The Gondwana Plate margin in the Weddell Sea sector: Zircon geochronology of Upper Paleozoic (mainly Permian) strata from the Ellsworth Mountains and eastern Ellsworth Land, Antarctica.

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Abstract.

Zircon geochronology has been applied to upper Paleozoic (mainly Permian) strata from the Ellsworth Mountains and from enigmatic outcrops in eastern Ellsworth Land to aid in constraining their locations in the Weddell Sea sector of the Gondwana plate margin. Detrital zircons from two Polarstar Formation (Ellsworth Mountains) sandstones yielded maximum depositional ages of ~270 Ma and ~260 Ma. Detrital zircons from Permian beds at Erewhon Nunatak and beds of uncertain age at FitzGerald Bluffs, both in eastern Ellsworth Land, gave maximum depositional ages of ~264 Ma and ~525 Ma respectively. Two Polarstar Formation tuffs gave ages of 258.0 ± 2.1 Ma and 262.6 ± 2.2 Ma. The Polarstar Formation probably spans the entire Permian. The quartzite at FitzGerald Bluffs is comparable in composition and detrital

zircon signature to Devonian sandstones in both the Ellsworth and Transantarctic Mountains. Evaluation of the Polarstar Formation with respect to Permian strata in the southern Karoo and Falkland Islands suggests deposition in a separate and distinct basin, which was related to that in the Transantarctic Mountains. A separate depositional basin forms an additional constraint on the location of the Ellsworth-Whitmore block adjacent to the Coats Land/Pensacola Mountains region. The eastern Ellsworth Land outcrops are inferred to document a small continental block located proximal to the Ellsworth-Whitmore Mountains block during Gondwana time.

Keywords: Gondwana, zircon, Antarctica, Ellsworth Mountains, Permian

1. Introduction

The Antarctic sector of the paleo-Pacific margin of Gondwana has long been an enigma because of the fragmentation of the margin on break-up and the subsequent movements of those continental fragments to form the present collage of blocks that constitute West Antarctica and the Antarctic Peninsula. Two continental blocks, the Ellsworth Mountains in Antarctica and the Falkland Islands off South America, highlight the complexity of the margin and its break-up history. The geology of both of them shows unequivocally that there have been major translations and rotations. The importance of the Ellsworth Mountains was evident at the time of their first investigation (Craddock et al., 1964) and subsequently Schopf (1969) proposed that the mountain range was originally located between Africa and Antarctica. The geology of the Falkland Islands was recognized by Halle (1912) as having similarities with the Karoo of South Africa, but it was Adie (1952) who realized that the geology of the Falkland Islands could be most readily understood as involving considerable translation and rotation, which then made the stratigraphy and structure compatible with that of the eastern Cape Province of South Africa.

Following Schopf's (1969) proposal, the reconstruction of the Antarctic sector of the Gondwana plate margin has remained the subject of discussion (Dalziel and Elliot, 1982; Dalziel et al., 2013 and references therein). Although the position of the Falkland Islands is tightly located by stratigraphy and structure (see Curtis and Storey, 1996; Trewin et al., 2002), that of the Ellsworth Mountains is not as well constrained because of the inherent uncertainties (α_{95}) in paleomagnetic data and the lack of any "pinning point".

There are several objectives for this study. The first is to establish zircon-based age constraints for the Permian Polarstar Formation in the Ellsworth Mountains, and for the Permian *Glossopteris*-bearing beds at Erewhon Nunatak and quartzose beds of uncertain age at FitzGerald Bluffs, the latter two both in eastern Ellsworth Land (**Fig. 1**). The second is to evaluate relationships to the Beacon Supergroup in the Transantarctic Mountains and to the Karoo sequence in South Africa and the equivalent strata in the Falkland Islands. The third is to reassess Gondwana reconstructions in the Weddell Sea sector in light of new data for the Ellsworth Mountains and eastern Ellsworth Land.

2. Ellsworth Mountains and Eastern Ellsworth Land geology

The Ellsworth Mountains comprise a stratigraphic sequence more than 13 km thick spanning the Cambrian to Permian (**Fig. 2**) (Webers et al., 1992a). The Lower Paleozoic Heritage Group, 7.5 km thick, is entirely Cambrian and is overlain by the Crashsite Group, a thick (3 km) sequence of quartz-rich sandstones that is divided into three formations (Webers et al., 1992a). The transition beds between the two groups contain a possible Upper Cambrian fauna (Shergold and Weber, 1992), but the only other biostratigraphic age control on the Crashsite Group is confined to a Lower Devonian brachiopod fauna in the Mount Wyatt Earp

Formation, the upper of the three formations (Webers et al., 1992b). The Mount Wyatt Earp Formation is overlain conformably by the Whiteout Conglomerate, a 1,000 m thick unit of beds interpreted as glacial deposits (Matsch and Ojakangas, 1992) and assigned, by correlation with other glacial units in Antarctica, a Carboniferous(?)–Permian age. The glacial beds are overlain conformably by the Permian Polarstar Formation (**Fig. 3**), which in its upper part contains elements of the *Glossopteris* flora (Collinson et al., 1992). The lowest Polarstar fine-grained beds contain outsize grains and quartz pebble dropstones that are interpreted as residual ice-rafted debris deposited during the retreat of the ice sheets (Collinson et al., 1992), implying that there is no hiatus between the two formations. There is no uninterrupted sequence of the Polarstar Formation. The estimate of a minimum 1.2 km thickness is based on stacking several measured sections, but is hampered by the lack of distinctive features for correlation and the true thickness may be considerably greater. Three facies are recognized in the Polarstar Formation: an Argillite Facies at the base, a Mixed Sandstone–Argillite Facies in the middle, and at the top a *Glossopteris*-bearing Coal Measures Facies. Sandstones in the sequence are dominantly volcanoclastic, and tuffs are locally present. The Polarstar Formation has been interpreted as an extension of the Permo-Triassic Transantarctic Basin (Collinson et al., 1994).

The Ellsworth Mountains have a NNW-SSE structural grain imparted by large-scale folds, which in the southern part swings to a more NW-SE direction (Craddock et al., 1964, 1992; Spörli and Craddock, 1992; Curtis, 2001). Vergence of folds is predominantly easterly or northeasterly. The unconformity between the Heritage and Crashsite groups has been interpreted in terms of the Ross Orogeny (Goldstrand et al., 1994; Duebendorfer and Rees, 1998), however, analysis by Curtis (2001) suggested no structural break and a single principal

episode of deformation, which was dextral transpressive. A second deformation overprints the principal event, but is interpreted as a late stage episode in the structural history. The timing of deformation is constrained only to being late Permian or late Permian-early Triassic, and is regarded as part of the Gondwana Orogeny (Du Toit, 1937), which affected the whole of the paleo-Pacific margin of the supercontinent.

In eastern Ellsworth Land (Fig. 1) most of the outcrops are Jurassic and Cretaceous fossiliferous strata, volcanic beds, and plutonic bodies (Kellogg and Rowley, 1991; Rowley et al., 1992; Hunter and Cantrill, 2006), but there are also several small enigmatic outcrops within the western part of that Mesozoic belt. At Erehwon Nunatak a 2-m-thick sequence of fine-grained beds carries *Glossopteris* leaves, demonstrating their age and possible affinities (Gee, 1989; Laudon, 1991; Laudon and Fanning, 2003). Two unfossiliferous sequences (<30 m thick) with similar lithology (forming an unnamed outcrop 25 km to the NW and one on the NE side of Henkle Peak 15 km to the SE) were tentatively correlated with the Erehwon beds, but the latter is now known to be Jurassic (M.A. Hunter, pers. comm. to T. Laudon, 2003). All sets of beds dip moderately to the SSW. At FitzGerald Bluffs ~300 m of unfossiliferous quartzite crops out as a sequence of beds dipping north-northeastly (Laudon, 1991). Quartzite clasts of similar aspect occur locally as glacial erratics. Such clasts also occur in conglomerates of the Jurassic Latady Group (Willan and Hunter, 2005; Hunter and Cantrill, 2006) in eastern Ellsworth Land, and in other Mesozoic rocks in central Alexander Island (Tranter, 1986). Sandstone petrology also indicates a significant continental provenance (Laudon and Ford, 1997; Willan and Hunter, 2005). Locations and illustrations of Erehwon Nunatak and FitzGerald Bluffs are in, respectively, Rowley et al. (1992) and Laudon and Craddock (1992).

The structure and stratigraphy of the Ellsworth Mountains show that they are part of the fold

and thrust belt of the Gondwana active margin (Curtis, 2001). Ellsworth Land encompasses Thurston Island and the base of the Antarctic Peninsula. It is comprised of three parts: Thurston Island which is clearly part of the late Paleozoic Gondwana margin (Pankhurst et al., 1993; see also Elliot, 2013), the enigmatic Erehwon Nunatak-FitzGerald Bluffs region, and the base of the Antarctic Peninsula which is predominantly Mesozoic in age (Vaughan and Pankhurst, 2008). A major discontinuity between eastern Ellsworth Land and the Thurston Island region was suggested by Kellogg and Rowley (1991).

Zircon grains have been analyzed from two tuffs and two sandstones in the Polarstar Formation. Stratigraphic locations of these samples from a composite section measured at Mt Weems are given in **Fig. 3**. An Erehwon beds siltstone and a FitzGerald beds quartzite have also been analyzed. Petrographic descriptions are given in the appendix.

3. Analytical procedures

Zircon grains were separated from total rock samples using standard crushing, washing, heavy liquids (Sp. Gr. 2.96 and 3.3), and paramagnetic procedures. The zircon-rich heavy mineral concentrates were poured onto double-sided tape, mounted in epoxy together with chips of the Temora reference zircon, sectioned approximately in half, and polished. Reflected and transmitted light photomicrographs were prepared for all zircons, as were cathodoluminescence (CL) Scanning Electron Microscope (SEM) images. These CL images were used to decipher the internal structures of the sectioned grains and to ensure that the ~20µm SHRIMP spot was wholly within a single age component within the sectioned grains.

The U-Th-Pb analyses for three Polarstar Formation samples (MW 210.5, MW 274.5, MW 420.4) were made using SHRIMP RG at the Research School of Earth Sciences, The Australian

National University, Canberra, Australia following procedures given in Williams (1998, and references therein). Each analysis consisted of 4 scans through the mass range, with Temora reference zircon grains analyzed for every 5 unknown analyses. Detrital sample MW 54.3 was analyzed using SHRIMP II, with 5 scans through the mass range, and with the same procedures for the Temora reference zircon. Samples L112a and DL14 were analyzed using SHRIMP I and SHRIMP RG, respectively, with reference zircon SL 13. The data have been reduced using the SQUID Excel Macro of Ludwig (2001). The $^{206}\text{Pb}/^{238}\text{U}$ ratios have been normalized relative to a value of 0.0668 for the Temora reference zircon, equivalent to an age of 417 Ma (see Black et al., 2003) and 0.0928 for SL13 (age of 572 Ma). The uncertainty in the reference zircon calibration for each analytical session is given in the Table footnotes for each sample. Uncertainties given for individual analyses (ratios and ages) are at the one sigma level (Appendix Tables 1-6).

Correction for common Pb was either made using the measured $^{204}\text{Pb}/^{206}\text{Pb}$ ratio in the normal manner or for grains younger than say 800 Ma (or those low in U and radiogenic Pb) the ^{207}Pb correction method has been used (see Williams, 1998). When the ^{207}Pb correction is applied it is not possible to determine radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ ratios or ages. In general, for grains younger than 800 Ma (and for areas that are low in U and therefore radiogenic Pb) the radiogenic $^{206}\text{Pb}/^{238}\text{U}$ age has been used for the probability density plots. The $^{207}\text{Pb}/^{206}\text{Pb}$ age is used for grains older than say 800 Ma, or for those enriched in U. Tera and Wasserburg (1972) concordia plots, probability density plots with stacked histograms and weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age calculations were carried out using ISOPLOT/EX (Ludwig, 2003).

