – 2.5 m thick.

Site 385 (HBF$_2$). There are two small lakes in this „dump-heap" valley, separated by a threshold built of strongly jointed greenish sandstones which continue south-west and become strongly weathered.

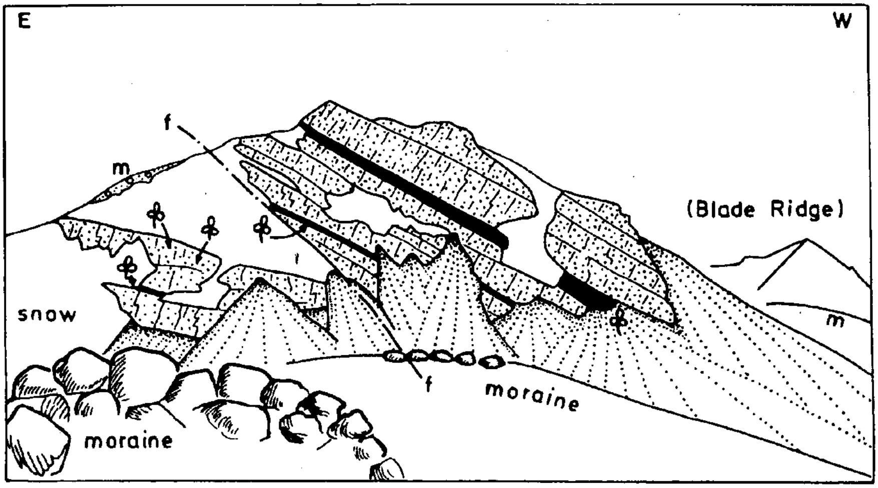

Fig. 5. Exposure of the Hope Bay Formation below Mount Flora (for location see Fig. 3. Sandstones stippled; shales and siltstones in black; f — fault; m — moraine; plant detritus shown by conventional symbol

Site 364 (HBF_2). The exposure is in a cliff 50 m high at the foot of Mount Flora (Fig. 5). It shows massive, medium-grained grey sandstones in bands 3—5 m thick, traversed by a vertical fault with strike azimuth 150° (trace of this fault is marked by *f* in Fig. 5), with several thicker black shale-siltstone rhythmite bands showing bioturbation. Thicker black shale intercalations visible in the exposure (Fig. 5) are in fact rhythmites composed of black (rusty-weathered) silty shales with black rippled siltstone intercalations, 1—5 cm thick (Figs 7A—C).

In the upper part of the exposure, the sandstone becomes medium- to fine-grained, grey-greenish to light-grey. It shows black shale streaks 1—10 mm thick. Streaks of black angular shale pellets 0.5—10 cm in diameter mark tops of particular beds within amalgamated sandstone sets. Parallel lamination and convoluted lamination are visible here and there.

Plant detritus in form of small silver-shining (anthracitic) fragments is frequent in silty shale and sandstone intercalations within the shale bands (rhythmites); larger carbonized plant remains (twigs) appear in the sandstone to the north of the fault (Fig. 5).

Site 375 (HBF_2). This exposure corresponds to the upper part of Site 364 (Fig. 5). Greenish sandstones form here bands 1—1.5 m thick, alternating with black shale 0.5—1 m thick. There appear small clastic sandstone dykes arranged in networks resembling mudcracks. Plant detritus is common in the sandstones.

Site 386 (HBF_2). The site is in a high cliff on the western shore of Hope Bay, between Little Arena and Great Arena glaciers (Fig. 3). We see here folded, thermally altered, grey to greenish medium-grained sandstones (probably amalgamated), in bands up to several metres thick, with intervening bands of rhythmites, 2–4 m thick, consisting of alternating black shale and thin greenish siltstone or fine-grained sandstone with traces of rippling. The shales are very hard, silicified, often hornfelsic in appearance.

Sites 390 (HBF_2) and **389** (HBF_3). Small whitish-grey, pinkish to whitish porphyrite dyke 3–5 m thick cuts through black, very hard („hornfelsic") shale (Site 390). The shale underlies brownish, medium-grained sandstone with rusty-coloured plant detritus: there occur large fragments of plants, mostly twig and stem fragments up to 20 cm long, but also some leaf imprints resembling *Glossopteris* (Site 389).

Sites 365, 366, 368, 388 (HBF_3). Grey sandstones, quartzitic, medium-grained, in bands 1–4 m thick, with brownish-weathered surfaces, uniformly dipping 30–35° due west. Low-angle, medium to large-scale trough cross-lamination occurs in the sandstones which are intercalated by black shale with thin brownish-grey siltstone and fine-grained sandstone interbeds showing lamination and asymmetric ripplemarks (Figs 10, 11). Small, irregular sandstone dykes often densely cut through the shales. Cementation concretions 5–10 cm in diameter, lighter coloured than the enclosing sandstone, occur near a 1-m thick porphyritic dyke at Site 388.

