POLSKA AKADEMIA NAUK · KOMITET NAUK GEOLOGICZNYCH

PAŃSTWOWE WYDAWNICTWO NAUKOWE . WARSZAWA

acta geologica polonica

Vol. 35, No. 1-2 Warszawa 1985

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Onset of Tertiary continental glaciation in the Antarctic Peninsula sector (West Antarctica)

ABSTRACT: At the close of the Cretaceous, the Antarctic Peninsula sector had a rather warm and dry climate, differentiated into summer and winter seasons, as indicated by annual growth-rings in petrified logs. Vegetation cover was probably patchy due to low amount of precipitation. There is no indication of contemporaneous continental glaciation, however small ice-caps may have grown on tops of stratovolcanoes and in high mountain groups.

The Early Tertiary saw climatic and environmental conditions initially similar to the precedent ones. Increase in amount of rainfall with time resulted in wide spreading of vegetation cover, with *Nothofagus* forests rich in fern undergrowth, including tree ferns, and with *Araucaria*, during Palaeocene and Eocene, followed by *Nothofagus*-podocarp forests poorer in fern undergrowth during Oligocene. Climatic seasonality is well marked in petrified wood logs as annual growth-rings. Terrestrial animal life (marsupials, large birds) is recorded at the beginning of Palaeogene. There is no indication of continental glaciation in the Antarctic Peninsula sector during the whole Palaeogene. The uppermost Oligocene plant-bearing beds (dated at about 24.5 Ma) still evidence a non-glacial climate. There are, however, evidences from lahar-type debris-flow agglomerates of existence of local ice-caps on tops of stratovolcanoes.

The onset of continental glaciation (ice-sheet at sea level) in the Antarctic Peninsula sector, slightly post-dates the Oligocene/Miocene boundary. Early Miocene brachiopod-bearing shallow-marine sediments contain pieces of carbonized wood, and are still devoid of convincing glacial-climate indicators. The succeeding Early Miocene highly fossiliferous glacio-marine strata are crowded with iceberg-rafted debris, often of large dimensions, of Antarctic continent provenance. Andesite dykes which cut through these strata have been K-Ar dated at about 20 Ma. The K-Ar dating of the geological events leaves a narrow bracket for the onset of continental glaciation in the Antarctic Peninsula sector at between 24 and 20 Ma.

INTRODUCTION

Palaeomagnetic data indicate that Antarctica occupied a high latitude polar or near-polar position since Late Palaeozoic (FRAKES, 1979). The initial break-up of the southern hemisphere supercontinent, Gondwanaland, commenced close to the Jurassic/Cretaceous boundary, some 135 Ma ago, and continued through Cretaceous to final separation and dispersion of the continents during Early Tertiary.

The separation of Australia from Antarctica began in Late Paleocene (CROOK 1981) or Early Eocene (WEISSEL & *al.* 1977; KEMP, 1981), and of South America from Antarctica at a much later date — in Late Oligocene, by initial opening of the Drake Passage at about 29 Ma (KENNETT & *al.* 1975; BARKER & BURRELL 1977).

The separation of Antarctica from other southern hemisphere continents by ever-growing oceanic stretch, had a decisive effect in form of increased precipitation in its coastal zone, and was a primary cause for cooling of climate and appearance of continental ice-sheet. The cooling at high southern latitudes proceeded along with formation of the Circum-Antarctic Current once the Drake Passage has been fully opened at about 25—22 Ma, and oceanic depths were achieved (BARKER & BURRELL 1977; KENNETT 1977, 1980). This current, and the gradually developing Antarctic Convergence, had isolating effects on the continent, screening it from influences of poleward heat transport. The convergence zone lay during Eocene probably within a few hundred kilometres of Antarctic coast but steadily moved northward in Oligocene and Miocene. A shift of slightly more than 10° of latitude took place between 55 and 5 Ma ago (KEMP & *al.* 1975; FRAKES 1979).

There is no indication of ice-cap formation in Antarctica in the Late Cretaceous. Lahar-type agglomerates recognized in the South Shetland Islands, indicate a possibility of ice-growth and local glaciation restricted to the highest volcanoes and mountain groups. Quartz grains interpreted as ice-rafted material of Antarctic origin, appear in deep-sea cores of south-east Pacific since Early Eocene (MARGOLIS & KENNETT 1970, 1971). There is no direct proof that they were ice-rafted, and other mechanisms may have been involved. *e.g.* plant-rafting, submarine currents, and wind transportation. In case of ice-rafting, this fine quartz material may not necessarily be considered an evidence for glaciation in Antarctica, as coastal winter ice may pick and redistribute littoral sediment over large areas (*see* SPJELDNAES 1981).

Variation in quantity of ice-rafted debris observed in deep-sea cores around Antarctica, have provided one of primary bases for palaeoclimate study of that area. The sediment-laden icebergs are however scarce in Antarctic waters today, most icebergs being barren of debris. ANDERSON & *al.* (1980) caution against using ice-rafted debris as a sole indicator of palaeoclimates. The iceberg-related sedimentation is best evidenced by glacially striated and polished dropstones often of considerable dimensions, haphazardly distributed in glacio-marine sediment (BIRKENMAJER 1980d).

Isolated centres of glaciation, initially restricted to higher mountains, mountain groups, highlands and elevated polar plateaus, had formed during Eocene and Oligocene, eventually merging into continental ice-cap at the boundary of Oligocene and Miocene. Coastal regions of Antarctica were vegetated persistently throughout Palaeogene, until the Late Oligocene inclusively (KEMP & BARRETT 1975; KEMP 1981; ZASTAWNIAK & *al.* 1985). The latest Oligocene through Early Miocene glacio-marine sediments give the first good evidence for glaciation at sea level in West

Antarctica. According to KENNETT (1977), the East Antarctic ice-sheet has been a semi-permanent feature since Middle Miocene.

The onset of the Cenozoic continental glaciation in Antarctica was probably a diachronous event. In Marie Byrd Land (West Antarctica), the oldest basaltic hyaloclastites interpretated as products of eruption beneath continental ice-sheet, have been dated at 27±1 Ma — a good early Late Oligocene date (Le MASURIER & REX 1977). In the Ross Sea sector, there is an evidence of glacio-marine iceberg--related sedimentation in the latest Oligocene (about 25 Ma), following a non-glacial climate marine deposition near sea level at about 26 Ma. Highly elevated adjacent Transantarctic Mountains may have been the site of significant ice development as early as Mid-Late Eocene, 44—45 Ma (WEBB 1983a, b). The Late Oligocene gla-

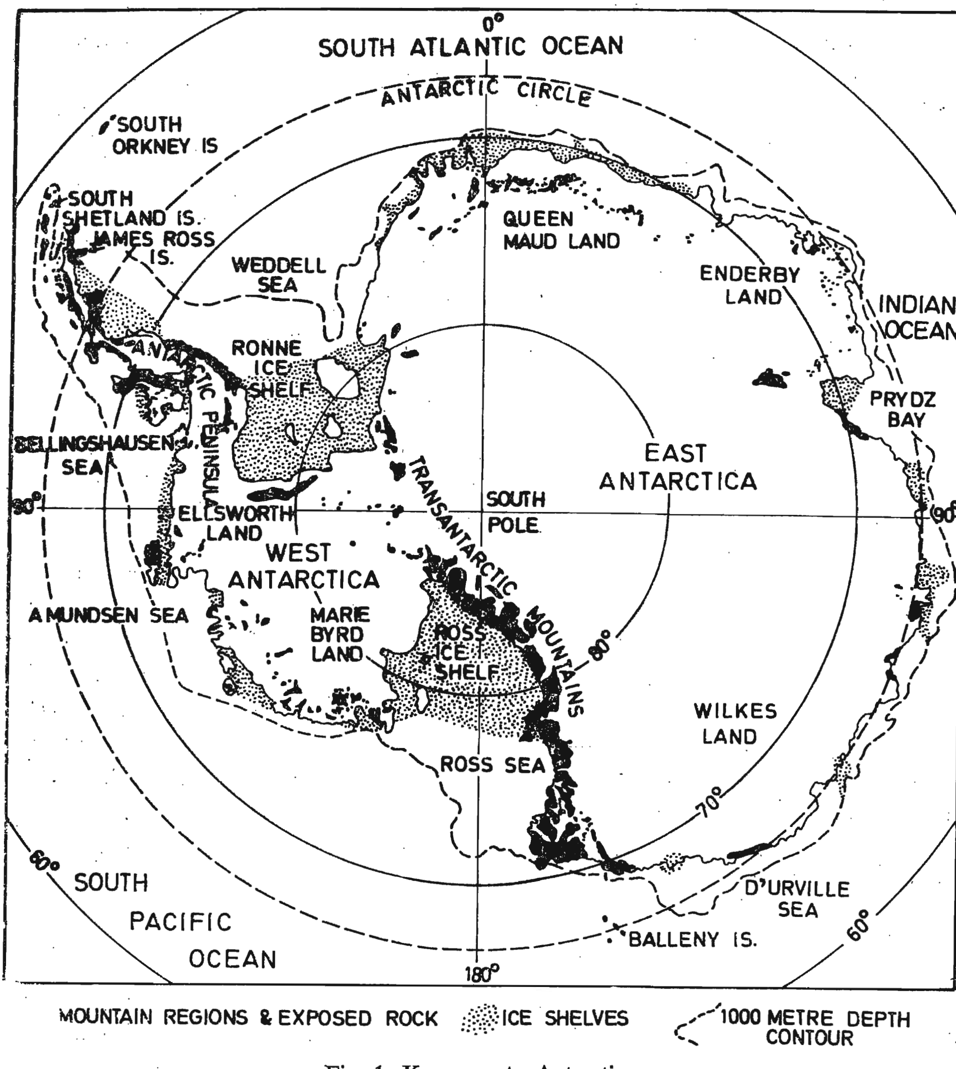
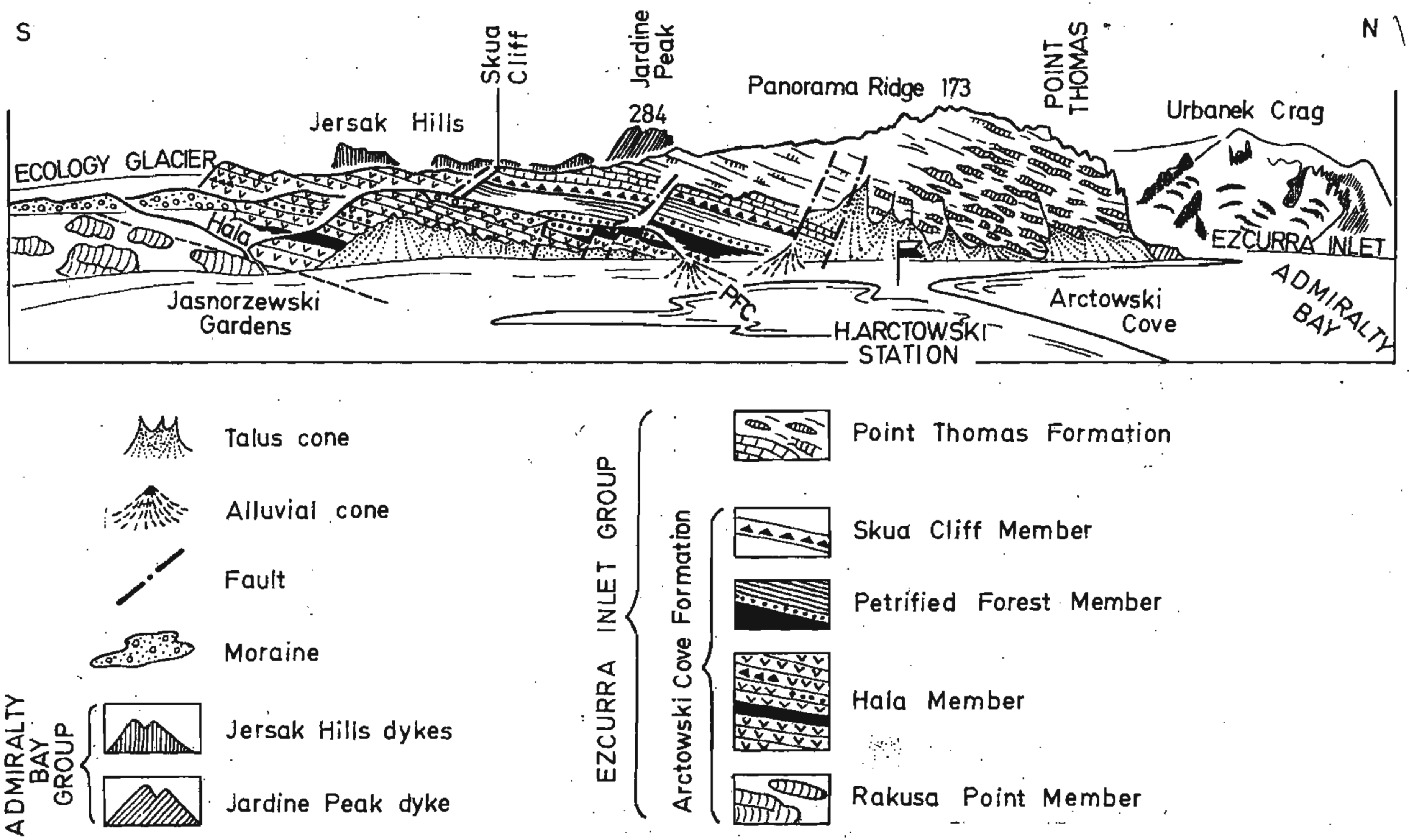


Fig. 1. Key map to Antarctica

Geological panorama around the Arctowski Station, Admiralty Bay



PFC Petrified Forest Creek

ciation extended into Early Miocene (LECKIE & WEBB 1983), and further into Mid-Late Miocene and Pliocene-Pleistocene (WEBB 1981, 1983a, b).

