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# A multi-proxy detrital study from Permian-Triassic fluvial sequences of Victoria Land (Antarctica): Implications for the Gondwanan basin evolution

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A R T I C L E I N F O

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A B S T R A C T

One of the most complete Permian-Triassic fluvial sequences of the Beacon Supergroup, characterizing the infilling of the Transantarctic Basin, is recorded in the Allan Hills in Victoria Land (Antarctica). The multidisciplinary provenance approach carried out in this study includes UPb analysis on detrital zircons, chemistry on detrital mineral phases (garnet and white mica), and sandstone petrography. These, coupled with the data regarding the stratigraphic/sedimentological framework, provide a reconstruction of the geological history of the Permian-Triassic portion of the Beacon Supergroup, showing shifting clastic provenance from different source rocks. Results obtained from this integrated study support a source for the Permian Weller Coal Measures from the local basement, made up of very low- to high grade metamorphic rocks. A compositional shift is recorded with the Lower Triassic Feather Conglomerate, mainly linked with changes in the fluvial style, likely associated with tectonic activity. The Middle to Upper Triassic Lashly Formation shows the main provenance change, supporting a distal source region: the fluvial system received a volcanoclastic input derived from the Permian-Triassic arc located to the east of the basin. The compositional and provenance variations, together with paleocurrent indicators, compared to the coeval units in the central Transantarctic Mountains, allow the reconstruction of the basin evolution and of the changing clastic drainage patterns. Data support the occurrence of articulated sub-basins where alluvial sedimentation settled, in which a morphological-structural divide was represented by the Ross High, separating during the Permian up to the Early Triassic the Victoria Land sub-basin from the main Transantarctic Basin. According to the changed composition of the Lashly Formation sandstones, it appears that in the Middle/Late Triassic, the Ross High was not more a morphological barrier, and that the Victoria Land sub-basin was joined with the Transantarctic foreland Basin.

## 1. Introduction

In the late Paleozoic and Mesozoic, the southern supercontinent Gondwana underwent geological upheavals up to its fragmentation which led to the present-day continental framework: the Permian-Triassic Ellsworth Orogeny and, since Early Jurassic, the emplacement of the Ferrar Large Igneous Province, related with the initial stages of the Gondwana breakup (see Talarico et al., 2022 for a review). Since Devonian up to the Early Jurassic, southern Gondwana hosted widespread sedimentary basins mainly alluvial in environment (i.e. South America, South Africa, India, Australia, and Antarctica basins), which recorded the geological evolution of the supercontinent. Within this framework, East Antarctica was flanking the Panthalassan margin in the far south of Gondwana (Torsvik and Cocks, 2017), and the Transantarctic basin system recorded the regional environmental, climatic, and tectonic evolution in the Permian to Jurassic Beacon Supergroup (Barrett, 1991; Collinson et al., 1994; Elliot, 2013; Elliot et al., 2017).

Rock exposures of these sedimentary successions throughout the Transantarctic Mountains (TAM) have allowed to reconstruct the erosional and depositional history of the basin as well as the assemblage and orogenic evolution (Barrett, 1981, 1991; Collinson et al., 1986, 1994). Provenance studies, mainly based on sandstone petrography,

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highlighted abrupt compositional changes throughout the stratigraphy (Barrett, 1969, 1991; Korsch, 1974; Barrett and Kohn, 1975; Walker, 1980; Vavra et al., 1981; Collinson et al., 1983, 1987; Barrett et al., 1986). Moreover, regional differences in basin fills and transport direction indicate that deposition occurred in separated sub-basins: the most extensive Transantarctic Basin in central TAM, and the Victoria Land sub-basin in Victoria Land (Barrett, 1981, 1991; Collinson et al., 1994). The geodynamic models of the Beacon Supergroup basins have been debated in the literature, with support for either an intracratonic setting (Barrett, 1981, 1991; Woolfe and Barrett, 1995) or a foreland-basin setting (Collinson, 1990; Collinson et al., 1994).The adoption of geochronological technique (i.e., UPb on detrital zircons) allows to constrain the provenance shifts within the Beacon Supergroup and the timing of the magmatic events that produced the source rocks (Elliot et al., 2015, 2016, 2017, 2019; Paulsen et al., 2017; Craddock et al., 2017, 2019; Zurli et al., 2022). Moreover, detrital zircon ages allow to hypothesize that, in the central TAM, the intracratonic basin evolved into a foreland basin in the Permian (Elliot et al., 2017). Sandstone petrology highlighted differences between central TAM and SVL, assuming that the Victoria Land sub-basin may need its own tectonic model, at least for the timing of the events. However, Victoria Land sections thus far lacked detrital geochronological studies needed to strengthen a solid source-to-basin framework. This study provides the first detrital single-grain age dataset and mineral chemical compositions (garnet and white mica) from a Permian-Triassic succession in southern Victoria Land (Allan Hills). The comparison with geochronological signature of outcrop geology, coupled with modern sedimentological and petrographic data (Gulbranson et al., 2020; Cornamusini et al., 2023), allows the reconstruction of the fluvial system catchment area and its evolution through time, which also involve the Permian-Triassic Boundary that represents a global-scale climatic and biotic episode. Comparison with the coeval successions of the CTAM and NVL (Elliot et al., 2015, 2017, 2019; Goodge and Fanning, 2010; John, 2014; Elsner et al., 2013; Bomfleur et al., 2021) allows to corroborate the evolution models proposed for the Transantarctic Basin and the Victoria sub-basin (Collinson et al., 1994).

## 2. Geological setting

Allan Hills is located in the inland flank of the Transantarctic Mountains (Fig. 1), a ca. 3500 km long mountain range developed from Late Cretaceous throughout Cenozoic (Fitzgerald, 2002; Olivetti et al., 2018).

In the Paleozoic to Mesozoic, Antarctica was part of the Gondwana supercontinent. The Beacon Supergroup has been deposited, between Devonian to Early Jurassic, in an elongated basin in the Panthalassan margin of East Antarctica, which occupied the southern part of Gondwana. Through an important erosional surface (i.e., Kukri Erosion Surface), the Beacon Supergroup unconformably lies on the basement rocks referable to the Ross Orogen and rock assemblages from older orogenies (Barrett, 1991; Stump, 1995; Elliot et al., 2016; Goodge, 2020).

