1 **Miocene Antarctic ice dynamics in the Ross Embayment (Western Ross Sea, Antarctica):**
2 **insights from provenance analyses of sedimentary clasts in the AND-2A drill core**

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15 Abstract

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17 A detailed study of gravel-size sedimentary clasts in the ANDRILL-2A (AND-2A) drill core reveals
18 distinct changes in provenance and allows reconstructions to be produced of the paleo ice flow in
19 the McMurdo Sound region (Ross Sea) from the Early Miocene to the Holocene. The sedimentary
20 clasts in AND-2A are divided into seven distinct petrofacies. A comparison of these with potential
21 source rocks from the Transantarctic Mountains and the coastal Southern Victoria Land suggests
22 that the majority of the sedimentary clasts were derived from formations within the Devonian-
23 Triassic Beacon Supergroup. The siliciclastic-carbonate petrofacies are similar to the fossiliferous
24 erratics found in the Quaternary Moraine in the southern McMurdo Sound and were probably
25 sourced from Eocene strata that are currently hidden beneath the Ross Ice Shelf. Intraformational
26 clasts were almost certainly reworked from diamictite and mudstone sequences that were originally
27 deposited proximal to the drill site. The distribution of sedimentary gravel clasts in AND-2A
28 suggests that sedimentary sequences in the drill core were deposited under two main glacial
29 scenarios: 1) a highly dynamic ice sheet that did not extend beyond the coastal margin and

1 produced abundant debris-rich icebergs from outlet glaciers in the central Transantarctic Mountains
2 and South Victoria Land; 2) and an ice sheet that extended well beyond the coastal margin and
3 periodically advanced across the Ross Embayment. Glacial scenario 1 dominated the early to mid-
4 Miocene (between ca. 1000 and 225 mbsf in AND-2A) and scenario 2 the early Miocene (between
5 ca. 1138 and 1000 mbsf) and late Neogene to Holocene (above ca. 225 mbsf). This study
6 augments previous research on the clast provenance and highlights the added value that
7 sedimentary clasts offer in terms of reconstructing past glacial conditions from Antarctic drill core
8 records.

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11 **Keywords:** provenance, Cenozoic, Ross Sea, sedimentary clasts, ANDRILL

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13 **1. Introduction**

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15 Access to Antarctica's geological record of environmental variability through the Cenozoic is limited
16 by the continent's ice cover. Geological drill cores recovered from the Ross Sea continental shelf
17 and coastal margin of South Victoria Land (SVL) over the past 40 years (Barrett, 2001, 2007;
18 Hambrey et al., 2002; Fielding et al., 2008; Naish et al., 2007, 2009; Harwood et al., 2008-2009)
19 offer a means to examine the region's hidden sedimentary archives. These drill core records
20 provide fundamental paleoenvironmental and tectonic information that, when integrated with
21 seismic data, enable reconstructions to be produced of the glacial climate and tectonic evolution of
22 the region.

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24 Consistent with previous drill cores, the two ANDRILL drill holes have further documented the
25 highly dynamic character of the glacial system in the Southern McMurdo Sound (SMS) area during
26 the last 20 Ma (Naish et al., 2009; McKay et al., 2009; Passchier et al., 2011; Fielding et al., 2011;
27 Del Carlo et al., 2009; Giorgetti et al., 2009; Monien et al., 2012; Talarico et al., 2012; Talarico and
28 Sandroni, 2009, 2011; Sandroni and Talarico, 2011).

1 The SMS project, with the recovered 1138.54 m thick section of the AND-2A drill core, also
2 provided a significant advance in our knowledge of the stratigraphic record in the time window that
3 includes the mid-Miocene climatic optimum (MMCO, ca. 17 to 15 Ma in Zachos et al., 2001) and
4 the onset of major cooling (ca. 14.5 to 13.5 Ma), which is generally interpreted as marking the
5 formation of a quasi-permanent ice sheet in East Antarctica (Marchant et al., 1996; Shevenell et
6 al., 2004; Haywood et al., 2009).

7 The ANDRILL projects and the recovered physical record of past ice fluctuations also led to 3-D ice
8 sheet and ice shelf modelling to simulate Antarctic ice sheet variations during the Plio-Pleistocene
9 and Miocene (Pollard & DeConto, 2009). The numerical modelling played a key role by connecting
10 local variations at the core sites with the larger-scale picture, which involves advances and retreats
11 of the West Antarctic ice sheet and variations in the outlet glaciers of the Transantarctic Mountains
12 (TAM).

13 In this framework, provenance data are one of the very few types of geological evidence that can
14 directly be compared with model predictions of trajectories of the glacier flow from the mouths of
15 the major Transantarctic glaciers to the ANDRILL drill sites near Ross Island, directly connecting
16 the core data with further afield variations. In the AND-2A core data published so far, ice dynamic
17 models, including flow patterns during the ice minima and maxima, were deduced from the
18 basement (crystalline rocks) component in the gravel-fraction (Sandroni and Talarico, 2011;
19 Talarico and Sandroni, 2012; Talarico et al., 2012) and from sand grain modes (Hauptvogel and
20 Passchier, 2012).

21 The research presented here intends to build on these previous findings by adding to the available
22 interpretative frame information and constraints by providing a detailed characterization of the
23 sedimentary clasts, which represent a subordinate but persistent lithological group in the coarse
24 (gravel-size) rock clast record of the AND-2A drill core. Within the framework of numerical models,
25 the new petrographical and distribution pattern data demonstrate the value of sedimentary clasts in
26 terms of contributing new constraints on the Late Cenozoic glacial evolution in the McMurdo Sound
27 region, and, on a larger scale, in the Ross Embayment.

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2. Geological Setting

2.1. Pre-Cenozoic geology of the Southern McMurdo Sound area

The SMS area is characterized by the occurrence of two main structural elements: a 300 km long segment of the TAM and the southern part of the Victoria Land Basin (VLB) (Fig. 1).

The TAM developed in terms of length over about 3500 km, and constitute a major physiographic and geologic boundary between East and West Antarctica. The geology of the TAM reflects: a prolonged tectonic and sedimentary evolution recorded in a crystalline basement, which is part of the Neoproterozoic Ross Orogen; and an up to 2.5 km thick Devonian-Triassic sedimentary cover (Beacon Supergroup). Both the basement and the cover are intruded on or overlain by sills and volcanic units of the Jurassic Ferrar Supergroup.

The basement of the Ross Orogen in the SMS area (SVL) (Fig. 1) is characterized by metamorphic and magmatic rocks belonging to the Koettlitz Group, the Skelton Group (extended to include the Koettlitz Group in most recent work) and the Granite Harbour Intrusive Complex (Stump 1995 with references therein; Cox et al., 2012). The Koettlitz Group consists of polydeformed lower to upper amphibolite-grade metamorphic rocks exposed between the McKay and Koettlitz glaciers, and includes gneisses, schists, marble, calc-schists, amphibolites, and quartzites (Grindley and Warren, 1964, Findlay et al., 1984, Allibone, 1987), with probable depositional ages as old as 840 Ma (Adams and Whitla, 1991).

The Skelton Group is composed of metamorphic rocks of a mainly greenschist-grade, with dominant metalimestones, metaconglomerates, metasandstones, and subordinate metabasalts (Skinner, 1982; Cook, 2007), which crop out in limited areas around the Skelton Glacier, Mulock Glacier, Mt. Cocks, and Teall Island.

From the late Neoproterozoic to the Ordovician, the metasedimentary rocks of the above two groups were cross-cut by huge volumes of syn- and post-tectonic plutons with later mafic to felsic dike swarms, all of which are collectively attributed to the Granite Harbour Intrusive Complex (Gunn and Warren, 1962; McKelvey and Webb, 1962; Grindley and Warren, 1964; Findlay, 1985; Allibone et al., 1991; Cox and Allibone, 1991; Smillie, 1992). The main rock types that are

1 extensively exposed in this sector of the TAM are different kinds of granitoid and gabbroid,
2 including both undeformed and strongly-sheared varieties (e.g. orthogneisses), as well as a
3 distinctive alkaline-type suite, with alkali-feldspar granite, syenite, and carbonatite (ca. 550-530 Ma,
4 Cooper et al., 1997), which are apparently restricted to the area between the Mulock and Koettlitz
5 glaciers. A suite of mainly deformed granodiorites and tonalites with similar emplacement ages
6 (Stump et al., 2005) is exposed in areas restricted to the Byrd-Darwin glaciers' region and is
7 associated with medium to high grade metasediment (i.e. Horney Fm, migmatites, and
8 paragneisses).