In the Antarctic Peninsula sector of West Antarctica, which includes the South Shetland Islands and the James Ross Island Basin (Fig. 1), the oldest evidence for land-ice development, probably in form of ice-caps on tops of stratocones, is provided by Late Cretaceous and Early Tertiary (mainly Eocene ?) lahars. The latest Oligocene terrestrial plant-bearing strata, K-Ar dated at 24.5 ± 0.5 Ma, indicate non-glacial climatic conditions in the South Shetlands at the close of the Palaeogene (BIRKENMAJER & *al.* 1983c; ZASTAWNIAK & *al.* 1985). Surface palaeotemperatures of Pacific seawater off Antarctic Peninsula calculated at 14°C for Late Eocene (FRAKES 1979, p. 193, Fig. 7—2), drastically dropped to 3°C during Oligocene (FRAKES 1979, Fig. 7—3). There is no evidence of continental ice-sheet at sea level in the Antarctic Peninsula sector until Early Miocene, when the first glacio--marine sediments rich in iceberg-rafted Antarctic debris often of large dimensions (Cape Melville Formation) had formed in King George Island. They are the evidences for the first large-scale continental Cenozoic glaciation (ice-sheet) in Antarctica, called the Melville Glaciation (BIRKENMAJER 1982b, c, e, 1984).

The largest Cenozoic glaciation recorded in deep-sea cores around Antarctica by ice-rafted debris of Antarctic provenance, had occurred during the Miocene and Early Pliocene times (KENNETT & *al.* 1975; CRADDOCK & HOLLISTER 1976; KENNETT 1977, 1978; KEANY 1978). This was the only Cenozoic ice-sheet that, at its maximum extension, had crossed the Bransfield Strait and reached as far north as the South Shetland Islands (BIRKENMAJER 1890d, 1982a, 1983).

EVIDENCES OF LATE CRETACEOUS AND PALAEOGENE CLIMATES

SOUTH SHETLAND ISLANDS

The best information as to palaeoclimatic conditions in the South Shetland Islands during the Late Cretaceous and Palaeogene times is provided by fossil plant assemblages. The plant remains occur at numerous levels within the stratiform pile some 2500 m thick of predominantly andesitic and basaltic lavas alternating with tuffs, breccias etc., subordinately with water-laid tuffites, shales and conglomerates (BARTON 1961, 1964, 1965; ADIE 1964; BIRKENMAJER 1980a-c), distinguished as the King George Island Supergroup by BIRKENMAJER (1980a-c). This supergroup (Fig. 2) reveals an island-arc calc-alkaline trend of vulcanicity related to Late Mesozoic through Palaeogene subduction of the south-east Pacific oceanic plate under Antarctic Penisula (*see* BIRKENMAJER & NARĘBSKI 1981).

MODE OF OCCURRENCE OF PLANT REMAINS

The plant remains occur in the Upper Cretaceous and Palaeogene terrestrial sediments of the King George Island Supergroup in the form of five types of assemblages.

(*1*) Silicified, sometimes also sideritic or limonitic wood fragments occur within conglomerates, debris-flow (lahar-type) breccias and coarser tuffs, more seldom in finer tuffs, clays and, exceptionally, in basal breccias of lava flows. The fragments usually lie parallel with stratification of the sediment as a result of redeposition from their place of growth by mass movements, water action and/or volcanic eruptions. The trunks have never been found in upright position rooted in palaeosol. The fossilization processes (silicification, sideritization, limonitization) of the trunks may have been subsequent to burial in case of larger trunks; there are also frequent wood fragments which

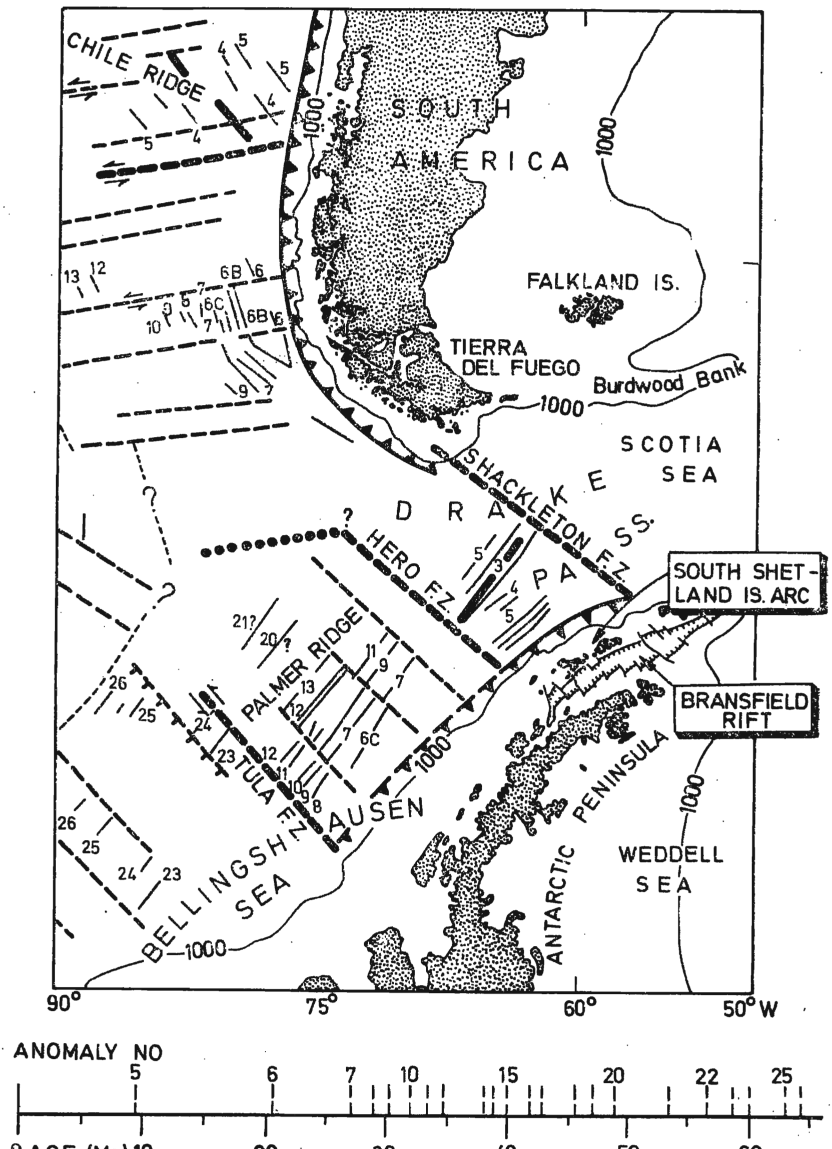


Fig. 2. Geotectonic position of the Antarctic Peninsula sector, northern part

Magnetic anomalies and fracture zones from Herron and Tucholke (Craddock & Hollister, 1976), simplified; continental plate margins barbed

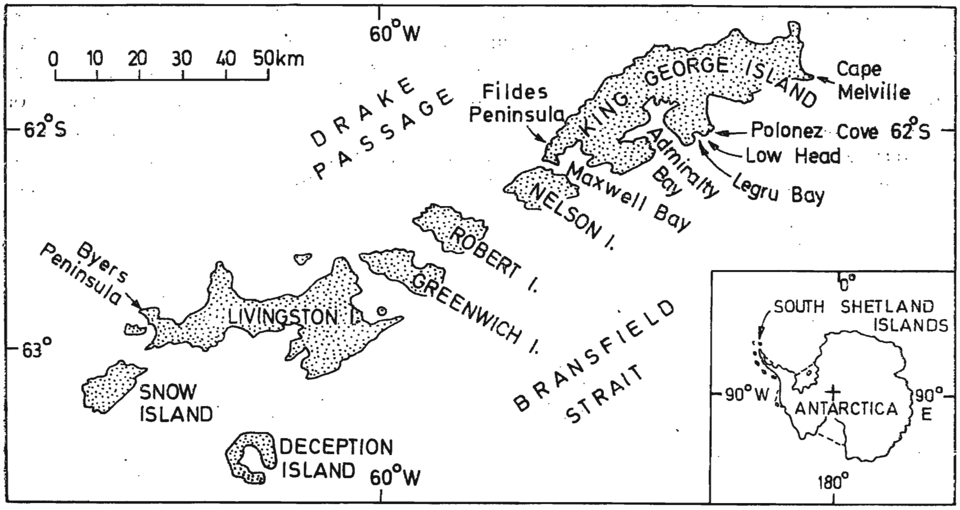


Fig. 3. Key map to the South Shetland Islands, central part

underwent reworking and further fragmentation after silicification. Carbonized organic matter may occur on some petrified wood fragments. The majority of fragments show rather dense, well preserved annual growth-rings.

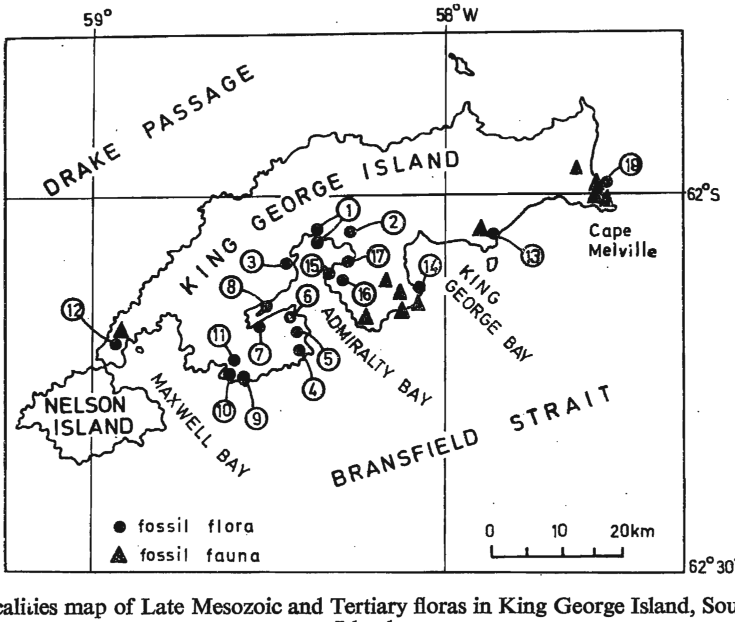
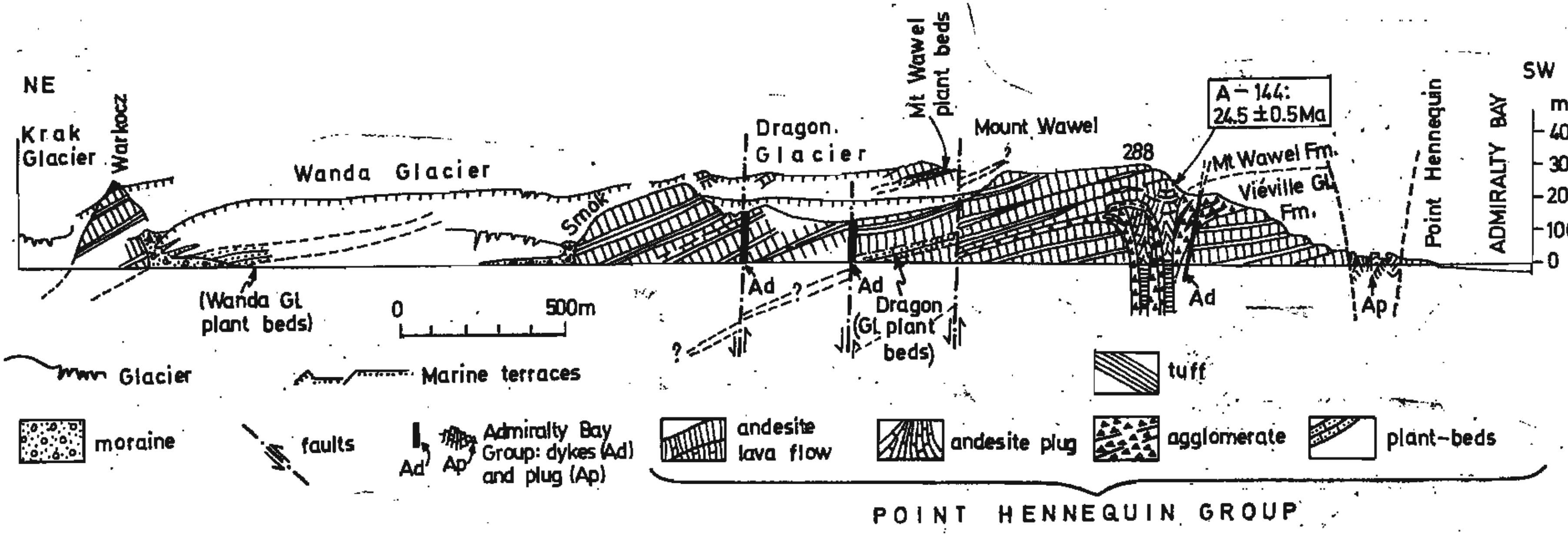