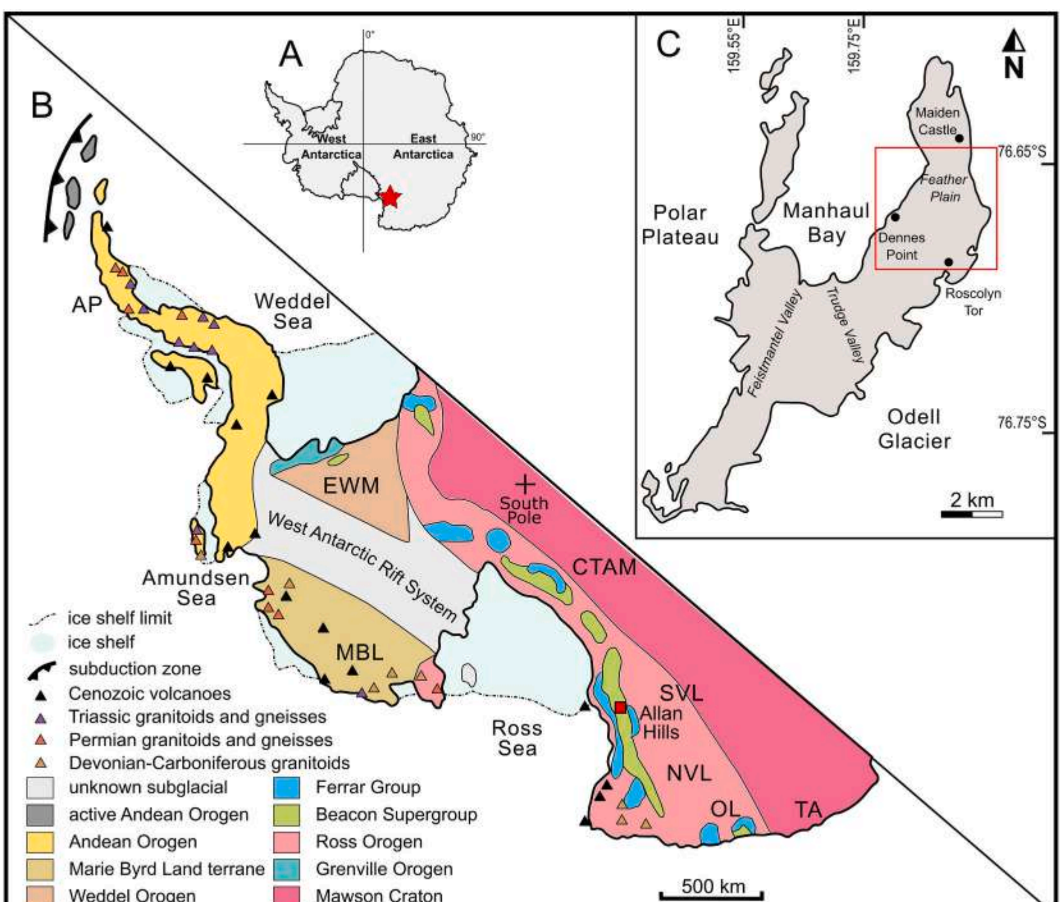


**Fig. 1.** Schematic geological setting of the study area. A) Map of Antarctica; B) schematic geological map of the Transantarctic Mountains sector of East Antarctica and West Antarctica with the main geological provinces (modified from Elliot et al., 2017, 2019; Kleinschmidt, 2021; Talarico et al., 2022). The position of Allan Hills is shown. AP: Antarctic Peninsula; CTAM: Central Transantarctic Mountains; EWM: Ellsworth-Whitmore Mountains; MBL: Marie Byrd Land; NVL: northern Victoria Land; OL: Oates Land; SVL: southern Victoria Land; TA: Terre Adélie; C) Map of the Allan Hills (modified from Cornamusini et al., 2023). Red box shows the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 2.1. Geology of the basement

East Antarctica comprises amalgamated Precambrian cratons (older than 1.5 Ga), which along the TAM are currently exposed in the Nimrod Glacier area where the Mawson Craton crops out (see Stump, 1995; Goodge, 2020; Kleinschmidt, 2021 and Talarico et al., 2022 for reviews). The cratons are flanked by accretionary belts (Fig. 1) which developed since the Mesoproterozoic (i.e., Grenvillian Orogeny, 1300–900 Ma; see Talarico et al., 2022 for an updated review). The oldest rocks of the TAM are the sedimentary and volcanic units formed during the rift margin phase (760–680 Ma) of the Rodinia breakup (Goodge, 2002; Goodge et al., 2002, 2004; Wysoczanski and Allibone, 2004; Cooper et al., 2011), then involved in the Ross Orogeny greenschist to granulite facies metamorphism (Goodge, 2020 and references therein). Since the Neoproterozoic, the rift-margin transformed to a convergent active margin in relation to the Gondwana assemblage (Goodge, 2020); during the early Paleozoic, mainly molasse-like sedimentation occurred, whose deposits along the Gondwana margin were involved in the Ross Orogeny. These rocks, showing a very low-grade metamorphism, constitute part of the Wilson, Bowers, and Robertson Bay terranes in NVL and the Byrd Group in the central TAM. A further correlative of the Robertson Bay Terrane units is the Swanson Formation, which largely crops out in Marie Byrd Land (Bradshaw et al., 1983). At the same time, the Bowers Terrane in the NVL recorded the oceanic-arc volcanism and volcaniclastic deposition, while the central TAM successions preserved well-developed lower Cambrian carbonate platforms (Goodge, 2020). Lower Paleozoic strata lack in southern Victoria Land (Fig. 1).

The convergent margin led to the intrusion of the upper Neoproterozoic to Ordovician batholiths of the Granite Harbour Intrusive Complex (GHIC; Gunn and Warren, 1962). In SVL, pluton emplacement ages range between 520 and 480 Ma, with an acme at 515–505 Ma (Allibone et al., 1993; Cox et al., 2000; Hagen-Peter and Cottle, 2016), while the older Koettlitz Glacier Alkaline Province emplaced between 550 and 530 Ma (Rowell et al., 1993; Hall et al., 1995; Encarnación and Grunow, 1996; Read et al., 2002; Cottle and Cooper, 2006; Cooper et al., 2011; Cox et al., 2012; Hagen-Peter and Cottle, 2016). Evidence of earlier igneous magmatism (590–565 Ma) is provided by glacial erratics in central TAM and Adélie Land (Goodge et al., 2010, 2012; Goodge and Fanning, 2010; Goodge, 2020).

During the Devonian and Carboniferous, plate subduction along the Panthalassan margin of Gondwana led to magmatic activity, recorded in NVL and Marie Byrd Land (Fig. 1). Bowers and Robertson Bay terranes, between 370 and 350 Ma, were intruded by the Admiralty Intrusives coupled with the effusive activity of the Gallipoli Volcanics (Grindley and Oliver, 1983; Vetter et al., 1983; Kreuzer et al., 1981, 1987; Stump, 1995; Fioretti et al., 1997; Henjes-Kunst and Kreuzer, 2003). MBL was involved by magmatism in the Late Devonian to Early Carboniferous (375–345 Ma) with the intrusion of the Ford Granodiorite (Pankhurst et al., 1998; Mukasa and Dalziel, 2000; Siddoway and Fanning, 2009; Yakymchuk et al., 2013, 2015). Upper Carboniferous granitoids and orthogneisses were recorded in eastern MBL and Thurston Island (Pankhurst et al., 1993, Pankhurst et al., 1998) and as a distinct age population in the detrital zircons of Permian-Triassic sandstones (Elliot et al., 2016, 2017). During the Permian and Triassic, the Gondwanide Orogeny reached a peak phase, albeit magmatic outcrops are restricted to the Antarctic Peninsula and MBL (Elliot et al., 2019); however, its extent must have been wider because Permian-Triassic detrital zircons are widespread within the Beacon Supergroup (Elliot et al., 2015, 2016, 2017, 2019; Paulsen et al., 2017).

### 2.2. Beacon Supergroup stratigraphy

Since the Devonian, an elongated epicratonic basin developed where the TAM currently occur (Elliot, 2013). The Devonian part of the Beacon Supergroup is named Taylor Group (Harrington, 1965), and the deposition occurred in alluvial environment with few shallow marine episodes (Barrett, 1981, 1991). The Taylor Group is truncated at the top by the Maya Erosion Surface (Harrington, 1965; McKelvey et al., 1977), which formed an articulated paleomorphology onto which the Late Paleozoic Ice Age tillites, which represent the base of the Permian-Jurassic Victoria Group, were deposited (Isbell et al., 2008, 2012; Isbell, 1999, 2010; Zurli et al., 2022). Deposition passes from initially glaciomarine and glaciolacustrine to alluvial (Barrett, 1991; Collinson et al., 1994). The SVL stratigraphy is begins by the Permian Weller Coal Measures (WCM), a succession of lacustrine to high-sinuosity river deposits characterized by alternation of subarkosic sandstone sheets (feldspatho-quartzose sandstone sensu Garzanti, 2019), coal, and carbonaceous mudstone bodies (Cúneo et al., 1993; Collinson et al., 1994; Isbell and Cúneo, 1996; Gulbranson et al., 2020; Cornamusini et al., 2023). The WCM preserves abundant *Glossopteris* fossil leaf impressions, as well as fossilized logs and woody debris (Townrow, 1967; Cúneo et al., 1993; Tewari et al., 2015; Gulbranson et al., 2020, 2022; Cornamusini et al., 2023); moreover, palynological content constrains the depositional age to Permian (Kyle, 1977; Kyle and Schopf, 1982; Farabee et al., 1990; Askin, 1997), up to Middle-Late Permian (Awatar et al., 2014; Corti, 2021). Through a transitional interval, which recorded the terrestrial end-Permian Extinction event (EPE; Cornamusini et al., 2023), the WCM pass into the Lower Triassic Feather Conglomerate, which represents the deposition of a sandy-braided fluvial system (Barrett and Fitzgerald, 1985; Gulbranson et al., 2020; Cornamusini et al., 2023); the uppermost part of the Feather Conglomerate, the Fleming Member (Barrett et al., 1971), recorded a change of the fluvial style, testifying an higher sinuosity of the river system (Barrett et al., 1971; Cornamusini et al., 2023). The Fleming Member passes upward to the Lashly Formation, which is divided into four members (A to D upwards) on the basis of sedimentological features (Barrett and Webb, 1973; Barrett and Kohn, 1975). Member A features indicate a high sinuosity rivers, which is also characterized by the occurrence of volcanoclastic detritus (Collinson et al., 1983; Cornamusini et al., 2023); palynomorphs of the Fleming Member and Member A of the Lashy Fm constrain their age to the late Early to Middle Triassic (Kyle, 1977; Kyle and Schopf, 1982). An increase in grain size, coupled with the decrease of mudstones, mark a change of the fluvial style during the deposition of Member B, which is represented by a sandy-braided system (Collinson et al., 1983; Isbell, 1990; Gulbranson et al., 2020; Cornamusini et al., 2023). Member B contains abundant fossilized logs, peat, and woody debris (Gulbranson et al., 2020, 2022); palynomorphs constrain its deposition to Middle to Late Triassic (Kyle, 1977; Kyle and Schopf, 1982). The deposition of Member C occurred in the Late Triassic (Kyle, 1977; Kyle and Schopf, 1982) in a meandering fluvial system, which flowed in a highly vegetated alluvial plains (Collinson et al., 1983; Liberato et al., 2017; Gulbranson et al., 2020); *Dicroidium-Heidiphyllum* leaves are preserved within mudstones (Gabites, 1985; Escapa et al., 2011; Gulbranson et al., 2020). In the Allan Hills, the Member D does not crop out, nor does the overlying Lower Jurassic volcanoclastic unnamed unit (Elliot and Grimes, 2011; Unverfärth et al., 2020). The Jurassic Mawson Formation unconformably overlies the Member C in the Allan Hills outcrop and then topped by the Kirkpatrick Basalt (Ballance and Watters, 1971). Jurassic dolerite sills and dykes of the Ferrar Group largely cut the Beacon Supergroup.