Sedimentary features — a summary

The Hope Bay Formation at Hope Bay shows a variety of sedimentary features attributable mainly to turbidities, visible usually inside amalgamated homogenous sandstone layers, less commonly preserved on top or bottom surfaces of these layers. Their distribution in the stratigraphic column of the formation is given above (see: Site description).

The turbidite facies environment is generally accepted for all Trinity Peninsula group deposits (*e.g.*, Dalziel and Elliot 1973; Elliot 1965; Hyden and Tanner 1981; Smellie 1987), but only in a few cases sedimentological evidence was presented to support this view (Elliot 1965; Birkenmajer 1988; Birkenmajer and Doktor 1988).

(1) Massive sandstones

The majority of sandstones, particularly in the Hut Cove and Seal Point members, are fine- to medium-grained, homogenous. They usually represent incomplete *Ta, Tab* or *Tac* Bouma turbidite units (Figs 6A–C, 7F, 8A–C) welded together to form amalgamated sandstone bands of considerable thickness. The sandstone soles are sharp against underlying shale, and often

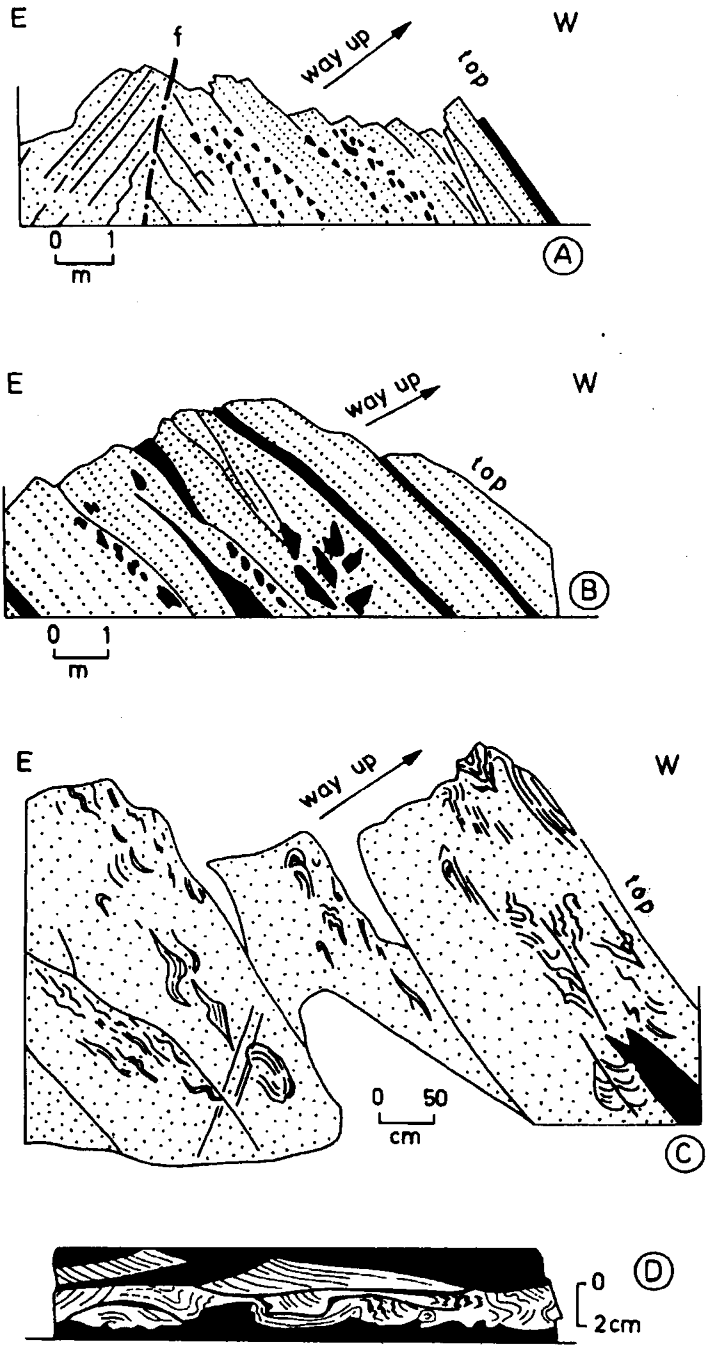

Fig. 6. Sedimentary features of the Hope Bay Formation at Hope Bay. A, B — amalgamated homogenous sandstones with shale intercalations and clasts (in black). C — slumping visible in deformation of lamination and current ripples within amalgamated homogenous sandstone. D — asymmetric current ripples, load-casted in the lower part of figure. A – C — coastal exposures at Hut Cove, eastern part (Site 369). D — coastal exposures at Hut Cove, western part (Site 404)

transitional to the overlying one. Sole markings are seldom preserved due to compaction and low-grade metamorphic alteration of the deposits. Traces of slumping are often visible as contortions of parallel and ripple lamination (Fig. 6C). Shale-clast breccia intercalations and stripes often occur in the sandstones, particularly of the Hut Cove Member (Figs 6A, B, 8A, B).

