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Tertiary Glaciation and Sea-level Changes: Record from King George Island (South Shetland Islands), West Antarctica

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Abstract: Correlation exists between the first two Tertiary glaciations recorded from King George Island (South Shetland Islands, West Antarctica) and low stands of world ocean level well marked on eustatic curve of Haq *et al.* (1987). The Kraków Glaciation (c. 50 Ma) would correlate with the Early/Middle Eocene low stand of world ocean level, indicating that an icecap of considerable size had already formed in Antarctica. The transgression of the Polonez Glaciation ice-sheet (30-32 Ma), the largest ever Cenozoic glaciation of Antarctica, from Antarctic Peninsula across Bransfield Strait to King George Island, would correlate with low stand of world ocean level at the Early/Middle Oligocene transition, resp. base of the Chattian. Recession of this ice-cap back to Antarctic Peninsula resulted in sea-level rise by about 20 m.

There is no good correlation between low stands of world ocean level and the Late Oligocene Legru Glaciation (c. 26-30 Ma) and the Early Miocene Melville Glaciation (20-22 Ma). The Oligocene/Miocene transition was the time of opening of the back-arc Bransfield Rift between the South Shetland arc and the Antarctic Peninsula. Up- and down-warping of tectonic blocks during rifting were probably responsible for the recorded marine regressions and transgressions.

The history of the Tertiary glaciations on King George Island gives arguments for instability of Antarctic ice-sheet from Eocene through Early Miocene times. The ice-sheet became strongly volumetrically reduced, separated into isolated ice-caps and even totally disappeared during interglacial epochs. The data from King George Island suggest that the circum-Antarctic Current did not form prior to the Melville Glaciation (20-22 Ma).

Key words: Antarctica, King George Island, Tertiary, glaciation, sea-level change

INTRODUCTION

Four Tertiary glaciations separated by three interglacials have been recognised on King George Island, South Shetland Islands, West Antarctica (Figs 1, 2) between the Early/Middle Eocene, c. 50 Ma, and Early Miocene, 20 Ma (Birkenmajer, 1980, 1982, 1984, 1987, 1988, 1990, 1991, 1992a). Their age is based on K-Ar dating of associated volcanics (e.g., Birkenmajer *et al.*, 1985, 1986, 1988, 1989) and on stratigraphic evaluation of abundant fossils present in glacio-marine strata (e.g., Birkenmajer, 1987, 1988; Birkenmajer & Gazdzicki, 1986; Birkenmajer & Luczkowska, 1987; Birkenmajer & Dudziak, 1990).

The glacigenic deposits are part of a thick, terrestrial and marine, volcanic and sedimentary suite (Upper Cretaceous-Lower Miocene) of the South Shetland magmatic arc (Birkenmajer, 1994). Their glacio-marine and terrestrial glacial components (Fig. 3) record: (i) global climatic changes and related fluctuations of world ocean level, and/or (ii) local up-and downwarping, caused by strike-slip and extensional gravity faulting in an active volcanic arc supported by continental crust wedge, overriding subduction zone along the Pacific margin of West Antarctica (Fig. 2).