4. Results

Polarstar Formation sandstone sample MW 54.3. The detrital zircon grains are dominantly Permian in age, with a small component at *ca.* 500 Ma (**Fig. 4**). Most of the zircons are whole or broken euhedral grains, and include some that are strongly elongate indicating volcanic or sub-volcanic crystallization. The dominant age peak lies at *ca.* 270 Ma, and since this sample was analyzed in the higher precision 5 scan mode per grain, it is possible to calculate a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 268.9 ± 1.4 Ma (MSWD = 0.38, for 38 of 70 grains analyzed). There is a small group of grains between 480 and 520 Ma, similar in age to post-tectonic magmatic rocks in the Ross Orogen of the Transantarctic Mountains (Goodge et al., 2012); three late Mesoproterozoic (Grenvillian) grains are also present.

Polarstar Formation sandstone sample MW 210.5. The zircons grains are predominantly euhedral, many are doubly terminated crystals or fractured pieces of such, and most show either oscillatory or length parallel zoning. The U-Pb age spectrum is dominated by those of Permian age (**Fig. 5**), although these 54 grains (from a total of 70 analyzed) have a rather irregularly shaped age distribution. Deconvolution using the mixture modeling algorithm (ISOPLOT) suggests that there are sub-groups for which the weighted mean ages are 253.3 ± 1.7 Ma, 260.4 ± 1.5 Ma and 267.2 ± 1.5 Ma. The youngest grouping of 8 grains at ~ 253 Ma is considered to reflect radiogenic lead loss, although these analyses are effectively within error of the ~ 258 Ma magmatic age for an overlying tuff (MW 274.5; see below). There is a small cluster at ~ 500 Ma, and as noted above, is similar to that of post-tectonic magmatic rocks of the Ross Orogen.

Polarstar Formation tuff sample MW 274.5. The zircons are dominantly elongate, prismatic grains with length parallel or broad to weak internal zoning, both of which are typical for volcanic or sub-volcanic crystallization. All grains analyzed (n=20) record Permian

$^{206}\text{Pb}/^{238}\text{U}$ ages; the distribution shows a dominant peak at ~258 Ma with a tail on the older age side. The weighted mean for the 16 analyses forming the dominant grouping gives an age of 258.0 ± 2.1 Ma (MSWD = 1.07), indicating a Late Permian (Lopingian) age for the tuff (**Fig. 6**).

Polarstar Formation tuff sample MW 420.4. Like the other tuff, the zircons are elongate, prismatic grains with mostly length parallel zoning. All 20 grains analyzed record Permian $^{206}\text{Pb}/^{238}\text{U}$ ages, showing a simple bell-shaped age distribution with a slight tail on the older age side. The weighted mean age for the 18 grains forming the dominant peak is 262.6 ± 2.2 Ma (MSWD = 0.42) (**Fig. 7**). The discrepancy in the ages between the upper and lower analyzed tuffs is discussed later.

Erehwon beds siltstone sample DL-14. Many zircons in this sample are euhedral grains with pyramidal terminations and simple igneous CL zoning. Round and sub-round more clearly detrital grains are also present. The dominant euhedral igneous zircons record $^{206}\text{Pb}/^{238}\text{U}$ ages between 240 and 280 Ma, with a bimodal distribution having a more prominent grouping with a weighted mean age of 263.3 ± 3.6 Ma and a lesser group with a weighted mean age of 275.0 ± 4.0 Ma (**Fig. 8**). Four grains record latest Carboniferous to earliest Permian dates (~300 Ma), with a more prominent Late Carboniferous sub-group at ~325 Ma. There are scattered older ages, with minor clusters in the range 490-650 Ma and 850-960 Ma. The former matches the Gondwana margin detrital zircon signature (Ireland et al., 1998), but the latter has uncertain affiliations.

FitzGerald beds quartzite sample L112a. A heterogeneous population of detrital zircon grains is present in this sample. The grains are round to subround in shape with a wide variety of internal CL structures. The majority record ages in the range 510-630 Ma, with a scattering of older ages to ~1200 Ma and a few younger ages to ~460 Ma (**Fig. 9**). With respect to these youngest analyses, they plot above the Tera-Wasserburg concordia and the areas analyzed are

interpreted to have lost radiogenic Pb. The main clustering of analyses forms a broad and irregular distribution of $^{206}\text{Pb}/^{238}\text{U}$ ages with a prominent group at ~570 Ma, a lesser group at ~525 Ma and more diffuse sub-group at ~615 Ma. There are scattered older grains between ~720 and 840 Ma, clusters around 950 to 1150 Ma and ~1500-1600 Ma, and a spread of Archean grains. The principal probability peaks at 570 and 525 Ma are typical of the Gondwana margin signature, and the ages around 1 Ga form a weak Grenville-age cluster.

5. Summary

The Polarstar Formation and Erehwon Nunatak samples all indicate the presence of a Permian magmatic arc, with the tuff beds recording a time of active volcanism during the accumulation of at least part of the sequence. Sandstone MW 54.3 from the Argillite Facies, which is the lowest sandstone with unequivocal volcanic rock fragments (available for analysis), yields a maximum depositional age of 268.9 ± 1.4 Ma, or lowest Guadalupian. Sandstone MW 210.5 in the Mixed Sandstone-Argillite Facies provides a maximum age of deposition of ~253 Ma, but when compared with the age of 258.0 ± 2.1 Ma for the lower tuff (MW 274.5), it is probable that the youngest detrital grains have lost radiogenic Pb. The more prominent, next youngest grouping at ~260 Ma (Guadalupian/Lopingian boundary) is regarded as the best estimate of the maximum age of deposition of sandstone MW 210.5. Compared with the lower tuff (MW 274.5; 258.0 ± 2.1 Ma), the apparent older age (262.6 ± 2.2 Ma) for the upper tuff (MW 420.4) may be explained in terms of the petrographic characteristics of the samples, and examples elsewhere of apparently older tuffs stratigraphically overlying younger tuffs. Microscopically, sample MW 274.5 has identifiable glass shards whereas that is not the case for the upper tuff (MW 420.4). It is possible, but unlikely given the facies setting and the thickness

of the tuff bed (1-2 cm), which is continuous in outcrop, that it was reworked from older deposits and the glass shards were never present or were eliminated during the course of transport and redeposition. Alternatively, this apparent age inversion has been observed in other sequences and has been attributed to evolving and episodic magmatic processes (see for example: Bowring et al., 1998; Mundil et al., 2001; Bowring and Schmitz, 2003). A possible, and in fact common scenario is for later magmatic events to carry with them earlier crystallized elements from previous, episodic events. In this manner, an initial eruption may involve high-level crystallizing magma and then subsequent eruptions either tap into deeper levels in the magma chamber where crystallization had started earlier or are contaminated by earlier formed, xenocrystic, zircon. Overall, these results suggest the Coal Measures Facies must be late Lopingian (latest Permian) in age. Both of the Polarstar sandstones have a small component of ~500 Ma grains, suggesting dilution of the arc source by zircons derived from Upper Neoproterozoic to Cambrian sources along, or adjacent to, the Transantarctic Mountains. Previously, Craddock et al. (2008b) had reported Permian detrital zircon ages (probability peaks at 262 and 280 Ma) for a Polarstar sandstone.

The Erewhon beds siltstone contains detrital zircon grains whose provenance was clearly dominated by sources in the Permian magmatic arc (summarized in Elliot, 2013). Upper Carboniferous granitoids are also known from the arc but are not as widespread as those of Permian age. A small component was derived ultimately from Upper Proterozoic to Cambrian sources. The persistence of such zircons is also seen in the volcanoclastic Permian and Triassic sandstones from the Shackleton Glacier area (Fig.1) (Elliot and Fanning, 2008) and from Mt Bowers at the head of the Beardmore Glacier (Fig.1) (Elliot et al., 2014).

The quartzite from FitzGerald Bluffs carries the Gondwana margin detrital zircon signature

(Ireland et al., 1998) although the Grenville-age component is very minor. As noted previously (Laudon, 1991), the sandstone is lithologically similar to the Cambrian-Devonian Crashsite Group in the Ellsworth Mountains and to the Devonian sandstones in the Transantarctic Mountains. The Mount Wyatt Earp Formation in the Crashsite Group has a significant detrital zircon probability peak at *ca.* 570 Ma, a scattering of Grenville-age zircons and, in contrast, also a significant number of Archean grains (Flowerdew et al., 2007). Craddock et al. (2008b) reported similar results, with the addition of a Cambrian probability peak, for a sandstone from the top of the Crashsite Group. The Devonian(?) Alexandra Formation in the central Transantarctic Mountains (CTM) has a detrital zircon signature that is similar to the FitzGerald Bluffs sample (Elliot et al., 2014). The two probability peaks at 570 and 525 Ma are also similar to probability peaks recorded for the Mt. Bowers Permian sandstones (Elliot et al., 2014).

6. Discussion.

6.1. Ellsworth Mountains

Interpretation of this data set has to be in the context of the reconstruction of the Permian Gondwana Plate margin (**Fig. 10**). As noted previously, the Ellsworth Mountains have stratigraphic and structural similarities with the Cape and Karoo supergroups of South Africa, and the West Falkland and Lafonian groups in the Falkland Islands (*e.g.* Curtis and Storey, 1996). Although the Ellsworth Mountains Carboniferous(?)–Permian stratigraphy has some similarities with the Permian beds of the Victoria Group and correlatives in the Pensacola Mountains (Collinson et al., 1992, 1994), the structural history is markedly different. In particular, the early Paleozoic Ross Orogeny and the pre-Devonian Kukri Erosion Surface, which

is the defining contact in the Transantarctic Mountains, are not recorded in the Ellsworth Mountains (Curtis, 2001).

Within the Carboniferous-Permian stratigraphic sequence in the eastern Karoo and Falkland Islands (**Fig. 11**) the Paleozoic glacial beds (Dwyka and Fitzroy tillites, respectively) are overlain by shale-dominated sequences (Prince Albert and Whitehill formations, and the lower members of the Port Sussex Formation, respectively). These pass up into turbidite strata (Collingham Formation of the Eccu Group and the upper member of the Port Sussex Formation), which become increasingly sandy upwards (Veevers et al., 1994; Trewin et al., 2002; Catuneanu et al., 2005; Milani and De Wit, 2008; Tankard et al., 2009). Both sequences have been interpreted in terms of relatively deep water accumulation of fine-grained beds, which included organic-rich deposition during an anoxic interval. Deposition took place in a major intracratonic basin for which there is no demonstrable marine influence except in the western Cape Province of South Africa (Milani and de Wit, 2008). A non-marine setting was proposed on geochemical grounds by Faure and Cole (1999) for the Whitehill Formation, but others have argued that the entire Eccu succession is marine (Tankard et al., 2009). The overlying sandstone-shale sequences of the Ripon and Fort Brown formations are interpreted as pro-delta and delta-front deposits, comprising shales and turbidites, which gradually pass into delta-top deposits in which *Glossopteris* is found. The three facies recognized by Collinson et al. (1992) for the Polarstar Formation are also interpreted as a sequence of distal fine-grained deposits merging upward into delta-front deposits and then delta-top deposits. However, the Argillite Facies of the Polarstar Formation, although organic-rich, lacks the distinctive pyrite-rich beds of the Prince Albert, Whitehill and Port Sussex formations.

Tuff beds are present in the upper part of the Dwyka Tillite, and in the Prince Albert and

Whitehill formations along the northern edge of the Cape Fold Belt. A tuff in the tillite has given an age of *ca.* 297 Ma and tuffs from the base of the Prince Albert Formation ages of *ca.* 288-289 Ma (Bangert et al., 1999). Beds equivalent to the uppermost Prince Albert Formation in Namibia have yielded an age of *ca.* 279 Ma (Stollhofen et al., 2008). An age of *ca.* 278 Ma has been determined by Santos et al. (2013) for Irati Formation beds in the Parana basin, beds which are equivalent to the Whitehill Formation. A tuff at the base of the Collingham Formation (Fildani et al., 2007) has yielded an age of *ca.* 275 Ma (eight grains forming a single cluster). An undated crystal tuff occurs in the overlying Ripon Formation (Johnson et al., 1997). In the western Cape Province, Lanci et al. (2013) reported an age of *ca.* 268 Ma for a tuff 50 m above the base of the Beaufort Group, and in the eastern Cape Province ages of *ca.* 261-255 Ma have been determined by Rubidge et al. (2013) for Beaufort Group strata higher in the section (upper Koonap to lower Balfour formations). In the Falkland Islands, bentonite beds occur in the top of the Port Sussex Formation and together with pyroclastic rocks at the base of the overlying strata (Curtis and Hyam, 1998; Trewin et al., 2002) suggest magmatism that is correlative with that seen in the Karoo beds, but there are no radiometric dates for the those tuffs. Widespread tuffs in the Permian beds in the Karoo Basin and its extension into the Falkland Islands are distal documentation of the magmatic arc along the Gondwana margin. In addition, petrographic and paleocurrent studies of the eastern Cape Province Permian beds (Johnson, 1991, Johnson et al., 1997) indicated a provenance that included a magmatic arc to the south and southeast (present co-ordinates).

