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U-Pb ages and number of Cenozoic glaciations on King George Island, West Antarctica

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Abstract: King George Island, in the South Shetland Islands, is pre-eminent for containing evidence for potentially up to five Antarctic glaciations, including two Eocene examples. U-Pb ages of zircons in basalts and new field observations are presented for the glacial units. Following the disproval of the Eocene Kraków Glaciation, the so called 'Hervé Cove tillite' was also proposed as the oldest terrestrial glaciogenic sediment in Antarctica, but it does not display any diagnostic features characteristic of glacial till. It is reinterpreted as a (non-glacial) lahar deposit, thus removing all known evidence for Eocene ice on the island. New U-Pb ages on two basalt lavas in the Polonez Cove Formation constrain their eruption to *ca.* 26 Ma (early Chattian) and unambiguously confirm a correlation of the Polonez Glaciation with global oxygen isotope stage Oi2b. Zircon xenocrysts from the same rocks include early Cretaceous, Cambrian, Ediacaran, late Neoproterozoic to early Mesoproterozoic and early Paleoproterozoic ages, mirroring published U-Pb ages on cobbles and boulders from the same formation. They strengthen interpretations that indicate a remarkably distant provenance (*ca.* 3000 km) and extensive ice in the Late Oligocene, early in the development of the Antarctic Ice Sheet. The youngest zircons in a dyke that intrudes the Vauréal Peak tillite (Legru Glaciation) yielded latest Oligocene to earliest Miocene ages (27–23 Ma), However, grains of these zircons are not idiomorphic. They were most probably derived from older rocks and consequently do not determine the age of the intrusion itself. Hence, the age of the Vauréal Peak tillite, the youngest Cenozoic glacial unit on King George Island, remains uncertain. There are thus only three unambiguous Cenozoic (pre-Quaternary) glacial units on King George Island, representing the Polonez, Melville and Legru glaciations.

Keywords: Antarctic, Antarctic Peninsula, glacial history, zircon chronology.

Introduction

Cenozoic ice sheet history in Antarctica began in the late Eocene to early Oligocene when the Tasman Seaway started to open (Kennet and Exon 2004; Lagabrielle *et al.* 2009; Westerhold *et al.* 2020). The Antarctic Peninsula was glaciated possibly as early as the Eocene, and certainly by Oligocene times (Davies *et al.* 2012). However, the timing of opening the Tasmanian Passage and initiation of the Antarctic Circumpolar Current, implicated in the development of continental Antarctic ice, seems to postdate the first glacial episodes in Antarctica inferred from the sedimentary record (Carter *et al.* 2017) and eustatic sea level curves (Miller *et al.* 2020).

Within West Antarctica, King George Island, in the South Shetland Islands, is pre-eminent for containing evidence for potentially up to five glaciations (Birkenmajer 1980, 1982, 1990, 1996). They include two Eocene episodes presented as evidence for the oldest Cenozoic glaciations in Antarctica. One of them, the Kraków Glaciation, dated at 49.5 ± 5 Ma with the K-Ar method by Birkenmajer *et al.* (1986), was disproven by $^{87}Sr/^{86}Sr$ dating of shelly fossils, which yielded Late Oligocene ages (mean age 28.5 ± 0.64 Ma; Dingle and Lavelle 1998). A second Eocene glacial event was described as a Middle Eocene alpine-style glaciation (un-named) is represented by the 'Hervé Cove tillite' and is preserved at only a single locality (Birkenmajer *et al.* 2005). Published isotopic ages

($^{40}Ar/^{39}Ar$) indicate that the age of the 'Hervé Cove tillite' is bracketed between 47.6 ± 0.4 and 48.1 ± 0.2 Ma, thus immediately postdating the early Eocene climatic optimum (Nawrocki *et al.* 2011). Additional SHRIMP U-Pb zircon dating confirmed the age of one of the Ar-dated samples from the host lavas, *i.e.*, 48.9 ± 0.7 Ma; (Nawrocki *et al.* 2010). Although the diagnostic characteristics that support its supposed glacial origin have never been published, leading to skepticism about the validity of their origin (Davies *et al*. 2012; Smellie *et al.* 2021a), it has never been disproven and continues to be cited in syntheses of Antarctic ice history (*e.g.* Barker 2007; Anderson *et al.* 2011; Galeotti *et al.* 2022).

