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Review of Tertiary Glaciation in King George Island, West Antarctica: Preliminary Results

(Glaciation | Tertiary | West Antarctica)

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INTRODUCTION

Outcrops of Tertiary glaciogenic sediments available for study are relatively rare in Antarctica and most geological evidence for the reconstruction of the Cenozoic glacial paleoenvironmental history of the continent derives from marine sediments (Webb, 1991).

Reports of a glacial terrestrial and glacial-marine succession of Paleogene-Neogene age cropping out along the coast of King George Island interpreted as involving several alternating episodes of glaciation and interglacials present, therefore, considerable interest (Birkenmajer, 1980; 1982a,b; 1984; 1987; Birkenmajer *et al.*, 1983; 1985; Paulo & Tokarski, 1982; Porebski & Gradzinski, 1987; see Birkenmajer, 1991 for a recent review of the Tertiary glacial history of the South Shetland Islands). These exposures are particularly important because of the opportunity they offer for the study of lithofacies types and associations, geometry of the sedimentary bodies, processes involved in their deposition, depositional environments and associated biofacies.

Another important aspect of the occurrences regards their tectonic setting as part of a Mesozoic-Tertiary volcano-sedimentary subduction complex associated with the roughly southern plunge of the Pacific Plate under the Antarctic Plate (Birkenmajer, 1992).

In this respect, as well as in terms of stratigraphy and sedimentary facies, the glaciogenic strata of King George Island may be compared with the glaciomarine Late Cenozoic Yakataga Formation cropping out along the rising coastal mountains around the Gulf of Alaska forearc basin (Eyles *et al.*, 1989). Both sequences were deposited in an active margin basin and were preserved due to the active subsidence that characterizes this type of tectonic environment. The Yakataga Formation is widely accepted as representing the earliest, most complete and yet accessible record of northern hemisphere glaciation (Eyles *et al.*, 1989). Because of its long, continuous record (Late Miocene-Pleistocene), the Gulf of Alaska Cenozoic glacial strata may provide an adequate analogue and reference section for comparative studies with other Cenozoic glacial sequences.

RESUMÉ OF THE TERTIARY GLACIAL SEDIMENTATION IN KING GEORGE ISLAND

Tertiary glacial strata of King George Island have been made known since 1980 in a series of important contributions by K. Birkenmajer and other Polish scientists. Birkenmajer (1991) lists the main published references on the stratigraphy, facies, depositional environments, paleogeography, paleontology and age of these beds. Additional discussion on the interpretation of K/Ar dating of igneous rocks associated with the glaciogenic strata appear in Birkenmajer *et al.* (1989; 1990). The resumé below is mainly based on these references.

According to these data, the strata record four glacial episodes encompassing the Early Eocene-Early Miocene interval (around 30 Ma) denominated, from bottom to top: Kraków, Polonez, Legru and Melville (Fig. 1).

The Kraków glaciation is represented by a thin (3.6 m exposed thickness) isolated outcrop of glacial marine diamictite at Magda Nunatak, overlain by basaltic breccia and lava flow. Long-ranging Tertiary bivalves, scaphopods, and reworked Cretaceous, and rare Tertiary coccoliths are known from the glacial-marine bed. More diagnostic Middle Paleocene-lower Early Eocene discoasters were obtained from the basaltic breccia and a single K-Ar determination of 49.4 ± 5 Ma (Middle Eocene) has been obtained for the lava. The diamictite is interpreted as related to local moun-