Structural and geochronologic investigations in the western Cape Fold Belt suggest several episodes of deformation, all showing northerly vergence, spanning the early Permian to mid Triassic (277 ± 5 Ma, 259 ± 5 Ma, 246 ± 5 Ma, 229 ± 5 Ma; Hålbich et al., 1983; Gresse et al., 1992).

323 However these ages are for $^{40}\text{Ar}/^{39}\text{Ar}$ determinations on phyllosilicates and therefore are unlikely
324 to represent primary tectonic events. Tankard et al. (2009) argue that the Cape Orogeny was
325 initiated in the Early Triassic. The intensity of deformation decreases eastward with only one
326 episode recognized in the eastern Cape Province.

327 Investigations of the Falkland Islands sequence (Curtis and Hyman, 1998) show structural
328 correlation with Karoo rocks in the eastern Cape Province. Vergence is north-directed (in the
329 restored Gondwana position and present co-ordinates for Africa) and there is a single major
330 deformation episode as in the adjacent Cape Province. The first increments of this principal
331 episode are observed in the Fitzroy Tillite, but the deformation is inferred to be principally due to
332 a single Permo-Triassic event. Superimposed on the major structures is a lesser deformation
333 event, which is considered to be early Mesozoic. The intensity of deformation decreases in the
334 Falkland Islands, continuing the eastward trend of diminishing intensity in the Cape Fold Belt.

335 In the Ellsworth Mountains there are two episodes of deformation (Curtis, 2001), an
336 earlier localized event followed by the superimposed principal dextral transpressive event, both
337 of which are interpreted only as late or post-Permian. Folds and reverse faulting have
338 predominantly easterly vergence in present co-ordinates (Curtis, 2001). In comparison with the
339 Falkland Islands, the intensity of deformation indicates that the Ellsworth Mountains were
340 located well inboard of the structural front.

341 Paleomagnetic studies (Watts and Brammall, 1981) on hematitic argillites of Late Cambrian
342 age in the Ellsworth sequence indicate that a 90° clockwise rotation is needed to bring the pole
343 position into line with the Paleozoic polar wander path. Later, Grunow et al. (1987) showed
344 that hornfelsed red siltstone beds in the Nash Hills (Fig. 1) (the Nash Hills Formation of Storey
345 and Macdonald, 1987) have a thermally stable component of magnetization giving a paleopole

position similar to that for the Ellsworth Mountains. Reinvestigation of the Ellsworth sequence (Randall and Mac Niocaill, 2004) reconfirmed previous studies. Rotation of the Ellsworth block is demanded by the paleomagnetic data, but, based on the that data alone, there is uncertainty in the amount of translation. A simple rotation would place the Ellsworth-Whitmore Mountains block adjacent to the Pensacola Mountains, but this is geologically unreasonable given the absence of Ross-age structures and granitoids in the Ellsworth sequence (Curtis, 2001).

The paleomagnetic and structural data suggest the Ellsworth-Whitmore block should have been located adjacent to Coats Land and outboard of the Gondwana structural front observed in the eastern Cape Province/Falkland Islands and the Pensacola Mountains. Analysis of the early Paleozoic setting of the Ellsworth Mountains (Curtis, 2001) suggested it was involved in Cambrian back-arc extension, and hence might be expected to have responded differently during the Gondwanan Orogeny.

Stratigraphically, such a position is supported by the fact that the pre-glacial strata of the Ellsworth Mountains are more similar to the Cape Supergroup and West Falkland Group than to the Transantarctic Mountains pre-Devonian basement. Depositional settings in the Permian Polarstar strata are broadly similar, trending upward from distal deepwater deposits to delta-top deposits, although the Ellsworth Polarstar Formation lacks the distinctive pyrite-rich beds of the basal Karoo sequence. Nevertheless, on the basis of paleocurrent data the Polarstar Formation has been linked to the Victoria Group basin in the central Transantarctic Mountains (CTM), part of the Transantarctic Basin of Collinson et al. (1994). That basin changed character toward the Weddell Sea (Fig. 11). The glacial beds in CTM are succeeded by shales and fine sandstones (Mackellar Formation), which are overlain by sandstones of the deltaic to fluvial Fairchild

Formation and then by coal-bearing strata of the Buckley Formation (Collinson et al., 1994). The Mackellar beds were deposited in brackish to marine environments (Miller and Collinson, 1994; Jackson et al., 2012), which in the Scott Glacier region and towards the Weddell Sea, thickened markedly and became marine based on C/S ratios and marine trace fossils. The Fairchild Formation can be traced into the Scott Glacier region, but loses its identity by the Ohio Range. The lower Buckley Formation (the base of which is recognized by quartz-pebble conglomerates) and its equivalents in the Scott Glacier region are interpreted as deposition from braided streams, but in the Ohio Range the setting for the lithostratigraphically equivalent beds is marine-deltaic (Bradshaw et al., 1984). The upper Buckley Formation, informally identified by the incoming of significant volcanoclastic detritus, has equivalents in the coal measures of the Scott Glacier region and the Ohio Range. The increasing marine influence from CTM to the Ohio Range can be projected into the Ellsworth Mountains, as pointed out by Collinson et al. (1994), where the Polarstar Formation is interpreted as marine in the lower part and passing up into marine-deltaic environments for the upper coal-bearing strata.

However, the detrital zircon geochronology leads to further interpretation of the relationships. Deposition of the volcanoclastic upper Buckley Formation is no earlier than *ca.* 267 Ma (Elliot and Fanning, 2008). This age is essentially the same as that of sandstone MW 54.3 in the Argillite Facies of the Polarstar Formation. Thus the Mackellar, Fairchild and lower (pre-volcanic) Buckley formations are age equivalent to the Argillite Facies below that analyzed sample. The lowest Polarstar beds include dropstones and floating sand grains resulting from deposition from floating ice. This suggests an age for the lowest Polarstar beds only slightly younger than the Whiteout Conglomerate. Therefore, the lower Argillite Facies up to sandstone MW 54.3 spans a 20-25 Ma time interval covering deposition of the Mackellar through lower

Buckley formations, assuming end of glaciation in the Dwyka Tillite and Whiteout Conglomerate was synchronous. Age control is insufficient for a time-stratigraphic chart, nevertheless three observations can be made, which are presented in Table 1. Given the paleoflow directions, above the basal post-glacial strata the transitions from one depositional environment to the succeeding one are incompatible with a single Permian depositional basin.

Thus, the contrasts between the Polarstar Formation and the eastern Cape Province/Falkland Islands sequence (the inferred regional paleocurrent direction of the Polarstar Formation and the timing of events) suggest that it was deposited either in a different sub-basin than the Karoo/Falklands successions or in a distinct unconnected basin (**Figs. 11 and 12**). The Polarstar basin must have had a connection, across the developing magmatic arc, to the open ocean throughout most of its history, unlike that for the Karoo/Falklands basin, which is demonstrably marine only in the far western Cape Province. Further, the inferred marine environment for the Argillite Facies of the Polarstar is in marked contrast to the lacustrine/non-marine depositional setting for the Whitehill Formation (Faure and Cole, 1999). Strengthening the possibility of deposition in a separate basin, the paleoflow for the Karoo/Falklands Permian strata was off an outboard landmass (Johnson, 1991; Johnson et al. 1997; Trewin et al., 2002), that is the incipient Gondwana Orogen, and argues for the Ellsworth Mountains Permian basin lying sufficiently distant from the Falkland Islands (in Gondwana) to accommodate the source region of the Karoo/Falkland Islands Permian strata.

The Ellsworth-Whitmore Mountains block (EWB), including the Haag Nunataks region, is commonly regarded as a single entity, although the Haag Nunataks and the adjacent block east of the Ellsworth Mountains are now separated by grabens probably formed in the late stages of the rotation and translation (Doake et al., 1983). The structural grain of the Ellsworth

Mountains swings from NNW-SSE in the Sentinel Range to a NW-SE orientation in the Heritage Range (Fig. 1). The few isolated outcrops of metasedimentary rocks adjacent to the Middle Jurassic granites (Millar and Pankhurst, 1987; Pankhurst et al., 1991; Craddock et al., 2008a) in the Ellsworth structural domain (Storey and Dalziel, 1987), which is located between the Whitmore Mountains and the Ellsworth Mountains, have a similar NW-SE structural grain. In the accepted orientation of the EWB in Gondwana reconstructions, those NW-SE structures are trending in toward the craton margin. This could reflect buttressing against a basement block or distortion of the EWB on translation and rotation. The changes in trend in the marginal domain of the EWB (Storey and Dalziel, 1987; Dalziel et al., 1987) are more abrupt, and recent work by Jordan et al. (2013) suggests that the marginal domain is an extensive shear zone. It is possible that crust similar to the Grenville-age rocks of the Haag Nunataks (Millar and Pankhurst, 1987) underlies the EWB, based on aeromagnetic data (Maslanyj and Storey, 1990; Jordan et al., 2013) and Nd isotope systematics from the Jurassic granites (Storey et al., 1988; Curtis and Storey, 1996). It would imply extensive Grenville-age basement to the Gondwana Orogen in this sector of the margin; it would be consistent with Proterozoic rocks of that age in Coats Land (Loewy et al., 2011) and Dronning Maud Land (Jacobs, 2009), and in the Namaqua-Natal Belt of South Africa (Jacobs et al., 1993), as discussed by Dalziel (1991). However, the possible EWB Grenville-age crust would then have extended greatly, and enigmatically, that province into the proto-West Antarctic sector. Rocks of the upper Neoproterozoic-Cambrian Saldanian Orogen, exposed in the Cape Fold Belt region (Scheepers and Poujol, 2002; Scheepers and Armstrong, 2002) and offshore to the south (Tankard et al., 2009), might also be present in the unexposed roots of the Gondwana Orogen, below the Permian arc. The Permian arc and underlying crustal rocks of the Saldanian Orogen formed the source of the detrital component of the Permian

post-glacial strata in the southern Karoo and Falkland Islands.

6.2. Ellsworth Land

The Permian Erehwon beds and Devonian(?) FitzGerald quartzite beds in eastern Ellsworth Land are anomalous in that they are located within what is now the Paleozoic magmatic belts that formed the active margin of Gondwana (summarized in Elliot, 2013), and suggests that they are part of a small continental block displaced from its original position. The Erehwon beds are fine-grained and detrital, and zircons indicate derivation in large part from the Gondwana active margin, although lacking the volcanic/sub-volcanic zircon morphologies of the Polarstar sandstones. In this sense they are similar to Permian beds in the Transantarctic Mountains in which detrital zircons are predominantly of Permian age (Elliot and Fanning, 2008). The Erehwon beds zircons, lacking clear volcanic/sub-volcanic characteristics, have a much broader spectrum of ages than those in the Polarstar sandstones, indicating input from a variety of sources. Their original location must have been closer to the axial region of the inferred TAM-Ellsworth Permian basin (Transantarctic Basin), rather than on the Permian arc flank.

The FitzGerald beds, with strong resemblance to the Crashsite Group and quartz-rich sandstones along the TAM (Laudon, 1991; Laudon and Ford, 1997), are a stable margin sequence and therefore out of place within the Paleozoic active margin of Gondwana. Quartzite clasts also occur in Middle Jurassic conglomerates of the Latady Group in eastern Ellsworth Land (Willan and Hunter, 2005; Hunter and Cantrill, 2006) and in conglomerates of uncertain Mesozoic age in central Alexander Island (Tranter, 1986). The former could have been derived locally from FitzGerald beds, but the latter suggest a source in the adjacent part of the Antarctic

Peninsula and a more widespread belt of quartzite beds.