By contrast, deposits linked to the much better-known Oligocene Polonez and Melville glaciations are exposed widely on eastern King George Island and are well documented as a result of numerous investigations (Birkenmajer 1982; Porębski and Gradziński 1987; Troedson and Riding 2002; Troedson and Smellie 2002; Smellie *et al.* 2021b). Abundant erratics within the associated Polonez Cove Formation indicate a provenance that includes the South Shetland Islands, Antarctic Peninsula and other localities in the Transantarctic Mountains, *ca.* 3000 km away, making it one of the geographically most extensive glaciations in Antarctica (Birkenmajer *et al.* 1985; Birkenmajer and Weiser 1985; Dingle and Lavelle 1998; Gaździcki 2008). U-Pb isotope ages obtained on a variety of the erratics confirm the widespread and distant provenance (Nawrocki *et al.* 2021). However, despite abundant marine fossils in the Polonez Cove Formation, it has proven difficult to determine an unambiguous age for the Polonez Glaciation from fossils alone and a general early to middle Oligocene age is normally assumed (Gaździcka and Gaździcki 1986). The Polonez Cove Formation contains interbedded volcanic units (Porębski and Gradziński 1990), which have yielded an imprecise mean age of 26.64 ± 1.43 Ma (Late Oligocene) leading to the suggestion that the Polonez Glaciation represents the Oi2b isotope event (Miller *et al.* 1991 Troedson and Smellie 2002; Smellie *et al.* 2021b). Somewhat older $^{87}Sr/^{86}Sr$ ages of 28.5–29.8 Ma have also been determined on shelly fossils in the formation (Dingle *et al.* 1997; Dingle and Lavelle 1998).

Glaciomarine sedimentary rocks also crop out on King George Island at Cape Melville, representing the Melville Glaciation (Birkenmajer 1982; Birkenmajer *et al.* 1985; Dingle and Lavelle 1998; Troedson and Riding 2002). Dating of hornblende in a tuff interbedded with the Cape Melville Formation provided an imprecise age of 21.25 ± 3.14 Ma (Smellie *et al.* 2021b) that is close to the $^{87}Sr/^{86}Sr$ age of 22.6 ± 0.4 Ma obtained on skeletal carbonate from the upper part of the formation (Dingle and Lavelle 1998). Erratics in the Cape Melville Formation also indicate a remarkably distant provenance comparable to the Polonez Cove Formation (Dingle and Lavelle 1998).

The youngest pre-Quaternary glacial deposit on King George Island is the Vauréal Peak tillite, representing the Legru Glaciation (Birkenmajer 1982; Birkenmajer *et al.* 1989). Although undated, an age *ca*. 25 Ma was inferred based on supposed field relationships with underlying units dated by the K-Ar method (Birkenmajer *et al.* 1989). However, the Vauréal Peak tillite overlies a widespread, profound angular unconformity that mimics the present-day deeply-indented coastline of the island, suggesting a much younger age, estimated as ≤ 10 Ma by Smellie *et al.* (2021b).

In summary, evidence for at least four significant glacial periods may be present on King George Island, excluding the disproven Kraków Glaciation. However, their isotopic ages are not well established despite their importance for documenting and, particularly, understanding the early glacial history of Antarctica. In this short note, we present new U-Pb zircon ages for deposits of two of the four glacial events, *i.e.*, the Polonez Cove Formation and the Vauréal Peak tillite, together with new field observations of the supposed Eocene 'Hervé Cove tillite' and associated Alpine glaciation, and assess the ages and number of undoubted glacial units in King George Island.

Material and methods

Sampling locations are shown in Figs. 1 and 2. Two samples, LK-1 (62.13389ºS, 58.16893ºW) and CR-1 (62.1399ºS, 58.12688ºW), were taken for isotopic dating from basalt lavas in the Polonez Cove Formation (Oberek Cliff Member) at Flabellum Bastion and Battke Point, respectively. In addition, a basaltic dyke intruding the Vauréal Peak tillite was sampled south-west of Harnasie Hill (sample SYR-2, 62.18678ºS, 58.24045ºW).