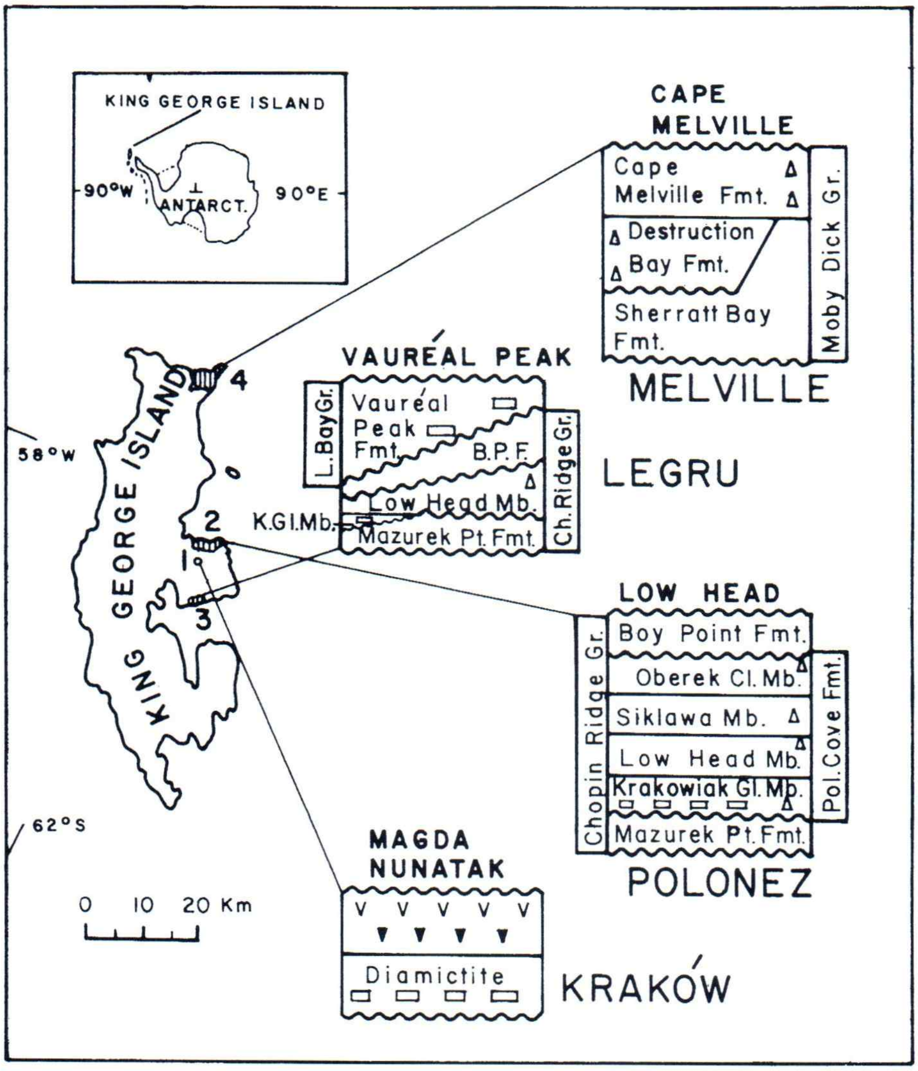

Fig. 1 — Location of sections of Tertiary glacial sediments, King George Island. Explanation: B.P.F. = Boy Point Formation; K.Gl.Mb. = Krakowiak Glacier Member; L. Bay Gr. = Legru Bay Group; Ch. Ridge Gr. = Chopin Ridge Group; Oberek Cl.Mb. = Oberek Cliff Member; Pol. Cove Fmt. = Polonez Cove Formation; open triangles = dropstones; black triangles = volcanic breccia; rectangles = diamictite (data from Birkenmajer, 1991).

tain glaciers on the Antarctic Peninsula which reached the sea.

In the > 50 m thick Polonez Cove Formation cropping out between Low Head and Lions Rump (King George Bay), the Krakowiak Glacier Member (5-15 m thick) is described as consisting of a lodgement tillite and glacial-fluvial deposits containing faceted and striated clasts up to 2 m in diameter of local and continental Antarctic provenance. A detailed description of the stratigraphy, facies and environment of deposition of the Polonez Cove Formation appears in Porebski & Gradzinski (1987; 1990).

The glaciogenic strata rest disconformably on an irregular substrate of lavas of the Mazurek Point Formation, which at its type locality yielded a Late Cretaceous K-Ar age (around 74 Ma). Younger ages (*e.g.* 49 Ma at Magda Nunatak; see above; 34 Ma at Mersey Spit), however, have been obtained elsewhere for basalts correlated with the Mazurek Point Formation (Birkenmajer *et al.*, 1989; 1990).

The Krakowiak Glacier Member is overlain by glacial-marine sediments and basaltic flows and breccias containing large, dispersed clasts of exotic lithologies, including many ice-rafted dropstones up to 1.5 m in diameter. The entire sequence is disconformably overlain by andesite-dacite lavas (Boy Point Formation) which yielded K-Ar apparent, probably minimum ages of more than 22.4-23.6 Ma. The rich shallow, high energy, inner shelf, shelly invertebrate fauna recovered from the Polonez Cove Formation, of general Tertiary affinity, and the associated *in situ*, and possibly recycled, calcareous nannofossil assemblage are interpreted as mostly of Early Oligocene age.

Glaciogenic sedimentation in the Polonez Cove Formation was assigned by Birkenmajer (1982a) and Porebski & Gradzinski (1987) to a phase of extensive continental glaciation, when ice streams flowing from continental Antarctica reached King George Island (Polonez glaciation).

Terrestrial, subglacial tillites over 100 m thick filling valleys deeply cut into subaerial andesitic lavas, and lahar-type debris flows of the Legru Bay Group cropping out at Admiralty Bay make up the record of the Legru glaciation. Striae on the underlying volcanic rocks and pseudomorphs of ice wedges in the diamictites containing clasts of local provenance testify to mountain glaciation of restricted extent. A Late Oligocene age for this event is suggested by K/Ar dates of 26 Ma at the top and 30 Ma at the base of the lava flows.

The youngest Tertiary glacial interval in King George Island, also of local extent, is recorded by the glacial-marine deposits of the Cape Melville Formation (Melville glaciation). The unit is a sequence about 200 m thick of alternating fine bathyal and deep shelf sediments with abundant, exotic ice-rafted clasts (up to 2 m in diameter).