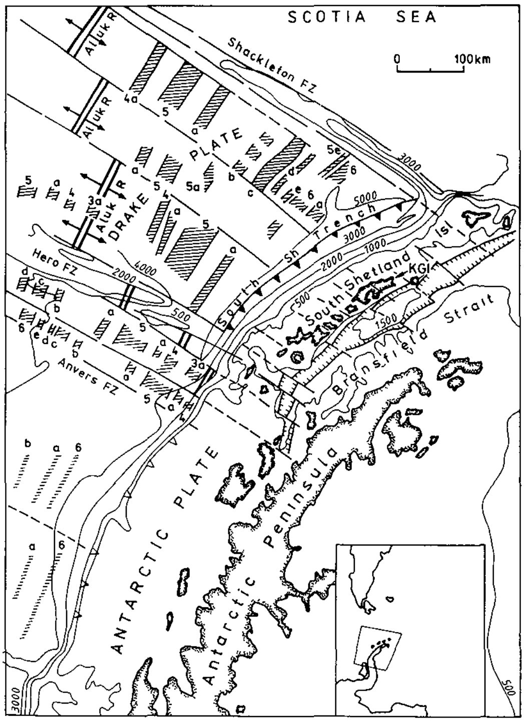

Fig. 1. Plate tectonic setting of the northern Antarctic Peninsula and the South Shetland Islands (KGI-King George Island). Bransfield rift barbed; convergent plate boundary marked by heavy barbs; spreading ridge divergently arrowed; fracture zones (FZ) dashed; magnetic anomalies obliquely shaded and numbered (adapted from British Antarctic Survey, Tectonic Map of the Scotia arc, 1985, and Meissner *et al.*, 1988)

The very complete Tertiary glacial/interglacial succession exposed on King George Island, spanning some 30 Ma from Eocene (50 Ma) to Early Miocene (20 Ma), is a unique record of past climatic and environmental changes at southern high latitudes, so far without equivalents elsewhere in Antarctica where terrestrial exposures are scarce and fragmentary (e.g., Webb, 1990; Barrett, 1991; Moriwaki *et al.*, 1992). With its terrestrial and marine fossil assemblages and lithostratigraphic units radiometrically-dated on associated volcanics, the King George Island Tertiary succession provides a standard applicable also for correlation with submarine drillhole data around Antarctic continent.

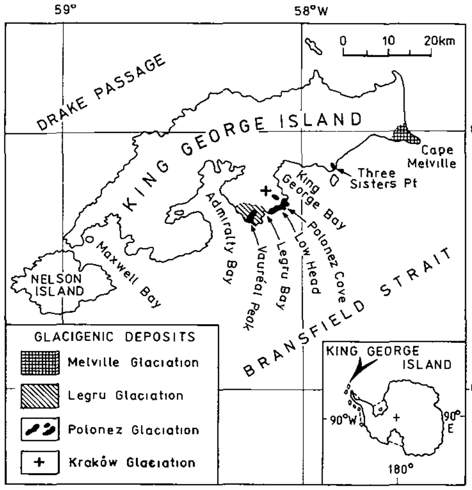

Fig. 2. Distribution of Tertiary glacial deposits on King George Island

KRAKOW GLACIATION

Strata and age

The Kraków Glaciation (Early/Middle Eocene, about 50 Ma) is represented by shallow-water, fossiliferous glacio-marine deposits with iceberg-rafted clasts, grading upward into fossiliferous basaltic hyaloclastites alternating with basaltic lava flows. The calcareous nannoplankton recovered from the matrix of hyaloclastite indicates a Paleocene-Eocene age (e.g., Birkenmajer, 1988, 1991; Birkenmajer and Dudziak, 1990). The K-Ar date of 49.5 ± 5 Ma from basaltic lava overlying the glacio-marine deposits (Birkenmajer *et al.*, 1986) indicates an Early/Middle Eocene age.

Evidence for glaciation

The evidence for glaciation is provided by the presence of numerous small to moderate-size ice-scratched dropstones brought to the shallow-marine environment by drifting icebergs from an area in Antarctic Peninsula. This was probably a local ice cap developed perhaps at some 2000 m a.s.l., with valley glaciers descending to the sea. This glaciation has not been recorded on oxygen isotope curves for the Paleocene-Eocene deep sea deposits in southern Atlantic (Miller *et al.*, 1989, Fig. 1).

The Eocene Krakow Glaciation of King George Island is the oldest Cenozoic Antarctic glaciation