The lavas of Oberek Cliff Member contain *ca.* 51% SiO_2 and *ca.* 3.2 % of the sum of Na_2O and K_2O (Smellie *et al.* 2021b). Plotted on a total alkalis *vs.* silica (TAS) classification diagram (Le Maitre *et al.* 1989), the composition plots within the basalt field, but in the vicinity of the basaltic andesite field. It should be stressed that the basaltic andesite from the Mount Wawel and Herve Cové sections, *ca.* 10 km and 20 km distant from the outcrops of Polonez Cove Formation provided very similar both the zircon U-Pb and whole rock $^{40}Ar/^{39}Ar$ isotope ages (Nawrocki *et al.* 2011). This fact indicates that zircons crystalized at approximately the same time as the magma coming to the surface and solidifying.

A basaltic dyke intruding the Vauréal Peak tillite belongs to hypabyssal intrusions of the Cape Syrezol Group (Smellie *et al.* 2021b). These intrusions with *ca.* 47% of SiO_2 and *ca.* 3.2 % of the sum of Na_2O and K_2O (Smellie *et al.* 2021b) on TAS classification diagram occupy a central part of the basalt field.

Samples containing zircon grains were analysed using the SHRIMP IIe/MC ion microprobe in the Micro-area Analysis Laboratory of the Polish Geological Institute. Samples for zircon separation were crushed and screened after a thorough examination of the thin sections. Heavy mineral fractions were separated using conventional heavy liquid and magnetic techniques. All separated zircon crystals were hand-picked and mounted in epoxy with zircon standards, polished and documented by transmitted and re-