9 The rocks of the basement were deeply eroded, resulting in an important Palaeozoic regional
10 erosional surface called Kukri Peneplain. This separates the Ross Orogen (Stump, 1995; Isbell,
11 1999) from the overlying non-conformable Devonian to Triassic Beacon Supergroup. This last
12 succession, which is a maximum of 2500 m thick and consists mainly of a continental environment,
13 extends for 2500-3000 km over the Ross Orogen from the northern Victoria Land (NVL) to the Ohio
14 Range (Barrett, 1981; Collinson, 1991) and represents the bedrock of the Cenozoic sedimentary
15 successions of the VLB recovered at the Cape Roberts CRP-3 drill hole (Cape Roberts Science
16 Team, 2001). Moreover, during the Jurassic, the Beacon Supergroup was greatly intruded on by
17 the dolerite of the Ferrar Supergroup, forming a dyke and sill complex (Tingey, 1991). A
18 lithostratigraphic overview of the Beacon Supergroup in the SVL segment of the TAM is shown in
19 Fig. 1c. The Devonian fms (Taylor Group) mainly consist of mature quartz-rich sandstone
20 (quartzarenite and subarkose), particularly for the thickest Beacon Heights Orthoquartzite Fm.,
21 whereas the Permo-Triassic fms (Victoria Group), particularly the Lashly Fm. (Matz et al., 1972;
22 Korsch, 1973), are mainly characterized by more immature feldspathic compositions (arkose,
23 arkosic litharenite).

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26 2.2. Cenozoic geological setting of the Southern McMurdo Sound and the AND-2A drill core

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1 The uplift of the TAM started at 110 Ma as a major result of the onset of rifting in West Antarctica
2 (Fitzgerald et al., 1986; Stern and ten Brink, 1989). The documented uplift history includes a major
3 phase during and after ca. 55 Ma (Gleadow and Fitzgerald, 1987; Fitzgerald, 1992; Stump and
4 Fitzgerald, 1992), but with very low exhumation rates in the Royal Society Range (Wilson, 1999) –
5 the nearest onshore area to the AND-2A drill site - during the last 20 Ma (Zattin et al., 2010, 2014).
6 In the adjacent offshore area, the structural and stratigraphical features of the continental shelf are
7 the result of the evolution of the VLB, which is subdivided into a northern and a southern part and
8 rifted during the Jurassic and developed as an half-graben basin until the Quaternary (Cooper and
9 Davey, 1985; Davey and Brancolini, 1995; Karner et al., 2005). During the Miocene-Quaternary, the
10 sedimentary processes were accompanied by the building of several volcanoes, some of which are
11 still active today (McMurdo Volcanic Group) (LeMasurier and Thomson, 1990; Kyle, 1991).

12 The AND-2A drill core considered in this paper was recovered in the austral season 2007/2008 in
13 the southern VLB, which is flanked to the west by the TAM (i.e. the Royal Society Range) and to
14 the east by the Coulman High. It is filled by a 1500-2000 m thick Eocene to Pleistocene
15 glacial-marine sedimentary succession, which unconformably overlies Paleozoic strata of the Beacon
16 Supergroup (Cape Roberts Science Team, 2000; Barrett, 2007). This shows a west-dipping
17 monocline and is internally subdivided by several unconformities, as revealed by the drilling
18 campaigns and the seismic interpretations (Barrett, 2007, with references therein).

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20 The AND-2A drill core recovered the upper stratigraphic portions of the sedimentary infilling of the
21 extensional southern VLB, and these range from the Early Miocene to the Pleistocene (Harwood et
22 al., 2008-2009; Di Vincenzo et al., 2010). Other drill cores also recovered older sediment (e.g.
23 CIROS-1, Wilson et al., 1998; CRP-3, Galeotti et al., 2012) down to the Upper Eocene strata at the
24 bottom of the basin filling. Fielding et al. (2008) recognized seismic surfaces, interpreted as
25 unconformities, allowing to subdivide the infilling succession into six seismic units (see also Henrys
26 et al., 2007; Harwood et al., 2008-2009; Speece et al., 2010).

27 The succession of the AND-2A core (1138.54 m thick) consists of several lithologies, which are
28 mainly diamictite with occurrences of minor mudstone, siltstone, sandstone, conglomerate and

1 diatomite or volcanogenic strata (Fielding et al., 2008-2009) (Fig. 2). The age model (Acton et al.,
2 2008-2009a) resulted from the integration of magnetostratigraphic reversals (Acton et al., 2008-
3 2009b), diatom data (Taviani et al., 2008-2009), $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ data on bivalves (Marcano et
4 al., 2009) and $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric ages on volcanogenic materials (Di Vincenzo et al., 2010). The
5 succession was subdivided into portions separated by major disconformities (Fielding et al., 2008-
6 2009): a lower portion from the core-bottom up to ca. 775 mbsf that is Early Miocene in age, a
7 middle portion from 775 to 225 mbsf that is Early to Middle Miocene in age, and an upper and
8 lesser chronostratigraphically constrained portion, from 225 mbsf to the top, which is Late Miocene
9 to Pliocene in age.

10 The stratigraphic and sedimentological characteristics of the AND-2A drill core have been detailed
11 by Fielding et al. (2008-2009, 2011) and Passchier et al. (2011). Fielding et al. (2008-2009), on the
12 basis of major lithological and sedimentological features, divided the core into 14 lithostratigraphic
13 units (LSUs), with the recognition of 13 lithofacies. They interpreted the lithofacies as belonging to
14 a wide spectrum of environments, ranging from ice-distal to ice-proximal, which are vertically
15 stacked to form three stratigraphic “motifs”, with related glacial advance-retreat-advance cycles.
16 Thereafter, based on the vertical stacking pattern of the lithofacies, the same authors subdivided
17 the succession into sequences (74 high-frequency sequences and 13 3rd order sequences, *sensu*
18 Catuneanu et al., 2009). They organized these into six stratigraphic “motifs” (1, 2, 3, 4a, 4b and 5)
19 on the basis of the dominant lithologies or facies and their stacking patterns. Passchier et al.
20 (2011) recognized nine facies, organized into three associations, which were representative of
21 particular paleoenvironmental and paleoclimatic conditions.

22 In summary, the most significant and diffuse lithofacies of the core-succession are massive and
23 stratified diamictites, indicating different advancing phases of the glaciers (respectively, from a
24 subglacial/ice-proximal glacimarine to a more distal glacimarine environment) and characterizing
25 the 1 and 2 “motifs” of Fielding et al. (2011). In contrast, the bioturbated mudstone has been
26 interpreted as being indicative of shallow-marine, ice-distal, and warmer conditions (Fielding et al.,
27 2008-2009; Fielding et al., 2011).

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3. Materials and methods

Sedimentary rock clasts larger than 2 mm (granules to boulders) were investigated. With the support of the Antarctic Marine Geology Research Facility (Florida State University, Tallahassee, U.S.A.), they were first counted, logged, and sampled on the basis of their lithologies during the on-ice logging phase and later more extensively during the science-documentation phase. A total of 103,696 clasts (magmatic, metamorphic and sedimentary) were logged, and igneous and metamorphic clasts (358 basement clast samples, i.e. supplied by source areas in the pre-Ordovician crystalline basement) were used to constrain previous regional ice dynamic models (Sandroni and Talarico, 2011; Talarico and Sandroni, 2011).

The petrography and distribution patterns of the sedimentary clasts were partially and preliminarily investigated in Panter et al. (2008-2009) and Cornamusini (2010). For the current research, a total of 111 sedimentary samples were collected along the entire core and prepared for thin-section microscopic examination (Fig. 2), using both an Olympus BX50 polarized microscope equipped with a mechanical stage and an Olympus digital camera. Lithology, dimension and shape were examined for the occurrence depth of each clast. All the samples are currently stored at the Antarctica National Museum – Section of Earth Sciences (Siena, Italy).

4. Results

4.1. Sedimentary clast lithologies, petrography and stratigraphic distribution

The sedimentary gravel clasts in the AND-2A core were grouped as follows into 10 petrofacies (A, A', B, C, D, L, Q, E, K, and K') based on a petrographical analysis:

Petrofacies A – arkose/lithic arkose.

Petrofacies A' – arkosic litharenite.

1 Petrofacies B – quartzarenite.

2 Petrofacies D – subarkose.

3 Petrofacies C – hybrid/mixed arenite (calcareous sandstone).

4 Petrofacies L – microsparite limestone.

5 Petrofacies Q – intraformational volcanic litharenite or breccia.

6 Petrofacies E – intraformational mudstone.

7 Petrofacies K – diamictite (intraformational clasts).

8 Petrofacies K' – conglomerate/very coarse sandstone (intraformational clasts).

9 A detailed petrographical description of all the identified petrofacies is set out in Table 1, and their
10 stratigraphical distribution throughout the core is shown in Fig. 2. Key mineralogical and textural
11 features of the petrofacies are illustrated in Fig. 3.