## 3. Materials and methods

Analyzed samples were collected in the Allan Hills (Convoy Range), in the northern part of southern Victoria Land (Antarctica) during the 2014–2016 Italian PNRA expeditions, where a Permian-Triassic sedimentary succession extensively crops out. The stratigraphic-sedimentologic framework of the studied section was discussed in Gulbranson et al. (2020) and in Cornamusini et al. (2023). The latter study provide evidence for a conformable sequence along the Permian-Triassic Boundary in the Allan Hills, highlighting the occurrence of a transitional interval with intermediate features between the Permian Weller Coal Measures and the Triassic Feather Conglomerate.

A total amount of 103 sandstone samples was collected from the entire stratigraphic sequence in the Allan Hills (see Cornamusini et al., 2023). Petrographic thin sections of these samples were analyzed following the Gazzi-Dickinson point-counting method (Gazzi, 1966; Ingersoll et al., 1984).

Five fine-medium to medium-coarse, sometimes pebbly, sandstone samples across the sedimentary succession were selected for detrital zircon analysis. In this study, differently from the heavy liquids method (see Andò, 2020), samples were crushed, sieved and the fraction smaller than 230 μm were separated using the water flow procedure adopted by Cheong et al. (2013). Ca. 200 random zircons per sample, in order to avoid as much as possible the bias of the operator, were mounted in epoxy coupled with reference standard zircons - Plesovice (Sláma et al., 2008) for external standard and Z91500 (Wiedenbeck et al., 1995, 2004) for primary standard - and then polished. Mounted grains were analyzed using a scanning electron microscope JEOL JSM-6610 at the Korea Polar Research Institute (KOPRI) to obtain backscattered electrons (BSE) and cathodoluminescence (CL) images which allow the identification of internal chemical zoning, mineral inclusions, and fractures. BSE and CL images were used to identify the best position of analytical spots, avoiding fractures, inclusions, and inherited cores. The U-Th-Pb isotopic analysis was performed at KOPRI with a laser ablation - inductively coupled plasma - mass spectrometer (LA-ICP-MS) using 8.64 J $cm^{-2}$ energy density sets at 5 Hz. Between 135 and 165 grains per sample were analyzed with a ca. 25 μm laser spot for 30 s of background acquisition and 30 s of data acquisition. Primary reference standard zircon (Plesovice) has been analyzed every five unknown grains, while external standard (Z91500) every ten unknown grains. Raw data were elaborated with IgorPro-Iolite (Paton et al., 2011) and VisualAge (Petrus and Kamber, 2012), while Tera-Wasserburg concordia diagrams (Tera and Wasserburg, 1972) and probability density plots were obtained with Isoplot/Ex (Ludwig, 2003). Concordance was calculated using the ratio of the $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages or the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages (Spencer et al., 2016) and the discussion is based only on zircons with a concordance between 85% and 105% (Elliot et al., 2015). The $^{206}Pb/^{238}U$ age has been selected for grains younger than 1 Ga, while the $^{207}Pb/^{206}Pb$ age is adopted for older grains (Estrada et al., 2016).

Mineralogical analyses on detrital garnets and white micas were performed from 11 and 9 samples respectively, distributed along the stratigraphic succession; sandstones range in size from fine-medium grained to medium-coarse and sometimes are pebbly. Analyses were performed both on whole rock thin sections (for white micas and part of garnet samples) and on residual material obtained from the detrital zircon separation process (for the remaining garnet samples); in the latter case, heavy minerals were mounted in epoxy and then polished. Both types of samples were graphite-coated before analysis. Based on garnet abundance within samples, a number of 2 to 61 grains per sample were analyzed, while in the case of white micas, a number of 12 to 80 grains per sample have been analyzed. Analyses were carried out with an energy-dispersive X-ray systems (EDAX DX4 and Thermofisher UltraDry EDS detector) coupled with an electron scanning microscope (Philips XL30 and FEI Quanta 400 respectively) at the University of Siena. Analytical conditions were 20 kV accelerating voltage, 15 μA emission current, 0.1 nA beam current and a beam spot size of 0.2 μm. Natural mineral standards were used for calibration.

## 4. Results

### 4.1. Sandstone petrology

The sandstone composition strongly varies throughout the lithostratigraphy of Allan Hills, implying changes in the source rock supply (Fig. 2).

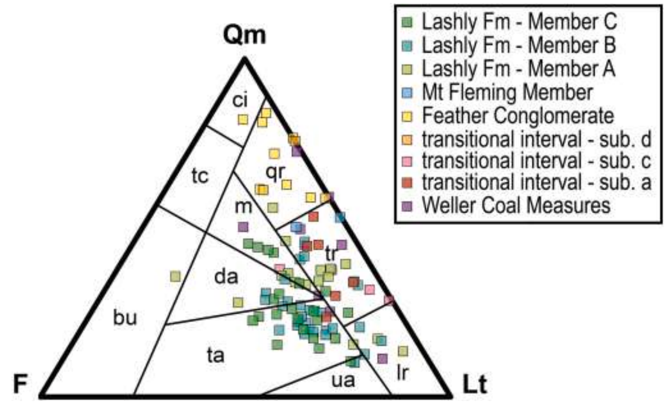


**Fig. 2.** Detrital mode of Allan Hills sandstones according to provenance-oriented ternary diagram of Dickinson (1985). bu: basement uplift; ci: craton interior; da: dissected arc; lr: lithic recycled; m: mixed; qr: quartzose recycled; ta: transitional arc; tc: transitional continental; tr: transitional recycled; ua: undissected arc.

The Weller Coal Measures sandstones, as well as those of the subunits a and c of the transitional interval and the Fleming Member ones, mainly plot in the transitional recycled orogen field of the Qm-F-Lt diagram (Fig. 2). Quartz is the main mineralogical constituent while plagioclase, alkali feldspars, and metamorphic lithic fragments are subordinate (Figs. 2, 3). By contrast, samples from subunit d of the transitional interval and the Feather Conglomerate sandstones indicate an origin from a quartzose recycled orogen; quartz dominates while alkali feldspar (microcline) and metamorphic lithic fragments are rare (Figs. 2, 3). Lashly Formation Member A sandstones show a wide variability from transitional and lithic recycled up to mixed field and dissected arc setting (Fig. 2). Lashly Formation Member B sandstones mainly fall in the transitional arc field, while those of the Member C span from transitional arc to dissected arc up to mixed (Fig. 2). Upper part of Member A, Member B, and Member C of the Lashly Formation sandstones are characterized by abundant volcanic and sub-volcanic grains, mainly felsic in composition and sometimes showing trachytic texture (Fig. 3). Based on petrographic features, grain size and relative abundance of heavy minerals, Cornamusini et al. (2023) mapped the occurrence of different petrofacies along the entire stratigraphic sequence. The latter are shown associated with the stratigraphic log in Fig. 4, while specific descriptions can be found in Cornamusini et al. (2023).

### 4.2. Zircon UPb geochronology

A total of 773 zircons were analyzed, 600 of which fall in the acceptable range of concordance. Analyzed zircons span in age from Mesoarchean to earliest Jurassic/Late Triassic (Fig. 5). The occurrence of few grains younger than the stratigraphic age of the sediments containing detrital zircons is most probably due to radiogenic Pb loss (Elliot et al., 2015).

The Weller Coal Measures sample (26–12-15 C14) is dominated by grains fitting in the Ross Orogen age interval (58%), with the main peaks at ca. 507 Ma and 479 Ma; the second population in abundance ranges in the Grenvillian Orogeny time span (14%) with the main peak at ca. 1080 Ma. 8% of grains are in the Devonian-Carboniferous magmatism time interval (peak at ca. 373 Ma). Archean and Paleoproterozoic grains occur (Fig. 4).