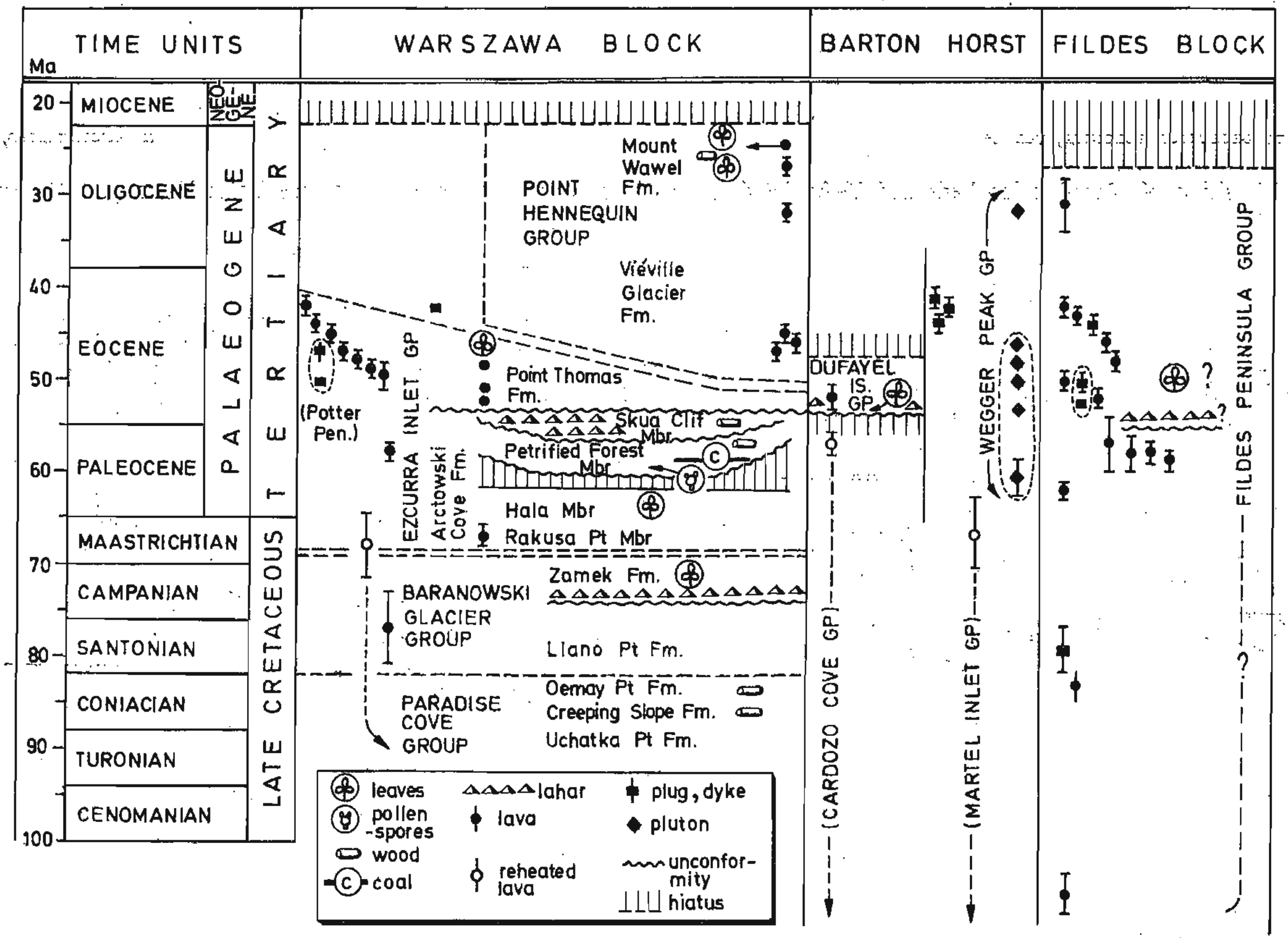
Fig. 4. Localities map of Late Mesozoic and Tertiary floras in King George Island, South Shetland Islands

1 Keller Peninsula; 2 Precious Peaks; 3 Admiralen Peak (Late Mesozoic); 4 Paradise Cove (Late Cretaceous); 5 Zamek (Late Cretaceous); 6 Petrified Forest Creek and vicinity (?Palaeocene and Eocene); 7 Cytadela, Ezcurra Inlet (Eocene); 8 Dufayel Island (Eocene); 9 Stranger Point (?Eocene); 10 Potter Peninsula (?Eocene); 11 Potter Cove (?Late Cretaceous); 12 Fildes Peninsula (?Eocene or older); 13 Three Sisters Point (Late Cretaceous); 14 Lions Rump (?Palaeogene or ?Late Cretaceous); 15 Point Hennequin, Dragon Glacier (Late Oligocene); 16 Point Hennequin, Mount Wawel (Late Oligocene); 17 Point Hennequin, Wanda Glacier (Late Oligocene); 18 Wrona Buttress, Destruction Bay (Early Miocene)

Position of plant-bearing beds and K-Ar-dated sample in geological cross-section of the Point Hennequin Group, Admiralty Bay



Stratigraphic position of fossil floras and lahars in King George Island



Radiometric dates *from* WATTS (1982), BIRKENMAJER *& al.* (1983b,c) and PANKHURST & SMELLIE (1983)

(2) Deciduous leaves (angiosperms), shoots, fruits and seeds of conifers, fern fronds, horsetail and other plant fragments, occur as impressions in varved tuffs, shales and siltstones, moreover in sandy tuffs, sometimes also in coarser tuffs. As a rule, the leaves and shoots are devoid of organic layer which has been recognized only exceptionally in some fruits and seeds. The organic matter disappeared due to diagenetic changes in which both water circulation and reheating of volcanic--sedimentary pile by recurrent volcanic activity did play a part.

The above assemblage characterizes ephemeral pool and intermittent running-water regimes which developed at the feet of volcanic cones. The leaf-bearing sediments may sometimes contain fragments of petrified wood but, as a rule, are devoid of pollen and/or spore assemblages.

(3) Assemblages of pollen and spores are preserved only exceptionally in brown-coloured, carbon-rich clayshales within fresh-water sediments intercalated in the volcanic pile discussed. Petrified wood fragments and a brown-coal intercalation have been found in the same fresh-water sequence which was devoid of leaf imprints.

(4) The only brown-coal intercalation found consisted of small, brittle, carbonized wood fragments. It was devoid of pollen and spores. This is an allochthonous type of coal probably representing a charcoal deposit resulting from fire ignited by a volcanic eruption or lightning in forests which covered volcanic cones of the South Shetlands. No sitter sandstone resp. regolith with imprints of rootlets were found associated with this coal.

(5) Tuff-sandstone fragments with imprints of carbonized plant rootlets were found only occasionally in beds containing leaf imprints.

LATE CRETACEOUS FLORAS OF ADMIRALTY BAY

The Late Cretaceous plant remains occur (Figs 3—4) within terrestrial sediment intercalations of the oldest Paradise Cove Group and the succeeding Baranowski Glacier Group of the King George Island Supergroup (BIRKENMAJER 1980a, b, e).

Paradise Cove Group (Fig. 4: *4*). This group is subdivided into three formations. The lower Uchatka Point Formation consists entirely of high-Al basaltic lavas which yielded a Late Cretaceous K-Ar date of 67.7±3.5 Ma. This is a minimum stratigraphic age of these lavas as an indication exists of argon loss due to Tertiary reheating (BIRKENMAJER & *al.* 1983c). The basalts are followed by the Creeping Slope Formation about 60 m thick which is an entirely sedimentary unit of terrestrial origin consisting of red shale with green tuffite flake-conglomerate horizon in the middle. The conglomerate contains large fragments of silicified wood with perfectly preserved annual growth-rings. The upper Demay Point Formation (*see* Fig. 10) is represented mainly by igneous rocks — altered porphyritic dacite lava, plug and dykes, rhyolite tuff, tuff-breccia, lapilli tuffs, moreover by conglomerate with petrified wood fragments.

Baranowski Glacier Group (Fig. 4: *5*) This group consists of two formations. The lower Llano Point Formation is a monotonous sequence more than 1100 m thick of basaltic andesite lava sheets alternating with pyroclastics, with subordinate water-laid sediment intercalations. The lavas yielded (*see* Fig. 10) a Late Cretaceous (Santonian — Campanian) K-Ar date of 77±4 Ma (BIRKENMAJER & *al.* 1983c). The upper Zamek Formation, more than 40 m thick, consists of basaltic andesite lavas alternating with scoria and tuff, with a horizon about 1 m thick rich in plant remains, mainly deciduous leaf (*Nothofagus* sp.), conifer and fern frond imprints

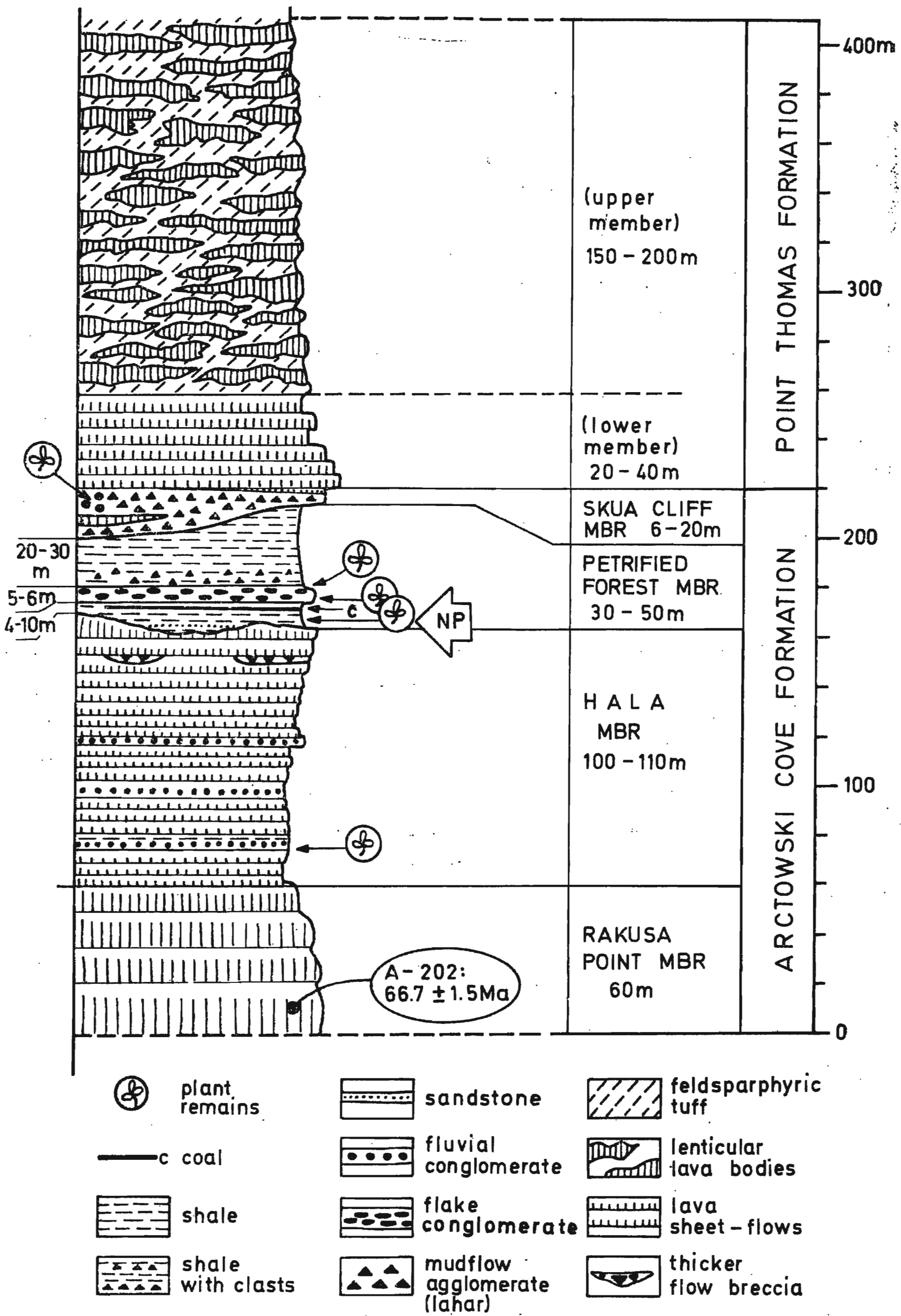


Fig. 6. Lithostratigraphic column of the Ezcurra Inlet Group in the vicinity of Arctowski Station, Admiralty Bay, with position of plant-bearing beds, and K-Ar-dated sample
NP — *Nothofagus*-Pteridophyta pollen-spore assemblages (*see* Fig. 7)

(BIRKENMAJER 1980a; BŁASZYK & GAŹDZICKI 1980). The flora has not been eleborated as yet. An agglomerate 2-5 m thick of debris-flow (lahar) characteristics occurs below the plant-bearing bed of the Zamek Formation.