The strata rest disconformably both on shallow marine to estuarine beds of the Destruction Bay Formation and the underlying Sherratt Bay Formation basalts. The former is dated as Early Miocene on the basis of paleontological and K-Ar data; the latter is considered as Late Oligocene on scarce K-Ar data. The Cape Melville Formation contains an abundant and diversified Tertiary, and reworked Cretaceous fauna of marine invertebrates and forams, the latter indicative of an Early Miocene age. The same age was obtained by K/Ar dating of andesitic and basaltic dykes which cut through the whole sedimentary succession.

Fluvial and debris flow sediments, and plant-bearing (*Nothofagus* – podocarp assemblage) beds intercalated, respectively, between the Polonez Cove Formation and Legru Bay Group, and between this and the Cape Melville Formation are interpreted as indicating climatic amelioration or "interglacial" conditions.

OBJECTIVES OF THE PRESENT PROJECT

The systematic characterization of styles of glacial sedimentation resulting from different combinations of tectonic and paleoclimatic history, sediment supply, depositional facies and stratigraphic succession, and their respective long-term preservation potential (Eyles *et al.*, 1985) is a promising yet not well explored area of research in glacial sedimentology. Because of their occurrence in a variety of tectonic settings (*e.g.* young rift basins, passive margins, backarc and forearc basins), Cenozoic glacial sequences may offer analogues and serve as reference for comparative studies with those of older basins.

The above methodological approach forms the basis of a broad research project initiated in 1992 aimed at investigating several Cenozoic and pre-Cenozoic glacial sequences as examples within the spectrum of known geological settings. The study involves the detailed review of stratigraphy, facies, sedimentary environments, tectonic history and paleogeography and the comparison of the main features of the sequences examined. As discussed above, the Tertiary glacial strata of King George Island were taken as representative of a sequence formed and preserved in what is considered to be a Cenozoic subduction complex.

During January-February, 1993, geological field work was performed in King George Island under the auspices of the Brazilian Antarctic Program (PROANTAR) and included stratigraphic and sedimentological analysis of the Polonez Cove Formation cropping out on a cliff along the eastern coast of the island between Low Head and Lions Rump (King George Bay). Some preliminary results of this research mostly referring to the glaciogenic sediments of the Krakowiak Glacier Member and their geodynamic context are briefly summarized below. Stratigraphic relationships and sedimentary history of the whole Polonez Cove Formation will be treated in a following paper.

PRELIMINARY RESULTS

The comments below refer to sections examined in the northern outcrop area of the Krakowiak Glacier Member (Stations 5-8 in Porebski & Gradzinski, 1987, figs. 3-4).

Glacial sediments

Facies and sedimentary environment. Fine striae of possible glacial origin were recorded for the first time in the area on basalts of the Mazurek Point Formation (Cretaceous). They furnish additional evidence in favor of a glacial origin for the diamictites and associated sediments of the overlying Krakowiak Glacier Member. The direction of the striae (N316°-326°) is consistent with the northwesternly sense of movement of the glaciers which reached King George Island, deduced on the basis of provenance studies on clast petrography (Birkenmajer & Wieser, 1985; Birkenmajer & Butkiewcz, 1988). According to these authors, ice streams flowed to King George Island from the Antarctic Peninsula, Ellsworth and Transantarctic Mountains.

Subangular clasts of metamorphic rocks up to 10 cm in diameter were observed within lavas of the Mazurek Point Formation in one locality at Mazurek Point. The subaerial nature of the lava flows and subordinate pyroclastic rocks of the Mazurek Point Formation (Birkenmajer, 1982a) suggest that the clasts may have been incorporated while the lava was flowing. Another question raised by the exotic nature of the clasts is the history of their transportation to the area prior to the volcanic event.

Although a grounded ice margin may be implied during sedimentation of the Krakowiak Glacier Member, no evidence of true subglacial terrestrial deposition of lodgement tillite (Porebski & Gradzinski, 1987; Birkenmajer, 1991) was found.

The unit occurs as a body of varied thickness (4-15 m) and complex geometry, exposed along about 1,000 m, resting on a very irregular floor of Mazurek Point Formation basalts (Fig. 2). The Krakowiak Glacier Member and the other strata of the Polonez Cove Formation vary from subhorizontal to gently tilted, and are displaced by several normal faults.