12 Sedimentary rock clast lithological associations, based on their stratigraphic distribution, allow us
13 to subdivide the sedimentary succession into 13 stratigraphic Sedimentary Petrographic Units
14 (SPUs), which are characterized by specific lithological clast markers or associations (Tab. 2).

15 In general, the most abundant sedimentary rock clast lithologies occurring throughout the core are
16 very coarse to fine sandstone, in particular arkose/lithic arkose, subarkose, and quartzarenite. Also
17 relevant is the amount of diamictite intraformational clasts. The other types occur more rarely and
18 sometimes represent marker-tracking clast lithologies.

19 Sedimentary clasts, like clasts of other lithological compositions (particularly the volcanic ones, see
20 Panter et al., 2008-2009), are common, particularly in the diamictite deposits (facies Dm and Ds of
21 Passchier et al., 2011; facies 7 and 8 of Fielding et al., 2011), which are, in absolute terms, the
22 most abundant type of deposit in the core. Both intraformational and extraformational sedimentary
23 clasts occur mainly in massive diamictites for the upper and lower parts (from the top to ca 250
24 mbsf - m below the sea floor - and from ca 720 mbsf to the bottom) of the core, and in stratified
25 diamictites for the middle part (from ca. 250 to ca 720 mbsf). They are subordinate in other finer
26 deposits.

27 Intrabasinal diamictite and conglomerate clasts (petrofacies K and K' respectively) are widespread
28 in the core (Fig. 2), with the former from the core bottom to ca. 1020 mbsf (SPU 1), and from ca.

1 225 mbsf to the core top (SPUs 12 and 13), where they are dominant, with rare and non-persistent
2 occurrences of other types of sedimentary clast. In the other core sections, they occur in
3 association with other sedimentary clasts, particularly between ca. 745 mbsf and ca. 690 mbsf (K'
4 in SPU 4), ca. 565 mbsf and 540 mbsf (K in SPU 6), and ca. 415 mbsf and ca. 320 mbsf (K' in SPU
5 9). Other uncommon, different intraformational clasts, such as the mudstone of petrofacies E,
6 occur, albeit very occasionally, at ca. 250 mbsf (SPU 11) and ca. 485 mbsf (SPU 7).
7 Extraformational clasts (petrofacies A, A', B, C, D and L) are common throughout the core (Figs. 2,
8 3), with the exceptions of the intervals between the core bottom and ca. 1000 mbsf (SPU 1),
9 between ca. 905 mbsf and ca. 780 mbsf (SPU 3), and between ca. 225 mbsf and the core top
10 (SPUs 12 and 13), where they are substantially lacking. The main concentration of
11 extraformational clasts occurs between ca. 775 mbsf and ca. 415 mbsf (SPUs 4 to 8). Of these, the
12 most abundant and scattered are arkoses, arkosic litharenites, and subarkoses (petrofacies A, A'
13 and D, respectively) between ca. 765 mbsf and 415 mbsf (SPUs 4, 5, upper part of SPUs 6 and 8),
14 whereas quartzarenites and subarkoses (petrofacies B and D respectively) prevail significantly
15 between ca. 645 mbsf and 620 mbsf (lower part of SPU 6), and between ca. 540 mbsf and 480
16 mbsf (SPU 7).
17 Other types of extraformational clast, such as hybrid/mixed arenites (petrofacies C) and
18 microsparite limestones (petrofacies L) (Fig. 3), are very subordinate. These occur in associations
19 (Fig. 2) between ca. 780 mbsf and ca. 650 mbsf (SPUs 4 and 5), whereas the former also occur
20 scattered between ca. 255 mbsf and 225 mbsf (upper part of SPU 11), and the latter between ca.
21 565 mbsf and 555 mbsf (upper part of SPU 6) and ca. 310-315 mbsf (SPU 10).
22 The volcanic breccia and sandstone clasts of petrofacies Q probably represent the intraformational
23 reworking of Cenozoic volcanites and intrabasinal sediment. Their occurrence is rare.

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26 *4.2. Comparison with potential source rock units and provenance inferences*

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1 The sedimentary clasts generally form a subordinate and non-persistent component in the AND-2A
2 clast assemblages. Indeed, the dominant clasts in the gravel-size fraction of the AND-2A
3 succession were sourced from volcanic, intrusive and metamorphic rock units, which previous
4 provenance studies have identified in: the volcanic apparatus of the McMurdo Volcanic Complex
5 (mainly the Mt Discovery – Mt Morning area, Di Vincenzo et al., 2010; Del Carlo et al., 2009; Di
6 Roberto et al., 2012; Nyland et al., 2013), and the crystalline basement of the TAM in the wider
7 region between the Ferrar and Nimrod glaciers (Sandroni and Talarico, 2011; Talarico and
8 Sandroni, 2011; Talarico et al., 2012; Hauptvogel & Passchier, 2012; Zattin et al., 2014) (Fig. 1).
9 As already reported by Cornamusini (2010) and Panter et al. (2008-2009), clasts consisting of
10 diamictite, conglomerate, mudstone (clayey/silty marl) or volcanic breccia probably represent
11 intrabasinal/intraformational reworking processes. In particular, diamictite intraclasts could indicate
12 the intrabasinal reworking of older diamictite strata, whereas microconglomerate intraclasts
13 indicate the intrabasinal reworking of fluvio-glacial deposits. Clayey/silty marl intraclasts, which are
14 often fossiliferous, testify to the reworking of distal glacialmarine deposits (see in Passchier et al.,
15 2011). It is important to note that some of the analyzed diamictite clasts have strong petrographical
16 similarities with “till pellets”, as described and reported by Cowan et al. (2014) in the Pliocene-
17 Pleistocene section of the ANDRILL MIS AND-1B core (Naish et al., 2007, 2009). The
18 sedimentological analysis of this clast component is beyond the scope of this paper, and detailed
19 microtextural investigations are underway on these specific clasts and their host sediment in order
20 to confirm this interpretation.

21 In contrast, all the other types of sandstone claim a derivation from extraformational rock units.
22 They were probably mainly sourced from the dismantling of the Beacon Supergroup, which is
23 exposed in the inner TAM, or from unexposed sedimentary sequences that were eroded by
24 grounded ice sheets or mountain caps along their pathway across either the offshore coastal area
25 (presently covered by the Ross Ice Shelf) or in the back-side of the TAM within the large drainage
26 areas of the main outlet glaciers.

27 Sedimentary rock clasts belonging to petrofacies A, A', B and D (respectively, arkose to arkosic
28 litharenite, quartzarenite and subarkose) are all consistent with a provenance from the Beacon

1 Supergroup (Panter et al., 2008-2009; Cornamusini et al., 2010). Provenance inferences based on
2 crystalline clast lithologies (Sandroni & Talarico, 2011; Talarico & Sandroni, 2011) and heavy
3 minerals (Hauptvogel & Passchier, 2012) indicate that the main source areas for the AND-2A
4 debris were located in a broad region including SVL and the central TAM. When compared to the
5 Beacon Supergroup lithological range of this region, the compositionally less mature sandstones
6 like arkoses and arkosic litharenites are consistent with a provenance from the formations of the
7 Victoria Group or from correlatable formations of the central TAM (Korsch, 1974; Bernet and
8 Gaupp, 2005). Meanwhile, the more mature sandstones, i.e. quartzarenites and subarkoses,
9 indicate sources such as the Taylor Group, particularly the Beacon Heights Orthoquartzite Fm (or
10 correlatable in the central TAM). The present day outcrops of the Taylor Group in the area nearest
11 to the AND-2A drill site are located in the Royal Society Range and the upper Dry Valleys. The
12 Victoria Group occurs more extensively in outcrops closer to the East Antarctic Ice Sheet, such as
13 in the area including the upper Ferrar Glacier and Skelton Glacier (Fig. 1).