PALAEOGENE FLORAS OF ADMIRALTY BAY

Several well defined plant-bearing horizons have been recognized in fresh-water volcaniclastic sediment intercalations of the Palaeogene volcanic stratiform complex at Admiralty Bay. There are up to four plant-bearing horizons in the Ezcurra Inlet Group, one in the Dufayel Island Group, and three in the Point Hennequin Group (Fig. 10).

Ezcurra Inlet Group (Fig. 4: *6, 7*). This group includes two formations (Figs 5—6). The lower Arctowski Cove Formation consists mainly of basaltic andesite lava flows, massive and thick in the lower part (Rakusa Point Member), and thinner, often scoriaceous higher up (Hala Member) where between the lavas there appear thin conglomerate and tuff-shale intercalations. The basal lavas (Rakusa Point Member) correspond to a latest Cretaceous resp. Cretaceous/Palaeogene boundary volcanic event: their K-Ar age is 66.7±1.5 Ma (BIRKENMAJER & *al.* 1983c); the succeeding Hala Member lavas and sediments may already belong to Paleocene. Petrified wood fragments have been found in thin, well-rounded conglomerate intercalations in the lower part of the Hala Member.

There follows the Petrified Forest Member maximum 30—50 m thick, consisting of fresh-water sediments filling erosional depression cut into underlying lavas. The sediments consist, in the succession, of: clayshale and tuff-sandstone; clay which yielded pollen-spore assemblages, with a horizon containing petrified wood fragments with annual growth-rings; allochthonous charcoal-type coal layer; tuff-flake conglomerate with petrified wood fragments; top clayshale.

The pollen-spore spectrum from the lower part of the Petrified Forest Member includes 36 types of pollen and spores and represents a *Nothofagus*-Pteridophyta assemblage (STUCHLIK 1981). It suggests the presence of *Nothofagus* forests with well developed undergrowth in which ferns, *i.a.* probably also tree ferns, played the most important role, and the Rhamnaceae were present. The abundance of pteridophyte spores and their high frequencies in the diagram (Fig. 7), generally indicate moist and warm climatic conditions, comparable to those of the present-day frost-free Auckland Province lowlands (STUCHLIK 1981).

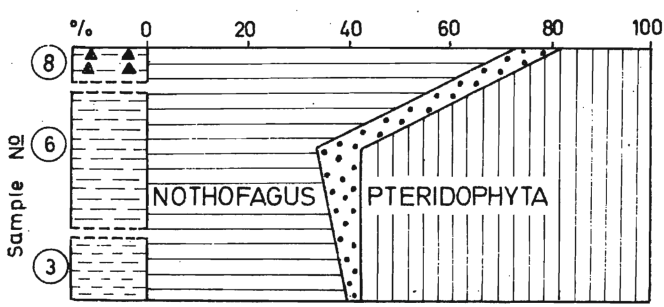


Fig. 7. Pollen diagram showing percentages of *Nothofagus* and Pteridophyta with respect to other pollen grains (*stippled*); Petrified Forest Member, Arctowski Station (*after* STUCHLIK 1981)

The age of the above pollen-spore assemblage by palaeobotanic data should not be older than Late Eocene — Early Oligocene (STUCHLIK 1981). However, the K-Ar dating of the Ezcurra Inlet Group lavas and associatied plugs, suggests a Paleocene or Paleocene/Eocene boundary age of the discussed flora as being more probable (Fig. 10). The radiometric evidence taken into account is the following: (*1*) the andesite plug at Jersak Hills which cuts through the Arctowski Cove Formation has been dated at 42 Ma (Late Eocene) (ELLIOT & *al.*; *fide* PANKHURST & SMELLIE 1983, p. 219); (*2*) the samples of volcanic rocks from the Point Thomas area (Point Thomas Formation lavas?) yielded Early Eocene $^{40}Ar/^{39}Ar$ ages of 48, 51, and 52 Ma (dating by ELLIOT & *al.*; *fide* PANKHURST & SMELLIE 1983 ,p. 219); (*3*) andesite lavas and associated plug (Three Brothers Hill) at Potter Cove, Maxwell Bay, yielded Paleocene-Eocene ages of between 49.1 ± 0.9 and $57.9\pm\pm0.8$ Ma (WATTS 1982; PANKHURST & SMELLIE 1983).

Petrified wood fragments which occur at two levels within the tuff-flake conglomerate of the Petrified Forest Member, deserve special attention: they are the only determined so far wood fragments, belonging to the genus *Araucaria*, and forms intermediate between *Fagus* and *Nothofagus* (CORTEMIGLIA & *al.* 1981). These fragments show the presence of dense annual growth-rings, and are often coated with black coal films or crusts. Finally, some petrified wood fragments have also been found in lahar-type debris-flow agglomerate intercalated by high-Al basalt lava and by fluvial conglomerate (lag-concentrate), attributed to the Skua Cliff Member (Fig 10). The radiometric dating discussed above applies also to these fragments, indicating their age as being close to the Paleocene/Eocene boundary.

The Point Thomas Formation contains only one good plant-fossil locality at Cytadela, Ezcurra Inlet (Fig. 4: *7*), known already to BIBBY (1961) and BARTON (1965). This flora consisting *i.a.* of *Nothofagus* leaf and fern frond imprints preserved in a tuff intercalation between basaltic lavas (BIRKENMAJER 1980a, 1982b, p. 193) is yet to be determined. Its stratigraphic age could be Eocene (Fig. 10).

Dufayel Island Group (Fig. 4: *8*). The lower part of this group, *i.e.* the Gdynia Point Formation, is represented by coarse to very coarse agglomerate and edgewise conglomerate, often of debris-flow (lahar) type. The upper Dalmor Bank Formation consists mainly of tuffaceous rocks with several basaltic andesite lava flows. Plant fossils, known already to BIBBY (1961) and BARTON (1964, 1965), occur in tuff just above the Gdynia Formation agglomerates, at the base of the Dalmor Bank Formation, below a thick basaltic andesite lava (BIRKENMAJER 1980a) which has been dated at 51.9 ± 1.5 Ma K-Ar age, *i.e.* Early Eocene (BIRKENMAJER & *al.* 1983b). Altered and folded andesite lavas of the late Mesozoic Cardozo Cove Group below the basal unconformity at Dufayel Island, yielded a K-Ar age of 56.8 ± 1.2 Ma; these lavas have most certainly been affected by Tertiary reheating which had caused argon loss (BIRKENMAJER & *al.* 1983b, c).

The leaf flora determined from the Dalmor Bank Formation (BIRKENMAJER & ZASTAWNIAK 1985) consists exclusively of angiosperum plants: mostly dicotyledonous but also monocotyledonous ones. The dicotyledonous leaves are represented by the genus *Nothofagus*, moreover aff. *Cochlospermum*, ?Dilleniaceae, „Lauraceae", *Leguminosites* sp., *Tetracera patagonica* BERRY, Myrtaceae, ?Sapindaceae, and others. The majority of dicotyledonous leaves belong to arborescent forms from multispecific broad-leaved forests which at present grow in mild, temperate, or even warm-temperate climatic zones. The presence of *Nothofagus* leaves of *Calucechinus* section indicates cool-temperate elements in the South Shetland Early Tertiary forests. The Dufayel Island flora is most similar to the Fildes Peninsula flora described by ORLANDO (1963, 1964) and attributed to Paleocene-Middle Eocene by ROMERO (1978), moreover to the Seymour Island flora (DUSÉN 1908) of the James Ross Island Basin.

Point Hennequin Group (Fig. 4: *15—17*). There are three plant-bearing horizons within the Point Hennequin Group (Figs 8—9). This group includes two units of formation rank: the lower unit, called the Viéville Glacier Formation, yielded no plant fossils, the upper one called the Mount Wawel Formation, yielded numerous plant remains from three stratigraphic levels (BIRKENMAJER 1981; ZASTAWNIAK 1981; ZASTAWNIAK & *al.* 1985).

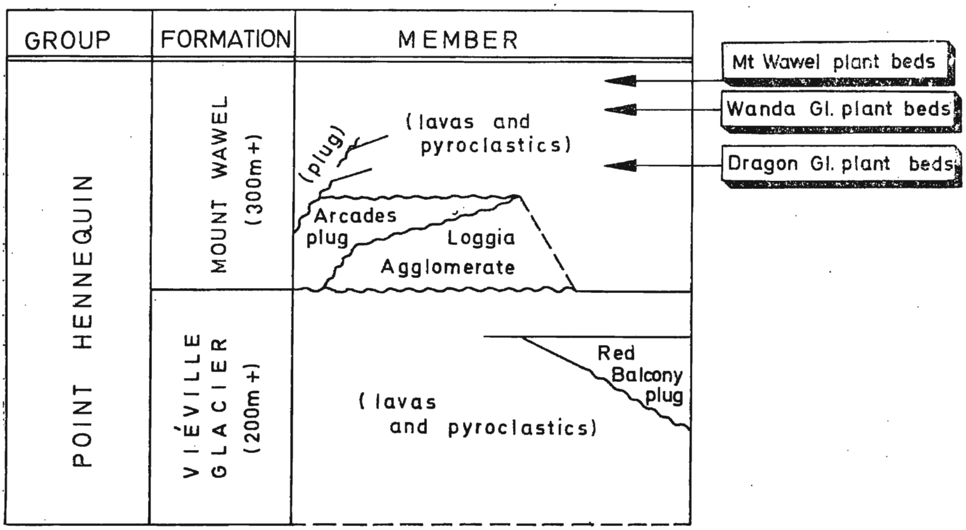


Fig. 8. Stratigraphic position of plant-bearing horizons in lithostratigraphic standard of the Point Hennequin Group

The two lower fossil floras are known exclusively from blocks in the moraines of Dragon Glacier and Wanda Glacier. These blocks derived from two separate horizons (*see* BIRKENMAJER 1981), the Dragon Glacier plant beds (lower), and the Wanda Glacier plant beds (upper). The third and the youngest of all plant-bearing beds of the King George Island Supergroup, has been recognized *in situ* at the top of Mount Wawel (BIRKENMAJER 1982b, p. 193; ZASTAWNIAK & *al.* 1985).

The Dragon Glacier plant beds consist of tuff, shaly siltstone and shale with numerous plant imprints, known already to DIAZ and TERUGGI (1956), BARTON (1961, 1964, 1965), ADIE (1964), and BIRKENMAJER (1980a). According to ZASTAWNIAK (1981), this is a *Nothofagus*-Podocarpaceae assemblage represented by imprints of deciduous leaves, shoots, seeds and fruits of conifers, moreover by infrequent imprints of horsetails and fern fronds. Among Podocarpaceae, the genera *Dacrydium* (*Dacrydioides*), *Acmopyle* and *Stachycarpus*, and among angiosperms — the genera *Nothofagus*, *Roophyllum*, *Rubus* and *Cupania* are characteristic. There occur also silicified wood fragments.

This flora has been compared with Early-Middle Miocene flora of South America (ORLANDO 1963, 1964), the K-Ar dating indicates, however, a Late Oligocene age (*see below*).

The Wanda Glacier plant beds consist of volcanogenic sediment — tuff with agglomerate and pellet-conglomerate intercalations, with plant rootlets, impressions of conifer branches, and fragments of silicified and sideritized wood.

The Mount Wawel plant beds have been recognized *in situ* at the top of Mount Wawel, just above andesite lavas which yielded (Fig. 9) a Late Oligocene K-Ar date of 24.5±0.5 Ma (BIRKENMAJER & *al.* 1983c). The fossil-plant assemblage (ZASTAWNIAK & *al.* 1985) is very similar to that of the Dragon Glacier plant beds: it consists mainly of leaf impressions of the genus *Notho-fagus* (various types), and the conifer family Podocarpaceae, moreover of leaf impressions of aff. Araliaceae and ?Rhamnaceae which are less frequent. In both taphocoenoses (Dragon Glacier and Mount Wawel plant beds), small leaf (microphyll and notophyll) classes are in excess of 95 per cent what corresponds with the values of the recent Australian Temperate (cool and warm) Rain Forest

PALAEOGENE FLORAS OF MAXWELL BAY

The Tertiary floras have long been known from Maxwell Bay, the western part of King George Island. The fossil plants were sampled at Potter Peninsula (Fig. 4: *9*—11), Fildes Peninsula (Fig. 4: *12*) and Ardley Island (Fig. 4: *13*).