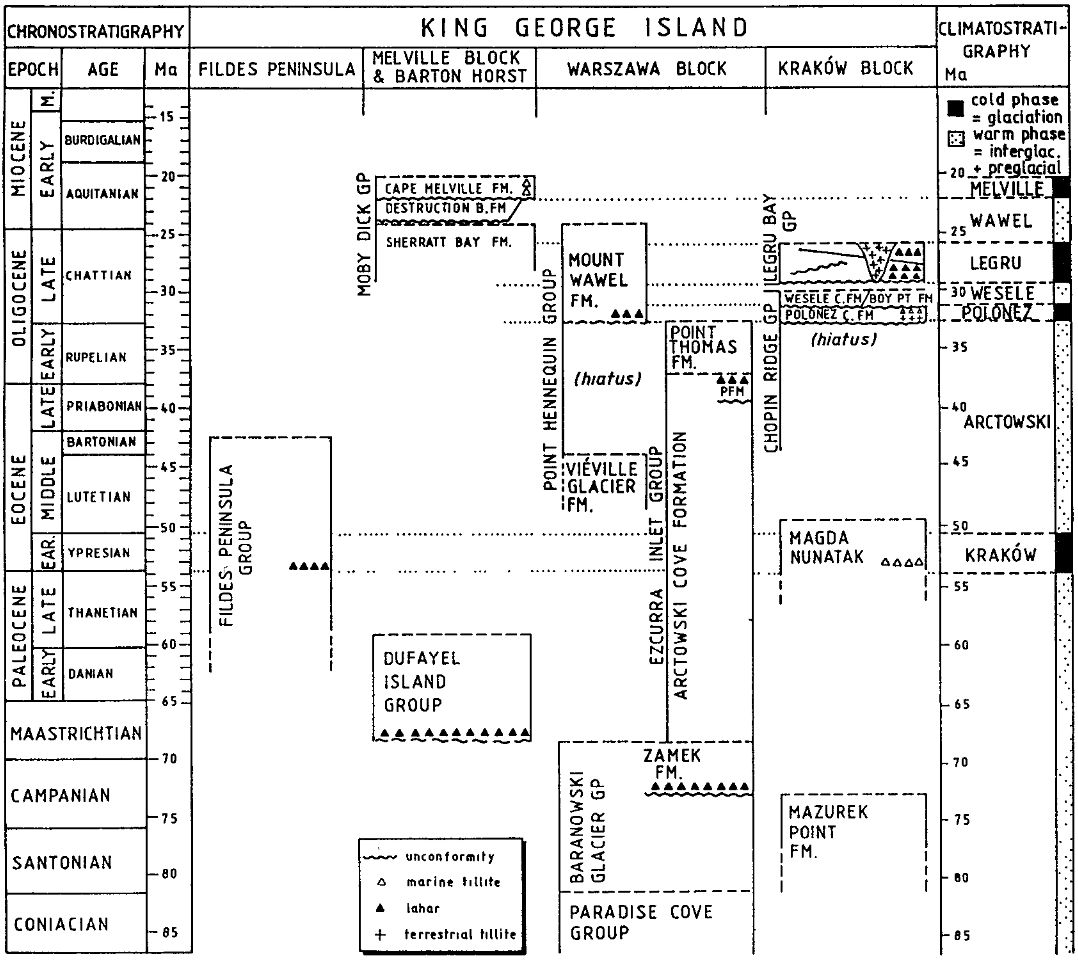

Fig. 3. Stratigraphic position of Tertiary glacial and interglacial deposits in particular tectonic blocks of King George Island. PFM-Petrified Forest Mbr.

recognized so far on land. No equivalent deposits have yet been found in continental Antarctica (see Barrett, 1991, Fig. 4.5; Moriwaki *et al.*, 1992, Fig. 2).

Correlation offshore Antarctica

The ODP Leg 119 drilling data from Prydz Bay, East Antarctica, gave evidence for the Lambert Glacier/Amery Ice Shelf complex grounded at sea bottom possibly in Late-Middle Eocene, and certainly by Early Oligocene time (Hambrey *et al.*, 1989). Moriwaki et al. (1992) accept that the glacier reached sea level in Prydz Bay at about 40 Ma.

Eustatic response to glaciation

King George Island, and probably the whole South Shetland Islands arc, were submerged by a shallow sea which extended southward over the present Bransfield Strait (Birkenmajer, 1992b). The Kraków Glaciation could correlate with the Early/Middle Eocene low stand of world ocean level (Fig. 4) as recorded on eustatic curve of Haq *et al.* (1987; see also Barrett, 1991, Figs 4, 5; Moriwaki *et al.*, 1992, Fig. 2). This could indicate that the Kraków Glaciation was of more than only local importance, and that already at about 50 Ma, the ice-sheet was of considerable dimensions not only in the West but also in the East Antarctica.