Here, the FitzGerald and Erehwon beds are regarded as part of a small allochthonous terrain displaced from an original position close to the Ellsworth Mountains or to the Transantarctic Mountains. Willan and Hunter (2005) suggested that rocks similar to the FitzGerald and Erehwon beds form the basement to the Latady depositional basin, thus the Erehwon-FitzGerald terrain possibly has a much greater extent than suggested by the limited outcrops.

Two possible locations are proposed (**Fig. 10**) for a small Erehwon-FitzGerald (EF) allochthonous block.. In one scenario, it was located outboard of the Ellsworth-Whitmore (EWB) block and close to the Ellsworth Mountains (EF₁). In this case the EF block moved independently and was rotated and translated to its present position on Gondwana break-up. In the other scenario, the EF block (EF₂) was part of the original Thurston Island block, and its location would have been at the opposite end of the EWB. This is a more satisfactory location with respect to stratigraphic and petrographic relationships., Further, the structural grain of the Erehwon and FitzGerald beds (WNW-ESE in present co-ordinates) would indicate little rotation relative to the inferred structural grain of the Gondwana Orogen as recorded in the Pensacola Mountains. On Gondwana break-up, the EF block broke from the Thurston Island block and moved independently. If part of a coherent Thurston Island block, it would have undergone extension (E-W in present co-ordinates) and clockwise rotation subsequent to Thurston Island block anticlockwise rotation and translation; this seems an unnecessarily complex scenario. In reconstruction of the Gondwana margin, the EF block is here interpreted as a displaced terrain that lay inboard of the active margin and within the retro-arc depositional belt, and was not originally located within the Permian magmatic arc itself. If the EF block extends beneath the

Latady Group then the second location is more probable, and it would have extended between the EWB and East Antarctica (dotted outline linked to EF₂ in Figs. 10 and 12).

6.3. Permian plate margin

Evidence for an active Gondwana plate margin during the Late Paleozoic is found in granitoids and orthogneisses of Late Carboniferous and Permian age in eastern Marie Byrd Land, Thurston Island and the Antarctic Peninsula, and also in southern South America (summarized in Elliot, 2013; see also Riley et al., 2012). Magmatism is also recorded by detrital zircons in Permian strata in the CTM (Elliot and Fanning, 2008), in the Trinity Peninsula Group in the northern Antarctic Peninsula (Barbeau et al., 2010; Bradshaw et al., 2012), and in Patagonia (summarized in Elliot, 2013). Further, tuff beds in the Karoo show inception of magmatism in that sector at least by *ca.* 300 Ma (Bangert et al., 1999). Stratigraphically, magmatism youngs from the western Karoo to the TAM, but this may be an artifact of Lower Permian paleotopography in West Antarctica trapping sediment close to the arc. Sources for the older TAM Permian strata remained quartzo-feldspathic even though detrital zircons in upper Permian sandstones suggest early Permian magmatism (Elliot and Fanning, 2008). Structures related to the active margin are expressed in the Sierra de la Ventana of Argentina, the Cape Fold Belt of southern Africa and its extension into the Falkland Islands, the Ellsworth Mountains, and the Pensacola Mountains.

A regional interpretation of the Permian Gondwana margin is presented in **Fig. 10**. The key elements include the allochthonous Erehwon Nunatak-FitzGerald Bluffs region, the largely sub-glacial part of the EWB which here is regarded as a somewhat broken region, and the Ellsworth Mountains themselves. These elements must lie outboard of the Gondwana

deformation front (and Gondwana craton) as seen in the Falkland Islands and the Pensacola Mountains. Further, the Polarstar Formation is the down paleoflow part of the depositional basin that originated in the CTM or even farther away in the TAM, and was connected with the Panthalassan Ocean through limited seaways crossing the magmatic arc along the plate margin.

In reconstructions of the Gondwana margin the Weddell embayment (Fig. 1) has often been ignored, but is most important, as noted by Dalziel and Lawver (2001). It is formed of stretched continental crust (Hübscher et al., 1996; Hunter et al., 1996), and even if the extension is removed, it forms a significant impediment to the movement into place of the EWB from a position between Africa and Antarctica. The embayment has two components, one between Berkner Island and East Antarctica, and the other between Berkner Island and the Antarctic Peninsula. Berkner Island has been interpreted as a volcanic terrain linked to both the Dufek Massif and the Weddell Sea volcanic margin of Dronning Maud Land, and hence to have an Early Jurassic age (Hunter et al., 1996). However, the inferred magmatic rocks of Berkner Island are part of the break-up process and post-date the Permian-Triassic Gondwana margin. Given that the EWB may be floored by Grenville-age crust, the Filchner-Ronne block (FRB), which lies under the Filchner-Ronne Ice Shelf and the adjacent Weddell Sea continental margin, is most likely to have originated in the proto-Weddell Sea region as part of the possible Grenville-age basement that includes the EWB, the Namaqua-Natal Belt across southern South Africa, and Coats Land (Dalziel, 1991; Storey et al., 1994; Loewy et al., 2011). The South African flank of this region must also have included rocks of the late Proterozoic Saldanian Orogen (Scheepers and Armstrong, 2002; Scheepers and Poujol, 2002), which extended south offshore (Tankard et al., 2009). Cambrian granitoids are also known from the North Patagonian Massif (Pankhurst et al., 2014) and Tierra del Fuego (Pankhurst et al., 2003), suggesting an

extensive Cambrian magmatic province younger and outboard of the Saldanian Orogen. On break-up, the EWB migrated to its present position, relative to East Antarctica, and necessarily the FRB was translated to its present position after rotation and translation of the EWB (or accompanied translation of the latter). This part of the Gondwana margin must have been extending in a back-arc environment that post-dated the Gondwanide deformation. The youngest dated structures (in South Africa) are *ca.* 230 Ma (Hälbich et al., 1983) and orogen-derived detritus in the Karoo sequence is as young as Late Triassic (late Norian) (Turner, 1999); extension was initiated by *ca.* 200 Ma. The back-arc extension must have reached well into the Antarctic sector in order to provide the environment for long distance transport of Ferrar magmas (Elliot et al., 1999; Elliot and Fleming, 2000; Leat, 2008). Dalziel et al. (2000) have argued that extension in the proto-Weddell Sea region was related to the interaction between the Gondwanide Orogen and a plume, which also gave rise to the Ferrar-Karoo magmatism. Much of the movement of the continental blocks within this sector of the Gondwana margin must have occurred between magmatism dated at *ca.* 182-183 Ma (Encarnación et al., 1996; Burgess et al., 2011; Svensen et al., 2012) and 175 Ma (Grunow et al., 1987).

The Whiteout Conglomerate, the Paleozoic glacial strata in the Ellsworth Mountains, is lithologically correlated with the Dwyka Tillite, Fitzroy Tillite, and Gale Mudstone (Pensacola Mountains). The only definitive age on the termination of glaciation is the 288-289 Ma dates for tuff beds in the basal Prince Albert Formation in the Karoo. Although the end of glaciation was probably near synchronous, the Whiteout/Polarstar boundary may differ somewhat in age from the Dwyka/Prince Albert boundary. The occurrence of dropstones and floating sand grains in the basal Polarstar beds suggest that deposition was continuous. The zircon ages for the Polarstar Formation, however, indicate a maximum depositional age of ~269 Ma at 54.3 m

and ~257 Ma at 274.5 m in the Mt. Weems section. It is likely that the lower part of the Polarstar Formation is a condensed section as is the Prince Albert/Whitehill succession in the Karoo. By the same token, the upper informal member of the Polarstar Formation must be latest Permian in age. Assuming correlations between the Falkland Islands and the eastern Cape Province are correct, even if in the early Permian there was a connection between the Karoo and Polarstar basins, the timing of events differed markedly and suggest the lack of any connection between the basins later in Permian time.

7. Conclusions

Zircon geochronology of tuff beds in the Polarstar Formation yields a best estimate radiometric age of 258.0 ± 2.1 Ma (MW 274.5), or Lopingian Stage (late Permian), for beds in the middle informal member, the Mixed Sandstone-Argillite Facies of Collinson et al. (1992). A tuff (MW 420.4) higher in the succession gives an older age that is best explained as incorporation of earlier crystallized zircons into the erupting magma column. Detrital zircons from a sandstone in the Argillite Facies provides a depositional age no older than ~270 Ma. A sandstone low in the Mixed Facies (MW 210.5) has three probability peaks with weighted mean ages of 253.3 ± 1.7 Ma, 260.4 ± 1.5 Ma and 267.2 ± 1.5 Ma, the youngest of which is probably caused by radiogenic Pb loss because it is in conflict with the best estimate tuff age. The date of ~260 Ma is considered a maximum depositional age for that sandstone. These results suggest the lower Argillite Facies, which conformably overlies the Whiteout Conglomerate, may be a condensed section, and that the Coal Measures Facies is latest Permian.

Detrital zircons from a siltstone in the *Glossopteris*-bearing beds at Erewhon Nunatak have two Permian probability peaks at ~275 Ma and ~265 Ma (weighted mean ages of 275.0 ± 4.0

and 263.3 ± 3.6 Ma), and a late Carboniferous peak at *ca.* 325 Ma. The Carboniferous peak is linked to sparse granitoids of that age on the Gondwana margin, whereas the Permian zircons reflect near contemporaneous magmatism. Zircons from the FitzGerald beds quartzite are dominated by late Neoproterozoic to Cambrian grains, and are comparable with results for Devonian strata in the Ellsworth and Transantarctic mountains. Results for these two rock units in eastern Ellsworth Land strongly suggest they are part of an allochthonous block emplaced during the initial break-up of Gondwana, and not part of the basement of the late Paleozoic active margin of Gondwana.

Comparison of the Polarstar succession with the Karoo/Falklands beds and the Victoria Group of the Transantarctic Mountains, all of the same age, suggests that the Polarstar Formation is linked to a depositional system separate from the Karoo/Falklands basin. The Polarstar is part of a basin extending at least from the central Transantarctic Mountains into the proto-Weddell Sea region.

This interpretation suggests the Ellsworth Mountains were located in Gondwana reconstruction adjacent to Coats Land (as long suggested), but with an additional constraint imposed by the source region for the Karoo/Falklands sequence. The preferred location for the Erehwon Nunatak-FitzGerald Bluffs block (assuming a single small block) is adjacent to the Thurston Island block, from which it was detached during break-up or subsequent to major reorganization of the Gondwana plate margin.

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Appendices.

A. Petrographic descriptions of analyzed samples.

Polarstar Formation sandstone MW 54.3. Sandstone, fine-grained, subangular, well sorted, and containing streaks of carbonaceous matter. Mineral grains are quartz, commonly unstrained, and feldspar, mainly plagioclase (An_{35}) with a trace of K-feldspar, and a trace of muscovite and biotite. Volcanic rock fragments are abundant, principally cryptocrystalline and structureless, but with scattered grains consisting of aligned plagioclase laths. Abundant secondary carbonate replaces feldspar and forms the matrix.

Polarstar Formation sandstone MW 210.5. Sandstone, medium to fine grained, angular to subangular, moderately well sorted. Quartz both unstrained and with undulose extinction. Feldspar mainly plagioclase (An_{34}), commonly altered, and a trace of K-feldspar. Accessory biotite and muscovite. Abundant volcanic rock fragments; commonly cryptocrystalline to

cherty, but with about equal amounts showing feldspar microphenocrysts and/or trachytic textures. Pale green phyllosilicate forms a minor component of the matrix which is dominantly carbonate that also replaces mineral grains and rock fragments.

Polarstar Formation tuff MW 274.5. Tuff, very fine grained, siliceous in hand sample. Scattered angular quartz and more common biotite; grains less than 0.1 mm. Most of the rock is cryptocrystalline and siliceous, but with much carbonate replacement. Shard morphologies occasionally retained on carbonate replacement.

Polarstar Formation tuff MW 420.4. Tuff, very fine grained, siliceous in hand sample. Scattered angular quartz, less than 0.05 mm; scattered biotite flakes. Mineral grains set in a cryptocrystalline matrix which has much very fine grained carbonate replacement. Occasional ghost, platy, shard-like morphologies in the matrix.

Erehwon beds siltstone DL14. Siltstone with fine to very fine-grained sand laminae. Laminae include quartz, sparse plagioclase grains, and colorless and pale green phyllosilicate shreds along with carbonaceous matter.