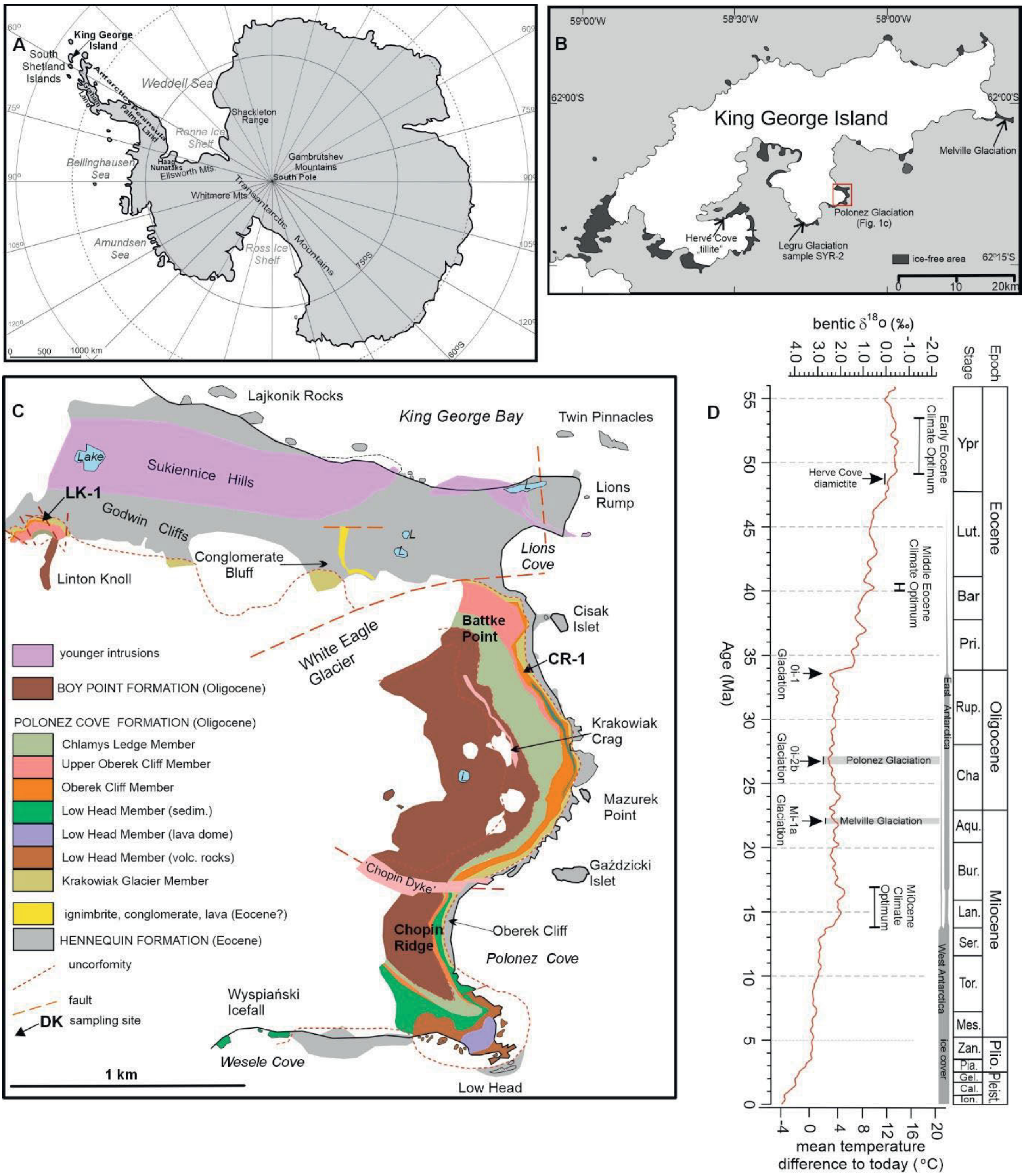

Fig. 1. Geological setting and climatostratigraphy. **A** - Location of the South Shetland Islands and King George Island in Antarctica. **B** - Location of the areas on King George Island discussed in the paper. **C** - Sampling sites in the Low Head–Lions Rump area of King George Island (Polonez Cove Formation); simplified geology after Smellie *et al.* (2021a, 2021b). **D** - Curve of Cenozoic benthic foraminifer $\delta^{18}O$ after Westerhold *et al.* (2020), with significant glacial events for King George Island shown. The age of the Vauréal Peak tillite (Legru Glaciation) is omitted as it is not well defined, see text for explanation.

flected light (optical microscope), and imaged by cathodoluminescence (CL) using a Hitachi SU3500 scanning electron microscope. The zircon standards were 91,500 (U = 78.5 ppm; Wiedenbeck *et al*. 1995, 2004) and TEMORA II ($^{206}Pb/^{238}U$ = 0.06683; Black *et al.* 2003, 2004) and the applied analytical procedure of Williams and Claesson (1987) were used. All analyses were acquired on the outermost rim of each zircon grain or within the core for detrital samples, when rims were not preserved. The following analytical conditions were used: 3 nA negative $O2^-$