Potter Peninsula floras (Fig. 4: *9—11*). There are three plant-fossil localities at Potter Peninsula. The first two are *in situ* in tuffs between andesite lavas at Stranger Point (Fig. 4: *9*), and close to Three Brothers Hill (Fig. 4: *10*). The plants are poorly preserved and so far undetermined. The succession of lavas and tuffs (described in considerable detail by FOURCADE 1960, and GONZÁLEZ-FERRÁN & KATSUI 1970), with red shale, conglomerate and agglomerate intercalations, lithologically resemble most the Baranowski Glacier Group (Llano Point Member; *see* BIRKENMAJER 1982b, p. 192) of Admiralty Bay, where it is of an Upper Cretaceous age (BIRKENMAJER & *al.* 1983c). However, the recent K-Ar dating of andesite lavas of Potter Peninsula, attributed to the Ezcurra Inlet Group by WATTS (1982), gave Paleocene-Eocene ages of considerable scatter: 49.7±1.7 Ma (lower lava), 57.9±0.8 Ma (middle lava), and 49.1±0.8 Ma (upper lava). Taking into account that the andesite plug of Three Brothers Hill which cuts through these lavas, gave according to Watts the age of 50.6±0.7 Ma (Eocene), some reheating of the lavas by plug intrusion, accounting for the scatter of K-Ar dates, may be postulated. The conclusion adopted by BIRKENMAJER & *al.* (1983c, p. 141) was that the volcanic complex of Potter Peninsula might represent a missing link within the Arctowski Cove Formation, between the Hala Member andesites and the high-Al basalts of the Skua Cliff Member and its superstratum (*i.e.* the Point Thomas Formation). The present correlation with the Ezcurra Inlet Group of the type area is shown in Fig. 10.

The third locality is a moraine site north of the Argentine Teniente Jubany Station (*see* FOURCADE 1960, Fig. 28). Numerous deciduous angiosperm leaves and fern fronds occur in tuff fragments lithologically comparable with those of the Zamek Formation (BIRKENMAJER 1982b, p. 192). It has not yet been solved, whether we deal here with a Late Cretaceous or an Early Tertiary plant fossil assemblage.

Fildes Peninsula flora (Fig. 4: *12*). The main plant-fossil locality at Fildes Peninsula (Fig. 4: *12*), designated as "Mount Flora", is situated south of the Chilean Presidente Frei Station. This important locality described by SCHAUER & *al.* (1961), and SCHAUER and FOURCADE (1963, 1964), yielded numerous impressions of ferns, conifers and angiosperm leaves, preliminarily described by ORLANDO (1963, 1964). According to him, the phanerogams consist of *Arthrotaxites ameghinoana* Spegazzini (Gymnospermae *incertae sedis*). *Fitzroya tertiaria* BERRY

(Cupressaceae), *Laurelia insularis* DUSÉN (Monimiaceae), *Lomatia antarctica* ORLANDO, *Lomatia* sp. (Proteaceae), *Myrtiphyllum* cf. *bagualense* DUSÉN (Myrtaceae), *Nectandra prolifica* BERRY (Lauraceae), *Nothofagus densi-nervosa* DUSÉN (Fagaceae), *Rhamnidium* sp. (Rhamnaceae), *Schinopsis* cf. *patagonica* BERRY (Anacardiaceae), *Sterculia washburni* BERRY, *S. patagonica* BERRY (Sterculiaceae), and *Tetracera patagonica* BERRY (Dilleniaceae) — see also ZASTAWNIAK (1981, p. 100). Based on comparison with the Magallanes "beds" of Patagonia, ORLANDO (1963, 1964) assumed a Neogene — boundary of Early and Middle Miocene — age for this flora. According to ROMERO (1978), this flora is of Paleocene-Eocene age, and that age seems to be also suggested by the K-Ar datings of the Fildes Peninsula Group lavas and plugs at Fildes Peninsula (Fig. 10): these lavas range in age between Late Cretaceous and Eocene, while the plugs which cut through these lavas, and probably also through the plant-beds, are of Eocene age (*see also* BIRKENMAJER & *al.* 1983c, Tab. II, Fig. 6; PANKHURST & SMELLIE 1983, Tab. 1).

JAMES ROSS ISLAND BASIN

Upper Cretaceous and Lower Tertiary sediments are well known from the western part of the Weddell Sea adjacent to Antarctic Peninsula (Fig. 1). They have formed in the James Ross Island Basin which includes, *i.a.* Snow Hill Island, Seymour Island, James Ross Island, and Vega Island.

UPPER CRETACEOUS MARINE STRATA

The Upper Cretaceous (Campanian — Maastrichtian) fossiliferous marine sediments of the James Ross Island Basin belong to the Weddellian Province. They are represented by a monotonous sequence of predominantly arenaceous rocks with fossiliferous concretions, called the Marambio Group, including the Campanian (and ?Maastrichtian) Lopez de Bertodano Formation (1067 m thick), and the Maastrichtian (and ?Danian) Sobral Formation (210 m thick) (RINALDI & *al.* 1978; DEL VALLE & MEDINA 1980; ZINSMEISTER 1982). Fine conglomerate intercalations are restricted to the basal part of the Sobral Formation. Carbonized plant detritus and logs, together with poorly preserved molluscs, are locally abundant in large-scale cross-bedded sandstones at the top of the Sobral Formation. The formation yielded sporomorph assemblages (ASKIN & FLEMING 1982), with podocarpaceous pollen predominating, with less common *Nothofagidites* spp. (*fusca* and *brassi* groups), some proteaceous species and pteridophyte spores.

PALAEOGENE FRESH-WATER AND MARINE STRATA

The Palaeogene sediments distinguished as the Seymour Island Group are well exposed at Seymour Island where they are separated by angular unconformity from the Upper Cretaceous (and ?Danian) Marambio Group (ELLIOT & *al.* 1975; RI-

NALDI & *al.* 1978; ELLIOT & TRAUTMAN 1982; ZINSMEISTER 1982). The Seymour Island Group is subdivided into the lower Cross Valley Formation, and the upper La Meseta Formation (ELLIOT & TRAUTMAN 1982).

Paleocene flora. The deltaic Cross Valley Formation (105 m thick) consists mainly of non-marine sandstones and pebbly sandstones (distributary channel fills) with interbedded silt and silty sand. Large coalified logs up to 1 m in diameter are locally abundant near the base of the formation. Numerous plant remains preserved as leaf impressions and coalified plant detritus occur in a higher part of the formation which also yielded pollen spectra indicating a Paleocene age (ELLIOT & TRAUTMAN 1982). A locality at Seymour Island yielded numerous taxons of ferns and phanerogams, mainly angiosperms, in form of leaf impressions (DUSÉN 1908; *see also* remarks *by* ZASTAWNIAK 1981, pp. 99—100). The phanerogams include: *Araucaria imponens* DUSÉN (Araucariaceae), *Caldcluvia mirabilis* DUSÉN (Cunoniaceae), *Drimys antarctica* DUSÉN (Winteraceae), *Ilciphyllum* div. sp. (Aquifoliaceae), *Knightia andreae* DUSÉN (Proteaceae), *Laurelia insularis* DUSÉN (Monimiaceae), *Lauriphyllum nordenskjoeldi* DUSÉN (Lauraceae), *Leguminosites* div. sp. (Leguminosae), *Lomatia angustiloba* DUSÉN, *L. brevipinna* DUSÉN, *L. serrulata* DUSÉN, *L. seymourensis* DUSÉN (Proteaceae), *Miconiiphyllum australe* DUSÉN (Melastomataceae), *Mollinedia seymourensis* DUSÉN (Monimiaceae), *Myrica nordenskjoeldi* DUSÉN (Myricaceae), *Myrtiphyllum* cf. *baguelense* DUSÉN (Myrtaceae), *Nothofagus dicksoni* (DUSÉN) van STEENIS, *N. magellanica* ENGELHARDT, *N. obscura* (DUSÉN) van STEENIS, and *N. pulchra* DUSÉN (Fagaceae).

A coal seam about 1 m thick, containing coalified logs, recently discovered in the upper part of the Cross Valley Formation, yielded abundant, well preserved pollen grains and rare fern spores. The assemblage is dominated by podocarpaceous pollen, mainly *Phyllocladidites* spp., and also contains angiosperm pollen, including *Nothofagidites* spp., proteaceous species and a tricolpate species (FLEMING & ASKIN 1982; ASKIN & FLEMING 1982).

Eocene to ?Oligocene marine strata. The La Meseta Formation (at least 450 m thick) consists of unconsolidated marine sands with shell banks. facially corresponding to delta-shelf slope (unit *I*), tide-dominated environment (unit *II*), and lagoonal environment (unit *III*). Abundant marine fossils dominated by bivalves and gastropods (*e.g.*, ELLIOT & *al.* 1975; RINALDI & *al.* 1978; WELTON & ZINSMEISTER 1980; ELLIOT & TRAUTMAN 1982; ZINSMEISTER 1982) indicate the ?Middle through Upper Eocene to ?Lower Oligocene ages of the formation. Besides molluscs, the formation yielded also shark teeth, vertebrae and teeth of teleost fish, reptile remains (*i.a.* turtle bones), bird remains (including penguins), sparse remains of large (probably marine) placental and, just recently, a jaw of primitive marsupial belonging to the extinct family Polydolopidae; most of the bones have been found in a beach-type setting at the top of the La Meseta Formation (WOODBURNE & ZINSMEISTER 1982). A faunal hiatus corresponding to Early Eocene is accepted at the base of the formation.

The formation contains also coarser material in form of conglomerates with well-rounded gravel consisting of igneous, metamorphic and sedimentary pebbles of Antarctic Peninsula characteristics. They are regarded to be storm-lag gravels.

SUMMARY OF PALAEOCLIMATIC EVIDENCE: LATE CRETACEOUS AND PALAEOGENE

LATE CRETACEOUS CLIMATE

TERRESTRIAL ENVIRONMENTS

The palaeoclimatic evidence from the Late Cretaceous terrestrial environments of the South Shetland Islands falls into two main categories: (*1*) palaeobotanic; (*2*) sedimentological-pedological.

Palaeobotanic evidence. The Late Cretaceous plant assemblages known mainly from terrestrial deposits of the South Shetland Islands, consist of silicified logs, deciduous-tree leaf (*Nothofagus*), conifer and fern imprints. The fossil flora is still too poorly known to allow a more detailed characteristics of the Late Cretaceous palaeoclimate of the Antarctic Peninsula sector. The presence of dense annual growth-rings in petrified wood fragments indicates a climate with warmer summer and cooler winter seasons. The vegetation cover was probably sparse due to semi-desert conditions, and no coal beds have formed.

Sedimentological-pedological evidence. The sedimentological evidence points to the presence of two distinctly contrasting terrestrial palaeoenvironments characterized by: (*a*) ephemeral fluvial and limnic facies; (*b*) catastrophic debris-flow facies.

The fluvial and limnic environments were widespread at the beginning of the Late Cretaceous, being however restricted areally to foothills and depressions between larger stratovolcanoes. Ephemeral systems of immature, probably braided rivers supplied sand-grade volcaniclastic material which accumulated as sparse bars and/or levees; lag concentrates with well-rounded pebbles and cobbles which formed in distributary channels, played insignificant role. The clayshales formed either in shallow pools or as overbank deposits during heavier rainfalls, farther off volcanic cones. The red colouration of clayshales, sandstones and conglomerates indicates intense, lateritic-type weathering of volcanic covers. This warm climate evidence is also supported by the presence of silicified wood fragments.

Several regolithic (palaeosol) surfaces have been recognized in the lava sequence of the Llano Point Formation (Baranowski Glacier Group: Maastrichtian); they are devoid of rootlets.

In the uppermost part of the Upper Cretaceous sequence, there appears a characteristic coarse agglomerate (Zamek Formation) interpreted as debris-flow deposit of lahar type. It is assumed that this is a catastrophic-type sediment that originated due to melting, triggered by eruption, of snow or ice cap on top of a stratovolcano, in fast-flowing stone avalanche regime. Compared with Tierra del Fuego, where snowline rises to 3500—4000 feet (about 1060—1220 m) and *Nothofagus*-forest timberline reaches 1400—1500 feet (about 430—450 m) above the sea (DARWIN 1845), we could suggest such values as minimal ones for the South Shetland Islands volcanoes during the Late Cretaceous.

MARINE ENVIRONMENT

The palaeoclimate evidence from the Upper Cretaceous marine sediments of the James Ross Island Basin is rather inconclusive, as no palaeoenvironmental and palaeotemperature studies of marine fossils of the Marambio Group have been made. Lack of ice-rafted material in the whole Marambio Group is an evidence against glacial climate in the Antarctic Peninsula sector.