FitzGerald beds quartzite L112a. Medium grained, well sorted, and subangular quartz-rich sandstone. Sutured quartz grains form more than 95% of the rock. Colorless to very pale green phyllosilicate occurs interstitially.

B. Supplementary items: Appendix Tables 1-6 are available from the online version of the

journal at <http://dx.doi.org/10.1016/j.gr.2014.XXXXXX>.

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Figure captions

Fig. 1. Antarctic map. Gondwana strata: Devonian to Permian in the Transantarctic and Ellsworth mountains; Permian at Erewhon Nunatak; Devonian(?) at FitzGerald Bluffs. Stretched continental crust underlies the Ross Sea, Ross Ice Shelf and West Antarctica (the Ross embayment) through to Ellsworth Land, and was generated during Late Cretaceous to Late Cenozoic time. Stretched continental crust also underlies the Filchner-Ronne Ice Shelf region and the adjacent Weddell Sea (the Weddell embayment), but was extended during Early Jurassic Gondwana break-up.

Fig. 2. Simplified stratigraphic column for the Ellsworth Mountains (modified from Webers et al., 1992a).

Fig. 3. Polarstar Formation stratigraphic column (modified from Collinson et al., 1992).

Fig. 4. U-Pb zircon age-probability plot and CL image for Polarstar sandstone sample MW 54.3. The precise age is the weighted mean age is derived from the 5-scan analyses. Spot numbers refer to the spot analyses in Table 1

Fig. 5. U-Pb zircon age plot and CL image for Polarstar sandstone sample MW 210.5. Spot numbers refer to the spot analyses in Table 2.

Fig. 6. U-Pb zircon age plot and CL image for Polarstar tuff sample MW 274.5. Spot numbers refer to the spot analyses in Table 3.

Fig. 7. U-Pb zircon age-probability plot and CL image for Polarstar tuff sample MW 420.4. Spot numbers refer to the spot analyses in Table 4.

Fig. 8. U-Pb zircon age-probability plot and CL image for Erehwon beds siltstone sample DL-14. Spot numbers refer to the spot analyses in Table 5.

Fig. 9. U-Pb zircon age-probability plot and CL image for FitzGerald beds quartzite sample L112a. Spot numbers refer to the spot analyses in Table 6.

994

995 Fig. 10. Reconstruction of the Permian Gondwana margin in the proto-Weddell Sea sector
996 (modified from a reconstruction provided by the PLATES Project at the Institute of Geophysics
997 at the University of Texas, Austin; see also caption for figure 5, Elliot, 2013). Alternate
998 positions for the Erehwon-FitzGerald block are indicated by EF₁ and EF₂, although the latter is
999 regarded as more probable. The dotted line linked to the EF₂ block is a hypothetical outline of a
1000 more extensive Erehwon-FitzGerald block (see text). This reconstruction omits the stretched
1001 continental crust of the Weddell Embayment that today is adjacent to the Ellsworth-Whitmore
1002 block region. That stretched crust is presumed to have been located in the region between
1003 Patagonia, southern Africa and the Ellsworth Mountains, and to have been displaced to its
1004 present position following the rotation, and probably accompanying the translation, of the
1005 Ellsworth-Whitmore block. Also the possible alternate position for the Haag Nunataks
1006 suggested by Grantham et al. (1997) and the strong argument for separating East Falkland and
1007 West Falkland in reconstructions (Thomas et al., 1997) are not considered because neither plays
1008 a significant role in the contention that the Polarstar Formation was deposited in a basin separate
1009 from that of the Karoo Permian beds. Further, the minor continental blocks of the Agulhas
1010 Plateau (off South Africa) and Maurice Ewing Bank (east of the Falkland Islands) are omitted.
1011 Berkner Island, which is part of a geophysically inferred widespread Lower Jurassic volcanic
1012 belt linked to Gondwana break-up, is excluded because of its age. Shortcomings exist in all
1013 reconstructions because of: limited geological data; the lack of pinning points for all parts of the
1014 Antarctic sector of the Gondwana magmatic arc, which leads to uncertainties in the positions and
1015 correlations of those lithospheric blocks; and the extent to which Patagonia might or might not
1016 have moved relative to southern Africa during Gondwana fragmentation (respectively Ramos,

2008, and Dalziel et al., 2013; versus Pankhurst et al., 2014). Nevertheless, if the Filcher-Ronne Block is formed of stretched lithospheric crust extended during break-up, then some movement of Patagonia outboard is required.

Fig.11. Stratigraphic correlations for the Permian strata in the Transantarctic and Ellsworth Mountains, and for the Falkland Islands and eastern Cape Province of South Africa. The sequence of depositional settings in the Polarstar Formation suggests similar environments to those of the Falkland Islands and Karoo of the eastern Cape Province, although paleocurrent data and event timing indicate separate depositional basins. The central Transantarctic Mountains section is based on Barrett et al. (1986), the Ohio Range on Long (1965), and the Ellsworth Mountains on Collinson et al. (1992). The Falkland Islands section is based on figure 4 of Trewin et al. (2002), the measured section of the Permian strata; the full thickness of the Bay of Harbours Formation is not illustrated here (the transition to a fluvial environment, if present, has not been documented). The eastern Cape Province section is based on figure 4 of Johnson et al. (1997) with the addition of the Waterford Formation from Rubidge et al. (2012). Tuff age determinations are in bold upright lettering, whereas detrital zircon ages are in bold italics. Dashed lines are inferred stratigraphic correlations.

Fig.12. Permian depositional basins in the proto-Weddell Sea sector of the Gondwana margin. The Karoo/Falklands and Beacon “foredeeps” represent the inferred regions of maximum stratal thickness, with the Permian strata thinning markedly onto the Kaapvaal Craton of southern Africa and the East Antarctic shield. The source region for the Karoo/Falkland Islands Permian beds (Cape Fold Belt and hinterland) is regarded as a developing fold and thrust belt involving

Mesoproterozoic rocks, the Saldanian Orogen, and Cape Supergroup strata (see text). The predominant source region for the Mackellar through lower Buckley formations in the central Transantarctic Mountains was continental and granitic (open arrows), but for the volcanoclastic upper Buckley beds was dominantly the Permian magmatic arc, although there is a small addition of detritus having the continental Gondwana margin detrital zircon signature. Regional paleoflow is indicated by the arrows along the “foredeep” of the Transantarctic Basin. Open arrows are for paleoflow in TAM strata prior to influx of arc-derived detritus, whereas the solid arrows indicate paleoflow involving arc-derived sources. Note that the regional paleoflow in CTM reversed with the influx of volcanic detritus, reflecting tectonism associated with the Gondwana plate margin.

Table 1. Timing of transitions in Permian depositional settings in the Polarstar Formation and the Karoo sequence of the eastern Cape Province.

Appendix Table 1. Summary of SHRIMP U-Pb zircon results for sandstone sample MW 54.3, Polarstar Formation.

Appendix Table 2. Summary of SHRIMP U-Pb zircon results for sandstone sample MW 210.5, Polarstar Formation.

Appendix Table 3. Summary of SHRIMP U-Pb results for zircon from tuff sample MW 274.5, Polarstar Formation.

Appendix Table 4. Summary of SHRIMP U-Pb results for zircon from tuff sample MW 420.4, Polarstar Formation.

Appendix Table 5 Summary of SHRIMP U-Pb zircon results for siltstone sample DL14,

1063 Erehwon beds.

1064 Appendix Table 6 Summary of SHRIMP U-Pb zircon results for sandstone sample L112a,

1065 FitzGerald beds.

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Table 1 Timing of transitions in Permian depositional settings		
Depositional settings	Ellsworth Mountains	Eastern Cape Province
Basin floor/pro-delta to delta front	270-260 Ma (~265 Ma?)	275-270 Ma (~272.5 Ma?)
Delta front to delta top	Younger than 257 Ma	Older than ~270 Ma
Delta top to fluvial	Not observed	Slightly older than ~268 Ma

Table 1. Summary of SHRIMP U-Pb zircon results for sandstone sample MW 54.3, Polarstar Formation.