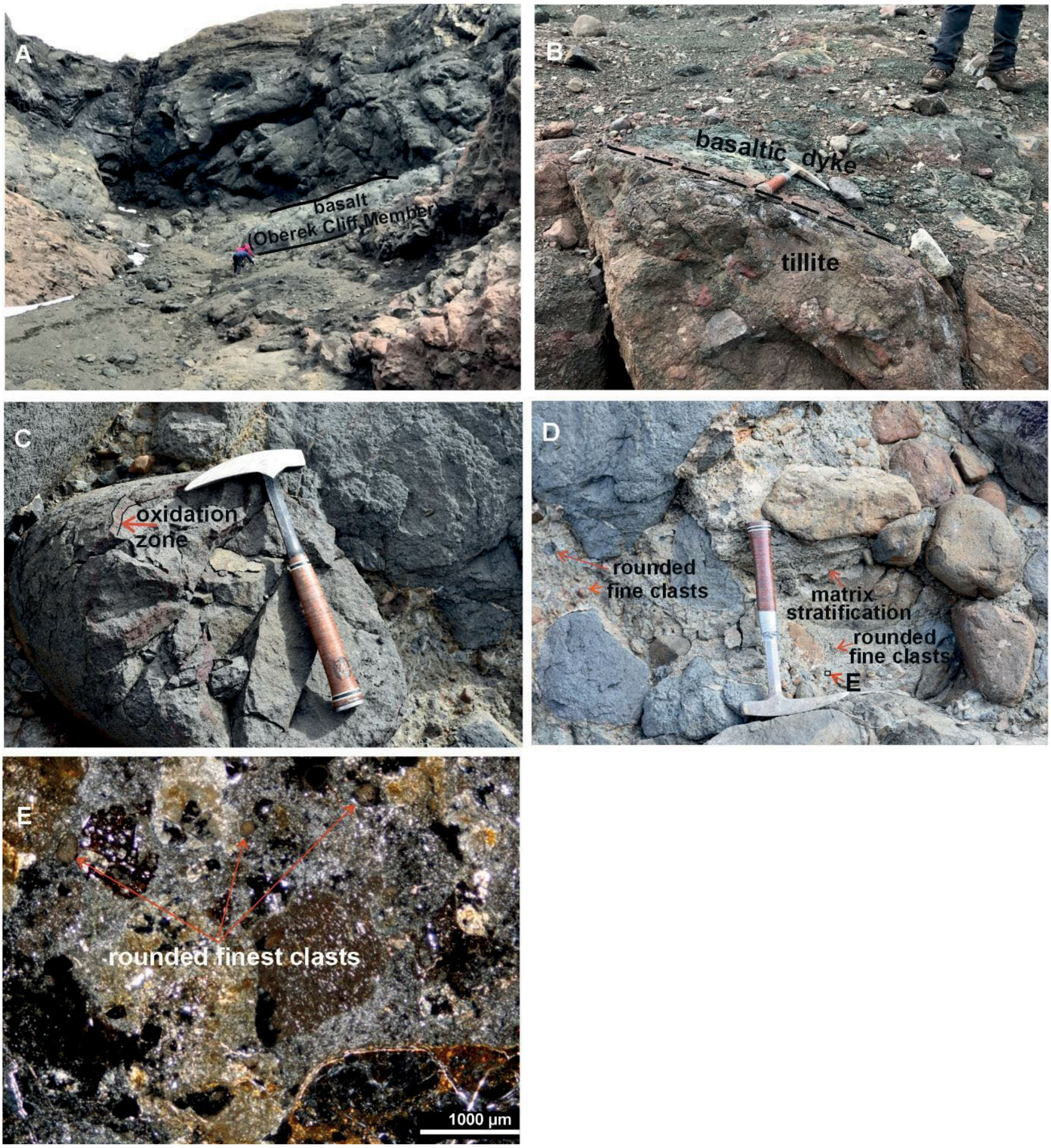

Fig. 2. Images of the examined localities. **A** - Basaltic lava flow within the Oberek Cliff Member (Polonez Cove Formation; Oligocene; Smellie *et al.* 2021b) just south of Battke Point. **B** - Basaltic dyke cutting the Vauréal Peak tillite (late Miocene or younger, Smellie *et al.* 2021b). **C** - Boulder with distinct oxidation rim in the 'Hervé Cove tillite' (Birkenmajer *et al.* 2005). **D** - Rounded clasts and faint restricted stratification in paraconglomerate of the 'Hervé Cove tillite '. **E** - Photomicrograph showing polymict lava clasts and sandy to muddy matrix in the 'Hervé Cove tillite'. The hammer is 31 cm in length.

primary ion beam focused to a *ca.* 25 μm diameter spot; mass resolution *ca.* 5500; isotope ratio measurement by single electron multiplier and cyclic peak stepping. The selected spots were analysed over six scans (^{196}Zr2O - 2s; ^{204}Pb - 5s; $^{204.1}$background - 5s; ^{206}Pb - 15s; ^{207}Pb - 10s; ^{208}Pb - 10s; ^{238}U - 5s; ^{248}ThO - 5s; ^{254}UO - 2s). The TEMORA standard was measured every three spots. All measurements of the zircons were corrected for common Pb content using the measured ^{204}Pb. The ages were calculated using the constants recommended by the IUGS Subcommission on Geochronology (Steiger and Jäger 1977). The SHRIMP results were plotted using ISOPLOT/EX (Ludwig 2012), and include a Tera-Wasserburg plot of ^{238}U/^{206}Pb versus ^{207}Pb/^{206}Pb. In addition, new detailed field observations relevant to the Eocene glaciation represented by the 'Hervé Cove tillite' (Fig. 2C–D) are also presented here.

Results

U-Pb dating

The zircon population separated from the basalt of Polonez Cove Formation (Oberek Cliff Member) sampled at Flabellum Bastion (sample LK-1; 62.13389ºS, 58.16893ºW) is not homogenous and contains slightly rounded crystals, angular crystal fragments and euhedral zircons with prismatic termination. The crystals vary between 60 and 300 µm in length. They display a wide spectrum of textures, including zoned crystals, rare crystals with inherited cores, and metamorphic zircons. In general, the grains are colourless and transparent. Cathodoluminescence images of some of these zircons are shown in Fig. 2A. The euhedral shape of the youngest zircons from sample LK-1 indicates that they date the crystallization of the host rock. Zircons from sample SYR-2 (basaltic dyke, Cape Syrezol Group; 62.18678°S, 58.24045°W) are homogeneous, rounded, better sorted than those in LK-1, and show only faint zoning. The crystals are > 120 µm in length. The zircon population from the basalt of Polonez Cove Formation (Oberek Cliff Member sampled at Battke Point (sample CR-1; 62.13992ºS, 58.12688ºW) contains only rounded and partly rounded crystals. Most of them are small, not exceeding 100 µm in length. They display different textures, from typical magmatic to metamorphic.