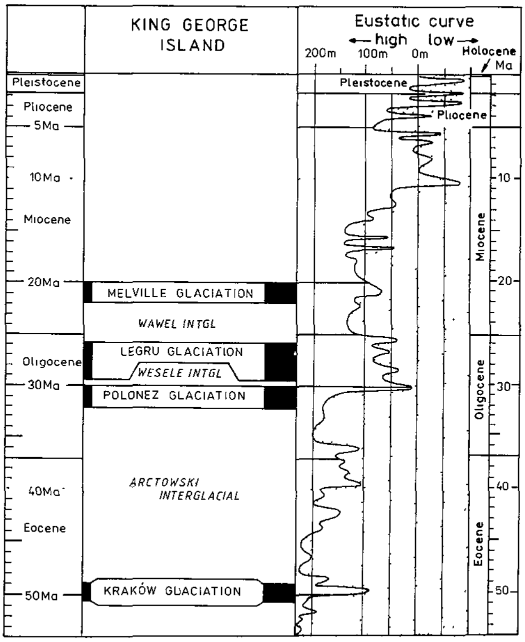

Fig. 4. Tertiary glaciations and interglacials of King George Island against eustatic curve of Haq *et al.* (1987).

ARCTOWSKI INTERGLACIAL

Strata and age

The Arctowski Interglacial epoch, dated at between c. 50 and c. 32 Ma (Middle Eocene-Early Oligocene), is represented in King George Island by terrestrial volcanics (lavas, tuffs) with plant-bearing volcaniclastic interlayers. Infrequent laharic agglomerates have been recognized (Fig. 3). There are no marine deposits of that age on King George Island, but there is evidence for a shallow Eocene sea in the Bransfield Strait (Birkenmajer, 1992a).

Environment and climate

Primitive terrestrial environments developed at that time, with stratovolcanoes dominating the scenery. There was a rich and diversified vascular plant cover, with pteridophytes dominating at lowlands where thin coal-seams formed. Southern beech (*Nothofagus*) forests grew on slopes of active stratovolcanoes, their tops covered by ice-caps. Catastrophic melting of these ice-caps caused by volcanic eruptions resulted in laharic debris flows (Fig. 3). As indicated by rich terrestrial flora, the climate was warm and moist, not very much different from that of Late Cretaceous (Stuchlik, 1981; Birkenmajer and Zastawniak, 1989a, b). This is also confirmed by the presence of numerous palaeosol surfaces, with the main components of regoliths consisting of smectite and kaolinite (Birkenmajer and Lydka, 1990).

Problem of eustatic response

The development of exclusively terrestrial environments on King George Island was the result of regression of the shallow sea which covered the island during the Early/Middle Eocene (Kraków Glaciation). This is in an apparent contradiction with the high stand of sea-level as would be expected in an interglacial epoch. Filling-up of a shallow marginal marine basin by voluminous volcanic products would probably be a plausible explanation of the lack of record of eustatic response to deglaciation in the Antarctic Peninsula area during the Arctowski Interglacial.

A shallow sea covered at least part of the Bransfield Strait as evidenced by pelitic volcaniclastic rock fragments with Eocene coccoliths found in volcanic agglomerates on Deception Island (Birkenmajer and Dudziak, 1991; Birkenmajer, 1992b).

Glaciation in Antarctica

Outside Prydz Bay (e.g., Hambrey *et al.*, 1989; Moriwaki *et al.*, 1992), there is scarce evidence for ice-sheet at sea level in East Antarctica at the Eocene/Oligocene transition. In Ross Embayment, beneath McMurdo Sound, submarine drillholes recorded Early Oligocene (c. 36 Ma) marine strata containing debris from glacier ice calving at sea level (Barrett *et al.*, 1989).