14 Particular interest should be paid to mixed carbonate-siliciclastic petrofacies C (hybrid/mixed
15 arenites) and L (microsparite limestones). These petrofacies, and the former in particular, were
16 also reported in the sedimentary clast assemblages in the Oligocene diamictite-rich sections of the
17 CRP2-2A and CRP-3 cores (Settimi et al., 2005). The question remains as to their most likely
18 provenance. In fact, at present, not a single outcrop of limestone or carbonate sandstone is known
19 to be present in the Ross Sea region, with the exception of: very rare, thin carbonate-bearing beds
20 interlayered with sandstone and siltstone of the Lashly Fm. (Walker, 1980) at the top of the Victoria
21 Group in the western Royal Society Range (Lashly Mts., Mt. Crean); and very rare limestone and
22 mixed carbonate-siliciclastic thin beds interlayered within the Aztec Siltstone Fm. at the top of the
23 Taylor Group in the area of the Portal Mountain close to the Skelton Névé, as outlined by
24 McPherson (1975). Alternatively, it could more probably be a derivation from the same sources of
25 Eocene limestone and calcareous sandstone that were reported as erratic boulders in Pleistocene
26 glacial deposits of the McMurdo Sound area (Black Island and Mt. Discovery) (McMurdo Erratics)
27 (Harrington, 1965; Hertlein, 1969). A sequence comprising marine sediment that was originally
28 deposited on a dismantled shallow continental shelf (Landis, 1974; Levy and Harwood, 2000) could

1 be the source of both the McMurdo erratics and the sedimentary clasts recovered from the drill
2 core records discussed herein. Stilwell et al. (1997), in discussing the provenance of Eocene
3 erratics, proposed a source region centered on the Discovery Deep, which is a 1000 m deep
4 elongate depression in front of the Byrd, Mulock and Skelton glaciers (Fig. 1). This source region
5 has been further documented by two independent studies: Paulsen et al. (2011) on the basis of a
6 zircon analysis; and, more recently, Talarico et al. (2014) on the basis of basement clasts
7 associated with the Eocene fossiliferous erratics.

8 In summary, the most likely sedimentary source rock units for AND-2A can be envisaged in the
9 Beacon Supergroup fms from Devonian mature sandstone to Permo-Triassic, less mature,
10 sandstone and possible sources located in the Discovery Deep (i.e. the same source proposed by
11 several authors for the “Eocene McMurdo Erratics”). Integration with provenance data based on
12 basement clasts and heavy minerals indicates that the main outcrops of the Beacon Supergroup,
13 which supplies debris to the AND-2A site, would be located in the SVL segment of the TAM, and,
14 subordinately and mainly during glacial minima periods (Hauptvogel and Passchier, 2012), in the
15 central TAM.

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17 4.3. *Sedimentary clast provenance changes down the core and integration with distribution* 18 *patterns of basement clasts and heavy minerals*

19

20 The distribution of the coarse sedimentary clasts can be integrated with: the distribution patterns
21 of the other clast types (igneous and metamorphic) (Panter et al., 2008-1009; Sandroni & Talarico,
22 2011; Talarico & Sandroni, 2011), and detrital sand grain compositions in the core section above
23 650 mbsf (Hauptvogel & Passchier, 2012). The analysis of the overall distribution patterns reveals
24 several compositional changes, and may highlight different erosional-depositional phases as a
25 result of the complex interplay of the paleoclimatic, paleogeographic, and tectonic changes that
26 occurred in the Ross Embayment in the last 20 My.

1 In this section, we will describe: the sedimentary clast distribution patterns, integrated with
2 datasets provided by previous provenance studies; and the resulting subdivision of the AND-2A
3 core in terms of clast composition/provenance informal sequences (Figs. 2 and 4).

4

5

6 *4.3.1. Sedimentary clast distribution patterns.*

7

8 The identified main sedimentary clast groups indicate a first-order subdivision of the AND-2A
9 core into intervals containing (Fig. 2): i) extrabasinal clasts; ii) intrabasinal clasts; and iii) both
10 extrabasinal and intrabasinal clasts.

11 Extrabasinal sedimentary clasts occur alone or accompanied by minor occurrences of
12 intrabasinal clasts in SPUs 4 to 11. In these units, sedimentary clasts were supplied by the
13 dismantling of both the basement and the Paleozoic-Triassic sedimentary cover (Beacon
14 Supergroup). Among these SPUs, differences can be emphasized on the basis of the relationships
15 among the sedimentary clasts. In particular, SPU11, SPU4 and SPU5 are quite similar, showing
16 reduced Beacon Supergroup involvement and the occurrence of mixed arenites and limestones
17 (Fig. 2), indicating the contribution of mixed carbonate sources.

18 SPU6, SPU7 and SPU8 are characterized by the most important occurrence of sandstone clasts
19 derived from the Beacon Supergroup. In SPU6 and SPU8, arkose and lithic arkose clasts are
20 dominant, indicating a main provenance from the Victoria Group (probably the Lashly Fm.). In
21 contrast, in SPU7 and the lower part of SPU6, quartzarenite and subarkose clasts are dominant,
22 indicating a main provenance from the Taylor Group (Fig. 2). In SPU2, the sedimentary coarse
23 clast drainage is much reduced, with intrabasinal reworking practically absent, whereas the scarce
24 extrabasinal provenance is relative to a generic Beacon Supergroup.

25 The occurrence of intrabasinal clasts has been detected significantly for SPU13, SPU12, SPU9,
26 SPU4 and SPU1 (Fig 2). In particular, SPU13 and SPU12 have the most diamictite intraclasts,
27 which are derived from the intrabasinal reworking of previous diamictites. Differently, SPU9

1 essentially records an intrabasinal reworking affecting the conglomerate or very coarse sandstone
2 deposits.

3 A significant mixed contribution from both extrabasinal (Beacon sandstone, mixed arenite and
4 limestone clasts) and intrabasinal sources (conglomerate clasts) is documented in SPU4 (Fig. 2).
5 This also represents the signal of the first significant involvement of the Beacon Supergroup as a
6 source, indicating a dominant provenance from the Victoria Group and a subordinate contribution
7 from the Taylor Group, as well as from a mixed siliciclastic-carbonate source, similar to SPU5 and
8 SPU11.

9

10

11 *4.3.2. Dataset integration: matching sedimentary clast distribution patterns, with changes in*
12 *basement clasts and detrital sand grain compositions*

13

14 The identified SPUs, when compared to the basement clasts' distribution patterns for the whole
15 AND-2A core (Sandroni and Talarico, 2011; Talarico and Sandroni, 2011) and the heavy mineral
16 record for the uppermost 650 m of the core (Hauptvogel & Passchier, 2012) (Fig. 4), suggest a
17 subdivision of the AND-2A core into three main intervals, each with internal clast
18 composition/provenance informal sequences (Fig. 4) that include a lower interval (from drill hole
19 bottom to ca. 775 mbsf - Early Miocene), a middle interval (ca. 775 to ca. 225 mbsf - Early-Middle
20 Miocene), and an upper interval (from 225 mbsf to the top, Late Miocene to Recent in age).

21

22 The lower interval includes two sequences with distinct clast compositions (Fig. 4). Sequence 1
23 (corresponding to SPU1) is characterized by a marked intrabasinal reworking, with TAM clasts
24 sourced only from the crystalline basement (particularly from the Koettlitz-Blue glacier area).
25 Sequence 2 (corresponding to SPUs 3 and 2 of Fig. 2) shows weak contributions from the Beacon
26 Supergroup (Taylor Group), reduced intrabasinal reworking, and TAM-basement clasts derived
27 from the Skelton-Mulock glaciers area (in massive diamictites), followed by an alternating
28 contribution from either the Skelton glacier or Koettlitz-Blue glaciers area during Ice Rafted Debris

1 (IRD) events in the overlying 900 to 775 mbsf interval.

2

3 The middle interval marks a fundamental change in the clast provenance, with four sequences,
4 including:

5 – Sequence 3 (comprehensive of SPUs 4 and 5 of Fig. 2) with Beacon-sourced clasts (both
6 Taylor and Victoria groups) and the distinctive occurrence of limestone, hybrid/mixed or
7 calcareous sandstone, and intrabasinal conglomerate clasts that are associated with
8 basement clasts mainly sourced from the Skelton-Mulock glaciers area.

9 – Sequence 4 (corresponding to SPUs 6 to 8 of Fig. 2), where intrabasinal clasts occur
10 subordinately, whereas the extrabasinal sedimentary clasts suggest a significant source
11 from the Beacon Supergroup (both Taylor and Victoria groups) associated with basement
12 clasts sourced from the Koettlitz-Blue glaciers area, with reworked clasts from the Skelton-
13 Mulock glaciers' area (Sandroni and Talarico, 2011);

14 – Sequence 5 (corresponding to SPUs 9 to 10 of Fig. 2), where basement clasts with the
15 same provenance as sequence 4 are associated with abundant intrabasinal conglomerate
16 clasts (particularly in SPU9), with only a few Taylor Group or Victoria Group sourced clasts
17 and intrabasinal diamictite clasts. In the uppermost part of the sequence (SPU10),
18 limestone pebbles occur as IRD, and Taylor Group- or Victoria Group-sourced clasts are
19 associated with basement clasts, indicating a provenance from the Koettlitz-Blue glaciers
20 area.