Grain. spot	U (ppm)	Th (ppm)	Th/U	²⁰⁶ Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total Ratios				Radiogenic Ratios							Age (Ma)				% Disc	
							²³⁸ U/ ²⁰⁶ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U		²⁰⁷ Pb/ ²⁰⁶ Pb	ρ	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²⁰⁶ Pb		±	±				
								±	±		±	±				±	±			±	±		
1.1	489	97	0.20	18.1	-	<0.01	23.225	0.267	0.0510	0.0007	0.0431	0.0005							272.0	3.1			
2.1	275	200	0.73	10.5	0.000132	0.04	22.500	0.278	0.0522	0.0009	0.0444	0.0006							280.2	3.4			
3.1	581	260	0.45	20.6	0.000212	0.12	24.246	0.273	0.0524	0.0007	0.0412	0.0005							260.2	2.9			
4.1	300	119	0.40	47.8	0.000032	0.05	5.404	0.062	0.0756	0.0006	0.1849	0.0021	1.916	0.027	0.0751	0.0006	0.811	1094	11	1072	16	-2	
5.1	601	359	0.60	22.7	0.000024	0.01	22.786	0.255	0.0518	0.0006	0.0439	0.0005							276.9	3.1			
6.1	51	30	0.59	8.3	0.000310	0.52	5.257	0.087	0.0758	0.0013	0.1903	0.0034	2.003	0.104	0.0763	0.0031	0.748	1123	19	1104	80	-2	
7.1	558	316	0.57	20.5	0.000085	0.10	23.322	0.265	0.0525	0.0007	0.0428	0.0005							270.4	3.0			
8.1	458	770	1.68	16.8	0.000080	0.21	23.381	0.272	0.0533	0.0008	0.0427	0.0005							269.4	3.1			
9.1	473	223	0.47	17.5	0.000114	0.03	23.175	0.269	0.0520	0.0008	0.0431	0.0005							272.2	3.1			
10.1	293	59	0.20	36.6	-	<0.01	6.888	0.080	0.0682	0.0013	0.1452	0.0017	1.367	0.030	0.0683	0.0013	0.526	874	9	878	39	0	
11.1	97	62	0.64	3.5	-	0.41	23.627	0.381	0.0549	0.0017	0.0422	0.0007							266.1	4.3			
12.1	697	449	0.64	26.3	0.000131	<0.01	22.745	0.251	0.0515	0.0006	0.0440	0.0005							277.5	3.0			
13.1	464	422	0.91	17.3	0.000060	<0.01	23.063	0.268	0.0513	0.0007	0.0434	0.0005							273.8	3.2			
14.1	81	67	0.83	3.0	-	<0.01	23.545	0.406	0.0513	0.0026	0.0425	0.0008							268.2	4.6			
15.1	639	418	0.65	23.3	0.000078	0.09	23.564	0.265	0.0523	0.0007	0.0424	0.0005							267.7	3.0			
16.1	341	142	0.42	23.6	0.000062	0.04	12.431	0.145	0.0575	0.0007	0.0804	0.0010							498.6	5.7			
17.1	135	101	0.75	5.0	0.000331	0.67	23.374	0.346	0.0570	0.0015	0.0425	0.0006							268.3	3.9			
18.1	334	254	0.76	12.1	0.000017	<0.01	23.667	0.287	0.0507	0.0009	0.0423	0.0005							267.1	3.2			
19.1	160	76	0.47	11.4	0.000062	<0.01	12.036	0.158	0.0570	0.0010	0.0831	0.0011							514.9	6.6			
20.1	207	150	0.73	14.9	0.000098	0.06	11.959	0.149	0.0581	0.0010	0.0836	0.0011							517.4	6.3			
21.1	506	115	0.23	19.2	0.000021	<0.01	22.582	0.259	0.0511	0.0007	0.0443	0.0005							279.6	3.2			
22.1	1022	682	0.67	36.7	0.000007	<0.01	23.946	0.253	0.0514	0.0004	0.0418	0.0004							263.8	2.8			
23.1	179	75	0.42	28.1	0.000046	0.08	5.476	0.064	0.0762	0.0006	0.1825	0.0021	1.900	0.029	0.0755	0.0007	0.783	1081	12	1082	19	0	
24.1	160	106	0.66	5.9	0.000293	<0.01	23.199	0.305	0.0516	0.0011	0.0431	0.0006							272.1	3.5			
25.1	182	154	0.85	6.7	0.000326	0.09	23.264	0.298	0.0524	0.0010	0.0429	0.0006							271.1	3.4			
26.1	172	215	1.25	6.7	0.003513	6.40	22.103	0.291	0.1029	0.0016	0.0423	0.0006							267.4	3.5			
27.1	261	244	0.93	9.4	0.000124	<0.01	23.825	0.288	0.0511	0.0009	0.0420	0.0005							265.2	3.2			
28.1	411	177	0.43	15.1	0.000021	0.04	23.450	0.267	0.0520	0.0007	0.0426	0.0005							269.1	3.0			
29.1	286	214	0.75	19.7	0.000052	<0.01	12.450	0.142	0.0564	0.0008	0.0804	0.0009							498.5	5.6			
30.1	453	250	0.55	15.7	0.000203	0.10	24.658	0.282	0.0522	0.0006	0.0405	0.0005							256.0	2.9			
31.1	160	137	0.85	5.6	-	<0.01	24.524	0.325	0.0500	0.0014	0.0408	0.0006							258.1	3.4			
32.1	281	258	0.92	10.0	0.000315	0.13	24.166	0.293	0.0525	0.0016	0.0413	0.0005							261.0	3.2			
33.1	247	150	0.61	9.0	0.000136	<0.01	23.486	0.285	0.0509	0.0009	0.0426	0.0005							269.0	3.2			
34.1	309	138	0.45	11.3	-	0.03	23.444	0.275	0.0519	0.0008	0.0426	0.0005							269.2	3.1			
35.1	207	84	0.40	7.5	0.000148	0.05	23.765	0.299	0.0520	0.0010	0.0421	0.0005							265.6	3.3			
36.1	209	149	0.72	7.7	-	<0.01	23.396	0.292	0.0514	0.0010	0.0428	0.0005							269.9	3.3			
37.1	233	167	0.72	8.6	0.000134	0.12	23.177	0.282	0.0526	0.0009	0.0431	0.0005							272.0	3.3			
38.1	165	115	0.70	6.2	0.000255	0.16	22.850	0.296	0.0531	0.0011	0.0437	0.0006							275.7	3.5			
39.1	90	48	0.54	3.4	0.003301	3.72	22.386	0.332	0.0815	0.0018	0.0430	0.0007							271.5	4.0			
40.1	2086	378	0.18	177.5	0.000072	0.29	10.094	0.103	0.0625	0.0002	0.0988	0.0010							607.2	6.0			
41.1	775	503	0.65	29.3	0.000017	0.07	22.748	0.244	0.0524	0.0005	0.0439	0.0005							277.1	2.9			
42.1	363	384	1.06	14.4	0.004868	6.79	21.706	0.256	0.1062	0.0040	0.0429	0.0006							271.0	3.5			
43.1	239	140	0.59	16.2	-	0.22	12.692	0.149	0.0587	0.0007	0.0786	0.0009							487.8	5.6			
44.1	220	94	0.43	8.0	-	<0.01	23.630	0.293	0.0509	0.0009	0.0424	0.0005							267.4	3.3			
45.1	795	209	0.26	28.5	0.000105	0.01	23.978	0.257	0.0516	0.0005	0.0417	0.0005							263.4	2.8			
46.1	317	193	0.61	11.5	0.000785	0.20	23.612	0.276	0.0532	0.0008	0.0423	0.0005							266.9	3.1			
47.1	31	33	1.09	1.1	-	0.08	23.324	0.524	0.0523	0.0027	0.0428	0.0010							270.4	6.1			
48.1	343	135	0.39	23.9	0.000095	0.19	12.315	0.138	0.0589	0.0006	0.0810	0.0009							502.4	5.5			
49.1	141	97	0.69	10.2	0.000099	<0.01	11.942	0.151	0.0571	0.0009	0.0838	0.0011							518.8	6.4			
50.1	349	209	0.60	13.5	0.000204	0.28	22.224	0.257	0.0542	0.0008	0.0449	0.0005							282.9	3.2			
51.1	337	160	0.48	12.3	0.000122	<0.01	23.555	0.280	0.0502	0.0009	0.0425	0.0005							268.5	3.2			
52.1	622	576	0.93	21.8	0.000176	<0.01	24.495	0.277	0.0510	0.0010	0.0408	0.0005							258.1	2.9			
53.1	174	114	0.65	6.4	0.000736	1.42	23.345	0.434	0.0630	0.0012	0.0422	0.0008							266.6	4.9			
54.1	129	74	0.57	4.8	0.000244	<0.01	23.268	0.347	0.0495	0.0012	0.0431	0.0007							272.0	4.0			
55.1	135	35	0.26	9.1	0.000076	0.21																	

Table 2. Summary of SHRIMP U-Pb zircon results for sandstone sample MW 210.5, Polarstar Formation.

Grain. spot	U (ppm)	Th (ppm)	Th/U	²⁰⁶ Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total Ratios				Radiogenic Ratios							Age (Ma)				% Disc	
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	ρ	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±		
1.1	695	484	0.70	25.4	0.000200	0.02	23.509	0.251	0.0518	0.0005	0.0425	0.0005							268	3			
2.1	175	63	0.36	6.8	0.000574	0.19	22.007	0.317	0.0535	0.0010	0.0454	0.0007							286	4			
3.1	187	98	0.52	7.1	0.000909	2.02	22.729	0.282	0.0679	0.0022	0.0431	0.0006							272	3			
4.1	310	68	0.22	28.7	0.000065	<0.01	9.270	0.271	0.0606	0.0026	0.1080	0.0032							661	19			
5.1	443	269	0.61	16.4	0.000167	0.14	23.253	0.257	0.0528	0.0007	0.0429	0.0005							271	3			
6.1	695	319	0.46	25.9	0.000064	<0.01	23.078	0.248	0.0516	0.0005	0.0433	0.0005							273	3			
7.1	54	8	0.15	5.4	0.000737	1.94	8.596	0.184	0.0786	0.0015	0.1141	0.0025							696	15			
8.1	412	235	0.57	15.1	0.000011	0.12	23.396	0.300	0.0526	0.0007	0.0427	0.0006							269	3			
9.1	162	87	0.54	5.9	0.000294	0.24	23.550	0.309	0.0536	0.0012	0.0424	0.0006							267	3			
11.1	336	152	0.45	12.2	0.000165	<0.01	23.699	0.271	0.0515	0.0008	0.0422	0.0005							266	3			
11.1	416	191	0.46	15.2	0.000081	0.16	23.444	0.266	0.0529	0.0007	0.0426	0.0005							269	3			
12.1	447	283	0.63	20.6	0.001090	0.67	18.587	0.326	0.0585	0.0018	0.0534	0.0010							336	6			
13.1	267	265	0.99	9.7	0.000017	0.06	23.510	0.277	0.0521	0.0009	0.0425	0.0005							268	3			
14.1	859	282	0.33	31.8	0.000052	0.07	23.245	0.253	0.0523	0.0005	0.0430	0.0005							271	3			
15.1	362	171	0.47	13.2	0.000108	0.16	23.498	0.274	0.0529	0.0008	0.0425	0.0005							268	3			
16.1	232	49	0.21	34.1	0.000043	0.07	5.848	0.076	0.0727	0.0009	0.1709	0.0022	1.699	0.031	0.0721	0.0009	0.718	1017	12	989	26	-3	
17.1	637	306	0.48	23.3	0.000794	1.49	23.502	0.254	0.0635	0.0008	0.0419	0.0005							265	3			
18.1	658	462	0.70	24.1	0.000099	0.05	23.421	0.258	0.0521	0.0006	0.0427	0.0005							269	3			
19.1	489	172	0.35	17.1	0.000144	0.28	24.596	0.278	0.0536	0.0010	0.0405	0.0005							256	3			
20.1	444	271	0.61	15.3	0.000152	0.37	24.911	0.296	0.0542	0.0009	0.0400	0.0005							253	3			
21.1	370	161	0.43	24.8	0.000340	0.76	12.830	0.154	0.0629	0.0009	0.0774	0.0009							480	6			
22.1	326	162	0.50	11.7	0.000670	0.45	23.948	0.309	0.0551	0.0015	0.0416	0.0005							263	3			
23.1	103	52	0.50	6.5	0.000283	0.66	13.542	0.217	0.0615	0.0017	0.0734	0.0012							456	7			
24.1	320	164	0.51	11.0	0.000550	0.28	24.914	0.340	0.0535	0.0012	0.0400	0.0006							253	3			
25.1	631	275	0.44	22.5	0.000188	0.39	24.085	0.282	0.0546	0.0008	0.0414	0.0005							261	3			
26.1	454	236	0.52	16.0	0.000217	0.13	24.365	0.363	0.0525	0.0008	0.0410	0.0006							259	4			
27.1	805	375	0.47	32.0	0.001377	1.52	21.616	0.243	0.0642	0.0008	0.0456	0.0005							287	3			
28.1	177	96	0.54	6.6	0.000072	0.39	22.927	0.328	0.0549	0.0015	0.0434	0.0006							274	4			
29.1	562	362	0.64	19.9	0.000107	0.33	24.262	0.281	0.0541	0.0008	0.0411	0.0005							260	3			
30.1	676	293	0.43	26.7	0.000949	1.73	21.741	0.244	0.0659	0.0013	0.0452	0.0005							285	3			
31.1	1012	363	0.36	37.5	0.000231	0.31	23.186	0.263	0.0542	0.0006	0.0430	0.0005							271	3			
32.1	275	128	0.46	9.8	0.000256	0.25	24.136	0.321	0.0534	0.0012	0.0413	0.0006							261	3			
33.1	666	290	0.44	23.5	0.000298	0.52	24.340	0.295	0.0556	0.0009	0.0409	0.0005							258	3			
34.1	247	194	0.78	8.8	0.000292	<0.01	24.238	0.324	0.0492	0.0012	0.0414	0.0006							261	3			
35.1	616	228	0.37	21.2	0.000248	0.24	24.994	0.294	0.0532	0.0010	0.0399	0.0005							252	3			
36.1	915	570	0.62	32.4	-	0.09	24.230	0.267	0.0522	0.0007	0.0412	0.0005							260	3			
37.1	344	154	0.45	12.5	0.000172	0.19	23.763	0.278	0.0531	0.0009	0.0420	0.0005							265	3			
38.1	260	268	1.03	10.3	0.007995	15.95	21.565	0.259	0.1789	0.0019	0.0390	0.0005							246	3			
39.1	193	66	0.34	7.0	0.000401	0.22	23.808	0.309	0.0533	0.0012	0.0419	0.0006							265	3			
40.1	373	151	0.40	13.6	0.000172	0.14	23.509	0.275	0.0527	0.0008	0.0425	0.0005							268	3			
41.1	143	62	0.43	5.2	-	0.32	23.557	0.329	0.0542	0.0015	0.0423	0.0006							267	4			
42.1	637	304	0.48	22.8	0.001045	1.69	23.942	0.271	0.0650	0.0015	0.0411	0.0005							259	3			
43.1	697	176	0.25	26.0	0.002851	4.79	23.000	0.268	0.0898	0.0022	0.0414	0.0005							261	3			
44.1	712	672	0.94	25.3	0.000412	0.63	24.195	0.332	0.0565	0.0006	0.0411	0.0006							259	4			
45.1	527	224	0.42	19.1	0.000172	<0.01	23.758	0.267	0.0515	0.0007	0.0421	0.0005							266	3			
46.1	92	73	0.80	5.2	0.017671	30.01	15.175	0.222	0.2933	0.0085	0.0461	0.0010							291	6			
47.1	625	306	0.49	24.0	0.000303	0.18	22.391	0.256	0.0534	0.0007	0.0446	0.0005							281	3			
48.1	133	59	0.45	4.6	0.000432	0.29	24.848	0.380	0.0536	0.0016	0.0401	0.0006							254	4			
49.1	566	272	0.48	37.8	0.000018	0.07	12.876	0.139	0.0573	0.0005	0.0776	0.0009							482	5			
50.1	251	145	0.58	8.9	0.000566	0.23	24.322	0.322	0.0532	0.0016	0.0410	0.0006							259	3			
51.1	575	230	0.40	20.3	0.000056	0.14	24.344	0.283	0.0526	0.0008	0.0410	0.0005							259	3			
52.1	247	111	0.45	8.6	0.000312	0.55	24.743	0.330	0.0557	0.0013	0.0402	0.0005							254	3			
53.1	438	237	0.54	15.4	0.000031	<0.01	24.462	0.292	0.0512	0.0009	0.0409	0.0005							258	3			
54.1	259	164	0.63	9.4	0.000102	0.14	23.776	0.309	0.0527	0.0012	0.0420	0.0006							265	3			
55.1	399	225	0.56	14.5	0.000299	0.13	23.605	0.299	0.0526	0.0010	0.0423	0.0005							267	3			
56.1	290	144	0.50	10.7	0.001159	1.63	23.324	0.327	0.0647	0.0017	0.0422	0.0006					</						

Table 3. Summary of SHRIMP U-Pb results for zircon from tuff sample MW 274.5, Polarstar Formation.