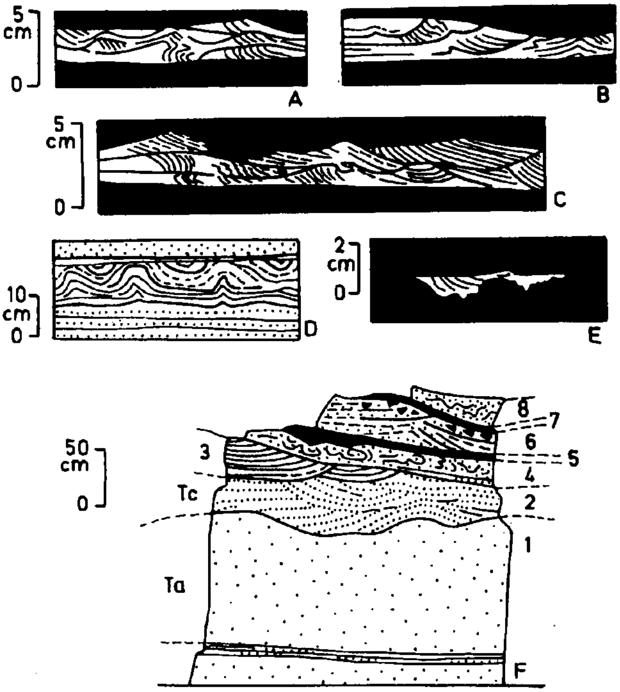

Fig. 7. Sedimentary features of the Hope Bay Formation at Hope Bay: Hut Cove Member (Sites 371, 404) and Seal Point Member (Sites 364, 399). A – C — internal structure of asymmetric current ripples showing deformations caused by load of successive ripples (Site 364). D — convolutions in laminated siltstone truncated by sandstone lamina (Site 399). E — load-casted and flattened isolated ripple (Site 371). F — composite structure of three successive sandstone layers separated by shales (in black), detailed description in the text (Site 404), Ta, Tc — Bouma turbidite units

Compared with turbidite environments, such as known for example from Mesozoic to Tertiary Alpine and Carpathian flysch (*e.g.*, Birkenmajer 1959; Bouma 1962; Dżułyński and Walton 1965), the variability of grading types in the sandstones is very small in the Hope Bay Formation. These sandstones originated from medium- to high-density turbidity currents.

The sandstones from the southern coast of Hope Bay (mainly from the Scar Hills Member?) fall within the IIb petrofacies of Smellie (1987, Fig. 1), which is characterized by volumetrically dominant quartz and feldspar, an admixture of basic volcanic clasts, and the lack of garnet. The clastics were derived from a magmatic are composed of unroofed highly dissected batholiths and their metamorphic envelope, capped locally by isolated volcanoes (Smellie 1987, p. 205).

(2) Rhythmites and shales

Rhythmic repetitions (rhythmites) of black silty shale, thin grey siltstone and fine-grained sandstone often replace thicker horizons of black shale and silty shale. The rhythmites are usually richer in sole and top markings than thick massive sandstone beds, and may contain trace fossils. Their mode of occurrence as replacement of shales between thicker sandstone bands (Fig. 8C), and their internal sedimentary character, classify them as formed by diluted (low-density) turbidity currents.

(3) Shale-clast breccies

Intraformational breccia intercalations within the sandstones consist of angular, usually flat shale clasts, sometimes also of rhythmite clasts. Coarse and fine breccias may be distinguished, both regarded as formed by subaqueous slumping of disintegrated shale and/or rhythmite (Figs 8A, B). The shale clasts may also appear as markers of grading in amalgamated sandstones, at the bottom (Fig. 8A, C), and at the top (Fig. 6A, B) of individual turbidite units.