Detailed results of the isotopic analyses are listed in Appendix 1. Sample CR-1 did not contain any Eocene or younger zircons. Part of the SHRIMP spots from the youngest zircon population isolated from sample LK-1 gave results that are not concordant. The lower intercepts for this population point to an age of 26.7 ± 0.61 Ma. After rejecting the most discordant results, the calculated concordia age is recalculated as 27.19 ± 0.77 Ma (Fig. 3B). It is noticeable that the ages obtained on all the young zircons are very similar. Samples LK-1 and CR-1 contained several populations of significantly older zircons, the oldest being Mesoarchean (Appendix 1).

Oligocene ages were obtained from three youngest zircons of sample SYR-2 (30.1 ± 3, 27.7 ± 5, and 26.4 ± 0.9 Ma) but the crystals are evidently rounded (Fig. 3C). This shape indicates that they cannot date the crystallization of the host rocks and the studied dyke must be younger than *ca.* 26 Ma.

New observations of the Eocene 'Hervé Cove tillite'

Outcrops described by Birkenmajer *et al.* (2005) as the 'Hervé Cove tillite' crop out at a single locality (Breccia Crag) on the south side of Ezcurra Inlet (Fig. 1B). The outcrop is dominated by interbedded lavas currently assigned to the Point Thomas Formation (Birkenmajer *et al.* 2002; Mozer 2013). Published details are minimal (Birkenmajer *et al.* 2002, 2005). The glacial unit, which is interbedded with the lavas, is described as coarse diamictite up to 65 m thick formed of rounded cobbles and boulders of local lavas together with unspecified 'exotic boulders and debris'. The deposit rests on a very uneven erosional surface, said to be 'scoured' but not photographed or otherwise described, and there are additional features, such as frost-split boulders, fluvial sediments and clastic dykes that, together, suggested a glacial origin. Significantly, the earlier study by Birkenmajer *et al.* (2002) simply regarded the Breccia Crag diamictite as a normal lahar-type deposit.

The sediment is a composed of large to medium (60–10 cm), variably abraded basaltic or andesitic clasts. Most of them are cobbles and boulders surrounded by a sandy to muddy matrix containing dispersed smaller pebble-size clasts, most of which are noticeably rounded (Fig. 2 C–E). Reddish, up to 3 cm thick oxidation rims are present on the surfaces of some clasts (Fig. 2C). Faint traces of stratification are present in the matrix (Fig. 2D). Striations and faceting were not observed on any boulders, nor on the surface underlying the deposit.

Discussion

The U-Pb concordia age of the youngest population of zircons (27.19 ± 0.77 Ma) obtained on a basaltic lava flow in the Oberek Cliff Member of the Polonez Cove Formation clearly indicates that it was emplaced in the early Chattian. The basal unit of the Polonez Cove Formation, *i.e.*, the diamictite-dominated Krakowiak Glacial Member, deposited directly from, and close to, ice of the Polonez Glaciation, should not be substantially older. This is a glaciomarine unit regarded as integral to the Polonez Cove Formation which also includes the basaltic lava dated here.

Smellie *et al.* (2021b) published four somewhat disparate $^{40}Ar/^{39}Ar$ ages for the Polonez Cove Formation varying from 25.9 ± 1.3 to 27.56 ± 0.66 Ma obtained on the Low Head and Oberek Cliff members. A mean age of 26.64 ± 1.43 Ma was calculated as the best estimate for the depositional age of the Polonez Cove Formation, and they linked the Polonez Glaciation with the Oi2b cold event dated at *ca.* 26.7 Ma (Hauptvogel *et al.* 2017). Our new, more accurate U-Pb age for lava within the Oberek Cliff Member strongly supports this conclusion and it is unaffected by the potential loss of argon which often affects $^{40}Ar/^{39}Ar$ ages (Soliani and Bonhomme 1994).