The glaciogenic sequence often starts with a thin (up to 15-20 cm thick) bed of stiff, massive, planar or micro-cross laminated, medium sandstone which fills irregularities or wedge shape cavities or cracks in the basalt (Fig. 3). Higher up it shows a complex arrangement of alternating, mostly channelized, lenticular or tabular, discontinuous, decimetric to metric thick bodies of matrix-supported, coarse sandy conglomerates, coarse immature sandstones, coarse sandy diamictites and sandy mudstones. Conglomeratic beds intercalated between diamictites are both normally or inversely graded (Figs. 4-5). The latter may occur as superposed beds coalesced or separated by sharp or diffuse contacts, often marked by discontinuous, planar accumulations of clasts of diverse sizes, or thin (centimetric to decimetric) intercalations of fine-medium sandstones (Fig. 6). Sandstones are planar bedded, faintly graded or show wave-ripple lamination and wave-worked cross bedding (Figs. 6-7). Round or irregular pockets of conglomerate with diffuse boundaries are also included within the diamictites. Chaotically dispersed in each of the above lithologies are clasts (granules to boulders up to 40 cm in diameter) of varied composition, angular to subrounded, several bullet-shaped, many faceted, and up to 25% striated. Stringers or dispersed fragments of ma-

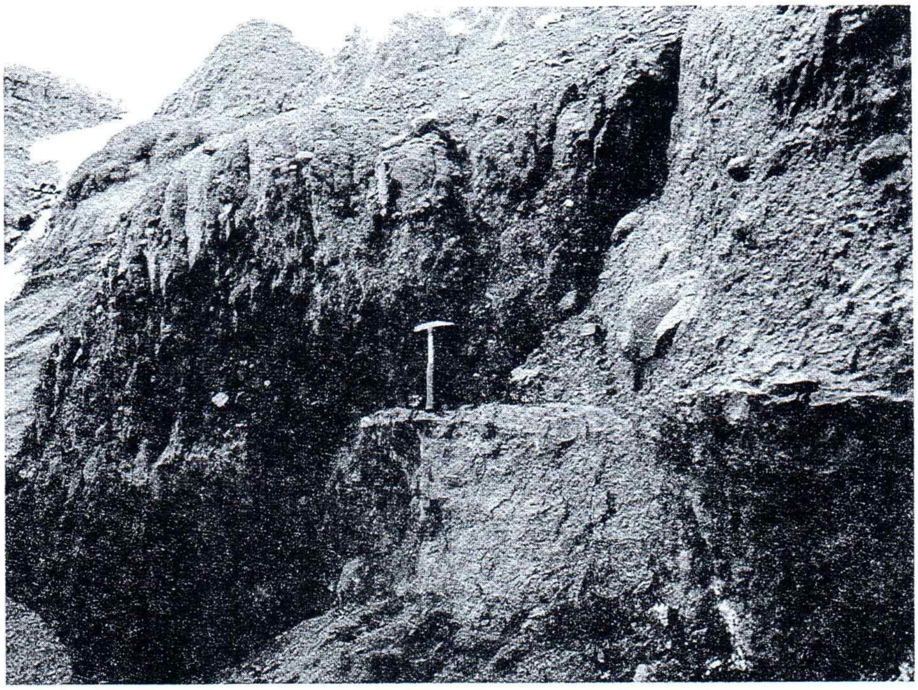

Fig. 2 — Contact between thick bed of coarse, sandy diamictite of the Krakowiak Glacier Member resting on Mazurek Point Formation basalt (Cretaceous). (Station 7 in Porebski & Gradzinski, 1987.)

Fig. 3 — Highly compact sandstone of the Krakowiak Glacier Member on top of Mazurek Point Formation basalt. Note cracks in the basalt filled with sandstone (marked by pen). (Same location as Fig. 2.)