(4) Ripplemarks

All ripplemarks observed in the Hope Bay Formation at Hope Bay belong to asymmetric current ripple type, usually crescentic, less frequently straight (Figs 10, 11). Trough-shaped small-scale cross-laminations in upper parts of some turbidite layers represent *Tc* Bouma units (Fig. 7F: Tc). Single or, more frequently, multiple asymmetric small-scale ripples, are unimodal (Figs 6D, 7A—C, E, 10, 11). They were formed by traction currents probably generated in the wake of turbidity currents. Internal convolution of cross-lamination originated due to overloading of the first ripples by the successive ones (Figs 6D, 7A—C). Load-casting of some ripple bases, associated with internal convolution of cross-lamination (Figs 6D, 7E) originated due to yielding of soft clay under the ripple load. Such mode of formation of load-casted current ripples is well known from turbidite environments (*e.g.*, Dżułyński and Walton 1965; Reineck and Singh 1973).

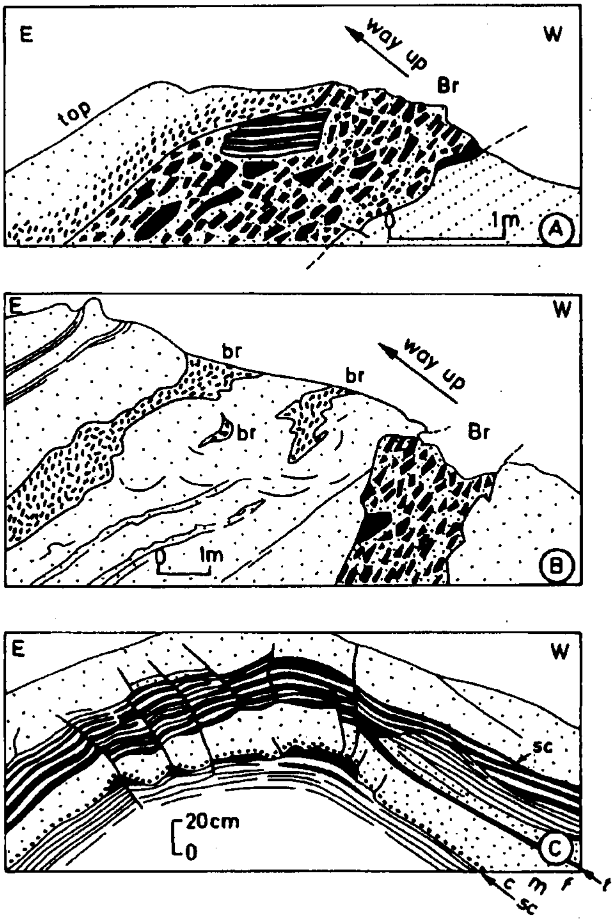

Fig. 8. Examples of shale-clast sedimentary breccias (A, B) in homogenous sandstones showing traces of lamination and slump structures (Br — coarse breccias. br — fine breccias). C — example of graded sandstone and laminated sandstone-shale unit (shales in black. sc — sharp contact; t — transition; c — coarse-grained. m — medium-grained. f — fine-grained). A—C — coastal exposures at Hut Bay, eastern part (Sites 370, 371)

(5) Convolutions not related to rippling

Besides convolutions related to the mechanism of ripple formation, there occur convolutions probably related to initial slumping of the whole laminated layer. They are expressed at top surfaces of thin sandstones as short, discontinuous subparallel ridges (Fig. 9A), sometimes passing into irregular polygonal network (Fig. 9B). In both cases, internal lamination of the sandstone is convoluted accordingly with the ridges, and the soles of the