21 – Sequence 6 (SPU 11), with scattered occurrences of Victoria Group-sourced clasts and
22 limestone, and hybrid/mixed calcareous sandstone associated with basement clasts,
23 indicating a major provenance shift to involve the Skelton-Mulock glaciers area.

24

25 The upper interval records another important change in clast provenance, with sequence 7
26 (corresponding to SPU12 and SPU13 of Fig. 2), which is characterized by a major intrabasinal
27 diamictite reworking, having basement clasts documenting dominant drainage from the Skelton-
28 Mulock glaciers area and very few Beacon-sourced (Taylor Group) clasts in the lower part only.

1 In all the sequences, volcanic clasts are the dominant component for the gravel fraction.
2 Petrological and geochronological data (Panter et al., 2008-2009; Di Vincenzo et al., 2010; Di
3 Roberto et al., 2012; Nyland et al., 2013) indicate that they were mainly sourced from the volcanic
4 centres of the Erebus Volcanic Province, which is located to the south of the drill site, and
5 specifically from the area around present-day Mount Morning, where the oldest known volcanic
6 rocks (ca. 19 Ma) are exposed (Kyle, 1990; Martin et al., 2010). However, contributions from
7 possibly older volcanic centres occurring beneath the Ross Ice Shelf (Behrendt et al., 1994, 1995)
8 cannot be ruled out.

9

10

11 **5. Discussion**

12

13 Sedimentary clasts of the lower interval (1138-775 mbsf) are part of a core section documenting a
14 first cold phase (Fig. 4), which is probably part of the Mi1a glaciation (Miller et al., 1996) (ca. 1138–
15 1040 mbsf, 20.2–20.1 Ma), followed by a probably lesser cold phase (ca. 1040-901 mbsf, 20.1–
16 19.4 Ma) and warmer conditions with an ice-distal setting (901- 775 mbsf, 19.4–18.7 Ma).

17 During the deposition of the middle interval (775-225 mbsf), a return to a probable, more ice-
18 proximal environment is recorded in the interval 775–650 mbsf (17.8–17.35 Ma), which possibly
19 correlates to the Mi1b glaciation of Miller et al. (1996). The overlying core section (650–607 mbsf:
20 17.35–17.3 Ma) records a further period of ice retreat, which may be associated with the onset of
21 the Mid-Miocene Climatic Optimum (MMCO). Overlying core sections document (Passchier et al.,
22 2011) an initial phase of a return to glacially-proximal conditions (607–471 mbsf: 17.3–16.7 Ma),
23 ice-distal conditions which may coincide with one of the warmer periods of the MMCO (471–436
24 mbsf: 16.7–16.5 Ma), and again, a record of increasingly ice-proximal and climatically-austere
25 conditions, probably including the Mi2 glaciation of Miller et al. (1996) (436-225 mbsf, 16.5–
26 14.5Ma, and younger).

27 In the upper interval, overlying the middle interval through a marked regional unconformity at 225
28 mbsf (Fielding et al., 2008-2009), a truncated and partial record of a post-14.5 Ma time is

1 composed mainly of amalgamated, ice-proximal diamictite units (Mi3 of Miller et al., 1996), but
2 includes a thick sandstone-dominated interval that is believed to coincide with a regional Early
3 Pliocene relative sea-level highstand at ~5.0–4.0 Ma. (Fielding et al., 2011; Passchier et al., 2011).

4 *5.1. Paleogeographic provenance stages*

5 The changes in clast compositions and their distribution throughout the AND-2A record can be
6 discussed within the interpretative stratigraphic framework provided by Fielding et al. (2011) and
7 Passchier et al. (2011), who identified some distinct stratigraphic motifs and interpreted them as
8 being the result of different paleoenvironmental conditions and relative sea level changes (Fielding
9 et al., 2000): i) massive diamictites related to an ice-proximal glacimarine up to subglacial polar
10 environments; ii) stratified diamictites as the result of proximal glacimarine conditions in the distal
11 portion of grounding-line fans; and iii) finer sediment and minor diamictites, which are related to
12 high-latitude, temperate, wet-based glacial regimes. It is noteworthy that the great majority of the
13 sedimentary clasts occur in diamictite-hosting deposits, although the finer facies are well
14 represented along the succession. Consequently, the erosion and drainage of the sedimentary
15 rock clasts – including also the intrabasinal reworked diamictite and conglomerate clasts – is
16 closely linked to the activity of both cold and warm-based glaciers.

17

18 Following the interpretative frameworks proposed by Fielding et al. (2011) and Passchier et al.
19 (2011), and taking into account ice-flow scenarios proposed by Sandroni and Talarico (2011),
20 Talarico and Sandroni (2011), and Hauptvogel & Passchier (2012), the sedimentary coarse rock
21 clast data and interpretations can be summarized in an evolutionary scenario with five main
22 paleogeographic/provenance stages, which are directly related to the informal sequences
23 described above (Fig. 4).

24

25 Stage 1 (sequence 1, 1138 – 1000 mbsf, ca. 20.2 – 20.05 Ma, early Burdigalian). In this phase,
26 the glacial maxima periods show basement clasts indicating a main drainage from the region of the
27 Koettlitz-Blue glaciers. The sedimentary cover units of the Beacon Supergroup were not involved.

1 On the contrary, the glacial intrabasinal reworking was very significant, affecting diamictites
2 deposited during previous glacial advances.

3

4 Stage 2 (sequence 2, 1000 – 775 mbsf, ca. 19.9 – 18.7 Ma, early-middle Burdigalian). This stage
5 shows the first, very weak, signal of clasts sourced from the Beacon Supergroup (Taylor Group)
6 (between 1000 and 905 mbsf, SPU2). The basement clasts mainly reflect a provenance from the
7 area of the Skelton-Darwin glaciers. Meanwhile, in the core section 950-900 mbsf, these clasts
8 also have a provenance from the region between the Mulock and Byrd glaciers. In the overlying
9 core section (ca 900-800 mbsf), evidence from basement clasts and diamictite clasts indicate
10 several ice-rafted debris events, which are supplied by erosional glacial processes and calving
11 processes in the coastal and valley mouths in the region between the Skelton and Koettlitz-Blue
12 glaciers (Talarico and Sandroni, 2011).

13

14 Stage 3 (sequence 3, 775 – 650 mbsf, ca. 17.8 – 17.35 Ma, middle Burdigalian). This stage is
15 characterized by an increase in the involvement of Beacon Supergroup rock sources (Taylor Group
16 and Victoria Group), and also shows a distinctive contribution from a source of mixed
17 siliciclastic/carbonate sandstone and limestone. The basement clasts indicate main source rock
18 units in the Skelton-Mulock Glacier area and, in the lowermost part of the section (ca. 775-750
19 mbsf), from the region between the Mulock and Byrd glaciers (Sandroni and Talarico, 2011;
20 Talarico and Sandroni, 2011). This provenance region is characterized by glaciers (Byrd, Darwin,
21 Carlyon, Mulock and Skelton glaciers), whose catchments are mainly incised in the Beacon
22 Supergroup and include extensive exposures of the Victoria Group. This scenario could therefore
23 explain the occurrence of both the Beacon Supergroup and the mixed siliciclastic/carbonate
24 sandstone and limestone, independently from the attribution of the latter (as discussed in section
25 4.2) to the Victoria Group or younger Eocene successions located in the Discovery Deep (along
26 the pathway of ice flows from the SVL valleys to the AND-2A drill site area; Fig. 4).

27

1 Stage 4 (sequences 4 and 5, from 650 to 300 mbsf, ca. 17.35 – 15.9 Ma, middle-late Burdigalian).
2 Braided rivers/fan deltas and ice distal open glacimarine environments developed in this phase
3 (Fielding et al., 2011), furnishing a heterogeneous clastic supply. Sandroni and Talarico (2011)
4 have shown that the major basement sources were the Koettlitz and Blue glacier areas, with a
5 variable reworking of debris that was primarily sourced from the Skelton Glacier area. This phase
6 also marks the most significant dismantling of the Beacon Supergroup, with evidence of a
7 contribution from different stratigraphical levels in both the Taylor Group and the Victoria Group.
8 Concomitantly, the intrabasinal reworking significantly increased, almost exclusively interesting
9 older outwash microconglomerates.