The sample from the lowermost Triassic (28–01-15 C32) at the base of the Feather Conglomerate just on top of the "transitional interval", is mainly constituted by the Ross Orogeny population (peaks at ca. 484 and 497 Ma). Grenville Orogeny time interval includes 14% of the zircons, with the main peak at ca. 997 Ma. Archean-Paleoproterozoic and Carboniferous-Devonian grains are rare (Fig. 4).

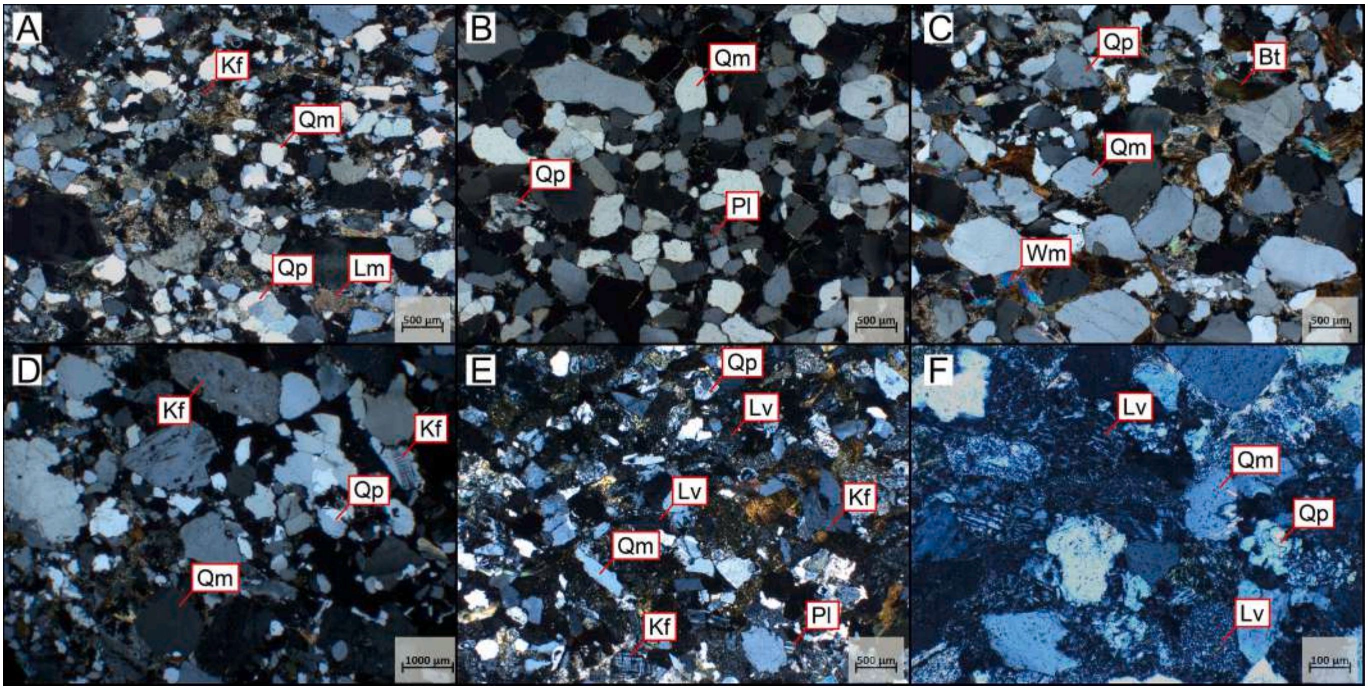


**Fig. 3.** Crossed polarized light microphotographs representative of the Victoria Group sandstones of Allan Hills; the main mineralogical constituent and rock fragments are labelled. A) Weller Coal Measures sandstone; B) Feather Conglomerate; C) Fleming Member of the Feather Conglomerate; D) lower part of the Lashly Formation - Member A; E) Lashly Formation - Member B; F) Lashly Formation - Member C. Bt: biotite; Kf: alkali feldspar; Lm: metamorphic lithic grain; Lv: volcanic lithic grain; Pl: plagioclase; Qm: monocrystalline quartz; Qp: polycrystalline quartz; Wm: white mica.

The sample from the middle-upper part of the Feather Conglomerate (22–12-15 C19) shows a similar trend, with 81% of grains falling in the Ross Orogen age interval, with peaks at ca. 509 Ma and 479 Ma, and a little amount (9%) in the Grenvillian Orogeny time span. Few Archean and Paleoproterozoic zircons occur (Fig. 4).

The sample collected in the middle portion of the Member A of the Lashly Formation (20–12-15 C14) shows the appearance of a Permian-Triassic population, which represents about half of the zircons (48%) with a peak at ca. 235 Ma. The second population in abundance falls in the Ross Orogeny interval (20%) with peaks at ca. 510 and 570 Ma. Devonian-Carboniferous and Grenvillian orogeny populations are poorly represented, forming 6% and 7% of the total number of grains respectively (Fig. 4).

The sample (16–12-15 C3) from the lower Member B of the Lashly Formation has a main peak at ca. 238 Ma, fitting with the Triassic time interval, which includes 35% of the zircons. The Ross Orogeny population is 32% of the total population, with peaks at ca. 504, 567, and 600 Ma. The Grenvillian Orogeny and Devonian-Carboniferous populations are present (11% and 5% respectively) with the main peaks at ca. 1074 Ma and 327 Ma respectively (Fig. 4).

### 4.3. Mineral chemistry

A total of 278 detrital garnet crystals were analyzed from 11 samples and 329 detrital white mica crystals from 9 samples distributed along the Permian-Triassic succession (Fig. 4). Based on chemical composition, samples from the Permian Weller Coal Measures and the “transitional interval” are treated together, forming a unique group; those of the Lower Triassic Feather Conglomerate Fm. including the Fleming Member form another group; the two garnet samples from Member B of the Middle-Upper Triassic Lashly Formation constitute a unique group; samples of the Middle-Upper Triassic Member C of Lashly Formation are considered as a unique group.

Garnets analyzed in the Weller Coal Measures and “transitional interval” samples (Fig. 6) have a low compositional variability and they are mainly Fe-rich (almandine composition) and Mg-poor with variable amount of Ca, even if few Ca-rich crystals (grossular composition) occur. In the ternary diagrams, these data mainly fall in the field of garnet derived from gneiss and amphibolite formed under low- to medium-grade metamorphism (amphibolitic facies), and to a minor extent from the same lithologies under upper-amphibolite/granulite facies. A very few grains derive from felsic to mafic granulites, as well as from intrusive rocks. Detrital white micas show a high compositional variability, and two populations are recognizable (Fig. 4): one clustering around muscovite end-member, while a minor one close to phengitic end-member. The upper WCM and “transitional interval” samples show a marked decrease of the phengitic population.

The garnet crystals analyzed from the Feather Conglomerate samples show a wider compositional variability rather than those of the Weller Coal Measures ones (Fig. 6). They are mainly Fe-rich (almandine composition) with little amount of Mg and variable amount of Ca; few grains are Ca-rich (grossular composition). Most of the grains have amphibolite facies source rocks, similar to those of the Weller Coal Measures, but a little few grains have generated under high-grade, upper-amphibolite/granulite facies, and granitoids rocks (Fig. 6). Only few grains are derived from granulites and/or eclogites. Detrital white mica from Feather Conglomerate and Fleming Member samples shows a low compositional variability and most of the grains form a cluster close to muscovite end-member (Fig. 4).

Garnet crystals in the Member B of the Lashly Formation show a strong compositional change rather than those of the lower samples (Fig. 6). Garnets are mainly Fe-rich (almandine composition) with variable amount of Mg, showing an intermediate composition between almandine and pyrope; crystals are usually Ca-poor. Most of the samples fall in the field of garnet derived from gneisses formed under amphibolite and upper-amphibolite/granulite facies; a considerable number of grains is derived from felsic or intermediate granulites, as well as from intrusive rocks, while from mafic granulites and/or eclogites are almost absent.