CONCLUSION

The conclusion of the above discussion is that the Late Cretaceous climate of the Antarctic Peninsula sector was: (*i*) generally warm, differentiated into warmer (summer) and cooler (winter) seasons; (*ii*) rather dry, continental, deficient in precipitation, thus not supporting any extensive vegetation cover and permanent river systems; (*iii*) with snow or ice caps localized on tops of higher volcanoes, probably at more than 1000 m above the sea, which appeared towards the close of the Late Cretaceous time.

PALAEOGENE CLIMATE

TERRESTRIAL ENVIRONMENTS

The palaeoclimatic evidence from Palaeogene terrestrial environments of the South Shetland Islands and the James Ross Island Basin areas, falls into three categories: (*1*) palaeobotanic; (*2*) palaeozoologic; (*3*) sedimentological-pedological.

Palaeobotanic evidence. There is a good palaeobotanic evidence indicating that the continental areas of the Antarctic Peninsula sector were densely overgrown with vegetation already since the Paleocene. The vegetation cover was persistent through Eocene and Oligocene, up to the latest Oligocene inclusively.

The present state of knowledge of fossil floras from King George Island and Seymour Island, does not allow to discriminate between stratigraphic and environmental differentiation of plant assemblages. The taphocoenoses described may represent accumulations of plant remains from different altitudes and environmental settings: *e.g.* the *Nothofagus*-Podocarpaceae forests with sparser undergrowth in higher parts of volcanic slopes, and the *Nothofagus* forests with tree ferns, rich in pteridophyte undergrowth — in lower parts of slopes and wet gorges on slopes of volcanoes, etc. Generally, these plants indicate a climate richer in precipitation than during the Late Cretaceous times, however similarly differentiated into warmer-temperate and cooler yearly seasons as shown by annual growth-rings recognisable in most of petrified wood fragments and logs.

Palaeozoologic evidence. The occurrence of primitive marsupial remains on Seymour Island, in the Upper Eocene (or ?Lower Oligocene) beach-type sedliment, together with turtle bone fragments, may be an evidence for warm climate. Palaeoclimatic significance of large fossil penguins recorded from the same strata is unknown.

Isolated bird-type footprints and trackways known from a higher part of the Fildes Peninsula Group (probably Paleocene — Eocene) which also yielded an important plant-fossil assemblage (Fildes Peninsula flora; *see above*), give a limited palaeoecological-palaeoclimatic information. Three morphotypes have been described (COVACEVICH & LAMPEREIN 1972; COVACEVICH & RICH 1982). The first morphotype attributed to a large nonvolant ground bird, probably ratite or phororhacoid, indicates good landbridge connections between King George Island and continental areas of Antarctica, along dry land Early Palaeogene dispersal route: South America — Antarctica — Australia. The presence of such birds in the Antarctic Peninsula sector suggests warm climatic conditions, as is also evident from the Fildes Peninsula flora. Two other morphotypes of bird-type footprints and trackways correspond to anatid birds, and to any type of avian groups respectively.

Sedimentological evidence. Three contrasting terrestrial environments may be distinguished, including ephemeral pools, ephemeral immature river systems, and catastrophic debris-flow regime. These Palaeogene environments differ from the Late Cretaceous ones in another type of weathering. Contrary to the Late Cretaceous ones, the Palaeogene sediments are rarely red, but mainly grey, grey-brown and drab, indicating a non-lateritic, rather kaolinitic-illitic weathering conditions. This could be a result of climate change towards warm-temperate and temperate one, along with increase in rainfall that caused vast expansion of vegetation cover. Carbon-enriched clays have sometimes been formed, and even thin coal seams accumulated. The coal seam investigated at Admiralty Bay seems to be a result of charcoal redeposition after a fire ignited by volcanic eruption or lightning. Much thicker coal seam from Seymour Island containing carbonized logs, seems to be also allochthonous in character.

Accumulation of varved tuff, clay and shale with leaf imprints (best represented in the Dragon Glacier plant beds) took place in shallow ephemeral pools at the foot of a volcano. Flake conglomerates which occur in clayey deposits (*e.g.* Petrified Forest Member) originated from fragmented tuff transported by running water in seasonal creeks, eventually deposited at their outlets. Thin well-rounded conglomerate intercalations between lava flows (*e.g.* in the Hala Member), and in marginal parts of lahar-type debris-flow agglomerates (Skua Cliff Member), are evidences of channel-lag concentrates that formed in intermittent streams.

Petrified wood fragments are as frequent, or even more numerous, than in the Upper Cretaceous terrestrial deposits. Besides silicified logs, we may often find sideritized and limonitized wood fragments, with or without coal films or crusts. It is also of interest to note that carbonized fruits and seeds appear here for the first time towards the close of the Palaeogene sequence.

Regolithic, often reddened, surfaces are particularly common in the Arctowski Cove and the Point Thomas Formations of the Ezcurra Inlet Group (BIRKENMAJER 1980a). Palaeosols are however thin and poorly developed, infrequently showing the presence of carbonized plant rootlets.

Lahar-type agglomerates are abundant in the Dufayel Island and the Ezcurra Inlet groups of Eocene age, but do occur also in the Fildes Peninsula Group (Fig. 10). The best example of a lahar is demonstrated by the Skua Cliff Member agglomerate. Such agglomerates are suggestive of the presence of ice-caps on tops of stratocones. Lahar-type agglomerates have not been recognized in the Oligocene part of the succession (Point Hennequin Group).

MARINE ENVIRONMENT

There is no indication of marine environment from the South Shetland Islands Palaeogene. In the James Ross Island Basin, the terrestrial Paleocene clastics interpreted as distributary channel fill, interbedded with plant-bearing (and coal-bearing) silt and silty sand (Cross Valley Formation), are covered (with a sedimentary break in Lower Eocene) by a shallow-marine sequence of Middle-Upper Eocene and Lower Oligocene ages (La Meseta Formation). The sedimentological character of the latter, points to a near-shore environment, changing with time from delta-shelf slope, through tide-dominated bay, to restricted lagoonal basin. Abundance of shell banks indicate favourable conditions for shallow-marine bottom fauna. There are no palaeotemperature and palaeocological studies available so far from the discussed strata. Rich and diversified, often thick-shelled bottom mollusc fauna may indicate seawater temperatures as higher than at present.

There is no indication in the published accounts of any material of glacial origin in the whole Seymour Island Group. Contemporaneous volcanic material in the form of clasts, glass shards and pumice fragments occurs in the Cross Valley Formation, but none of these have been explained as ice-rafted. Conglomerates with well rounded gravel consisting of igneous, metamorphic and sedimentary pebbles of Antarctic Peninsula characteristics, are regarded to be storm-lag gravels (ELLIOT & TRAUTMAN 1982).

CONCLUSION

The data discussed characterize the Palaeogene climate of the South Shetland — Antarctic Peninsula — James Ross Island sector of West Antarctica as: (*i*) warm to temperate, differentiated into warmer (summer) and cooler (winter) seasons; (*ii*) rather rich in precipitation what caused development of extensive vegetation cover, and local accumulation of coal beds, moreover restricted river delta systems (Seymour Island — at the foot of the Antarctic Peninsula mountain range; elsewhere — in the South Shetlands — there is an indication of unstable primitive river system only); (*iii*) supporting snow or ice-caps on tops of higher stratocones, mainly during the Eocene.

EVIDENCES OF NEOGENE GLACIATIONS

There are numerous evidences of continental glaciations (ice-sheets) in Antarctica during the Miocene. A glaciated pavement of Miocene age was reported from the Jones Mountains, Ellsworth Land (CRADDOCK & *al.* 1964; RUTFORD & *al.* 1968, 1972). The *DSDP* cores suggest that the maximum West Antarctic glaciation occurred during the latest Miocene and Early Pliocene times, with grounded ice-shelf near the Miocene/Pliocene boundary (KENNETT & *al.* 1975; CRADDOCK & HOLLISTER 1976; KENNETT 1977, 1978; KEANY 1978). The *DSDP* cores at Sites Nos 325 and 324, on the continental rise off Antarctic Peninsula (No 325), and off Ellsworth Land (No 324), showed ice-rafted debris mainly during the Late Miocene — Pliocene interval, the oldest beds with such debris were of Early or Middle Miocene age (HOLLISTER & CRADDOCK 1974, 1976; CRADDOCK & HOLLISTER 1976). According to KENNETT (1977) the East Antarctic ice-cap has been a semi-permanent feature since Middle Miocene.

SOUTH SHETLAND ISLANDS

The South Shetland evidence for the Neogene glaciation in Antarctica comes from King George Island (BIRKENMAJER 1980b—e, 1982a—d, 1983, 1984; BIRKENMAJER & *al.* 1983a; TOKARSKI & *al.* 1981; PAULO & TOKARSKI 1982). The character of sediments and the succession of deposits are already known in considerable detail, the palaeontological studies are in fast progress, however the stratigraphic dating including palaeontological and radiometric data of the whole diversified succession, are far from being completed. The glacigenic succession of King George Island provides clues for reconstruction of palaeoclimatic history of the Antarctic Peninsula sector, and evolution of Pacific margin of West Antarctica during the Neogene.

It was possible to elaborate lithostratigraphic standards for major tillite-bearing successions, corresponding to three glacial periods, namely the Melville Glaciation, the Polonez Glaciation, and the Legru Glaciation. An interglacial epoch between the latter two glaciations, called the Wesele Interglacial has been also distinguished.

MELVILLE GLACIATION

The first Tertiary sediments genetically related to Antarctic continental ice-cap occur (*see* Fig. 11) in the area of Cape Melville, easternmost part of King George Island (BIRKENMAJER 1982b, c, d, 1984). They belong to the Moby Dick Group which includes three formations: the Sherratt Bay Formation (lower), the Destruction Bay Formation (middle), and the Cape Melville Formation (upper). These formations are crossed by two generations of andesitic and basaltic dykes.

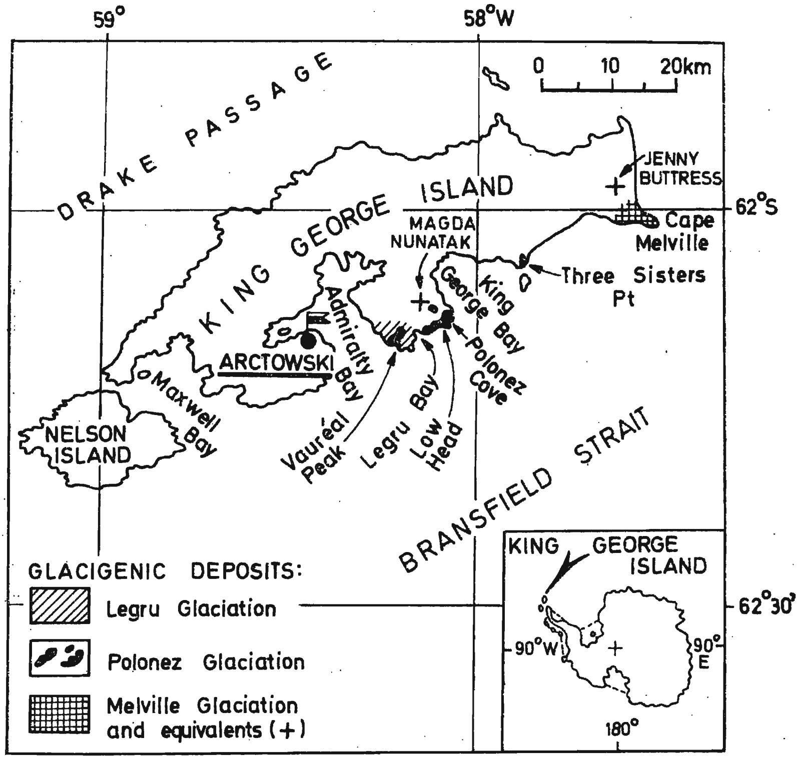


Fig. 11. Distribution of Neogene glaciogenic deposits in King George Island; inset shows position of King George Island in Antarctica

The Sherratt Bay Formation consists of olivine-augite basalts (leucobasalts) representing top part of a terrestrial plateau-basalt sheet more than 60 m thick. The lava was subject to alterations (zeolitisation) by hydrothermal solutions, and by subsequent weathering. The K-Ar date of $>17.4^{+0.2}_{-0.8}$ Ma determines the minimum age of the basalts (BIRKENMAJER & *al.* 1985a); the stratigraphic age of these effusives may be either Palaeogene or Late Cretaceous.

A stratigraphic hiatus has been recognized between the Sherratt Bay basalts and the overlying fossiliferous Miocene formations. Strong weathering of the upper part of the basalt lava pile could have occurred under climatic conditions much warmer than at present.

The Destruction Bay Formation (40—110 m thick) is developed best in the western part of the Melville Peninsula; it wedges out towards the east. The formation consists of reworked basaltic material from the underlying Sherratt Bay Formation, tuffaceous and psammitic rocks showing large-scale cross-bedding, with horizons rich in marine invertebrates. The fossils include *in situ* bivalves, gastropods, solitary corals and brachiopods. There occur also recycled Cretaceous belemnites. The brachiopods are represented by several species of the genera *Discinisca*, *Pachymagas*, *Neothyris*, *Rhizothyris*, *Magellania* and *?Magella*, analogous to those of the Early Miocene assemblages of New Zealand (BIERNAT & *al.* 1985). Recycled Late Cretaceous coccoliths and single Tertiary discoasters have been found (DUDZIAK 1984; BIRKENMAJER 1984).