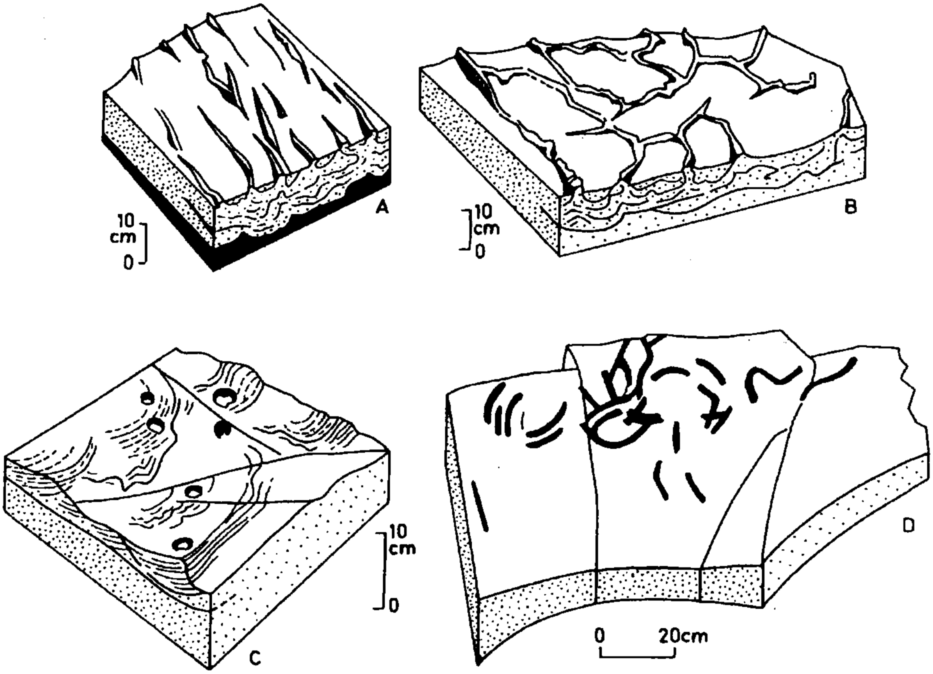

Fig. 9. Sedimentary features of the Hope Bay Formation: examples of top-surface markings. A — subparallel ridges on top of convoluted laminated sandstone with load-casted sole. B — polygonal ridges on top of laminated convoluted sandstone. C — openings of short vertical pipes (gas escape structures or vertical *Skolithos*-type burrows) in small-scale current ripple-laminated sandstone. D — traces of burrowing by unknown organisms. A—D — cliff exposures at Hut Cove, western part: Seal Point Member (Sites 404, 405)

sandstones are also involved in convolutions. Similar polygonal structures were described from turbidite environment as parting casts (Birkenmajer 1959).

(6) Trace fossils

Trace fossils are very rare in the units investigated. They have been found in the top part of the Hut Cove, and the bottom part of the Seal Point members. Some represent trails of mudeaters (Fig. 9D), others resemble to some extent *Skolithos* tubes (Fig. 9C); however inorganic origin of the latter structure cannot be excluded (see description of Site 404).

(7) Plant detritus

Plant detritus appears for the first time in the bottom part of the Seal Point Member which still has a turbiditic characteristics, and continues upwards this member and in the Scar Hills Member, the latter probably deltaic in origin. The detritus consists of allochthonous land-plant fragments brought to the basin from the coastal area directly by turbidity and traction currents, partly also settled at the reservoir bottom after floating for some time in the water. The latter mechanism seems more adequate for large fragments of twigs and *Glossopteris*-like leaf fragments which occur in the sandstones of the Scar Hills Member (*see* Site 389). Appearance of trace-fossils simultaneously with the first influx of plant-detritus to the basin stresses importance of organic matter as nutrient for bottom-dwelling clay-burrowing organisms.

(8) Palaeotransport of clastics

Hut Cove Member. Azimuths of small-scale foreset lamination in crescentic ripples present at tops of some thicker graded sandstone beds (Fig. 7F), and in thin sandstone intercalations within rhythmites, indicate unimodal south-west-flowing traction currents (Figs 10, 11). These currents are interpreted as generated in the wake of turbidity currents.

Short slump-ridges present on tops of some convoluted sandstone layers (e.g., Fig. 9A) are elongated NW-SE, at right angle to the mean traction current direction which is SW (Fig. 11). Originally, the cracks of initial slumping were penetrated by quicksand. They could have developed along contour lines of the sedimentary basin bottom.

Unit	Site No	l (cm)	h (cm)	l/h	Foreset azimuth	Type
HBF_1	404	10	0.5	20	210	crescentic
		10	1.0	10	260	—"—
		10	1.0	10	200	—"—
		11	1.0	10	210	—"—
		10	0.7	14	220	—"—
		—	—	—	240	—"—
		—	—	—	250	—"—
HBF_2	405	—	—	—	30	—"—
		—	—	—	240	—"—
	399	10	1-2	5-10	—	asymmetric
	364	5-10	2	2.5-5	260	—"—
HBF_3	365	5-10	1-2	2.5-10	—	—"—

Fig. 10. Ripplemark characteristics in the Hope Bay Formation. HBF_1 – Hut Cove Member. HBF_2 – Seal Point Member. HBF_3 – Scar Hills Member

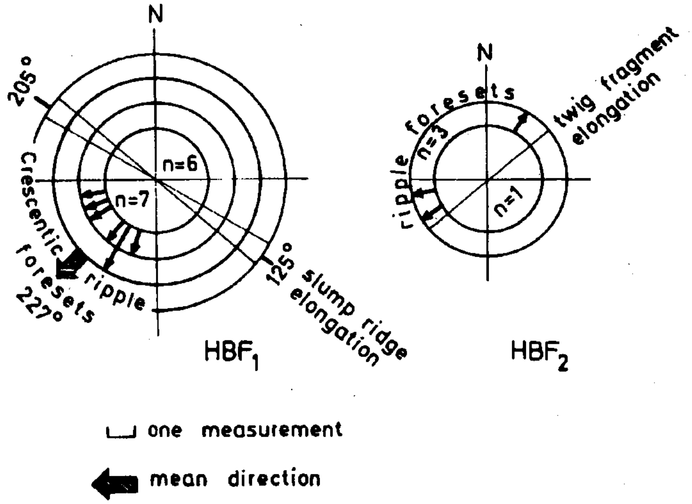

Fig. 11. Palaeotransport directions and bottom-contour indicators in the Hope Bay Formation. HBF$_1$ – Hut Cove Member; HBF$_2$ – Seal Point Member

The above data, although not numerous, indicate position of the source of clastics as located in the north-east.