In the samples from the Member C of the Lashly Formation, garnets

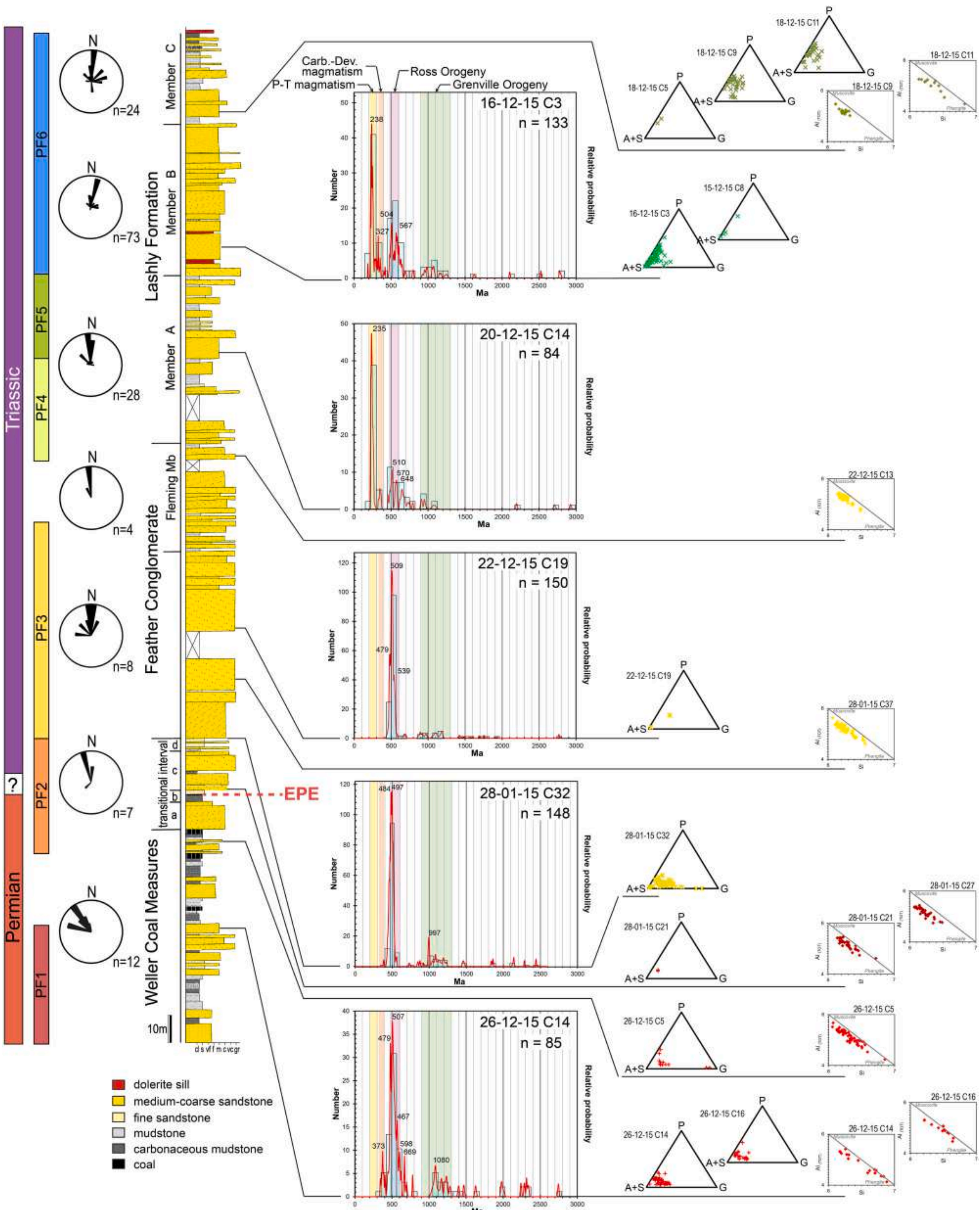


**Fig. 4.** Composite stratigraphic log of the Permian-Triassic succession of Allan Hills with distribution of the analyzed samples; lithostratigraphic units, rose diagrams of paleocurrent directions, and petrofacies (PF) are shown (after Cornamusini et al., 2023). EPE: end-Permian Extinction. U—Pb ages of detrital zircon are shown as histograms and probability density plots; time span of the main events described in the text are shown. Detrital garnet composition of each sample (ternary diagrams) is shown in terms of Pyrope (P), Almandine plus Spessartine (A + S), and Grossular (G) percentage. Detrital white mica composition (binary diagrams on the right) is shown in terms of Si versus Al (atoms per formula units); muscovite and phengite end-members are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

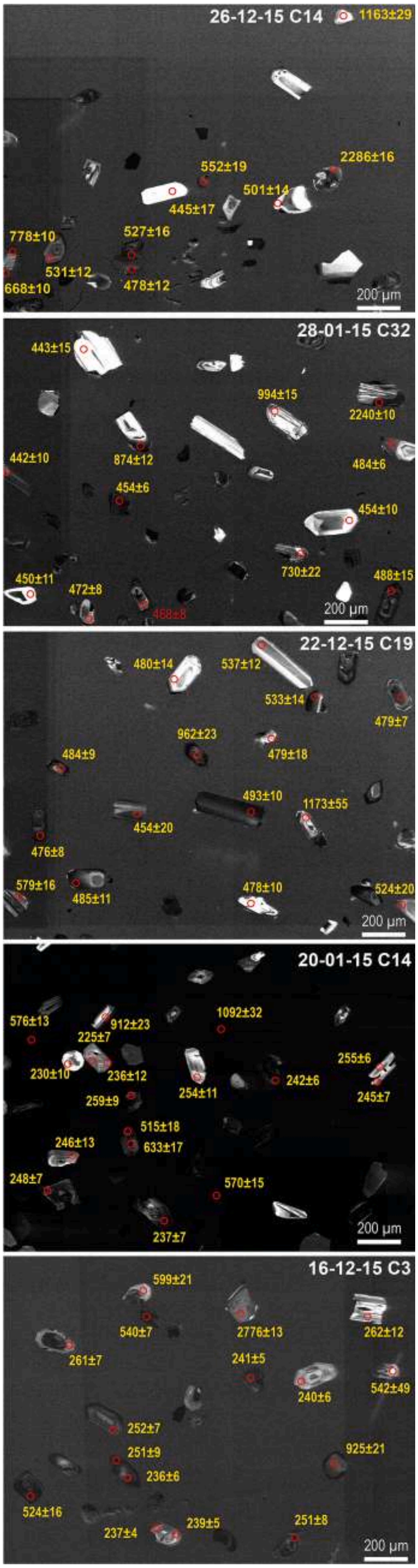


**Fig. 5.** Cathodoluminescence (CL) images of the analyzed zircon samples. The position of the spot analysis for each grain is shown, as well as the UPb age and the associate 2σ error.

show an intermediate composition between almandine and pyrope (Fe and Mg end-member respectively) with a variable content of Ca (Fig. 6). Grains form two distinctive groups: the most numerous derived from felsic to intermediate granulites, while the other, richer in Ca, is compatible with mafic granulites and/or eclogites. Detrital white mica forms a cluster close to the muscovite end-member, even if few grains are close to phengite composition (Fig. 4).

## 5. Discussion

### 5.1. Sandstone provenance

Detrital zircon geochronology, coupled with garnet and white mica mineral chemistry from sandstones suggest three different provenance stages in the Permian-Triassic deposits of the Allan Hills, which well fit with available literature paleocurrents and petrographic data (e.g. Cornamusini et al., 2023). Despite the multianalytical approach carried out in this study, it should be taken into account that the provenance and the contribution of the different source rock hypothesized by geochronological and minero-chemical analyses is qualitative. Indeed, the occurrence of heavy minerals and their concentration in the sedimentary rocks is strongly related with the fertility of the source rocks, hydraulic sorting during sediment transport, and diagenesis effects (Malusà et al., 2016); however, these parameters are difficult to take into account in the studied geological context due to the lack of significant outcrops, extensive ice cover, and the almost total dismantling of some source rocks.