10

11 Stage 5 (sequences 6 and 7, from ca. 300 mbsf to the top, <15.9 Ma, Middle-Late Miocene to
12 recent). During this stage, basement clasts were sourced from the Skelton Glacier areas, with a
13 main provenance shift of the source area from the areas closer to the drill site (Koettlitz Glacier) to
14 more distal areas with respect to the previous stage. A similar abrupt change caused a drastic
15 decrease in the contribution from the Beacon sources, with only minor feeding from the Victoria
16 and Taylor groups, accompanied by an initial weak sourcing from mixed siliciclastic/carbonate
17 sandstone and limestone rocks, analogous to *Stage 3*. The intrabasinal reworking, affecting older
18 diamictites, was very significant, with an upward increase.

19

20 In summary, the stratigraphical distribution and provenance of the AND-2A sedimentary clasts
21 provide useful data to reconstruct two contrasting provenance scenarios: 1) a scenario
22 characterized by the involvement of a few sources, with debris sources located in SVL, mainly
23 from glaciers probably located over the Royal Society Range (below 1000 mbsf in the core) and
24 adjacent areas in the Skelton and Mulock catchment areas (in the uppermost ca. 225 m); and 2)
25 a multi-source scenario, where the supply of glacial debris can be identified in the erosion along
26 several outlet glaciers of SVL (documented between ca. 1000 mbsf and 225 mbsf in the core,
27 including the MMCO). In both scenarios a minor contribution from rock sources located in the
28 central TAM is suggested by heavy minerals compositions (Hauptvogel and Passchier, 2012).

1

2 *5.2. Integration of provenance data with other paleoenvironmental proxies*

3 The collected provenance data can be confidently used to highlight a change in the source area,
4 and it is very likely that the two provenance scenarios may have been linked to distinctive
5 paleoclimatic and ice dynamic settings. However, the use of provenance data as a single proxy to
6 reconstruct the ice sheet extent and dynamics is challenging and complicated. Furthermore, links
7 to glacial dynamics may be ambiguous, since the transport of clasts to the drill site can be
8 achieved via a range of mechanisms, including deposition beneath the grounding line, or rainout
9 from ice shelves or debris-laden icebergs. In addition, changes in the clast assemblages may
10 reflect a within-catchment change in the area across which glacial erosion is occurring or might
11 reflect a complete shift in the drainage area.

12 Recent glacier flow-line models (e.g. Golledge and Levy, 2011) suggest that erosion along the TAM
13 outlet glacier catchments may show significant variations in response to climate change.
14 Specifically, under colder conditions (e.g. LGM and today), erosion is more localized, while under
15 warmer conditions (e.g. Pliocene warm period, Miocene Climate Optimum) it occurs across
16 broader regions of the catchment area. In the case of AND-2A sedimentary clasts, integration with
17 previous provenance data suggests that the two provenance scenarios, with their contrasting
18 number and areal extent of involved sources, probably reflect changes in paleoenvironmental
19 conditions, triggering erosion with different degrees of intensity/extent.

20 Figure 4 includes four different glacial scenarios, which show some of the possible
21 paleoenvironmental conditions, ranging from a state of glacial maxima with grounded ice
22 throughout the entire Ross Embayment (Fig. 4A), to scenarios dominated by active calving
23 processes with progressively retreated glaciers and wider open-marine conditions in the Ross
24 Embayment (Fig. 4 B,C, D). The four scenarios can collectively represent different depositional
25 settings, transport mechanisms, and variable levels of erosion, as well as the involvement of
26 several main source areas spanning the TAM segment, including the main outlet glaciers of SVL
27 and the central TAM. We are confident that the four different scenarios can all be documented in

1 distinct core sections of the AND-2A record, and a tentative attribution of the most likely scenarios
2 to the provenance stages based on the AND-2A sedimentary clasts is reported in Figure 4.
3 Consistent with paleoclimate interpretations by Fielding et al. (2011) and Passchier et al. (2011),
4 core sections with a provenance signature involving a few sources, such as the lowermost 140 m
5 (sequence 1, stage 1) and uppermost 225 m of the core (sequence 7, stage 5), are interpreted as
6 glacially-dominated depositional environments that are typical of a cold glacial regime with periods
7 of grounded ice with ice shelves, major ice growth to volumes larger than the present day, and only
8 brief intervals of ice-free coast climatic cooling, glacial expansion and localized erosion (i.e.
9 scenario A or B in Fig. 4).

10 An important feature of these core intervals is the absence of Beacon-sourced debris, whereas
11 associated basement clasts indicate a provenance from the Royal Society Range and areas further
12 to the south (Skelton Glacier). A peculiar feature of this region is the major amount of tectonic
13 exhumation (the TAM front: Gleadow and Fitzgerald, 1987; Fitzgerald, 1992; Zattin et al., 2014),
14 with an estimated erosion of up to 5-6 km of crust. Since the exhumation phases are all distinctly
15 older than the investigated sedimentary record (from the mid-Cretaceous to ca. 30 Ma, but only in
16 some restricted areas), it is very likely that the coastal region of the TAM could have been deeply
17 eroded to the extent that it promoted a partial to complete removal of the Beacon Supergroup
18 cover rocks a long time prior to the deposition of the investigated AND-2A sedimentary record. In
19 this scenario, glacial debris without Beacon-sourced clasts can be related to ice flows that mainly
20 pass across the coastal region where the Beacon Supergroup cover rocks were completely
21 scraped off or channelized in valleys deeply incised in the crystalline basement. This scenario has
22 been reconstructed in several time windows: from the Early Miocene to Middle Pleistocene, based
23 on provenance studies of the composite sedimentary record documented in the ANDRILL drill
24 cores (Talarico et al. 2012; Talarico and Sandroni, 2011). It is similar to the LGM setting (Denton
25 and Hughes, 2000, 2002; Licht et al., 2005).

26

27 In contrast, core section intervals with evidence of a multi-source provenance scenario, e.g.
28 those that include Beacon clasts and local intraclasts and show a mixed or alternating supply from

1 different basement rock units (e.g. sequences 2, 3, 4 and 5; stages 2, 3 and 4), could reflect a
2 change in glacier dynamics in response to a warmer climate, where faster flowing glaciers with
3 wetter basal conditions eroded material along the full length of the outlet glaciers. Furthermore, in
4 core interval from 650 to ~ 300 mbsf, increased ice velocity, erosion rates, and the flux of dirty
5 icebergs from the TAM to the AND-2A site could explain the co-occurrence of Skelton- and
6 Koettlitz-sourced basement clasts, Beacon clasts, and intraclasts.. The resulting possible
7 paleoenvironmental conditions may be represented in combined scenarios C/D or B/C in Figure 4.
8 There is, however, a caveat regarding core intervals ca. 1000-900 mbsf and 775-650 mbsf, namely
9 that a detailed analysis of an integrated proxy environmental dataset (Levy et al., 2016) has driven
10 a revised interpretation of these core sections, suggesting that even the D scenario would be more
11 likely. Following Levy et al. (2016) revision of previous interpretations by Talarico and Sandroni
12 (2011) and Passchier et al. (2011), in these core intervals a scenario, as shown in Fig.4 (A), may
13 be still documented, but only by major unconformities at ca 775 mbsf and ca. 965 mbsf, which are
14 inferred to represent times of ice advance and erosion at the AND-2A site.

15 It is evident that, when compared to scenario A, scenarios without grounded ice in the Ross
16 Embayment, like B, C (only ice shelf) or D, would imply completely different glacial systems, which
17 were able to erode the Beacon Supergroup more extensively. These sections are still well
18 preserved in the inner part of the TAM, which corresponds to the mountain region with the lowest
19 amount of exhumation and erosion (3-1.5 km, Fitzgerald, 1992).

20 According to the overall clast assemblages and related provenance inferences, the most likely
21 glacial system would consist of a mountain ice cap sitting on the Royal Society Range and upper
22 Skelton and Mulock glaciers. This is indeed the most likely TAM region, where the basement and
23 cover rocks show the lithological range that more closely matches the compositional variability of
24 the investigated AND-2A clasts. A series of prominent ice domes have been proposed as the
25 dominant feature of the East Antarctic Ice Sheet on the east (Ross Sea) flank of the TAM during
26 the Neogene (Smellie et al., 2011, 2013). In agreement with the geomorphological evidence
27 (Sudgen et al., 1999), and based on the AND-2A age model (Acton et al., 2008/2009a; SMS
28 Science Team, 2010), the reconstructed scenario indicates that most of the denudation in the

1 Royal Society Range was accomplished by the mid-Miocene, prior to the emplacement of volcanic
2 cones and lava flows, which demonstrate minimal modification of the low-altitude ice-moulded
3 landscape near the coast from ca. 12 Ma.