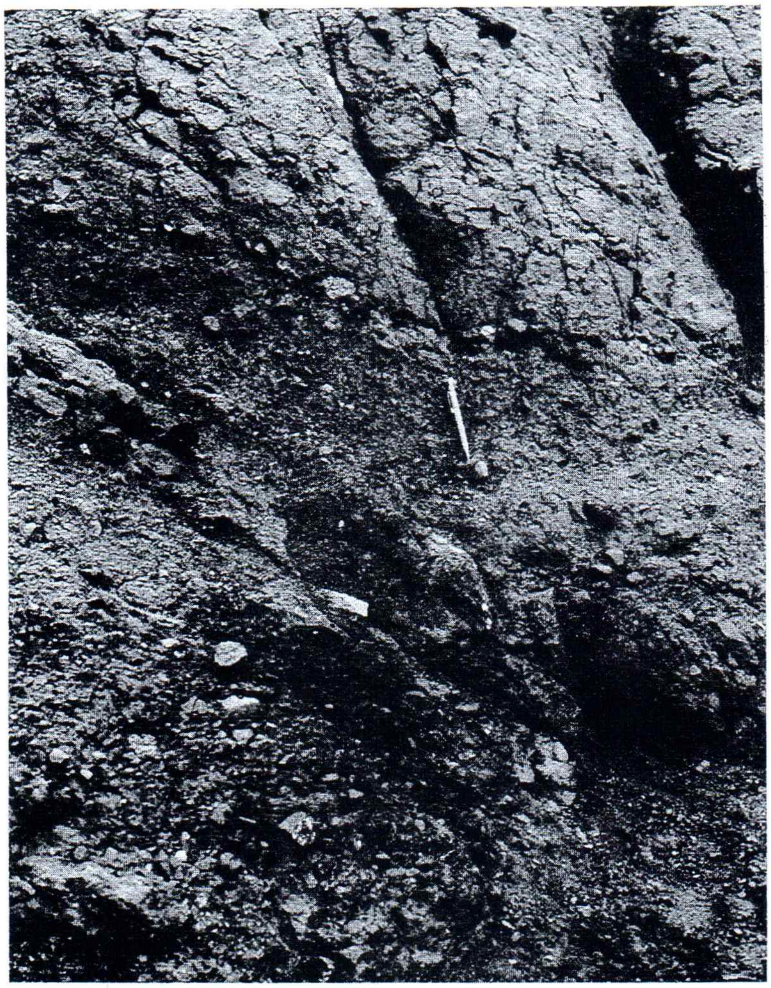

Fig. 4 — Intercalation of beds of coarse, sandy diamictite and conglomeratic sandstone. Note clast layer at contact between upper diamictite and conglomeratic sandstone (same location as Fig. 2).

rine fossils (mostly bivalve shells) have been found within the diamictites.

Most of the beds show signs of penecontemporaneous deformation by folds, normal and slump faults, sand dykes, loading and intraformational truncations which may juxtapose different lithologies (Figs. 6 and 8). Wide arcuate piles of diamictite and conglomerate beds also occur (Fig. 6).

The facies association and arrangement described above broadly conforms to available descriptions of sedimentary models of proximal, shallow glacial marine environment associated with a retreating grounded ice margin (*e.g.* Eyles *et al.*, 1985; Eyles & Clark, 1985, 1987; Powell & Molnia, 1989), as already pointed out by Porebski & Gradzinski (1987). No lithofacies representative of a basal or lodgement tillite, or any evidence of glaciotectonized sedimentary substrate has yet been recognized in the Krakowiak Glacier Member. The compact basal sandstone layer tightly plastered against the basalt floor and filling wedge-shaped cracks in the basalt may, however, be associated with compression under a moving glacier.

Most of the sediments probably accumulated quickly by successive and alternating episodes of downslope mass flow processes involving debris flows and high concentration, coarse-grained turbidity currents, along a subaqueous fan slope in a shallow marine environment. Absence of channelized gravel and cross-stratified sands

Fig. 5 — Sharp contact between coarse, sandy diamictite beds, with clasts concentrated on the top of the lower one. Note faceted (and striated) boulder (same location as Fig. 2).

(subaqueous outwash) on one hand and of laminated mud deposits on the other suggests an intermediate position of the sedimentary pile with respect to the ice margin (Eyles *et al.*, 1985; Powell & Molnia, 1989). That the flows were able to erode the substrate is indicated by the general channelized geometry. Sandstone intercalations record pauses between successive dense flows and reworking by wave action. Most of the penecontemporaneous deformation structures of the Krakowiak Glacier Member seem to have resulted from sedimentary oversteepening due to density loading. General absence of reverse, high angle faults seems to rule out collapse by melting of buried ice. Though the frequency of oversized clasts could suggest intense rafting by icebergs, identification of dropstones is hampered by soft sediment deformation of beds. The same applies to possible iceberg gouges.

In some of the sections examined, the coarse-grained deposits of the Krakowiak Glacier Member pass upwards transitionally into massive to faintly bedded sandy, pebbly mudstones, or to stratified conglomeratic sandstone and clayey sandstone, up to the lower contact with sandstones of the Siklawa Member (Fig. 1). These beds contain stringers of or dispersed fragments of bivalve shells and of other invertebrates (*e.g.* bryozoans) and rare, isolated, oversized (up to 40 cm) exotic clasts.

This part of the section corresponds to the "fossiliferous stratified conglomerate and bedded gravelly diamictites" which Porebski & Gradzinski (1987) assigned to the Low Head Member (Unit LH3) of the Polonez Cove Formation, described as being in erosional contact on the Krakowiak Glacier beds. The gravelly diamictites are interpreted by them as subaqueous lahar deposits filling wide channels cut into the lower coarse-grained sediments. Alternatively, the upper sandy, pebbly mudstones referred to above could represent rain out diamicts formed by ice-rafting of debris associated with the deposition of mud at the top of a fining (and deepening?) upward sequence, accompanying the retreat of the glacier front.

Age. The relatively long record of Tertiary glacier events interpreted for King George Island (Fig. 1), encompassing about 30 Ma (Early Eocene-Early Miocene; Birkenmajer, 1991), is undoubtedly of enormous importance for the reconstruction of the paleoclimatic glacial history

Fig. 6 — Arcuate (channel-like) structure of intercalated coarse conglomeratic sandstone, and matrix-supported conglomerate (top), separated by thin decimetric intercalations of micro-cross-laminated, fine-medium sandstone at top left of photo (see detail in Fig. 7). (Station 6 in Porebski & Gradzinski, 1987.)