The sediments of the Destruction Bay Formation formed in a shallow-neritic marginal shelf zone of the Pacific Ocean. Infrequent conglomerate intercalations contain material of Antarctic continent characteristics. The pebbles do not show any glacial striae or other indications of glacial transport, and cannot be treated as dropstones resulting from iceberg-rafting. The occurrence of recycled Cretaceous belemnites and coccoliths probably indicates the proximity of Upper Mesozoic marine sediment exposures. Fragments of carbonized wood that occur in estuarine-type deposits of the Destruction Bay Formation may be an evidence for forest cover in West Antarctica as late as Early Miocene. A possibility cannot be however excluded, that these fragments represent driftwood of distant origin.

The Cape Melville Formation (about 200 m thick) is represented by glacio-marine sediments: grey to greenish, brownish and black clayshales and silty shales, with subordinate intercalations of siltstones and fine-grained sandstones, sometimes also thin marls. The formation often begins with basal sandy conglomerate unconformable upon either the Destruction Bay or the Sherratt Bay formations. Numerous, usually angular erratics up to 2 m in diameter, randomly distributed in the clayey sediment, represent iceberg-rafted dropstones derived from the Antarctic continent (mainly Antarctic Peninsula, but also Ellsworth Mountains and Pensacola-Theron Mountains). They often show glacial striae and glacially polished facets, and give a good evidence for continental ice-sheet in Antarctica et sea level, called the Melville Glaciation (BIRKENMAJER 1982b, c, 1984).

The Cape Melville Formation is very rich in well preserved invertebrate marine fossils (BIRKENMAJER 1982b, c, 1984; GAŹDZICKI & WRONA 1982a, b;

BIRKENMAJER & *al.* 1983a; SZANIAWSKI & *al.* 1983): solitary corals, polychaetes, bivalves, gastropods, scaphopods, crabs (and their feeding burrows), echinoids, asteroids, ophiuroids, all of which represent the Tertiary element *in situ.* There are also fish fragments. Microorganisms are represented by numerous benthic calcareous and arenaceous foraminifera, diatoms, chrysomonad cysts, silicoflagellates, and sponge spicules. A part of these microorganisms may represent recycled Cretaceous element. Damaged calcareous nannoplankton consists exclusively of recycled Cretaceous coccoliths (DUDZIAK 1984; BIRKENMAJER 1984). There are also numerous recycled Cretaceous belemnites.

Stratigraphically the youngest faunal elements indicate a Tertiary age of the formation; the early stage of elaboration of the fossil collection does not allow to determine the age of the formation with much precision. The K-Ar dating of the first-generation andesite dykes that cut through the Cape Melville Formation and their substratum (BIRKENMAJER & *al.* 1985a) gave good Early Miocene dates of $20^{+0.2}_{-0.3}$ and $19.7^{+0.2}_{-0.3}$ Ma. This dating, together with Early Miocene brachiopod stratigraphic evidence from the underlying Destruction Bay Formation, supports the Lower Miocene age of the Cape Melville Formation, and the Melville Glaciation as well (Fig. 14).

An isolated occurrence of glacio-marine sediments (see Figs 11 and 14) has been recognized at Magda Nunatak, King George Bay (TOKARSKI & *al.* 1981; BIRKENMAJER & *al.* 1985b). These sediments yielded Tertiary bivalves and scaphopods (PUGACZEWSKA 1984), recycled Cretaceous coccoliths, and poorly preserved Tertiary discoasters (DUDZIAK 1984; BIRKENMAJER, 1984). The rocks lithologically resemble more those of the Cape Melville Formation than the Polonez Cove Formation and, consequently, have been included into the Moby Dick Group (Fig. 14). However, in the lack of radiometric dating of the overlying basaltic lavas and hyaloclastites, their ?Mid-Late Miocene age is hypothetical.

POLONEZ GLACIATION

Terrestrial tillites, lodgement-type tills and glacifluvial deposits, are well exposed in cliff sections between King George Bay and Admiralty Bay, mainly at Polonez Cove (Fig. 11). These deposits are considered to be an evidence of the Polonez Glaciation, probably the largest Cenozoic glaciation of Antarctica (BIRKENMAJER 1980b—e, 1982a, 1983).

The Polonez Cove Formation rests upon an effusive complex of the Mazurek Point Formation, developed either as basaltic lavas (type area) or as a sequence of basaltic and andesitic lavas with intercalations of tuffs — in the Turrett Point — Three Sisters Point area (PAULO & TOKARSKI 1982). An imprint of undeterminable leaf has been found in the tuffs. The K-Ar dating of the basalts at the type locality Mazurek Point, gave a Late Cretaceous date 74^{+1}_{-7} Ma (BIRKENMAJER, GAŹDZICKI, KREUZER & MÜLLER 1985). This indicates a long hiatus between the effusives (Upper Cretaceous) and the overlying glacial tills (supposedly Early Pliocene). Strong weathering of basaltic lava sheet in its uppermost part, just below glacigenic deposits, best visible at Polonez Cove, may be attributed to Palaeogene.

The upper part of the Mazurek Point lavas is often gouged in rather deep erosional furrows and depressions filled with glacifluvial-type till (BIRKENMAJER 1980d, 1982a). Roches moutonnées and glacial grooves occur only in case of hard basaltic substratum under bottom moraine of the Polonez Glaciation at Three Sisters Point (TOKARSKI & *al.* 1981; PAULO & TOKARSKI 1982); they are however missing in the area of Polonez Cove where the basaltic substratum is strongly weathered and soft (BIRKENMAJER 1980d, 1982a).

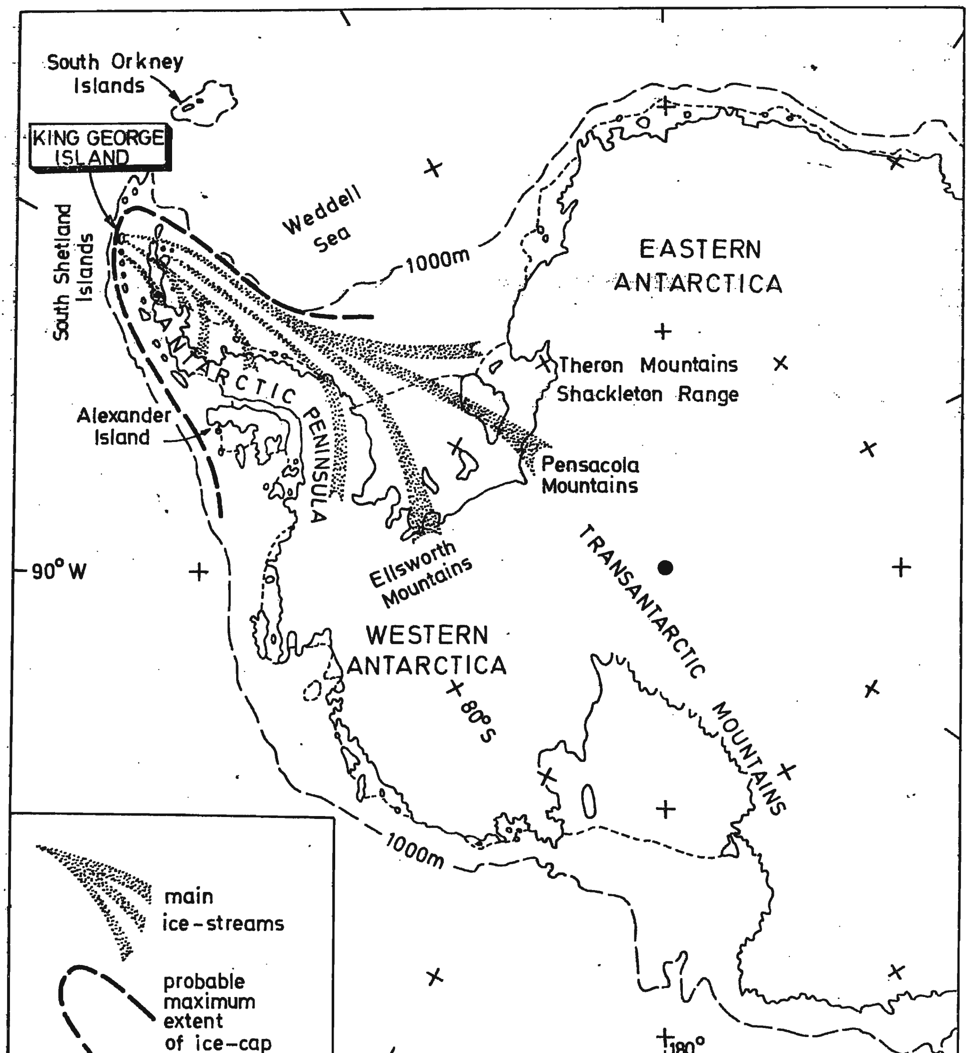


Fig. 12. Maximum extension of ice-cap during the Polonez Glaciation in West Antarctica: the Krakowiak Stage

The basal tillites distinguished as the Krakowiak Glacier Member, are developed as lodgement-till and glacifluvial deposits. The lodgement till is a massive mixtite with mainly angular blocks up to 2 m in diameter, showing no preferred orientation, sorting or grading. The glacifluvial deposits are represented by rather chaotically large-scale cross-bedded mixtite, with angular or poorly rounded blocks up to 2 m in diameter. The clastic fragments are poorly sorted and slightly oriented parallel to cross-sets. The erratic material, both in lodgement-till and glacifluvial tillites, is mainly of Antarctic continent provenance: it indicates the source areas in the Antarctic Peninsula, the Ellsworth Mountains and the Pensacola-Theron Mountains (BIRKENMAJER 1980d, 1982a); BIRKENMAJER & WIESER 1985). The local material from the South Shetland Islands is subordinate (*see* Fig. 12).

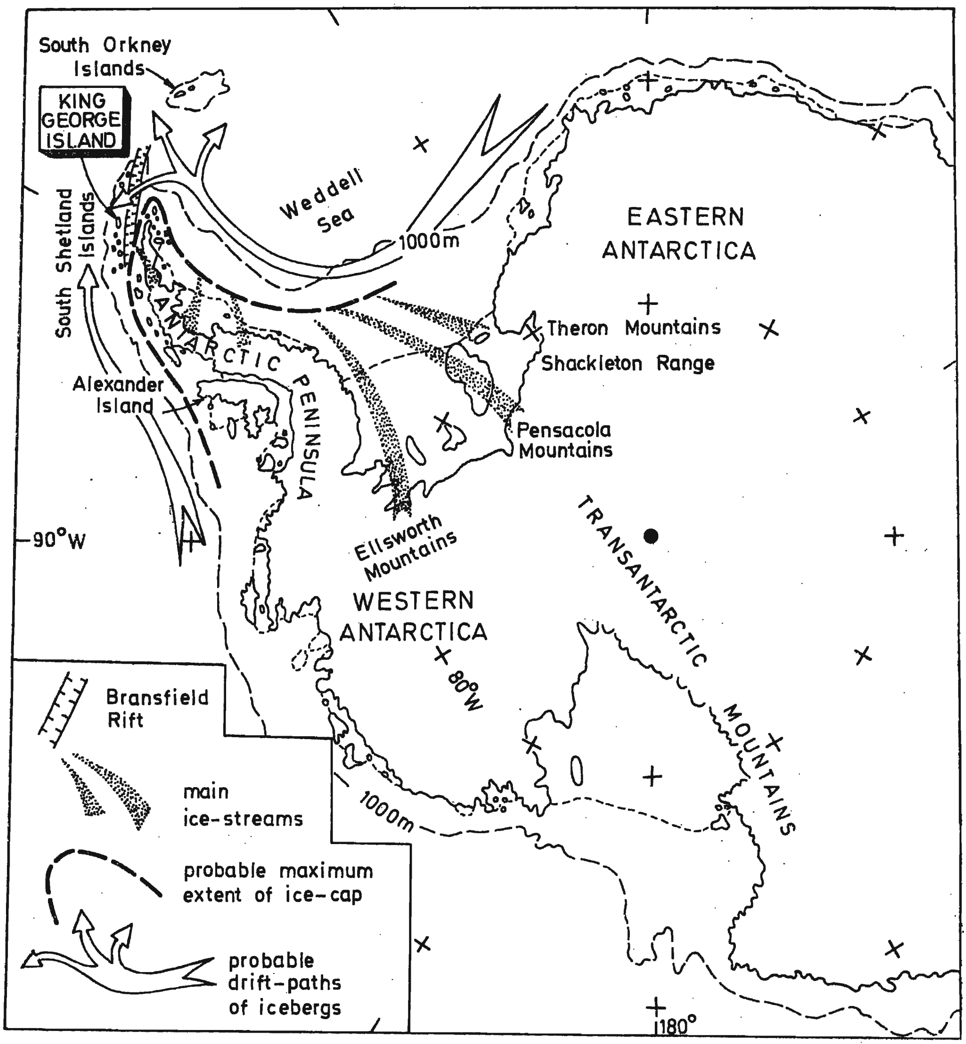


Fig. 13. Extent of the Polonez Glaciation in West Antarctica: the recession stage (Low Head through Oberek Cliff members time)

Glacial striae and glacially polished surfaces (faceted boulders) may often be recognized on erratic blocks.