6 **6. Conclusions**

- 8 1) Sedimentary clasts in the AND-2A core consist of both intrabasinal and extrabasinal clasts,
9 which can be grouped into seven main petrofacies. The petrographical features of the
10 extrabasinal clasts indicate a main provenance from the siliciclastic sedimentary cover of the
11 TAM, which is represented by the Devonian-Triassic Beacon Supergroup. The intrabasinal
12 clasts indicate the reworking of: older but penecontemporaneous glacial sediment, such as
13 diamictites; and more internally-organized deposits like conglomerates and marly mudstones.
- 14 2) Provenance analyses of sedimentary clasts – when integrated with provenance inferences
15 based on basement clasts and heavy minerals - indicate contrasting
16 paleoenvironmental/provenance scenarios: 1) a multi-source scenario with reduced or
17 fluctuating ice sheets and ice flows, or icebergs sourced in the outlet glaciers of the central
18 TAM and SVL (documented between ca. 1000 and 225 mbsf in the core, including the
19 MMCO); 2) a scenario with an extensive ice sheet in the Ross Embayment and restricted
20 debris sources located in SVL in more localized glaciers, most likely in the Royal Society
21 Range (below 1000 mbsf in the core) and adjacent areas in the Skelton and Mulock catchment
22 areas and the central TAM (in the uppermost ca. 225 m).
- 23 3) The relatively small amount of extrabasinal sedimentary clasts, with respect to the basement
24 clasts, suggests that a significant dismantling of the Beacon covers in the Royal Society Range
25 may have been accomplished by the Early Miocene.
- 26 4) The initiation and end of the Beacon-sourcing is associated with the involvement of a source of
27 mixed siliciclastic-carbonate rocks, which marks relatively cold phases that correspond to the
28 Mi1b and Mi2 glaciations, respectively. The source of these sedimentary clasts can be

1 tentatively identified in the same sources of the Eocene fossiliferous erratics (Stilwell et al.,
2 1997) (i.e. the Discovery Deep, a 1000 m deep elongated depression in front of the Byrd and
3 Skelton glaciers). This source area could have been crossed by ice flows from the Skelton
4 Glacier and other outlet glaciers to the south, where the source areas of associated basement
5 clasts were identified by previous provenance studies.

6 5) The changes in the sedimentary clast composition along the whole succession demonstrate
7 that the clast source and ice-flow drainage patterns were greatly influenced by the glacial
8 fluctuations and dynamics s.l., corroborating, as already documented by other provenance
9 datasets, a first order role of the paleoclimate change rather than the tectonics.

10 6) The study of the coarse gravel-size sedimentary rock clasts in the AND-2A core demonstrates
11 that although these clast lithologies occur in subordinate amounts, they represent an important
12 tool, particularly when matched with other provenance datasets, to further constrain
13 paleogeographic and ice dynamic modelling of the Miocene glacial evolution of the SMS-TAM
14 system.

15

16

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18

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6
7

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Figure captions

Table 1 – Lithology, rock type (intrabasinal vs extrabasinal) and main features of the sedimentary
clast petrofacies in the AND-2A core.

Table 2 - Distribution of the Sedimentary Petrographic Units in the AND-2A core, with their depth
(meters below sea floor), sedimentary petrofacies association, Lithostratigraphic Unit (¹ LSU of
Fielding et al., 2008-2009), stratigraphic sequences (² third-order sequences of Fielding et al.,
2011), and age (³ after SMS Science Team, 2010).

Fig. 1. A) Antarctica sketch showing the distribution of the Beacon Supergroup and associated
Ferrar Supergroup and crystalline basement rock units in the TAM. B) Simplified stratigraphic
panel showing the Beacon Supergroup in the Southern Victoria Land and the Darwin Mountains.
C) Geological sketch map of the area comprised between the Byrd Glacier and the Mackay
Glacier (after Gunn and Warren, 1962; Warren, 1969a, 1969b; Craddock, 1970; Borg et al., 1989;
Carosi et al., 2007). The CRP-1, AND-1B and AND-2A drill-sites and the present-day glacial-flow
lines of major outlet glaciers into the Ross Ice Shelf are shown (after Fahnestock et al., 2000 and
Drewry, 1983), including inferred catchments (based on the elevation data of Drewry, 1983).
Abbreviations: BB: Bareface Bluff, BG: Blue Glacier, BI: Black Island, CoG: Cook Glacier, CG:
Carlyon Glacier, CM: Cape Murray, DB: Delta Bluff, FB: Fontaine Bluff, MD: Mount Discovery, OP:
Olson Peaks, TI: Teall Island, and WI: White Island.

Fig. 2. Stratigraphic log of the AND-2A drill core (lithologies from Fielding et al., 2011) with the
petrofacies distribution, Sedimentary Petrographic Units (SPU), types of clast (subdivided

1 according to the lithostratigraphic units of Fielding et al., 2008-2009), and total number of clasts
2 and intraclasts from core logging (after Panter et al., 2008-2009). The age model is after the SMS
3 Science Team (2010), and the main glaciations after Miller et al. (1996). Lithology codes: Olive
4 gray — mudrock, yellow — sandstone, blue — diamictite, orange — conglomerate/breccia. Depth
5 in meters below the sea floor.

6
7 Fig. 3 – Clast microphotographs: a) sample 537.19, sub-rounded arkose clast (petrofacies A), 3.5
8 mm in size, within muddy diamictite; b) sample DA8, well-rounded clast of coarse quartzarenite
9 (petrofacies B), 1 cm in size; c) sample 668.64, well-rounded non-spherical, 8 mm in size, clast of
10 medium-fine calcareous sandstone (petrofacies C) within diamictite (lower right angle of the
11 photo); d) sample CA14, subrounded and discoidal, clast 2 cm in size, consisting of a well-sorted
12 sandstone that is: medium-coarse in grain-size, subarkose in composition (petrofacies D), and
13 located within diamictite (lower part of the photo); e) sample X10, well-rounded, non-spherical 2.5
14 cm in size intraclast of marly mudstone (petrofacies E) within diamictite; f) sample I6, rounded,
15 non-spherical 3 cm-in-size intraclast consisting of reworked diamictite (petrofacies K) within
16 diamictite matrix; g) sample DA10, rounded and bladed in shape, 2 cm-in-size intraclast consisting
17 of reworked very coarse sandstone (petrofacies K') within diamictite matrix; h) sample 743,98, sub-
18 rounded non-spherical 0.5 cm-in-size clast of recrystallized limestone (petrofacies L) within
19 diamictite.

20
21 Fig. 4 – Integration of sedimentary clast distribution patterns, with the basement clasts' provenance
22 analysis in the AND-2A core (this last after Sandroni and Talarico, 2011; Talarico and Sandroni,
23 2011) and resulting paleogeographic, glacial stages and settings (see the text for discussion). a)
24 AND-2A sedimentary lithofacies and interpretation of paleoenvironments (after Passchier et al.,
25 2011) (Z = diatomaceous siltstone; Zb = siltstone; MSm = muddy sandstone; Ss = sandstone; SMS
26 = sandstone/mudstone; SZs = sandstone/siltstone; Ds = stratified diamictite; Dm = massive
27 diamictite; G = conglomerate/sandstone) (mbfs – m below seafloor). b) Sedimentary sequences
28 and petrofacies (this study). c) Basement clast' provenance (Sk = Skelton-Mulock glaciers area;

1 Ko = Koettlitz-Blue glaciers area; Mix = core sections with clasts sourced from both the Skelton
2 and Koettlitz glacier areas). d) Representative ice drainage settings and
3 paleoenvironmental/provenance scenarios (as detailed in the text), as documented by the overall
4 clast assemblages in the AND-2A core. AND-2A and CRP-1 drill sites and reconstructed ice-flow
5 lines or iceberg tracks are reported. The outcrop areas of the McMurdo volcanic centres that
6 formed later than the Early Miocene are removed. The dashed line indicates the position of the
7 grounding line or the calving line in the case of the ice shelf. A) Maximum ice-sheet expansion
8 with grounded ice throughout the entire Ross Embayment; the mainly N–S ice-flow lines are
9 consistent with the identified provenance from the Skelton or Darwin–Carlyon glacier areas. B) A
10 glacial scenario similar to A, but with a lobe of ice derived from the Koettlitz Glacier area occupying
11 the AND-2A drill-site. C) A more likely scenario for the same core sections with outlet glaciers
12 fluctuating with dominantly W–E flow lines. D) A scenario dominated by active calving processes
13 and with more retreated glaciers.
14