Grain. spot	U (ppm)	Th (ppm)	Th/U	²⁰⁶ Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total				Radiogenic		Age (Ma)	
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁶ Pb/ ²³⁸ U	±
1.1	484	186	0.38	16.6	0.000083	0.09	25.05	0.30	0.0520	0.0007	0.0399	0.0005	252.1	3.0
2.1	732	368	0.50	26.2	0.000068	<0.01	23.99	0.26	0.0514	0.0006	0.0417	0.0005	263.3	2.9
3.1	492	333	0.68	17.1	0.000077	0.08	24.79	0.29	0.0520	0.0008	0.0403	0.0005	254.8	3.0
4.1	450	177	0.39	15.7	0.000015	0.14	24.66	0.29	0.0524	0.0008	0.0405	0.0005	255.9	3.0
5.1	156	40	0.25	5.7	0.000724	0.26	23.70	0.34	0.0537	0.0013	0.0421	0.0006	265.8	3.8
6.1	172	47	0.27	6.2	0.000439	0.17	23.83	0.35	0.0529	0.0014	0.0419	0.0006	264.5	3.9
7.1	162	58	0.36	5.7	0.000445	0.47	24.29	0.35	0.0552	0.0013	0.0410	0.0006	258.9	3.7
8.1	746	330	0.44	27.1	0.000062	0.07	23.61	0.26	0.0522	0.0006	0.0423	0.0005	267.2	2.9
9.1	312	93	0.30	10.9	0.000348	0.12	24.59	0.31	0.0523	0.0009	0.0406	0.0005	256.6	3.2
10.1	246	182	0.74	8.5	0.000534	0.22	24.76	0.32	0.0531	0.0011	0.0403	0.0005	254.7	3.3
11.1	536	165	0.31	18.8	-	0.26	24.48	0.28	0.0535	0.0007	0.0407	0.0005	257.4	2.9
12.1	402	76	0.19	14.2	0.000089	0.30	24.27	0.29	0.0538	0.0008	0.0411	0.0005	259.6	3.1
13.1	518	148	0.29	18.3	0.000000	<0.01	24.38	0.28	0.0513	0.0007	0.0410	0.0005	259.2	2.9
14.1	435	124	0.29	15.2	0.000102	0.19	24.61	0.29	0.0528	0.0008	0.0406	0.0005	256.3	3.0
15.1	846	317	0.37	30.8	0.000053	0.07	23.57	0.26	0.0522	0.0005	0.0424	0.0005	267.7	2.9
16.1	316	195	0.62	11.2	-	0.21	24.19	0.31	0.0531	0.0009	0.0413	0.0005	260.6	3.3
17.1	468	214	0.46	16.5	0.000040	0.10	24.37	0.28	0.0522	0.0007	0.0410	0.0005	259.0	3.0
18.1	465	220	0.47	16.5	0.000068	0.07	24.16	0.28	0.0520	0.0007	0.0414	0.0005	261.3	3.0
19.1	1189	616	0.52	44.3	0.000119	0.23	23.08	0.25	0.0536	0.0012	0.0432	0.0005	272.8	2.9
20.1	478	237	0.50	16.7	-	0.34	24.55	0.30	0.0541	0.0008	0.0406	0.0005	256.5	3.1

- Notes:
1. Uncertainties given at the one σ level.
 2. Error in Temora reference zircon calibration was 0.57% for the analytical session.
(not included in above errors but required when comparing data from different mounts).
 3. f₂₀₆ % denotes the percentage of ²⁰⁶Pb that is common Pb.
 4. Correction for common Pb for the U/Pb data has been made using the measured ²³⁸U/²⁰⁶Pb and ²⁰⁷Pb/²⁰⁶Pb ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).

Table 4. Summary of SHRIMP U-Pb results for zircon from tuff sample MW 420.4, Polarstar Formation.

Grain. spot	U (ppm)	Th (ppm)	Th/U	²⁰⁶ Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total				Radiogenic				Age (Ma)	
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁶ Pb/ ²³⁸ U	±		
1.1	322	203	0.63	11.5	0.000028	0.03	24.04	0.30	0.0517	0.0009	0.0416	0.0005	262.7	3.2		
2.1	247	116	0.47	9.0	0.000226	<0.01	23.61	0.30	0.0511	0.0010	0.0424	0.0006	267.6	3.4		
3.1	198	106	0.54	7.2	-	0.19	23.76	0.32	0.0530	0.0012	0.0420	0.0006	265.2	3.6		
4.1	86	89	1.04	3.1	0.000221	0.27	23.67	0.44	0.0537	0.0018	0.0421	0.0008	266.0	4.9		
5.1	168	116	0.69	5.9	0.000274	0.04	24.36	0.34	0.0518	0.0013	0.0410	0.0006	259.2	3.6		
6.1	496	261	0.53	17.8	0.000058	0.11	23.97	0.28	0.0524	0.0007	0.0417	0.0005	263.2	3.0		
7.1	604	287	0.48	21.8	-	0.08	23.86	0.27	0.0522	0.0007	0.0419	0.0005	264.5	3.0		
8.1	237	115	0.48	8.5	-	<0.01	24.08	0.32	0.0514	0.0016	0.0415	0.0006	262.3	3.5		
9.1	415	321	0.77	14.9	-	0.09	24.02	0.29	0.0522	0.0010	0.0416	0.0005	262.7	3.1		
10.1	621	495	0.80	22.0	0.000078	<0.01	24.29	0.28	0.0514	0.0007	0.0412	0.0005	260.1	2.9		
11.1	579	317	0.55	21.5	0.000144	0.15	23.17	0.26	0.0529	0.0007	0.0431	0.0005	272.0	3.0		
12.1	394	331	0.84	14.6	0.000299	0.49	23.24	0.28	0.0556	0.0008	0.0428	0.0005	270.3	3.2		
13.1	276	237	0.86	9.9	-	0.39	24.07	0.31	0.0546	0.0010	0.0414	0.0005	261.4	3.3		
14.1	122	90	0.74	4.4	-	0.51	23.85	0.37	0.0556	0.0015	0.0417	0.0007	263.4	4.0		
15.1	364	339	0.93	13.1	-	<0.01	23.90	0.29	0.0516	0.0009	0.0418	0.0005	264.2	3.2		
16.1	400	272	0.68	14.3	0.000122	0.09	24.00	0.29	0.0522	0.0008	0.0416	0.0005	262.9	3.1		
17.1	353	162	0.46	12.5	-	0.18	24.19	0.30	0.0529	0.0009	0.0413	0.0005	260.7	3.2		
18.1	271	144	0.53	9.7	-	0.18	24.11	0.31	0.0529	0.0010	0.0414	0.0005	261.5	3.3		
19.1	151	101	0.67	5.4	0.000326	0.15	24.12	0.35	0.0527	0.0014	0.0414	0.0006	261.5	3.8		
20.1	237	195	0.82	8.4	0.000078	0.41	24.27	0.34	0.0547	0.0011	0.0410	0.0006	259.2	3.6		

Notes: 1. Uncertainties given at the one σ level.

2. Error in Temora reference zircon calibration was 0.57% for the analytical session.

(not included in above errors but required when comparing data from different mounts).

3. f₂₀₆ % denotes the percentage of ²⁰⁶Pb that is common Pb.4. Correction for common Pb for the U/Pb data has been made using the measured ²³⁸U/²⁰⁶Pb and ²⁰⁷Pb/²⁰⁶Pb ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).

Table 5 Summary of SHRIMP U-Pb zircon results for siltstone sample DL14, Erewhon beds.