The Permian scenario involves the Weller Coal Measures Fm (Fig. 7). This shows prevalent paleocurrents trending WNW (present coordinates, Collinson et al., 1983; Isbell and Cúneo, 1996, Gulbranson et al., 2020; Cornamusini et al., 2023), i.e. towards present day East Antarctica. Zircon detrital ages from the WCM sample (26–12-16 C14) show a prevalent “Ross Age” population followed by Grenvillian ages and minor Devonian-Carboniferous ages. The possible source rocks that explain this age distribution are:

i) the Granite Harbour Intrusive Complex batholiths which presently crop out extensively in SVL, east of the Allan Hills (Fig. 1) and probably occurring in the West Antarctica flank of the basin at the time of deposition of Permian sandstones. Most of the batholiths cropping out along the TAM yield emplacement ages of 545–480 Ma (Allibone et al., 1993; Rowell et al., 1993; Hall et al., 1995; Encarnación and Grunow, 1996; Cox et al., 2000; Read et al., 2002; Cottle and Cooper, 2006; Cooper et al., 2011; Cox et al., 2012; Hagen-Peter and Cottle, 2016) even if older plutons (590–565 Ma) are inferred from glacial erratics (Goodge et al., 2010, 2012; Goodge and Fanning, 2010; Goodge, 2020);

ii) Paleozoic (meta)-sedimentary sequences (i.e. Robertson Bay Group, Byrd Group, Swanson Formation), which formed a portion of the Gondwana margin. These turbidite successions, which were themselves probably derived from the dismantling of Ross Orogen granitoids, contain detrital zircons of a broader Ross-Age spectrum and Precambrian ages, including Grenville age (Goodge et al., 2004; Estrada et al., 2016; Paulsen et al., 2016; Pankhurst et al., 1998; Ireland et al., 1998; Yakymchuk et al., 2015). These sequences, even if they could be an appropriate source for the Weller Coal Measures zircons, are not currently outcropping in SVL but only in NVL (Robertson Bay Group), MBL (Swanson Formation) and CTAM (Byrd Group). Still, it is probable that a continuation of these low-grade metamorphic terrains could have been present also close to SVL along the flank of the Ross Orogen; furthermore, high-grade equivalents of Swanson Formation rocks, i.e. paragneisses, are cropping out in MBL and show similar zircon spectra as their corresponding low grade units (Yakymchuk et al., 2015). Sandstone composition points towards a transitional recycled orogen (Fig. 2) which is consistent with a source made up of sedimentary and meta-sedimentary units;

iii) The upper Neoproterozoic Skelton Group rocks cropping out in SVL (Cox et al., 2012). These siliciclastic and calcareous

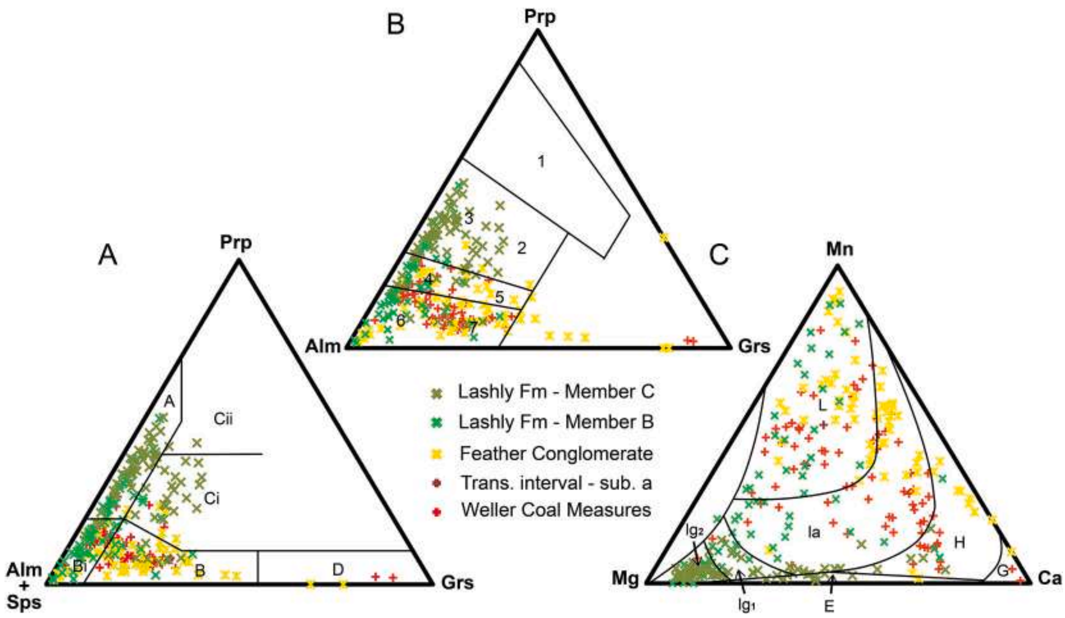


**Fig. 6.** Ternary diagrams used for garnet discrimination. A) Ternary discrimination diagram with proportion of pyrope (Prp), almandine plus spessartine (Alm + Sps), and grossular (Grs) as poles after Mange and Morton (2007) and Krippner et al. (2014). Range A: mainly from high-grade (granulite-facies) metasediments; Range B: mainly from amphibolite-facies metasedimentary rocks; Range Bi: mainly from intermediate to felsic igneous rocks; Range Ci: mainly from high-grade (granulite and eclogite) mafic rocks; Range Cii: mainly from ultramafics rocks with high Mg (pyroxenites and peridotites); Range D: mainly from metasomatic rocks, very low-grade metamafic rocks and ultrahigh temperature metamorphosed calc-silicate granulites; B) ternary discrimination diagram with pyrope (Prp), almandine (Alm), and grossular (Grs) compositions as poles after Aubrecht et al. (2009) and Krippner et al. (2014). Range 1: garnets derived from ultra-high pressure eclogites or garnet peridotites; Range 2: garnets derived from high pressure eclogites and high pressure mafic granulites; Range 3: garnets derived from felsic and intermediate granulites; Range 4: garnets derived from gneisses metamorphosed under transitional upper-amphibolite granulite transition metamorphic facies; Range5: garnets derived from amphibolites transitional upper-amphibolite granulite transition metamorphic facies; Range 6: garnets derived from gneisses metamorphosed under amphibolite-facies conditions; Range7: garnets derived from amphibolites metamorphosed under amphibolite-facies condition; C) ternary discrimination diagram with Mg, Mn, and Ca after Teraoka et al. (1998). L: low-pressure metamorphic and granitic rocks; Ia: amphibolite facies; Ig1 and Ig2: granulite facies; H high P/T; E: eclogite facies; G: grandite.

metasedimentary rocks, overprinted by a greenschist to upper-amphibolite facies metamorphism (Gunn and Warren, 1962; Findlay et al., 1984; Stump, 1995; Cook and Craw, 2001, 2002), have a zircon distribution with a preponderance of Grenville-age grains and minor Paleoproterozoic and Archean components with lack of Ross-age zircons (Wysoczanski and Allibone, 2004; Goodge et al., 2004; Estrada et al., 2016; Paulsen et al., 2016). Hence, these units may have provided Grenville-age and minor older zircons to the WCM sandstones as well as to the Cambrian-Ordovician low-grade meta-turbidites of the Robertson Bay Group, Swanson Formation and correlatives. Furthermore, garnet composition of WCM and of the “transitional interval” samples (Fig. 6) suggest an amphibolite to upper amphibolite/granulite grade felsic and mafic units (i.e. gneisses and amphibolites) as source terrain for Permian strata in the Allan Hills, and the Skelton Group rocks partially have these characteristics;

iv) Devonian-Carboniferous intrusives, currently cropping out in NVL (Admiralty Intrusives, Harrington et al., 1964, 1967, Stump, 1995) and in MBL (Pankhurst et al., 1998; Yakymchuk et al., 2015). These rocks could have provided the few Devonian zircons (peak at 373 Ma) to the WCM, also because it is thought that the suites in NVL and MBL are parts of a single magmatic arc, which was active until Devonian time along the Gondwana margin and therefore could have been still present in the Permian east of the Victoria Land basin (Elliot, 2013). Devonian and Carboniferous detrital grains have also been found in Late Permian strata of the Buckley Formation in the CTAM (Elliot et al., 2017).

In summary, WCM has a detrital zircon signature and a garnet composition that reflects a source terrain composed of GHIC granitoids or more likely Cambrian-Ordovician meta-sedimentary sequences, plus medium-grade lithologies (i.e. Skelton Group or correlatives) and Carboniferous-Devonian igneous rocks. In addition, white mica composition suggests a possible, albeit statistically minor, phengite-rich source. This source terrain, according to the paleocurrent data (Fig. 4), could have been located to the southeast of the basin, towards the region currently occupied by the Ross Sea.