Polonez Cove Formation samples CR-1 and LK-1 also contain numerous significantly older zircon grains. Among them early Cretaceous, Cambrian, Ediacaran, late Neoproterozoic to early Mesoproterozoic and early Paleoproterozoic populations can be distinguished (Appendix 1). The oldest single zircon grain was dated at *ca.* 3.2 Ga. Zircons with the same U-P isotope ages were found in pebbles collected from tillite in the basal Krakowiak Glacier Member (Nawrocki *et al.* 2021). Thus, it is likely that these zircons were derived from the matrix of the basal Polonez Cove Formation tillite, incorporated by mafic magma *en route* to eruption at the surface. It is notable that the same wide range of zircon xenocryst ages were obtained from Eocene to Miocene lavas on King George Island by Xing *et al.* (2025) who attributed them, in part, to derivation

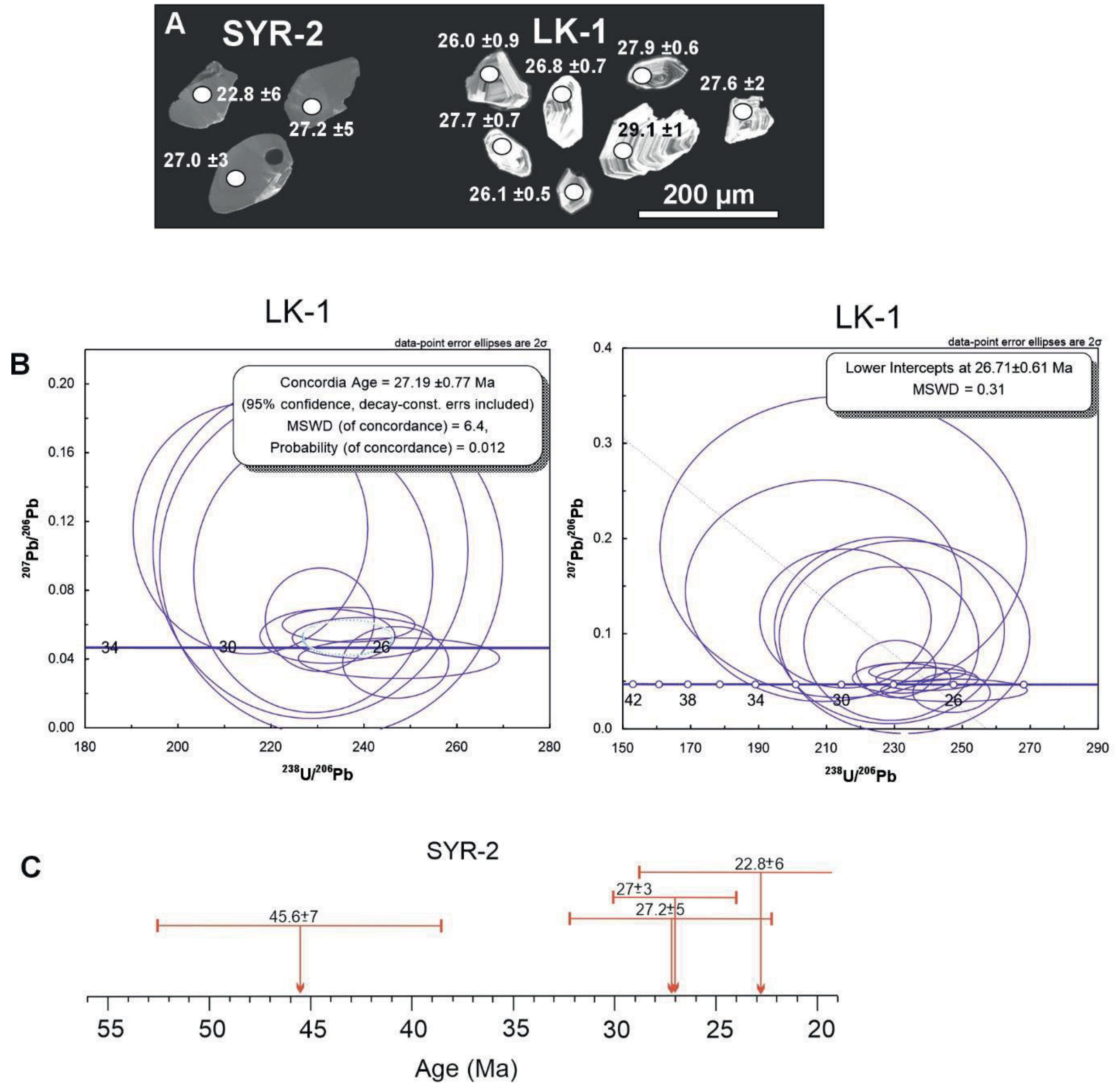

Fig. 3. **A** - Cathodoluminescence images of the youngest zircons from samples SYR-2 and LK-1 with the location of analysed spots shown and isotope ages. **B** - Tera-Wasserburg concordia and lower intercepts diagrams for the youngest zircons from sample LK-1. **C** - U-Pb isotope ages and analytical error bars for the youngest zircons in sample SYR-2.

from a Precambrian basement beneath the island. However, those authors did not take into consideration the possibility of contamination of their magmatic rocks by zircons from older than Eocene clastic deposits of the Antarctic Peninsula supplied with detrital material from the interior of Antarctica.

The youngest zircons found in the basaltic dyke cutting the Vauréal Peak tillite gave latest Oligocene to earliest Miocene U-Pb ages (27.2 ± 5 to 22.8 ± 6 Ma; Fig. 3C; Appendix 1). The grains are not idiomorphic but very well rounded (Fig. 3A) and were obviously derived from older rocks. The new ages are indistinguishable from published $^{40}Ar/^{39}Ar$ ages obtained on hypabyssal intrusions found at Harnasie Hill and Polonez Cove (27.1 ± 1.4 to 21.3 ± 1.6 Ma; Smellie *et al.* 2021b). Hence, the age of the Vauréal Peak tillite (thought to be *ca.* ≤ 10 Ma by Smellie *et al.* 2021b) is still undetermined.