Seal Point Member. Measurements of azimuths of foreset lamination in asymmetric ripples are too few (Fig. 11) to allow any generalization. Two ripple foreset azimuths lie in the SW quadrant, as in the case of the Hut Cove Member, and one in the NE quadrant. Elongation of a twig fragment has a NE-SW direction. One can only suggest that this incomplete picture is an expression of bimodality in traction current directions. If so, it could result from gradual shallowing of the basin, its bottom rising to depths influenced by tides.

Scar Hills Member. No measurements of current directions were possible due to generally poor exposure of bed surfaces. The ripple characteristics does not differ from that of the Seal Point Member (Fig. 10).

Sedimentary environment – conclusions

(1) The Hope Bay Formation is predominantly a marine turbidite sequence, that is indicated by a variety of sedimentary features typical for this facies. The sedimentary basin was generally poorly aerated, that resulted in anaerobic to dysaerobic conditions during its early and middle stages, expressed as black colouration of shales and rhythmites, the lack of marine microfossils, and the absence or paucity of traces of activity of bottom-dwelling invertabrates (trace-fossils).

(2) Fine- to medium grain grades in the sandstones, their apparent maturity reflected in grain homogeneity, and the lack of coarse-grained sandstones and conglomerates, point to a non-distrophic period of deposition from high- to low-density turbidity currents which originated in the coastal zone probably as a result of sediment overloading of a submarine delta. Homogeneity and amalgamation of the majority of sandstone bodies probably resulted from good sorting of fine- to medium quartz and feldspar grains achieved already during fluvial transport, before settling in a submarine delta.

(3) A petrofacies study of the Hope Bay Formation by Smellie (1987, 1991), which probably applies mainly to the Scar Hills Member, indicates the provenance of the clastics from highly dissected batholiths and their metamorphic envelope, capped locally by isolated volcanoes. Taking into account the Pb-U age of zircons from the Miers Bluff Formation at Livingston Island and the Legoupil Formation from Gandara Island (Miller *et al.* 1987), these source rocks would include Precambrian through Lower Carboniferous metamorphic, igneous and sedimentrary complexes. Rich detrital feldspar component in the sandstones may indicate an arid, rather warm climate at the time of deposition of the Trinity Peninsula Group.

(4) The location of the source rocks, as indicated by directional current structures was on the north-east and east (Fig. 11). This agrees with the sources of zircon grains in the Trinity Peninsula Group which are considered to have derived from Precambrian through Lower Carboniferous granitoids of South America, with the Antarctic Peninsula-South Shetland terrane being located west of it (Miller 1983; Miller *et al.* 1981; Hervé *et al.* 1991).

(5) Diagenesis of clayey material at the bottom of the Hope Bay Formation basin proceeded at a considerable pace, as is often the case in turbidity environments. Hardened shale disintegrated to angular clasts due to submarine slumping. Loose clasts were picked up and transported downslope by turbidity currents, finally settling either at the top (most frequently) or at the bottom of the turbidite unit. When transported at the bottom of the turbidity current, such angular clasts usually act as tools carving directional current markings in soft clayey bottom, subsequently preserved at the soles of sandstone bodies as casts. They leave no evidence for palaeocurrent direction in case of amalgamated sandstone bodies which originate by superposition of uniformly-grained (homogenous) turbidites.

(6) Almost complete lack of directional current markings at the sandstone soles investigated, despite frequent occurrence of shale clasts in intraformational breccias and within turbidite units, may be an effect of the subsequent history of the area, including low-grade regional metamorphism and multiphase deformation (*cf.* Hyden and Tanner 1981). It caused strong compaction and partial recrystallization of the deposits, and obliterated sole and top markings in the sandstones. Overloading by huge Mesozoic volcanic piles, and rise of ground isotherms due to Andean intrusive activity could have also been the cause.

(7) There is no indication of the proximity of shoreline in the deposits of the Hope Bay Formation; its basin classifies as an amputated one. Submarine transport from distant sources located in the east and north-east is suggested by the Hut Cove and Seal Point members, and silting of the basin due to prograding submarine delta – by the Scar Hills Member.