<i>Petrofacies</i>	<i>lithology</i>	<i>rock type</i>	<i>description</i>
A	arkose, lithic arkose	extrabasinal	Moderately to well sorted arenite. It is composed of monocrystalline undulose-extinction quartz, plagioclase, sericitized k-feldspar (microcline and orthoclase) and lithic clasts. Quartz overgrowth rims. Fine-texture lithic clasts are formed mainly by metamorphics and minor volcanics. Muscovite and opaque minerals. Calcite cement, plaths and recrystallized grains occur in some samples.
A'	arkosic litharenite	extrabasinal	Arkosic-litharenite has similar composition of arkose of Petrofacies A, but with minor textural maturity and with more fine-texture lithic fragments.
B	quartzarenite	extrabasinal	It is characterized by a good sorting, with > 90% well-rounded quartz grains, which are dominantly monocrystalline with slight undulose extinction, and subordinately polycrystalline. Quartz cement overgrowths are very diffuse and well-developed, whereas rare altered feldspar grains may occur.
D	subarkose	extrabasinal	Characterized by 75 - 90 % of quartz grains, mainly monocrystalline and with slight undulose extinction. Minor feldspar and lithic (metamorphic and volcanic) clasts are often deeply altered.
C	hybrid/mixed arenite or calcareous sandstone	extrabasinal	Mixed siliciclastic/carbonate arenites, ranging from coarse to fine in grain-size. Siliciclast and carbonate grains occur in variable ratios, ranging from carbonate lithic arkoses (calcareous sandstone) to calcarenites with siliciclasts; in the former case, they seem to show a transition to the arkosic litharenite with calcite of the petrofacies A'. Siliciclasts are formed by quartz, feldspars (plagioclase and k-feldspar), fine-texture lithics and micas, whereas carbonate grains, often recrystallized by microsparite calcite, sometimes show primary features indicating micritic carbonate lithics or intraclasts, to be defined as hybrid arenites <i>sensu</i> Zuffa (1980).
L	limestone	extrabasinal	Microsparite limestones constitute very rare and peculiar carbonate clast lithology. The clasts are sub-rounded to angular. Generally, they are totally recrystallized by microsparite calcite, but sometimes they preserve a micrite texture, and unidentifiable recrystallized allochem ghosts can be observed.
E	mudstone	intrabasinal	Mudstone and marly mudstone clast lithologies, probably represent intraformational clasts. Sometimes they contain partly recrystallized fossils and angular to subangular siliciclasts as quartz, feldspar, mica and lithic. The rare fossils are not identifiable.
K	diamictite	intrabasinal	Diamictite clasts lithologies represent intraclasts. They are very diffused along the core, particularly in some stratigraphic horizons, where they represent exclusive clasts. They show abundant matrix with dispersed grains. Generally they have similar heterogeneous compositional and textural features of the host diamictite sediments.
K'	conglomerate	intrabasinal	Conglomerate/very coarse sandstone clast lithologies, occur as intraclasts, particularly in some stratigraphic horizons. They have clast- to matrix-supported texture. Compositionally the grains are very heterogeneous.

Q	volcanic breccia/litharenite	intrabasinal	Volcanic litharenite and breccia clasts are characterized by large-sized lithic fragments and often volcanic glass in the matrix. The main volcanic lithics have porphyric and vithrophyric texture. Subordinate are other clasts, such as quartz, feldspar, mica, metamorphic lithics. They should represent intraformational clasts.
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1
2 Table 1. Lithology, typology (intrabasinal vs extrabasinal) and main features of the sedimentary clast
3 petrofacies.
4

<i>Sed. Petr. unit (SPU)</i>	<i>depth mbsf</i>	<i>sedimentary petrofacies association</i>	<i>Lithostratigraphic unit ⁽¹⁾</i>	<i>Sequence ⁽²⁾</i>	<i>Age ⁽³⁾</i>
SPU13	0-100	K, particularly between 40 and 100 mbsf. Extrabasinal clasts are totally lacking	LSU1 – LSU2.1 volcanic and volcanoclastic deposits and major massive diamictites with minor sandstones	13	Pliocene to Recent
SPU12	100-225	K and minor K', rare extrabasinal clasts (petrofacies A arkose and petrofacies B quartzarenites)	LSU 3.1 sandstones and conglomerates and LSU4.1 massive diamictites with minor sandstones and siltstones	12 – upper part of 11	Late Miocene
SPU11	225-295	lacking of intrabasinal diamictite clasts (occur only very rare marly mudstone intraclasts, petrofacies E) and the occurrence of scarce extrabasinal clasts, as arkoses (petrofacies A) and mixed arenites (petrofacies C)	LSU 5.1 diamictites with interbedded sandstones and minor conglomerates and siltstones	lower part of 11	Middle Miocene
SPU10	295-320	arkoses (petrofacies A) and subarkoses (petrofacies D) with very rare microsparitic limestone clasts (petrofacies L). Few intrabasinal diamictite clasts (K) are also present, particularly in the lower portion	upper part of the LSU6.1 diamictites, subordinate diatomites, conglomerates, sandstones and siltstones	top of the sequence 10	latest early Miocene
SPU9	320-415	microconglomerate intraclasts (petrofacies K'), with very minor extrabasinal clasts as quartzarenite and subarkose	lower part of the LSU 6.1 and middle-upper part of the LSU 7.1 stratified volcanic-bearing diamictites with significant interbedding of sandstones	middle-lower sequence 10 and upper sequence 9	Early Miocene
SPU8	415-485	extrabasinal clasts as arkose (petrofacies A) and subarkose (petrofacies D); scarce intrabasinal clasts (petrofacies K')	LSU 7.1 diamictite deposits, LSU8.1 volcanic-bearing mudstones with sandstones and stratified diamictites	lower sequence 9, sequence 8	Early Miocene
SPU7	485-535	extrabasinal sedimentary clasts, with prevailing quartzarenites (petrofacies B), subordinate subarkoses and arkoses (petrofacies D and A); few diamictite and conglomerate (petrofacies K and K') and rare clayey marl intraclasts (petrofacies E)	LSU 8.1 volcanic-bearing mudstones with sandstones and stratified diamictites in the upper part, and LSU 8.2 diamictite in the lower part	upper sequence 7	Early Miocene
SPU6	535-650	arkoses (petrofacies A) and quartzarenites (petrofacies B), with a slight contribution from diamictite intraclasts (petrofacies K); rare microsparitic limestone clasts (petrofacies L)	bottom part of the LSU 8.2 and the whole LSUs 8.3, 8.4 and 9.1 volcanic-bearing sandstones, conglomerates, mudstones and minor stratified diamictites for the upper and lower parts, while volcanic-bearing diamictites occur in the middle	lower sequence 7 and sequence 6	Early Miocene
SPU5	650-685	mixed arenites (petrofacies C), extrabasinal clasts, as arkose and arkosic litharenite (petrofacies A and A') subarkose (petrofacies D), and minor microsparitic limestone (petrofacies L); intrabasinal clasts are lacking	upper part of the LSU 10.1 regularly interstratified volcanic-bearing diamictites, sandstones and sandy mudstones	upper sequence 5	Early Miocene
SPU4	685-775	extrabasinal clasts (arkoses, subarkoses, quartzarenites, mixed arenites, microsparitic limestones); very diffused intrabasinal microconglomerate clasts (petrofacies K') and subordinate diamictite (petrofacies K)	middle-lower part of the LSU 10.1	middle-lower sequence 5	Early Miocene
SPU3	775-905	very poor association, lacking of extrabasinal sedimentary clasts, with low amount of intrabasinal diamictite clasts (petrofacies K)	LSU 11.1 fine sediments as sandy siltstones and sandstones	sequence 4	Early Miocene
SPU2	905-1000	very rare diamictite intrabasinal clasts (petrofacies K) and few extrabasinal clasts as subarkose (petrofacies D)	LSU 12.1 diamictites in the upper and lower parts and muddy sandstones in the middle part	sequence 3	Early Miocene
SPU1	1000-1138,54	significant amount of diamictite intrabasinal clasts (petrofacies K), with rare volcanoclastic clasts; extrabasinal sedimentary clasts are lacking.	finer sediments as sandstones and siltstones in the upper part (LSU 13.1) and diamictites with minor interbedding of sandstones and siltstones in the lower part (LSU 14.1)	sequences 2 and 1	Early Miocene

Table 2. Distribution of the Sedimentary Petrographic Units, with their depth (meters below sea floor), sedimentary petrofacies association, Lithostratigraphic units (¹ LSU of Fielding et al., 2008-2009), stratigraphic sequences (² third-order sequences of Fielding et al., 2011), and age (³ after SMS Science Team, 2010).