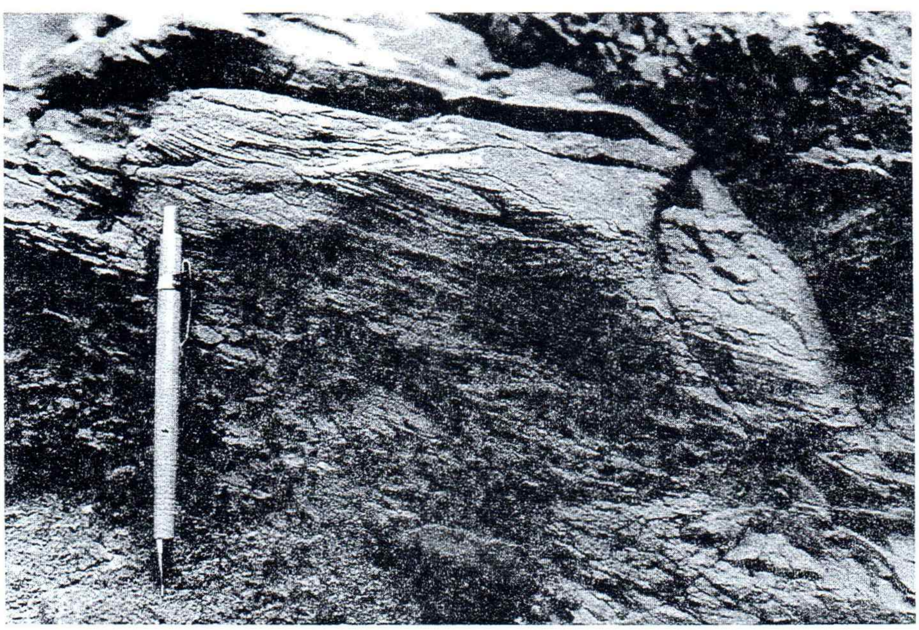

Fig. 7 — Micro-cross-laminated, fine-medium sandstone showing wave-worked (truncated) ripples (same location as Fig. 6).

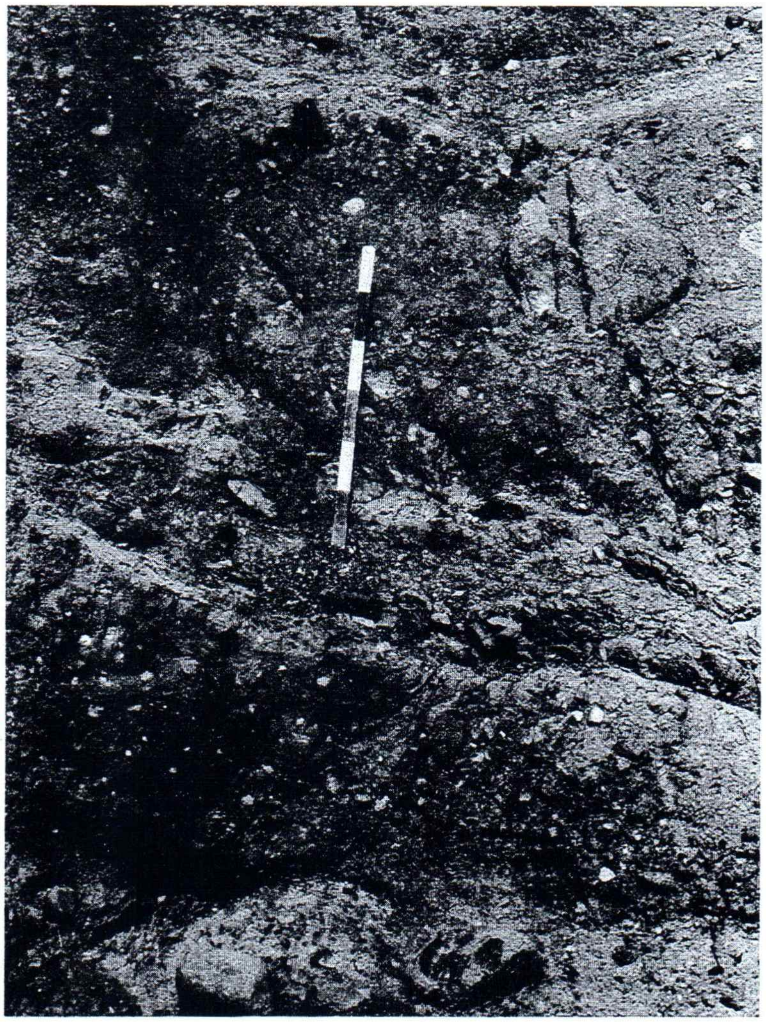

Fig. 8 — Complex intercalation of deformed, coarse sequence of conglomeratic sandstone, matrix-supported conglomerate, showing both normal and inverse grading, and thin, discontinuous intercalations of plane and wavy laminated sandstone (same location as Fig. 6).

of Antarctica. The exact dating of the sections involved is, therefore, of prime importance and some of more relevant problems related to paleontological and radiometric age determinations of the rocks have been recently discussed by Birkenmajer *et al.* (1989; 1990) and Birkenmajer (1991).