(8) The lower and middle parts of the Hope Bay Formation (Hut Cove and Seal Point members) were deposited in a marine basin strongly influenced by turbidite currents. Two facies are recognizable, correlatable with a submarine fan model in terms of middle-fan distributary channel-depositional lobe system:

(8.1) The channel fill facies is represented by homogenous, amalgamated sandstone bodies. Slump breccias may have been emplaced as a result of undercutting channel walls by oncoming turbidity currents and lateral slumping of channel-wall sediment;

(8.2) The rhythmite and shale facies probably represent basin-plain deposits or non-channelised fan lobe. These were formed mainly by low-density turbidity currents and suspension clouds.

Regional correlation

The Hope Bay Formation at Hope Bay (Fig. 12), lithologically resembles some, but not all, deposits of the Trinity Bay Group visited by the present author on Livingston Island and Antarctic Peninsula.

(1) At Hurd Peninsula, Livingston Island, it finds lithological and facies equivalents in the Miers Bluff Formation as described by Dalziel (1972), Tokarski (1991), Arche *et al.* (1991), and Doktor and Tokarski (*in* Birkenmajer 1992a). Arche *et al.* (1991) distinguished two main types of facies: channelized and non-channelized ones which, based on their description, correspond to the channel-fill and the rhythmite-and-shale facies of the Hope Bay Formation. Three lithofacies were distinguished by Doktor and Tokarski: the thick-bedded sandstone units with intraformational shale breccias (1), and medium-bedded fine-grained sandstones alternating with black shales (2), correspond to the channel-fill facies of the Hope Bay Formation; the thin-bedded sandstones and siltstones rhythmically alternating with shales, i.e. rhythmites (3), correspond to the rhythmite facies of the Hope Bay Formation.

(2) At Cape Legoupil (Chilean Base *General Bernardo O'Higgins*), the lithology of the Trinity Peninsula Group distinguished as the Legoupil Formation (Hyden and Tanner 1981) was described in particular by Halpern (1964, 1965), Thomson (1975a, b) and Tokarski (1989). There are facies similarities between the lower and middle parts of the Hope Bay Formation (Hut Cove and Seal Point members) and the rocks exposed at Schmidt Peninsula, Toro Island and Mount Jaquinot, in which Tokarski (1989) has