There follow glacio-marine sediments resting either upon basal tillites or directly upon basaltic substratum. They begin with basaltic conglomerate containing lenticular coquinas with *Myochlamys anderssoni* (Hennig) (Low Head Member); fine-grained sandstones, siltstones and shales (Siklawa Member) occur in the middle, and large-scale cross-bedded regressive conglomerates and sandstones (Oberek Cliff Member) terminate the Polonez Cove Formation (Fig. 14). Besides local basaltic material, there occur frequent iceberg-rafted dropstones up to 1.5 m in diameter distributed at random within the sediment. The dropstones often reveal glacial striae and glacially polished surfaces (faceted boulders). The erratic spectrum is very similar to that of the basal tills, and the supposed source areas are recognizable (*see* Fig. 13).

The glacio-marine sediments of the Polonez Cove Formation are highly fossiliferous. They contain (BŁASZYK & GAŹDZICKI 1980; GAŹDZICKI 1982, 1984; GAŹDZICKI & WRONA 1982; GAŹDZICKI & PUGACZEWSKA 1984; BITNER & PISERA 1984; JESIONEK-SZYMAŃSKA 1984; SZANIAWSKI & *al.* 1983): Tertiary discoasters, diatoms, chrysomonad cysts, rare planktonic foraminifera, numerous benthonic foraminifera, tube worms, numerous bryozoans, infrequent brachiopods, numerous bivalves with dominating *Myochlamys anderssoni* (HENNIG), moreover gastropods, crinoids, ophiuroids and echinoids. This assemblage generally corresponds to the so-called "*Pecten* conglomerate" fauna first described by ANDERSSON (1906) from Cockburn Island (James Ross Island Basin), and originally attributed to the Pliocene. This is a faunal assemblage different from those of the Destruction Bay and the Cape Melville formations, devoid also of recycled Cretaceous fossils. It is hoped that further studies on nannoplankton and foraminifera will help determine the stratigraphic age of these sediments with more precision. The K-Ar dating of overlying acidic lavas is in progress.

The Polonez Glaciation was correlated (BIRKENMAJER 1980d, 1982a) with the Queen Maud Glaciation (?Early Pliocene) of the Transantarctic Mountains sector dated at more than 4.2 Ma (MAYEWSKI 1975).

WESELE INTERGLACIAL

Dacite and quartz-andesite porphyritic lavas and pyroclastics (Boy Point Formation) overlie (*see* Fig. 14) glacio-marine sediments of the Polonez Cove Formation. The lavas are in turn covered by coarse conglomerates, agglomerates and coarse arkosic psammites (Wesele Cove Formation), consisting mainly of angular fragments from the underlying volcanics. They show large-scale cross-bedding and contain thin intercalations of rather well-rounded lag concentrates of fluvial distributary channel character. These clastic sediments fill a buried valley deeply incised in underlying lavas. The valley and its fill had formed during a non-glacial climatic epoch comparable with interglacial. The cross-bedded sediments may be regarded as deposited by fast-flowing, probably braided streams and by debris-flow or debris-avalanches (BIRKENMAJER 1980d, 1982a, 1983).

Characteristic position of the Wesele Interglacial between two glaciations: the supposedly Early Pliocene Polonez Glaciation, and the probably Late Pliocene (and ?Early Pleistocene) Legru Glaciation (Fig. 14), suggests the correlation with the Scallop Hill Interglacial of the Ross Sea ector, dated at 2.5 — 3.7 Ma (BULL & WEBB 1973).

LEGRU GLACIATION

The Legru Bay Group (about 300 m thick) consists of andesitic, subordinately also basaltic lavas and pyroclastics, alternating with coarse agglomerates of lahar characteristics. The whole complex had formed under conditions of glacial climate, probably during the Late Pliocene or at the boundary of Pliocene and Pleistocene,

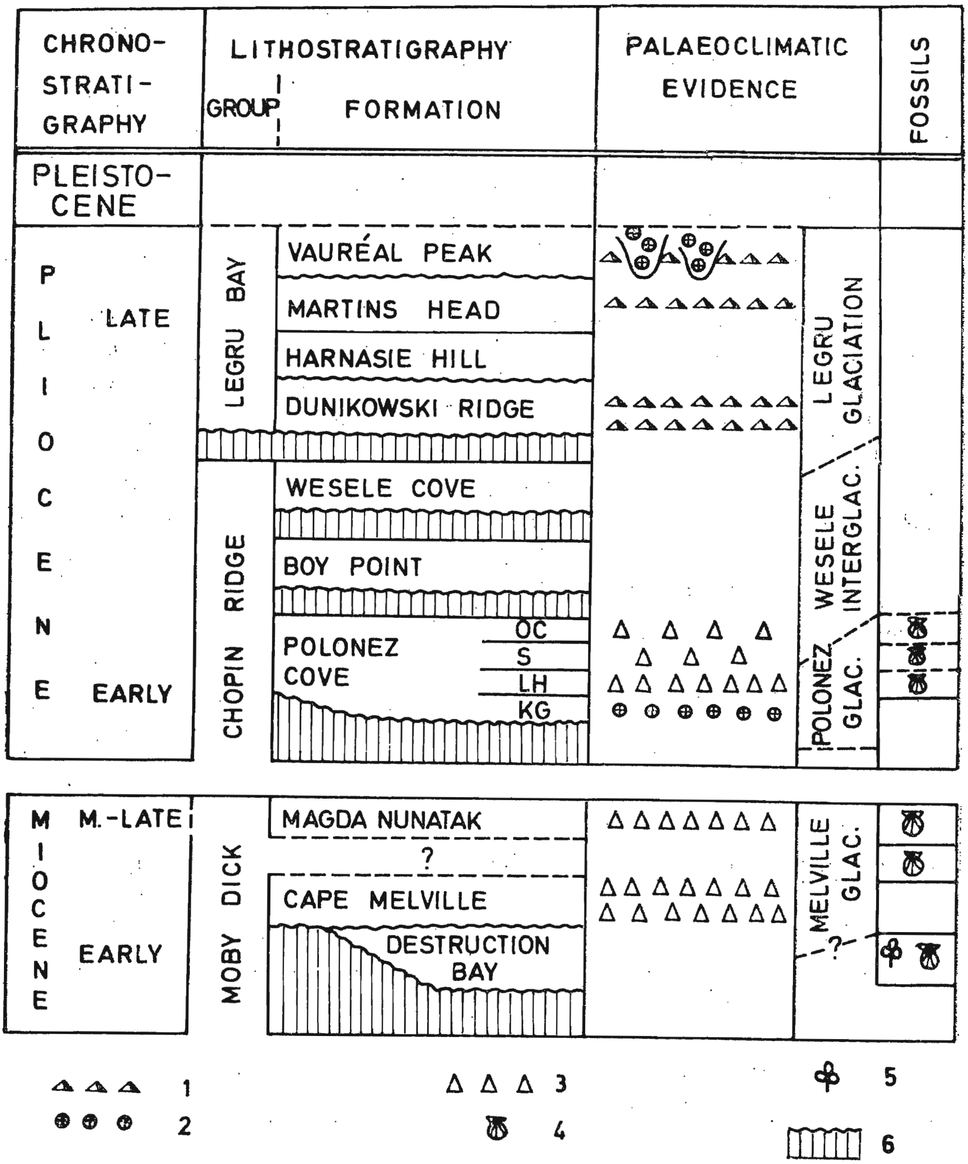


Fig. 14. Palaeoclimatic evidence in Late Tertiary sequences of King George Island
1 lahars; 2 terrestrial tillites; 3 marine tillites; 4 marine fauna; 5 terrestrial flora; 6 hiatus and unconformity

during a glacial epoch called the Legru Glaciation (BIRKENMAJER 1980d, 1982a, 1983). This glaciation has preliminarily been correlated with the Scott Glaciation of the Transantarctic Mountains sector, dated at 2.1—2.4 Ma (MAYEWSKI 1975).

The stratiform complex of the Legru Bay Group is deeply dissected by *U*-shaped valleys which radiate from a palaeoglacial centre at Mount Mariacki (between Admiralty Bay and Legru Bay). These buried valleys are filled by coarse, strongly diagenesized tillite containing andesite lava blocks of local origin. Fossil ice-wedges, and frost cracks in larger blocks healed by quick sand formed due to melting of till and injected into the cracks, may be considered the evidences for palaeoperiglacial zone at the close of the Legru Glaciation.

The Legru Glaciation was an insular-type ice-sheet of the South-Shetland archipelago, separated from the main continental ice-cap of Antarctica by the Bransfield Strait.

JAMES ROSS ISLAND BASIN

Evidences of Neogene glacial climates from the area of the James Ross Island Basin, are scarce and poorly known. As already mentioned, the "*Pecten* conglomerate" of Cockburn Island (ANDERSSON'S 1906, locality), may correlate with the Polonez Cove glacio-marine deposits of King George Island (BIRKENMAJER 1908d, 1982a). Biotite-granite and gneiss fragments reported from the Cockburn Island conglomerate by ANDERSSON (1906), but not found by ZINSMEISTER and WEBB (1982), may have been ice-rafted dropstones (BIRKENMAJER 1980d). According to ZINSMEISTER & WEBB (1982), the "*Pecten* conglomerate" at Cockburn Island can be no older than about 6 Ma.

High-altitude erratic blocks at Seymour Island, attributed to Late Tertiary and Quaternary glaciations, have been reported by ELLIOT & *al.* (1975). No more detailed information is available.

FINAL REMARK

The present state of knowledge leaves unresolved many problems, *e.g.*: the course of glaciation-deglaciation during Mid-Late Miocene times; the relation of the Polonez Glaciation to the Melville Glaciation; the ages of the Polonez and Legru Glaciations, and the Wesele Interglacial. The Polonez Glaciation, as based on evidence from the South Shetland Islands, was the largest Cenozoic glaciation in the Antarctic Peninsula sector, possibly also in the whole Antarctic. Its supposedly Early Pliocene age could correspond to the maximum extension of Antarctic ice-cap at the Miocene/Pliocene boundary, as suggested by deep-sea cores.

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POCZĄTEK TRZECIORZĘDOWEGO ZLODOWACENIA KONTYNENTALNEGO W SEKTORZE PÓŁWYSPU ANTARKTYCZNEGO (ANTARKTYKA ZACHODNIA)

(Streszczenie)

W rejonie Półwyspu Antarktycznego (Antarktyka Zachodnia)* panował z końcem kredy klimat raczej ciepły i suchy, z wyraźnie zaznaczonymi porami roku, co obserwuje się w postaci rocznych przyrostów na kopalnych pniach. Pokrywa roślinności była prawdopodobnie nieciągła z uwagi na niewielką ilość opadów. Nie ma żadnych wskazówek, iż kontynent antarktyczny był w tym czasie zlodowacony, jednakże mogły być zlodowacone grupy górskie, a wysokie wulkany mogły mieć czapy lodowe.

Z początkiem trzeciorzędu warunki klimatyczne-środowiskowe były zbliżone do górnokredowych. Wkrótce jednak, w wyniku zwiększenia się ilości opadów, pojawiła się gęsta pokrywa leśna z dominującym bukiem południowym (*Nothofagus*). W poszyciu tych lasów występiwały paprotniki (w tym paprocie drzewiaste), ponadto znane są araukarie. Z końcem paleogenu dominowały lasy liściasto-szpilkowe z *Nothofagus* i Podocarpaceae, jak się wydaje uboższe w poszycie paprotników. Sezonalność klimatu jest tu również zaznaczona w rocznych przyrostach drewien kopalnych. Z początkiem paleogenu w omawianym rejonie Antarktyki żyły również prymitywne torbacze i wielkie lądowe ptaki. Nie ma żadnych śladów zlodowacenia kontynentu antarktycznego w ciągu całego paleogenu. Są natomiast osady gruboblokowe, które można uznać za lahary powstałe w wyniku topienia się pokryw lodowych pod wpływem erupcji wysokich stratowulkanów.

Początek zlodowacenia kontynentalnego Antarktyki w sektorze Półwyspu Antarktycznego przypada na dolny miocen. Utworzyły się wtedy osady morsko-glacjalne z licznymi erratykami przyniesionymi przez dryfujące góry lodowe z kontynentu. Od tej pory, omawiany rejon wszedł w epokę lodową, która z przerwami trwa do dnia dzisiejszego.

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* Praca wykonana w ramach planu międzyresortowego PAN *MR. I-29*.