The Early Triassic scenario involves the Feather Conglomerate samples (Fig. 7) which have a relatively young Ross age detrital signature, with a narrow distribution of zircon ages, and very minor Grenville age grains (Fig. 4). This composition, according to the paleocurrent data oriented towards W-NW (Barrett and Fitzgerald, 1985; Cornamusini et al., 2023), suggests a shift in the source rocks from the underlying Permian WCM. This is also reflected in a change in petrographic composition of the sandstones, passing from transitional recycled orogen setting to quartzose recycled orogen (Fig. 2), prevalently arkose and sub-arkose (feldspatho-quartzose sandstone sensu Garzanti, 2019) in WCM to coarser grained quartzarenite and minorly subarkose (quartzose and feldspatho-quartzose sandstone sensu Garzanti, 2019) in the Feather Conglomerate (Cornamusini et al., 2023). The almost exclusive occurrence of a narrow Ross-age peak centered at ca. 484 Ma and 509 Ma for the two Feather Conglomerate analyzed samples suggests that the source rocks of the sandstones could belong to a not far GHIC unit. This is also supported by petrographic composition from this study and from the literature, which reveals a predominance of monocrystalline quartz in its first cycle of erosion (Barrett and Fitzgerald, 1985). The minor Grenville-age population could be ascribed to a small percentage of recycling from underlying successions (WCM and Devonian Taylor Group sandstones), or from a minor input of the Cambrian-Ordovician meta-sedimentary units and/or the Neoproterozoic ones (Goodge et al., 2004; Estrada et al., 2016; Paulsen et al., 2016; Pankhurst et al., 1998; Ireland et al., 1998; Yakymchuk et al., 2015). Garnets are rare heavy minerals in this formation (Cornamusini et al., 2023), but in one sample (28–01-15 C32) at the base of the formation, their composition suggests sources from mainly gneisses of amphibolite metamorphic

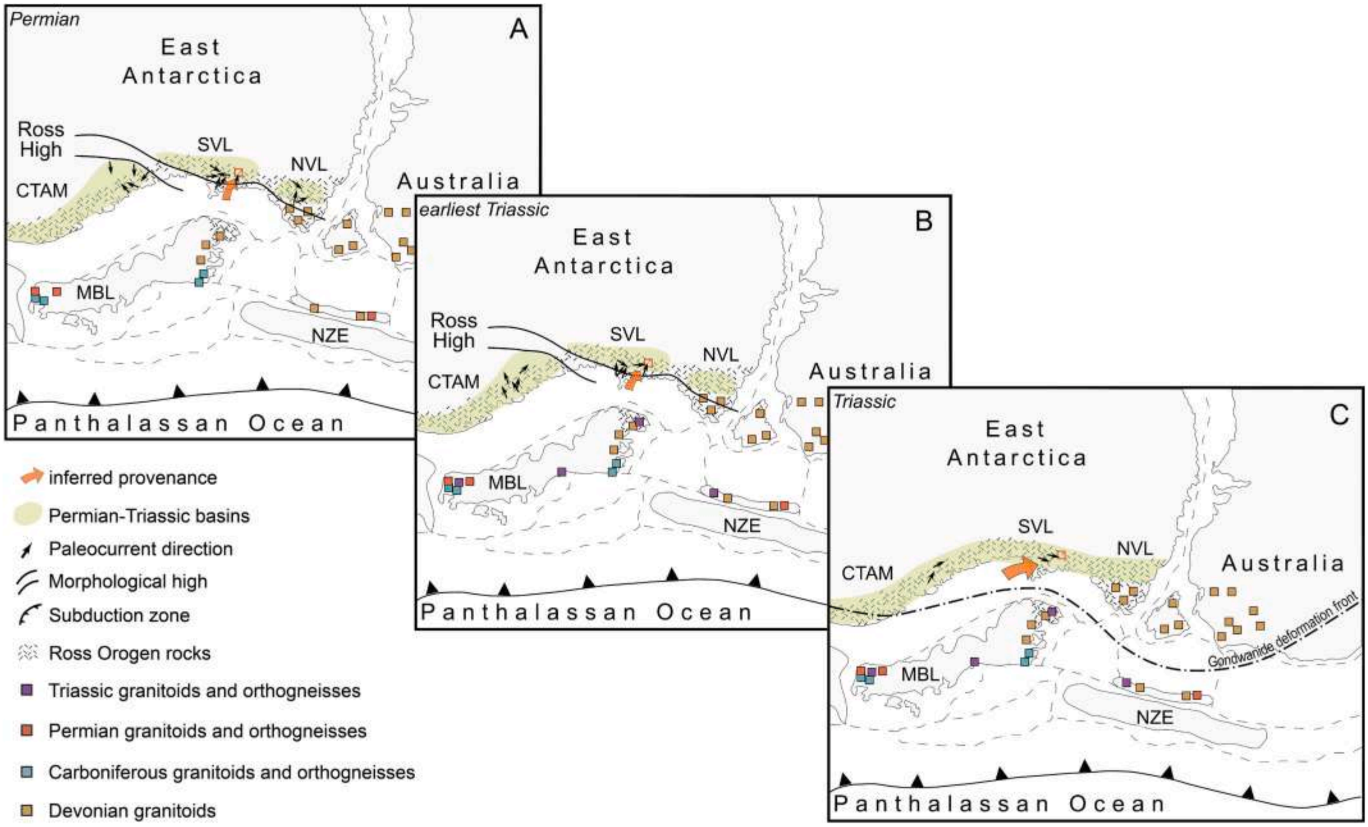


**Fig. 7.** Gondwana reconstruction and evolution of the Victoria sub-basin from Permian to Triassic (modified from Collinson et al., 1994; Elliot, 2013; Elliot et al., 2015, 2017, 2019; Zurli et al., 2022). The red square is the location of Allan Hills. Plutons and metamorphic rock outcrops of different ages discussed in the text are also shown. MBL: Marie Byrd Land; NZE: eastern New Zealand; CTAM: Central Transantarctic Mountains; SVL: Southern Victoria Land; NVL: Northern Victoria Land. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

grade (Fig. 6); based on the stratigraphic position of the sample, this garnet assemblage is in agreement with a reworking from WCM or a direct, albeit minor, erosion from the Neoproterozoic metasedimentary units. A minor but well-defined population of garnets derived from granitoid rocks is also recorded (Fig. 6), supporting the erosion of the GHIC plutons. Instead white mica composition, prevalently muscovites, reveals that metasedimentary units able to provide these minerals were available, albeit as minor sources, in the catchment area of the river system during the deposition of the Feather Conglomerates, supporting the data shown by zircon UPb.

The Middle-Upper Triassic Lashly Formation records the third scenario with a different provenance signature (Fig. 4), both as regards zircon, garnet, white mica, and in agreement with petrographic data by Cornamusini et al. (2023). Paleocurrents trend generally towards N along the formation, with a greater dispersion of data in Member C (Cornamusini et al., 2023). The two investigated samples for zircon geochronology (20–12-15 C14 in the middle of Lashly Member A and 16–12-15 C3 in the lower part of Lashly Member B) show the appearance of a major Permian-Triassic age population (peaks at ca. 235 and 238 Ma, respectively, Fig. 4). This age, together with an abrupt shift in composition of the sandstones suggesting a provenance from a transitional to dissected arc marked by a volcanoclastic detritus input in the sandstone of the Member A, points to a Triassic magmatic arc which could provide zircons of this age associated with volcanic lithic grains to the Victoria sub-basin. This arc, related to the Gondwanide Orogeny, is sparsely documented in West Antarctica with few outcrops (Pankhurst et al. 1993, Pankhurst et al., 1998; Mukasa and Dalziel, 2000; Elliot et al., 2015, 2017, 2019), while it is more evident from Zealandia and Antarctic Peninsula records (Wandres and Bradshaw, 2005; Barbeau et al., 2010). Notably, detrital zircons of Permian-Triassic ages have been found in Victoria Group sandstones from CTAM since the Late Permian (Elliot et al., 2017, 2019; Paulsen et al., 2017) and also from Cenozoic and recent sediments in the Ross Sea, supposed to be fed from present-day West Antarctica regions (Licht et al., 2014; Perotti et al., 2017; Marschalek et al., 2021; Olivetti et al., 2023; Balestrieri et al., 2024). The presence of the Gondwanide magmatic arc as the main source of detrital sediments has been suggested by Collinson et al. (1994), Elliot et al. (2017), and Paulsen et al. (2017) for the CTAM sector at least since the Late Permian. Other zircon populations (Devonian-Carboniferous, Ross, and Grenville ages), in accordance with paleocurrents and the preponderance of a Permian-Triassic source located in West Antarctic sector, could be associated to the Cambrian-Ordovician meta-sedimentary sequences (i.e. Swanson Formation and its equivalent high grade paragneisses) and Devonian-Carboniferous granitoids which could have flanked the Gondwanide arc during the Triassic. It is worth noting the shift of the Devonian-Carboniferous peak from the WCM to the Lashly Formation: the WCM sample shows a ca. 373 Ma Late Devonian peak while the Lashly Member C sample has a ca. 327 Ma mid-Carboniferous peak. The WCM peak is compatible with granitoids cropping out in NVL and MBL (Grindley and Oliver, 1983; Vetter et al., 1983; Kreuzer et al., 1981, 1987; Stump, 1995; Fioretti et al., 1997; Henjes-Kunst and Kreuzer, 2003; Pankhurst et al., 1998; Mukasa and Dalziel, 2000; Siddoway and Fanning, 2009; Yakymchuk et al., 2013, 2015). By Contrast, the Lashly Fm peak is more compatible with Carboniferous rocks that are only known in eastern MBL and Thurston Island (Pankhurst et al., 1993, Pankhurst et al., 1998), which are inferred to be the source of this age population in the Permian sandstones of the Ellsworth Land (Elliot et al., 2016). Garnet composition suggests a prevalent amphibolite to high-amphibolite/granulite felsic source for the Lashly Member B sample and a more evident shift towards granulite (both from mafic and felsic lithologies) and/or eclogite source in the sample at the base of Lashly C member. A Devonian-Carboniferous metamorphic phase of upper amphibolite/lower granulite facies is recorded from paragneisses in MBL (Korhonen et al., 2010; Yakymchuk et al., 2015; Siddoway, 2021) and this is consistent with data from Lashly Member B sample, since it is also associated with zircon data that suggest a common eastern source. Gneisses and low-grade equivalents of the Swanson Formation may have provided at the same time both garnets with higher Mg contents associated with Ross and Grenville age zircons. Instead, possible high grade rocks that experienced an eclogite facies metamorphic stage are present in the Nimrod Glacier region on the cratonic flank of the basin (Nimrod Complex and Argosy Schist in the Miller and Geologists Range; Grindley et al., 1964, Grindley, 1972, Goodge et al., 1991, Goodge and Fanning, 2016, Goodge, 2020, Peacock and Goodge, 1995; Brown et al., 2020, 2021) and in NVL at the tectonic boundary between Wilson and Bower terranes (Lanterman Range, Di Vincenzo et al., 1997, Palmeri et al., 2003, 2007). Interestingly, detrital studies from coeval Beacon strata in NVL show garnets with very similar composition of those found at Allan Hills (Di Giulio et al., 1999; Elsner, 2010; John, 2014). As the paleocurrents during this stage are prevalently directed towards the north, it seems to be unlikely that high-grade rocks from Lanterman Range could have provided detrital sediments deposited in SVL. Rather, they could be more plausible patches of high-grade terranes (likely remnants of Ross Orogeny event) along the eastern flank of the basin, parallel to the front of the Gondwanide arc, or belonging to the western flank, represented by the Nimrod glacier region or similar areas that experienced the same high-grade metamorphism. It cannot be completely ruled out that high-grade metamorphic terranes formed during the Carboniferous-Devonian Orogeny, even if their presence has not yet been demonstrated.