The East Antarctic ice-sheet was probably much smaller during most of the Arctowski Interglacial time than during the Krakow Glaciation. The oxygen isotope data from submarine drillholes in the Southern Ocean indicate an important cooling event close to the Eocene/Oligocene transition, ca 36 Ma ago (Shackleton and Kennett,1975). The oxygen isotope curve from southern Atlantic suggests the presence of continental ice-sheets in Antarctica since Eocene/Oligocene boundary, 36

Ma (Miller *et al.*, 1987, Fig. 1). This is in disagreement with the data from southern Pacific where the first significant cooling of seawater occurred much later, during mid-Oligocene time, 30 Ma (Miller *et al.*, 1987, Fig. 2).

During the Arctowski Interglacial, the West Antarctica probably consisted of islands and island groups, such as the South Shetland arc, Antarctic Peninsula and Marie Byrd Land, each having a separate ice cap/glacier cover restricted to higher altitudes. These islands were separated by shallow straits where products of surficial volcanic eruptions were the main marine deposit. There is no evidence so far for iceberg rafting in the Bransfield Strait, its coccolith-bearing pelitic Eocene sediments being devoid of dropstones.

The maritime West Antarctica was probably effectively screened from cold, glaciated East Antarctica by an open seaway which linked the Weddell and Ross embayments. In the absence of the Circum-Antarctic Current, these two embayments might have been entered by warmer currents generated in lower latitudes, mixing in the Weddell-Ross seaway. This would cause amelioration of the climate even at very high southern latitudes, enhancing expansion of *Nothofagus*-forests over the West Antarctic islands and the development of pteridophyte thickets which, in the warmest habitats (e.g. on King George Island), included also tree ferns.

POLONEZ GLACIATION

Strata and age

The Polonez Glaciation (early Late Oligocene, 30-32 Ma) is represented by a thick succession of terrestrial and fossiliferous marine tillites-the Polonez Cove Formation. This formation was first attributed to the Pliocene (Birkenmajer, 1980, 1982, 1983) following Barton's (1965) comparison of its "*Pecten* conglomerate" with that known from Cockburn Island, NE Antarctic Peninsula.

The Polonez Cove Formation begins with terrestrial (lodgement till) and submarine diamictites. They are followed by fossiliferous glacio-marine strata with strong volcaniclastic component, and with subordinate basaltic lavas (Birkenmajer, 1980, 1982, 1987, 1995; Porebski and Gradziński, 1987, 1990; Dos Santos *et al.*, 1990).

Invertebrate faunas, recovered from glacio-marine strata of the Polonez Cove Formation, contain both the recycled Late Cretaceous to Early Palaeogene fossils (Birkenmajer, 1987; Birkenmajer and Dudziak, 1990), and the Oligocene ones. The age of the formation, 30-32 Ma, is based on K-Ar dating of the underlying and overlying lavas and the dykes which cut the underlying and overlying lavas and the dykes which cut the succession (Birkenmajer and Gazdzicki, 1986; Birkenmajer *et al.*, 1986, 1989). The age of the formation needs to be refined by a new set of Ar-Ar dating of the samples which have been collected during the Brazilian Expeditions of 1993 and 1994 (Dos Sanots *et al.*, 1990; Birkenmajer, 1995).

Evidence for glaciation

The Polonez Cove Formation provides one of the best evidences for the continent-wide Antarctic Tertiary glaciation with grounded ice-sheet at sea level. The evidence includes, i.e.: (i) basal diamictites of terrestrial lodgement till type resting on ice-polished and striated bedrock, (ii) stratified basal diamictites which had formed below a relatively stagnant floating ice-front; (iii) numerous small to large erratics of Antarcric continent provenance present in basal diamictites; (iv) numerous small to large iceberg-rafted dropstones of Antarctic continent provenance in glacio-marine deposits (Birkenmajer, 1980, 1982, 1995; Porebski and Gradzinski, 1987).