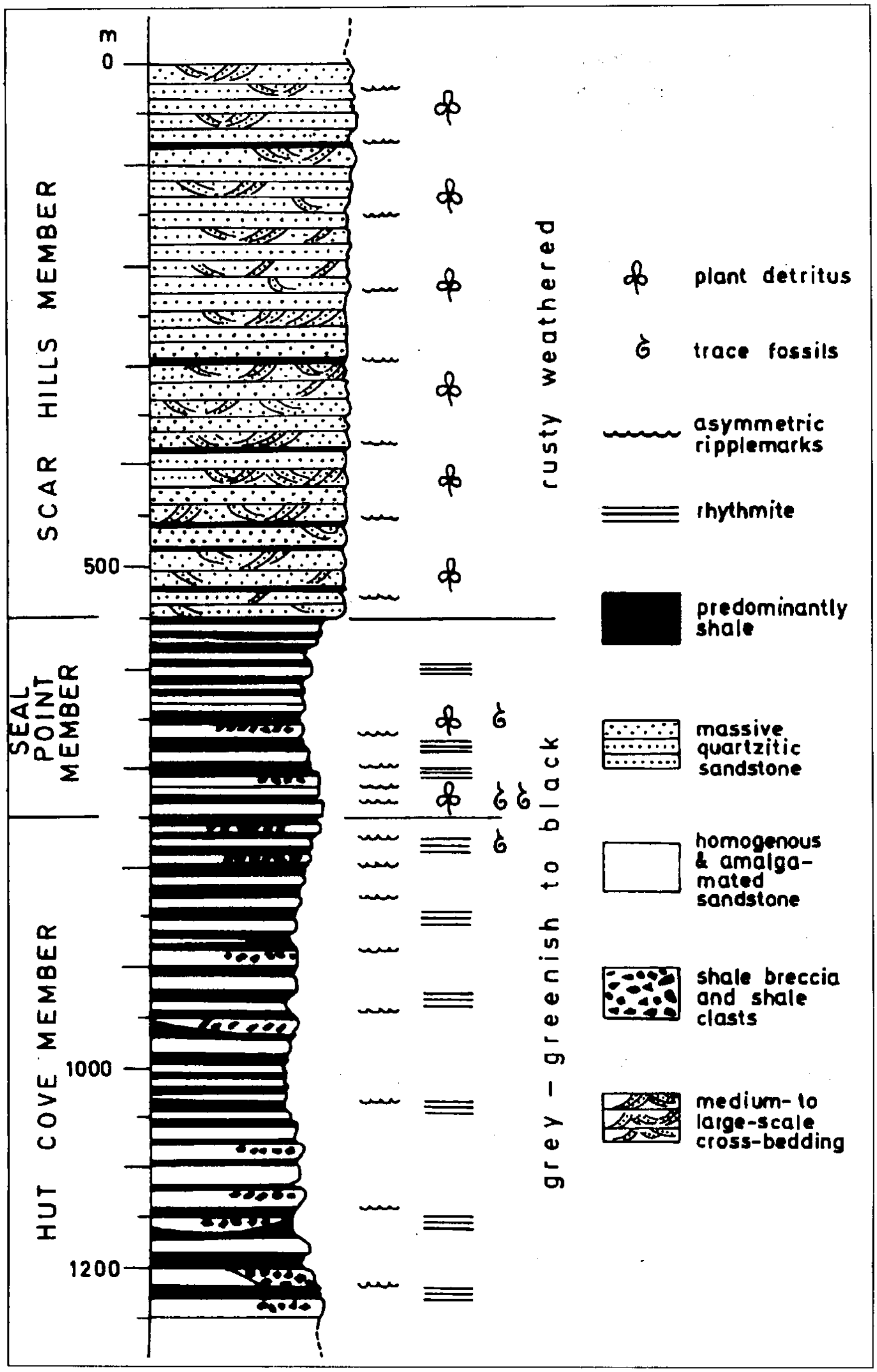

Fig. 12. Lithostratigraphic column of the Hope Bay Formation at Hope Bay

distinguished three facies: (1) massive dark argillite (corresponding to shale complexes at Hope Bay); (2) interlayered sandstone and argillite (corresponding to rhythmites at Hope Bay); (3) thick-bedded, unstratified sandstone with shale (corresponding to channel facies at Hope Bay).

Conglomerates and bivalve-bearing sandstones (Halpern, 1964, 1965; Thomson 1975a, b; Tokarski 1989) seem to represent a facies and lithostratigraphic unit different from those of Hope Bay. Some intraformational breccias occur in the facies (2) and (3) of Tokarski, the rest seem to form separate units.

(2) At Paradise Harbour (vicinity of Argentinian Base *Almirante Brown*), only the lower part of the succession, some 500 m thick (Paradise Harbour Fm.), which consists of grey-green to dark-grey and black siltstone-shale-quartzite sequence with infrequent ripplemarks (Birkenmajer 1987, 1988b, 1992b, Birkenmajer and Doktor 1988: Almirante Brown Mbr.) corresponds in facies and general appearance to the Hut Cove and Seal Point members of the Hope Bay Formation. The middle unit, 200 m thick (Skontorp Cove Member), consisting of reddish to variegated claystones, siltstones and fine-grained sandstones with very frequent ripplemarks, trace fossils *etc.*, and with channel-type quartzitic sandstone bodies, and the upper unit, 100 – 300 m thick (Mount Inverleith Member), consisting of grey-green to yellowish quartzites and quartzitic sandstones with traces of large-scale cross-bedding, alternating with black siltstones, find no equivalents at Hope Bay.

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Streszczenie

Osady klastyczne grupy Trinity Peninsula (permo-trias?) w rejonie Hope Bay (Półwysep Antarktyczny, Antarktyka Zachodnia — fig. 1) reprezentowane są przez formację Hope Bay, o miąższości ponad 1200 m. Wyróżniono w niej ogniwa (od najstarszego do najmłodszego): z Hut Cove, z Seal Point i ze Scar Hills (fig. 2—12). Ogniwo z Hut Cove (ponad 500 m miąższości, spąg nie odsłonięty) składa się z na ogół pozbawionych skamieniałości morskich utworów turbidytowych. Ogniwo z Seal Point (170—200 m miąższości) składa się z morskich utworów turbidytowych podobnych do ogniwa poprzedniego, ale z detrytusem roślin lądowych i skamieniałościami śladowymi. Ogniwo ze Scar Hills (ponad 550 m miąższości, strop nieznany) składa się w przewadze z masywnych piaskowców kwarcytowych z dużą ilością napławionych szczątkow roślin lądowych: prawdopodobnie utworzyło się ono w warunkach delty podmorskiej. Materiał klastyczny był przynoszony przez prądy z północnego-wschodu, prawdopodobnie z południowoamerykańskiego sektora Gondwany. Formacja Hope Bay została sfałdowana w czasie późnego triasu-wczesnej jury, zerodowana i niezgodnie przykryta floronośnymi klastycznymi utworami lądowymi jury środkowej-górnej.