Present paleontological uncertainties derive basically from scarcity of diagnostic species, complicated by evidence of recycling of assemblages of different ages within the Tertiary and Cretaceous (Birkenmajer, 1991). It is worth mentioning in this regard the recent identification of Late Oligocene planktonic forams in the Cape Melville Formation (Abreu *et al.*, 1992).

Radiometric age dating, on the other hand, poses other problems derived from the reliability of K-Ar determination on "young" lavas of a subduction volcanic-sedimentary pile, which was subjected to multiple heating episodes (Birkenmajer *et al.*, 1989; 1990). During field work additional sampling of the volcanic, intrusive and volcaniclastic rocks of the Polonez Cove Formation or associated with it was carried out for additional radiometric determinations.

Tectonic studies

Previous data. Studies mainly by A. K. Tokarski and summarized in his paper of 1987 and by Birkenmajer (1992) have provided an useful scheme for Cenozoic structural evolution of King George Island. Additional data on the orientation of joints and faults cutting through the Polonez Cove Formation, collected during field work in 1993, help to complement the available model.

Tokarski (1987) subdivided the thick pile of volcanic-sedimentary and intrusive rocks of King George Island into three structural units (lower, middle and upper) on the basis of the stratigraphic distribution of three sets of vertical joint trends, from oldest to youngest:

I. Average trend N105° (25 stations measured). These have been dated between 77-24 Ma on the basis of not very reliable K/Ar determinations;

II. Orientation between N130° and N220°, with average elongation at N17° (29 stations);

III. Average trend N240° (29 stations). These have been linked to the opening of the Bransfield Rift.

The three sets of joints (I to III) have been reported by Tokarski (1987) as cutting through the lower structural unit, while only sets II and III cut the middle unit.

As pointed out by Tokarski (1987), interpretation of set I as related to the episode of subduction of the Aluk (Shetland) Microplate under the Antarctic Plate presents some difficulties, as joints developed in this tectonic setting are horizontal ($\sigma3$ vertical) with $\sigma1$ parallel to the direction of subduction (N140°). Set II was associated by Tokarski (1987) with the interval of reorganization of plates during the transition between subduction and left lateral strike slip movement; $\sigma1$ and the associated joints then rotated clockwise from N105° to N240° (see below). Finally, set III was interpreted by him as resulting from rifting during opening of the Bransfield Strait.

Additional data. During field work the orientation of 140 joints and faults cutting the Polonez Cove and the underlying Mazurek Point Formations was measured, along a distance of approximately 2 km, between Low Head and Mazurek Point, in the central portion of King George Island (Fig. 1). Data obtained refer only to the lower (Mazurek Point Formation; Krakowiak Glacier and Low Head Members, Polonez Cove Formation), and middle (Siklawa and Oberek Cliff Members, Polonez Cove Formation) structural units of Tokarski (1987). (Fig. 1.)

Three sets of joints (A, B and C) could be recognized. Their pattern of intersection allows the interpretation of their relative chronology, as follows (from older to younger):

A) Subhorizontal joints with subvertical calcite fibers ($\sigma3$) occur in the Oberek Cliff Member (Fig. 9). In the underlying Siklawa Member, subhorizontal shear planes with tension gashes are associated with the joints. Three shear directions oriented N105°, N135° and N10° could be measured, one of them parallel to the direction of displacement of the Pacific Plate (N140°);

B) Subvertical joints and faults ($\sigma1$-$\sigma2$) trending between N100°–N130° with calcite fibers ($\sigma3$) subhorizontal and elongated roughly normal to the joint planes;

C) Subvertical joints and faults oriented N50°-N70°, with calcite fibers ($\sigma3$) horizontal and elongated at N140°.

In spite of the limited number and restricted geographical distribution of the data, a preliminary scheme of geodynamic evolution of the area is proposed.

— The first set of joints and faults with subvertical minimum stress ($\sigma3$) points out to a compressional episode not yet identified in the area. This compressional phase may have resulted from the subduction of a portion of the Pacific Plate, north of the Hero transform fault, below the Antarctic Peninsula Plate. Magnetic anomaly data (Roach, 1978; Barker & Dalziel, 1983) place the end of this subduction at about 5 Ma (Late Miocene). Movement of the Pacific Plate was slightly oblique to the subduction zone or trench, generating a series of dextral strike slip faults.

— A first extensional episode has $\sigma3$ oriented around N40° at a small angle (~ 20°) with the suture trend. The origin of this deformation is not yet well understood, but it may be associated with post-collision shearing and opening of the Scotia Sea.