The published evidence cited for the glacial origin of Eocene diamicts at Breccia Crag is unconfirmed. Within the diamictite at the locality, the prevalence of rounded clasts in sandy to muddy matrix, a locally developed weak stratification and a lack of glacial striations on either boulders or underlying substrate are most consistent with an origin as a lahar deposit, as interpreted by Birkenmajer *et al.* (2002) and Smellie *et al.* (2021a). The published isotopic dating indicates that it is *ca.* 49 Ma in age (Nawrocki *et al.* 2011). The absence of non-locally sourced ('exotic') erratics is also notable and all the evidence collectively supports a non-glacial origin for the deposit (Jensen and Wulf-Pedersen 1996), classified as a paraconglomerate.

Conclusions

Although King George Island has been cited as an important repository of multiple, potentially up to five Cenozoic glacial deposits, our study demonstrates that there is evidence for only three chronologically distinct glacial units. The so-called 'Hervé Cove tillite', a diamictite that was previously interpreted as evidence for a mountain-type Alpine glaciation of Eocene age, is a paraconglomerate that lacks any diagnostic glacial features and the lithofacies is much more confidently interpreted as a (non-glacial) lahar deposit. This removes all evidence for pre-Oligocene ice present on King George Island. Our new U-Pb ages unambiguously support a Late Oligocene (*ca.* 26 Ma) age for the Polonez Cove Formation and they substantially strengthen the correlation of the associated Polonez Glaciation with global isotope stage Oi2b. Zircon xenocrysts from the same rocks display early Cretaceous, Cambrian, Ediacaran, late Neoproterozoic to early Mesoproterozoic and early Paleoproterozoic ages, which support the ages of boulder erratics within the Polonez Cove Formation derived from other U-Pb investigations, and confirm the extremely wide geographical extent of the associated ice sheet. Although a basaltic dyke supposedly cutting the Vauréal Peak tillite at Harnasie Hill has yielded zircon grains with imprecise Late Oligocene to earliest Miocene ages, their shapes indicate their derivation from rocks older than the dyke. Consequently, the age of the Vauréal Peak tillite remains unconfirmed.

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Appendix 1. Results of U-Pb dating of zircons from basaltic lavas in the Oberek Cliff Member (samples CR-1 and LK-1) and a basaltic dyke cutting the Vauréal Peak tillite (SYR-2) are available at https://bazadata.pgi.gov.pl/storage/research/jnaw/Appendix-1-KGI-glaciations-Nawrocki-et.al-2025-PPR.zip

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