### *5.2. Implications for basin evolution*

The provenance data obtained from this multidisciplinary approach are helpful to propose a reconstruction of the Permian to Triassic basin evolution in the northern part of the SVL and to try to correlate it with that of the CTAM sector.

In the Permian, a source located in the eastern region facing the Victoria sub-basin is compatible with the paleocurrent data and Gondwana margin reconstructions (Fig. 7; Collinson et al., 1994, Elliot, 2013, Elliot et al., 2017). The presence of a Cambrian-Ordovician terrain involved in the Ross Orogeny, intruded by Devonian-Carboniferous batholiths is likely. The patchy occurrence of this kind of basement has been detected in the Ross Sea region (Mortimer et al., 2011; Olivetti et al., 2023), as well as hypothesized also for Lower Permian tillites (Zurli et al., 2022). It is therefore possible that there was an elongated basin in which rivers flowing from the east/south-east eroded this prevalently metamorphic terrain and carried sediments to the present-day Allan Hills position, forming Upper Permian strata (i.e., WCM). As paleocurrents from coeval strata in the Beardmore glacier region (CTAM) show opposite trends compared to those in SVL, a structural high, (named Ross High) dividing the two basins during the late Early Permian time has been proposed by Collinson et al. (1994). This is consistent with data from the WCM that lack volcaniclastic detritus and Permian-Triassic zircons which are instead a very important component since the Late Permian time in CTAM region (Elliot et al., 2015, 2017; Paulsen et al., 2017). This scenario (Fig. 7) is consistent with geochronological and geochemical data here collected for SVL.

The deposition of sandstones belonging to the Feather Conglomerate during Early Triassic marks a shift in data composition. This aspect suggests a change in the source terrain rather than a change of paleocurrents which remain almost the same as in the previous Permian depositional phase (Figs. 4, 7). A prevalently local sourcing with granitic composition is suggested by zircon UPb, sandstone petrology, and general coarsening of grain size: the distribution of coarser grained facies of the Feather Conglomerate is located south/southeast of Allan Hills (Barrett and Kohn, 1975; Barrett and Fitzgerald, 1985), suggesting that some high relief terrain may have been present, taking into account the high energy braided fluvial system. The Ross High could therefore be tectonically active during Late Permian to Early Triassic time (Collinson et al., 1994), which would have favored erosion and deposition in a high energy environment and a reduction of the size of the catchment areas of the fluvial system (Fig. 7). The hypothesis that the Ross High can represent the forebulge region of a foreland basin system active in CTAM and associated with the Gondwanide arc is consistent with its tectonic activity (Collinson et al., 1994). Instead, during the Early to Middle Triassic transition, the shift in sandstone composition (see in Cornamusini et al., 2023), corroborated by UPb zircon data, is evident from almost one third of the thickness from the base of Lashly Member A. This aspect is consistent with the progressive burial of the morphological barrier represented by the Ross High and the connection of the Transantarctic Basin with the Victoria Land sub-basin (Collinson et al., 1994; Elliot et al., 2017). In fact, Middle-Upper Triassic sandstones from CTAM and SVL are lithologically and compositionally similar, with paleocurrents oriented mainly towards the northern sectors and also in SVL began to appear abundantly volcanic lithics in the sandstones, suggesting that the Ross High was no longer an active barrier for the arc-derived detritus (Fig. 7; Collinson et al., 1994). In this time the main source is represented by the magmatic arc at the Gondwana margin, which provided abundant volcaniclastic detritus to the foreland basin. The main axis of the basin was parallel to the front of the Gondwanide arc and paleocurrents in the Allan Hills suggesting that this locality was close to the main axis. Therefore, rivers that mainly drained the eastern flank of the basin, had to flow into a central axis floodplain. However, the progressive enlargement of the catchment area opens up the possibility that sediments could be of mixed source origin and, especially in the axial regions, could come from erosion of both flanks of the basin. This is also suggested by the occurrence of garnets similar in composition to those from the Nimrod glacier area (Peacock and Goodge, 1995), pointing to a possible contribution from the cratonic side of the basin. However, the lack of UPb zircon ages unequivocally referable to the Mawson Craton (> 1.7 Ga; Goodge and Fanning, 2016 and reference therein) as for the sample of Lashly Member B, joined with detrital white mica lacking high-P phengite terms, may lead to hypothesize a contribution from a high-grade source located on the Gondwanide flank of the foreland basin.

In addition, the detrital zircon age for the samples from the Lashly Formation, showing peaks around the Middle/Late Triassic boundary, would indicate a likely Middle/Late Triassic age of deposition. This datum, even if the depositional age could not be strictly defined from detrital minerals, could imply that the age of the Lashly Formation could be more recent than established so far through palynological data by Kyle (1977), Kyle and Schopf (1982) and Awatar et al. (2014), who indicated an age ranging from Early/Middle Triassic up to earliest Late Triassic for the interested stratigraphic interval.

## 6. Conclusions

- A multianalytical study involving detrital geochronology (zircon UPb), mineral chemistry of garnets and white micas, and coupled with sandstone petrology literature data, has been conducted in the Permian-Triassic sequence of the Victoria Group in the Allan Hills, providing new and original data from Gondwana sequences in southern Victoria Land.
- Three distinct provenance signatures revealed by coupling zircon UPb spectra and mineral chemistry have been recognized, also reflected in changes in sandstone petrology.
- During the Late Permian, the Victoria Land sub-basin was prevalently fed by terrains located on the Gondwana margin flank, while contemporaneous deposition in CTAM region suggests that a structural high, namely the Ross High, separated the Transantarctic foreland basin from the Victoria Land sub-basin.

- Change in composition of sandstones and inferred source regions for Feather Conglomerate deposition points to a tectonically active Ross High at least until the Early Triassic.
- During the Middle to Late Triassic, when the Ross High was no longer active as a morphological barrier, the Transantarctic Basin and the Victoria Land sub-basin merged, and also in SVL the arc active at the Gondwana margin, became the main detrital source for Victoria Group strata, suggesting, as in other region of the margin, a much wider extension of arc-related lithologies than demonstrated by the few sparse outcrops.

## CRediT authorship contribution statement

**Luca Zurli:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Giovanni Pio Liberato:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Matteo Perotti:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Data curation, Conceptualization. **Jusun Woo:** Writing – review & editing, Resources. **Mi Jung Lee:** Writing – review & editing, Resources. **Gianluca Cornamusini:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

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