— A second extensional episode trending around N60°-70°, may be more safely related to the opening of the Bransfield Rift that separates the Antarctic Peninsula from the South Shetland Islands. Rifting of the Bransfield is differently dated as having initiated in the Late Oligocene (Birkenma-

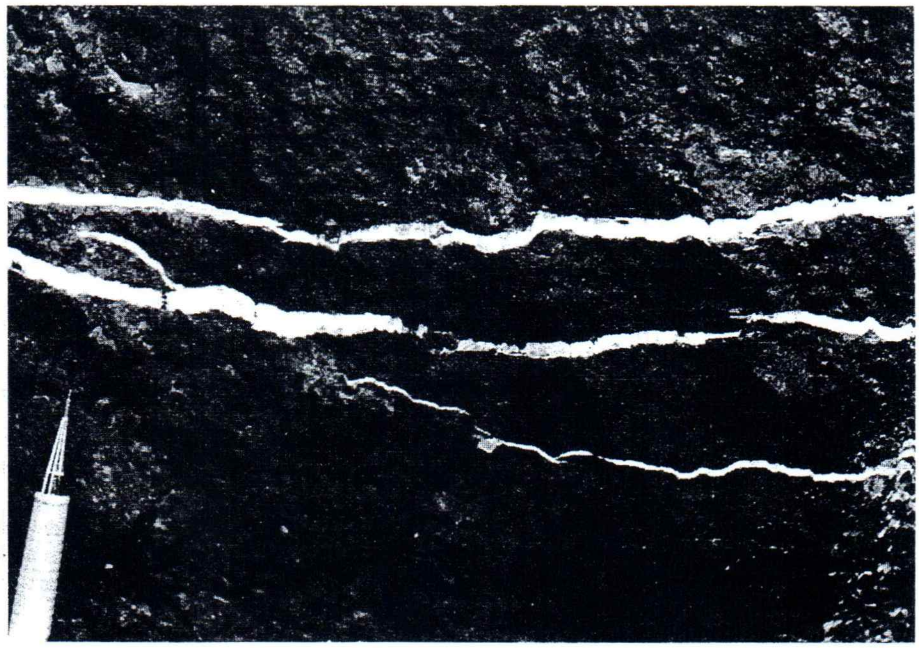

Fig. 9 — Horizontal, calcite-filled joints cutting through the Oberek Cliff Member (north of Station 8 in Porebski & Gradzinski, 1987).

jer, 1992) or Pliocene-Pleistocene (Jeffers *et al.*, 1991).

CONCLUSIONS

The relatively limited number of data obtained allows only preliminary conclusions to be drawn at this stage:

The horizontal orientation of the first set of joints (A) seems more clearly related to the subduction phase of the Aluk (Shetland) Microplate. This offers a possible solution to the difficulties pointed out by Tokarski (1987), who associated the vertical joints of his set I to subduction. As pointed out by many authors (*e.g.* Nakamura & Uyeda, 1980; Huchon, 1983), horizontal joints occurs typically in this type of geodynamic setting;

The oldest horizontal set of joints measured is well represented in stratified facies of Tokarski's middle structural unit, but has not been identified in the more massive basalts and basaltic breccias of the lower one. This strongly suggests that development of a set of joints may be dependent on lithology. Establishment of a relative chronology of the strata by using the presence or absence of a particular set of joints is, therefore, questionable.

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SUMMARY

Some preliminary results of a review of the Tertiary glacial sediments of King George Island, South Shetland Islands, West Antarctica, are presented on the basis of field work performed in the Austral summer of 1993 between Low Head and Lions Rump, King George Bay.

Interpretation of a glacial origin for the sediments of the Krakowiak Glacier Member (Polonez Cove Formation, Early Oligocene) is supported by the finding of striae on top of the underlying basalt of the Mazurek Point Formation (Cretaceous). Orientation of the striae towards N316°-326° is consistent with previously deduced sense of movement of glaciers

which reached King George Island during the Polonez glaciation.

Dominant facies types are lenticular or tabular, mostly channelized bodies of coarse sandy, normal- and reverse-graded, matrix-supported conglomerates, sandy diamictites, and sandy mudstones. Contacts are sharp or difuse, often marked by concentration of clasts. Strata are also separated by thin intercalations of fine-medium, massive, graded or micro-cross-laminated sandstone. Oversized clasts are abundantly dispersed in the sediments; stringers of fragments of marine fossils also occur.

No evidence of deposition of basal tillite associated with the advance of the grounded ice was found. The general sedimentary setting seems to have been a shallow submarine fan built up in front of a retreating grounded ice margin. Deposition was fast, predominantly by sediment gravity flow processes, including high density turbidity current and debris flow. Rafting from icebergs seems to have been common. Sandstone interbeds record pauses between successive dense flows with reworking by wave action. Penecontemporaneous deformation of strata, mostly by density loading, and sedimentary steepening is ubiquitous.

Structural data collected during field work also helped to test the available model of tectonic evolution of the area. One compressional and two extensional episodes were recognized on the basis of systematic measurement of joints and faults. The compressional episode is related to subduction of the Pacific Plate below the Antarctic Peninsula Plate ending at about 5 Ma; the first extensional episode may be associated with post-collision shear and opening of the Scotia Sea; and the second extensional phase is probably related to the opening of the Bransfield Rift.

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