Correlation within continental and offshore Antarctica

The Polonez Glaciation was the largest Cenozoic continental glaciation in Antarctica. Its grounded continental ice-sheet crossed the Bransfield Strait and reached King George Island, as is well evidenced by basal diamictites (Krakowiak Glacier Mbr) with clastic material derived principally from continental Antarctica (Antarctic Peninsula, Ellsworth Mountains, probably also Pensacola-Theron Mountains-Birkenmajer, 1980, 1982, 1987).

The Early/Late Oligocene transition, about 30-32 Ma, was the time of full-scale development of ice-sheet in West and East Antarctica, as it is known from many sites, both on land and in bottom drillings offshore (e.g., Barrett *et al.*, 1989; Barrett

1991; Moriwaki *et al.*, 1992).

A significant cooling of seawater at about 30 Ma is marked on the oxygen isotope curves obtained from deep sea cores in south Pacific (Miller *et al.*, 1987, Fig. 2). Such cooling shows up less clearly on the curves from south Atlantic (Miller *et al.*, 1987, Fig. 1). This difference could reflect a regional difference in dynamic state of the Antarctic ice-sheet at the beginning of the Chattian, which was rapidly expanding in West Antarctica but was relatively stagnant in East Antarctica. The formation of cold deep water in the Antarctic at the beginning of Oligocene (Kennett and Barker, 1990) does also correlate with the Polonez Glaciation.

Eustatic response to glaciation

The continental ice-sheet transgression of the Polonez Glaciation over King George Island (30-32 Ma) correlates well with rapid fall in world ocean-level at the Early/Late Oligocene transition, ca 30 Ma ago (Fig. 4; see also Barrett, 1991, Fig. 4.3; Moriwaki *et al.*, 1992, Fig. 2). This fall might correlate with the early stage of the ice-sheet transgression over Bransfield Strait which had deposited lodgement till (Krakowiak Glacier Mbr) on King George Island. In the Ross Embayment, a major shallowing at 30.5 Ma, with subsequent extension of grounded glacier ice offshore (Barrett *et al.*, 1989), correlates well with the Polonez ice-sheet transgression over King George Island.

The succeeding phase of relatively stangant floating ice-shelf which had deposited stratified diamictite of the (Polonez Cove Formation (Krakowiak Glacier Mbr), would indicate opening of the Bransfield Strait seaway as a result of slow rise of world ocean-level following gradual recession of ice-cap. The flooding of the strait was completed during the next stage represented by transgressive glacio-marine deposits of the Low Head Member which unconformably cover the basal diamictites and/or their substratum (Birkenmajer, 1995). This stage continued during the deposition of the succeeding Siklawa and Oberek Cliff members of the Polonez Cove Formation.

The glacio-marine deposits of the Polonez Cove Formation contain a wealth of iceberg-rafted dropstones of mainly distant provenance, the most frequent being those from Antarctic Peninsula, that indicates a wide opening of the Bransfield Strait seaway (Birkenmajer, 1992a, 1992b). A part of the South Shetland Island arc was covered by a local ice-sheet disconnected from the continental one; it supplied local clastic material in the form of ice- and/or iceberg-rafted dropstones.

Sedimentological analysis indicates that the sea of the Polonez Cove Formation was shallow, its embayment on King George Island only some 20 m deep (Porebski & Gradzinski, 1987). This value could be considered a measure of the eustatic sea-level rise at the stage when the continental ice-sheed receded back to Antarctic Peninsula.

WESELE INTERGLACIAL AND LEGRU GLACIATION

Strata and age

During the Late Oligocene (Chattian), from c. 30 Ma to 26 Ma, terrestrial interglacial and glacial deposits were formed on King George Island. There was a short period of deep dissection of the Early Oligocecne and older strata by fluvial erosion, followed by deposition of fluvial gravel and slope debris in V-shaped valleys during the Wesele Interglacial (c. 30 Ma).

Another, planar erosional unconformity cuts the Wesele Cove Formation deposits. It is followed by a thick sequence of andesitic and basaltic lavas alternating with laharic agglomerates. The K-Ar dating (Birkenmajer *et al.*, 1986, 1989) determined the age of the complex at between c. 30 Ma (bottom lavas) and 26 Ma (top lavas). Deep and narrow erosional valleys filled with glacial diamictite containing exclusively local material from King George Island cut the lava-agglomerate complex. They are the evidence of a local ice-cap on King George Island, disconnected from continental ice-sheet of West Antarctica.

Climate

No plant remains have so far been found in the deposits of the Wesele Interglacial (Wesele Cove Formation). The rich terrestrial vegetation characteristic of the Arctowski Interglacial was completely wiped out by the Polonez Glaciation. Consequently, King George Island remained barren of vegetation through the period of Late Oligocene (Chattian) betweem 32 and 26 Ma.

A major ice build-up is postulated for the

Weddell and Ross seas regions between 30 and 20 Ma, and a glacial maximum for the Prydz Bay-Prince Charles Mountains region. Several interglacial-type epochs of deglaciation or warm condition, some with *Nothofagus* forests, separated the glacial maxima (Barrett, 1991; Moriwaki *et al.*, 1992). The local glaciation of King George Island in maritime Antarctica was certainly subjected to similar ice-cover oscillations, and the Legru Glaciation might in fact cover several of them.

Problem of eustatic response

The period between c. 30 and 25 Ma is characterized by fluctuating world-sea level with four low stands and three high stands (Haq *et al.*, 1987). The oldest low stand is correlated with the transgression of the Polonez ice-sheet at the Early/Late Oligocene transition (Fig. 4). The succeeding rise of sea-level by about 20 m recorded by the Polonez Cove Formation is correlated with slow decrease of continental ice-sheet volume over Antarctica during the second phase of the Polonez Glaciation (see above).

It would be reasonable to expect a further marine transgression over King George Island during the Wesele Interglacial. However, on the contrary, we have only evidences for marine regression and land rise of the order of 100 m, followed by dissection (Birkenmajer, 1982, 1983). This was explained as a result of upwarping of the South Shetland curstal wedge due to updoming Strait (Birkenmajer, 1992a). Isostatic rebound following deglaciation in the South Shetland Islands could have also played a part, its scale being, however, difficult to assess.

WAWEL INTERGLACIAL AND MELVILLE GLACIATION

Strata and age

The thick terrestrial andesitic lava complex of the Mount Wawel Formation in the Warszawa Block contains in its upper part several thin plant-bearing tuffaceous intercalations, K-Ar dated on associated lavas at 24.5 ± 0.5 Ma (Birkenmajer *et al*.. 1983). These plant-bearing strata are the evidence for a Late Oligocene Wawel Interglacial (ca 26-22 Ma).

In the Meliville Block on King George Island, terrestrial basaltic lavas (Sherratt Bay Fm.) of closer not determined Tertiary age (probably age equivalent of the upper part of the Mt. Wawel Fm. -Fig. 3), underlie a thick marine sequence of Early Miocene age. It starts with fossilliferous tuffaceous deposits (Destruction Bay Fm.) K-Ar dated at 23.6 ± 0.7 Ma (Birkenmajer *et al.*, 1988). These deposits yielded Early Miocene foraminiferal assemblages (Birkenmajer and Luczkowska, 1987), bivalves, brachiopods and driftwood, as well as recycled Cretaceous calcareous nannoplankton and belemnites (Birkenmajer, 1984, 1987).

There follows a thick marine sequence of the Cape Melvelle Formation. It starts with a thin discontinuous conglomerate bed considered to be a fossil-beach deposit, followed by shallow-marine fossiliferous amalgamated sandstone and siltstone a few metres thick, with numerous large iceberg-rafted dropstones of mainly Antarctic continent provenance. They are followed by a complex about 200 m thick of fossiliferous dark shales with thin sandstone-siltstone and marl intercalations, with numerous small to large iceberg-rafted dropstones, mainly of Antarctic continent provenance. The shales contain a rich invertebrate bottom fauna (molluscs, recycled Cretaceous belemnites and Cretaceous calcareous nannoplankton.

The whole sequence of the Moby Dick Group (Sherratt Bay, Destruction Bay and Cape Melville formations-Fig. 3) is cut by andesitic dykes K-Ar dated at 20 Ma (Birkenmajer *et al.*, 1985).

Environment, climate and eustatic response

The plant-bearing volcanic complex of the Mount Wawel Formation had formed during the Wawel Interglacial. The well preserved *Nothofagus*-podocarp assemblages are the evidence for temperate (cool and warm) rain forests that recolonized slopes of andesitic volcanoes on King George Island arriving from refuges in Tierra del Fuego-Patagonia along island chains which still existed in relatively shallow and narrow Drake Passage (Birkenmajer and Zastawniak, 1989a, b).

Ingression of a shallow marginal sea at the close of the Wawel Interglacial, which deposited fossiliferous strata of the Destruction Bay Formation, could represent the terminal event of the world-ocean level rise following considerable reduction of Antarctic ice-sheet at the Oligocene/Miocene transition (Fig. 4). The lack of glacially striated iceberg-rafted dropstones, and the presence of driftwood in the Destruction Bay Formation, suggest an open marine environment as an effect of a considerable retreat of the West Antarctic ice-sheet. Recycled Cretaceous fossils (belemnites and coccoliths) which occur in this formation were supplied to the marginal marine basin from coastal area by subaqueous slumps/turbidites and, possibly, also by drifing winter ice. The driftwood could derive either from a forested area in maritime Antarctica, or from lands or islands or islands north of 60°S.

The Cape Melville Formation, with its basal conglomerate unconformable upon the Destruction Bay Formation and, landwards, directly upon the Sherratt Bay Formation, marks a new marine ingression and widening of the marginal marine basin. The benthic foraminifer assemblages from the Cape Melville Formation record two cycles of subsidence in the basin to outer shelf (500-550 m) and shelfbreak/upper slope (1,000-1,200 m) depths, followed by shallowing to inner shelf (150-200 m) depths (Birkenmajer and Luczkowska, 1987). Abundance of iceberg-rafted dropstones of all sizes, up to about 3 m across, derived from various continental sources (mainly Antarctic Peninsula, Ellsworth Mountains, possibly also Pensacola-Theron Mountains-Birkenmajer, 1984, 1987), is a good evidence for the existence of extensive Melville Glaciation ice-sheet in Antarctica. The character of fine-grained clastics which host these dropstones, points to a considerable retreat of coastline to the south.

Contrary to the eustatic curve of Haq *et al.*, (1987), which indicates a well marked fall in world-ocean level at 19-20 Ma, the Destruction Bay-Cape Melville succession records a two-step rise of sea-level and drowning of the South Shetland arc to the outer shelf/upper slope depths. The eustatic response to the Melville Glaciation (sea-level fall) was thus obliterated in the South Shetland arc by downwarping of crustal block of the South Shetland arc caused by a further stage of rifting in the Bransfield back-arc basin (Birkenmajer, 1992b).

Instability of Antarctic ice-sheet and Circum-Antarctic Current

The instability of the West Antarctic ice-sheet is obvious from the record of recurrence of glaciations and interglacial epochs on King George Island during the Eocene-Early Miocene times. During interglacial epochs, the ice-cap melted away and disappeared from King George Island, while the continental West Antarctic ice-sheet probably disintegrated into smaller ice-caps, and open seaways linked the Ross and Weddell embayments and probably also dissected the Antarctic Peninsula-Marie Byrd Land region.

According to Kennett (1977, 1980), the Circum-Antarctic Current had formed as a result of continental dispersion and opening of the Scotia seaway at about 25 Ma. However, this was the time of the Wawel Interglacial with its temperate (cool and warm) rain forests on King George Island (Birkenmajer and Zastawniak, 1989a, b). During this interglacial, ice-sheet disappeared completely from King George Island and was strongly reduced, perhaps even disintegrated into local ice-caps in the whole West Antarctica. Under such interglacial conditions, the formation of the circum-Antarctic Current seems unlikely. It is suggested that this current had formed for the first time during the Early Miocene Melville Glaciation, some 20-22 Ma ago. Since then, it has been a semi-permanent feature disappearing during interglacial and reappearing during glacial stages.

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