Grain. spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total Ratios				Radiogenic Ratios						ρ	Age (Ma)				% Disc
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±		²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	
1.1	114	73	0.64	7.9	0.000000	0.80	12.449	0.364	0.0636	0.0029	0.0797	0.0024						494	14			
2.1	1193	844	0.71	316.7	0.000011	0.02	3.236	0.073	0.1058	0.0006	0.3090	0.0070	4.501	0.105	0.1057	0.0006	0.965	1736	34	1726	11	-1
3.1	260	109	0.42	35.0	0.000084	0.14	6.394	0.155	0.0747	0.0015	0.1562	0.0038	1.582	0.051	0.0735	0.0015	0.757	936	21	1027	42	9
4.1	962	377	0.39	44.3	0.000123	<0.01	18.668	0.440	0.0525	0.0011	0.0536	0.0013						337	8			
5.1	165	159	0.96	14.8	0.000265	0.27	9.625	0.252	0.0631	0.0021	0.1036	0.0028						636	16			
6.1	274	281	1.03	12.1	0.000019	0.71	19.498	0.506	0.0585	0.0021	0.0509	0.0013						320	8			
7.1	714	3008	4.21	93.0	-	<0.01	6.592	0.152	0.0651	0.0009	0.1525	0.0036						915	20			
8.1	63	66	1.05	5.5	0.000926	0.47	9.964	0.329	0.0641	0.0035	0.0999	0.0034						614	20			
9.1	1162	343	0.29	51.8	-	0.28	19.266	0.443	0.0552	0.0011	0.0518	0.0012						325	7			
10.1	764	322	0.42	27.7	0.000202	<0.01	23.654	0.567	0.0513	0.0014	0.0423	0.0010						267	6			
11.1	643	657	1.02	23.1	0.000058	<0.01	23.917	0.580	0.0515	0.0015	0.0418	0.0010						264	6			
12.1	328	33	0.10	23.3	0.000653	2.24	12.067	0.342	0.0755	0.0072	0.0810	0.0025						502	15			
13.1	122	87	0.72	5.0	0.001257	5.47	20.760	0.735	0.0960	0.0051	0.0455	0.0017						287	10			
14.1	268	93	0.35	33.8	-	1.40	6.818	0.169	0.0797	0.0017	0.1446	0.0037						871	21			
15.1	360	77	0.21	31.9	0.000279	<0.01	9.689	0.266	0.0603	0.0024	0.1033	0.0029						634	17			
16.1	1451	333	0.23	61.2	0.000053	0.64	20.356	0.470	0.0577	0.0011	0.0488	0.0011						307	7			
17.1	513	213	0.42	19.3	0.000218	<0.01	22.873	0.605	0.0493	0.0018	0.0439	0.0012						277	7			
18.1	822	168	0.20	36.6	0.000263	0.26	19.292	0.457	0.0550	0.0013	0.0517	0.0012						325	8			
19.1	306	420	1.37	11.0	0.000936	0.68	23.802	0.660	0.0569	0.0026	0.0417	0.0012						264	7			
20.1	1361	290	0.21	47.8	0.000176	0.16	24.482	0.566	0.0527	0.0011	0.0408	0.0010						258	6			
21.1	639	135	0.21	21.3	0.000477	0.12	25.740	0.668	0.0521	0.0018	0.0388	0.0010						245	6			
22.1	499	98	0.20	63.0	0.000418	1.96	6.807	0.169	0.0842	0.0034	0.1440	0.0038						867	21			
23.1	143	72	0.51	20.5	0.000190	0.32	6.002	0.163	0.0774	0.0021	0.1661	0.0045	1.711	0.078	0.0747	0.0028	0.594	990	25	1061	74	7
24.1	160	197	1.23	17.7	0.000254	0.39	7.766	0.222	0.0683	0.0022	0.1283	0.0038						778	22			
25.1	556	323	0.58	19.9	0.000420	0.66	24.008	0.598	0.0567	0.0018	0.0414	0.0010						261	6			
26.1	283	156	0.55	10.6	0.000074	0.75	22.943	0.633	0.0577	0.0025	0.0433	0.0012						273	7			
27.1	414	188	0.46	14.4	-	0.27	24.670	0.634	0.0535	0.0020	0.0404	0.0011						255	7			
28.1	109	60	0.55	26.4	0.000232	0.37	3.547	0.097	0.1055	0.0024	0.2809	0.0077	3.964	0.147	0.1023	0.0026	0.738	1596	39	1667	46	4
29.1	226	178	0.78	8.0	0.000865	0.85	24.238	0.694	0.0582	0.0028	0.0409	0.0012						258	7			
30.1	400	198	0.49	15.7	0.000532	<0.01	21.930	0.562	0.0520	0.0019	0.0456	0.0012						287	7			
31.1	419	225	0.54	76.2	0.000226	0.38	4.720	0.111	0.0793	0.0025	0.2121	0.0050	2.347	0.092	0.0802	0.0025	0.600	1240	29	1203	62	-3
32.1	675	902	1.34	23.8	0.000072	0.12	24.331	0.284	0.0524	0.0007	0.0410	0.0005						259	3			
33.1	533	152	0.29	22.6	0.000137	0.32	20.252	0.238	0.0551	0.0008	0.0492	0.0006						310	4			
34.1	1001	1115	1.11	37.6	0.000055	<0.01	22.847	0.264	0.0503	0.0005	0.0439	0.0005						277	3			
35.1	347	141	0.41	13.0	0.000189	0.16	22.839	0.297	0.0530	0.0010	0.0437	0.0006						276	4			
36.1	820	199	0.24	37.5	-	0.11	18.784	0.209	0.0540	0.0006	0.0532	0.0006						334	4			
37.1	620	87	0.14	49.4	0.000029	<0.01	10.777	0.120	0.0589	0.0005	0.0928	0.0011						572	6			
38.1	544	71	0.13	49.5	-	0.39	9.428	0.112	0.0644	0.0010	0.1056	0.0013						647	8			
39.1	295	76	0.26	10.0	0.000283	0.05	25.421	0.353	0.0515	0.0011	0.0393	0.0006						249	3			
40.1	959	47	0.05	42.5	0.000024	0.04	19.384	0.216	0.0532	0.0006	0.0516	0.0006						324	4			
41.1	289	89	0.31	10.7	0.000226	<0.01	23.195	0.321	0.0506	0.0011	0.0432	0.0006						272	4			
42.1	310	173	0.56	54.9	0.000018	0.03	4.858	0.057	0.0787	0.0006	0.2058	0.0024	2.226	0.032	0.0784	0.0006	0.820	1206	13	1158	16	-4
43.1	359	118	0.33	12.7	0.000127	<0.01	24.241	0.320	0.0508	0.0010	0.0413	0.0006						261	3			
44.1	1725	504	0.29	65.0	0.000057	0.22	22.782	0.260	0.0536	0.0005	0.0438	0.0005						276	3			
45.1	427	156	0.36	17.4	0.000025	0.19	21.060	0.266	0.0538	0.0009	0.0474	0.0006						299	4			
46.1	299	188	0.63	20.7	0.000122	0.15	12.394	0.175	0.0584	0.0012	0.0806	0.0012						499	7			
47.1	1363	243	0.18	102.2	0.000038	0.18	11.455	0.125	0.0597	0.0006	0.0871	0.0010						539	6			
48.1	403	367	0.91	14.5	0.000001	<0.01	23.945	0.306	0.0513	0.0009	0.0418	0.0005						264	3			
49.1	459	228	0.50	55.7	0.000035	0.06	7.078	0.087	0.0740	0.0009	0.1412	0.0017	1.431	0.027	0.0735	0.0010	0.661	851	10	1027	28	17
50.1	679	361	0.53	25.1	-	0.08	23.195	0.314	0.0524	0.0011	0.0431	0.0006						272	4			
51.1	158	85	0.54	40.8	-	<0.01	3.315	0.044	0.1070	0.0010	0.3017	0.0040	4.463	0.072	0.1073	0.0010	0.834	1700	20	1754	16	3
52.1	1506	247	0.16	55.0	0.000216	0.47	23.514	0.278	0.0554	0.0006	0.0423	0.0005						267	3			
53.1	193	108	0.56	6.9	-	<0.01	23.925	0.408	0.0496	0.0016	0.0419	0.0007						265	4			
54.1	126	19	0.15	17.3	0.000131	0.22	6.219	0.092	0.0739	0.0012	0.1604	0.0024	1.594	0.043	0.0720	0.0016	0.554	959	13	987	45	3
55.1	756	58	0.08	30.3	0.000043	0.14	21.394	0.294	0.0533	0.0009												

- Notes :
1. Uncertainties given at the one σ level.
 2. f₂₀₆ % denotes the percentage of ²⁰⁶Pb that is common Pb.
 3. Correction for common Pb made using the measured ²⁰⁴Pb/²⁰⁶Pb ratio.
 4. For % Disc, 0% denotes a concordant analysis.

Table 6 Summary of SHRIMP U-Pb zircon results for sandstone sample L112a, FitzGerald beds.

Grain. spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total Ratios				Radiogenic Ratios						Age (Ma)					% Disc
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	ρ	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	
1.1	293	88	0.30	67.9	0.000011	0.02	3.705	0.048	0.0988	0.0010	0.2698	0.0035	3.672	0.061	0.0987	0.0010	0.781	1540	18	1599	19	4
2.1	181	70	0.39	49.0	0.000135	0.19	3.174	0.043	0.1746	0.0024	0.3145	0.0043	7.499	0.146	0.1729	0.0024	0.696	1763	21	2586	23	32
3.1	582	289	0.50	47.5	0.000149	0.31	10.541	0.138	0.0620	0.0008	0.0946	0.0013						583	7			
4.1	209	304	1.46	16.7	-	0.17	10.731	0.156	0.0606	0.0013	0.0930	0.0014						573	8			
5.1	128	97	0.76	19.8	0.000171	0.29	5.549	0.085	0.0788	0.0015	0.1797	0.0028	1.893	0.061	0.0764	0.0021	0.482	1065	15	1106	56	4
6.1	316	185	0.59	24.3	0.000284	0.25	11.159	0.156	0.0606	0.0012	0.0894	0.0013						552	8			
7.1	174	101	0.58	14.3	0.000324	1.53	10.483	0.165	0.0718	0.0024	0.0939	0.0015						579	9			
8.1	424	172	0.41	45.9	0.000209	0.87	7.924	0.108	0.0717	0.0015	0.1251	0.0018						760	10			
9.1	27	8	0.27	4.6	0.001053	1.78	5.132	0.142	0.0910	0.0033	0.1914	0.0058	2.005	0.290	0.0760	0.0108	0.209	1129	31	1095	283	-3
10.1	35	24	0.69	3.2	0.001314	2.24	9.579	0.251	0.0790	0.0038	0.1020	0.0028						626	16			
11.1	765	47	0.06	64.7	0.000028	0.07	10.165	0.129	0.0606	0.0007	0.0983	0.0013						604	7			
12.1	55	34	0.62	4.5	0.003005	9.52	10.472	0.225	0.1356	0.0042	0.0864	0.0023						534	13			
13.1	377	52	0.14	30.0	0.000034	<0.01	10.791	0.142	0.0577	0.0010	0.0928	0.0013						572	7			
14.1	109	78	0.71	43.2	0.000057	0.08	2.164	0.032	0.1892	0.0017	0.4617	0.0069	11.998	0.211	0.1885	0.0018	0.849	2447	30	2729	15	10
15.1	106	62	0.59	7.8	0.000152	0.53	11.691	0.212	0.0622	0.0021	0.0851	0.0016						526	9			
16.1	186	388	2.09	15.0	0.000155	0.26	10.675	0.161	0.0613	0.0014	0.0934	0.0014						576	9			
17.1	35	15	0.43	2.8	-	0.73	10.924	0.286	0.0648	0.0035	0.0909	0.0025						561	15			
18.1	212	72	0.34	32.7	-	<0.01	5.559	0.076	0.0772	0.0011	0.1804	0.0025	1.987	0.049	0.0799	0.0016	0.561	1069	14	1193	40	10
19.1	269	80	0.30	54.4	0.000050	0.08	4.253	0.055	0.0969	0.0010	0.2349	0.0030	3.117	0.051	0.0962	0.0010	0.787	1360	16	1552	19	12
20.1	224	102	0.45	34.5	0.000104	0.18	5.562	0.075	0.0759	0.0011	0.1795	0.0024	1.841	0.038	0.0744	0.0012	0.651	1064	13	1052	32	-1
21.1	212	106	0.50	32.7	-	<0.01	5.562	0.075	0.0729	0.0010	0.1801	0.0024	1.845	0.041	0.0743	0.0013	0.603	1068	13	1050	36	-2
22.1	267	165	0.62	119.1	-	<0.01	1.924	0.024	0.1861	0.0010	0.5198	0.0065	13.340	0.182	0.1861	0.0010	0.918	2698	28	2708	9	0
23.1	254	96	0.38	133.5	0.000020	0.02	1.637	0.021	0.2725	0.0064	0.6106	0.0080	22.926	0.618	0.2723	0.0064	0.485	3072	32	3319	37	7
24.1	173	74	0.43	17.9	0.000157	0.62	8.289	0.121	0.0688	0.0018	0.1199	0.0018						730	11			
25.1	352	152	0.43	164.2	0.000014	0.02	1.844	0.025	0.1659	0.0008	0.5422	0.0074	12.393	0.180	0.1658	0.0008	0.946	2793	31	2515	8	-11
26.1	369	146	0.39	54.9	0.000068	0.12	5.786	0.075	0.0749	0.0008	0.1726	0.0022	1.759	0.031	0.0739	0.0009	0.728	1027	12	1039	25	1
27.1	555	117	0.21	46.3	0.000101	0.04	10.308	0.134	0.0602	0.0008	0.0970	0.0013						597	8			
28.1	232	70	0.30	18.8	0.000419	<0.01	10.611	0.161	0.0589	0.0012	0.0943	0.0015						581	9			
29.1	518	131	0.25	48.2	0.000096	0.27	9.218	0.115	0.0638	0.0009	0.1082	0.0014						662	8			
30.1	254	110	0.43	20.1	0.000033	<0.01	10.891	0.162	0.0589	0.0012	0.0918	0.0014						566	8			
31.1	59	18	0.31	8.4	0.000220	0.37	6.067	0.135	0.0796	0.0026	0.1642	0.0037	1.732	0.119	0.0765	0.0050	0.331	980	21	1108	129	13
32.1	440	40	0.09	35.1	0.000034	0.11	10.774	0.149	0.0600	0.0011	0.0927	0.0013						572	8			
33.1	1243	224	0.18	253.0	0.000085	0.14	4.219	0.052	0.0961	0.0005	0.2367	0.0029	3.098	0.044	0.0949	0.0007	0.869	1369	15	1526	13	11
34.1	542	82	0.15	213.3	-	<0.01	2.182	0.029	0.2182	0.0019	0.4584	0.0060	13.809	0.218	0.2185	0.0019	0.827	2432	26	2970	14	22
35.1	248	13	0.05	18.8	0.000060	0.33	11.348	0.181	0.0610	0.0016	0.0878	0.0014						543	9			
36.1	1542	77	0.05	128.2	0.000097	0.09	10.330	0.107	0.0605	0.0003	0.0967	0.0010						595	6			
37.1	1350	56	0.04	84.1	0.000141	0.80	13.800	0.144	0.0624	0.0004	0.0719	0.0008						447	5			
38.1	540	127	0.23	43.9	0.000081	0.03	10.570	0.116	0.0596	0.0005	0.0946	0.0011						583	6			
39.1	85	28	0.34	6.3	-	2.45	11.583	0.197	0.0777	0.0023	0.0842	0.0015						521	9			
40.1	233	50	0.21	26.5	0.000060	0.49	7.547	0.094	0.0698	0.0006	0.1318	0.0017						798	10			
41.1	186	59	0.32	61.0	0.000015	0.02	2.622	0.031	0.1849	0.0019	0.3813	0.0044	9.709	0.151	0.1847	0.0019	0.750	2082	21	2695	17	29
42.1	226	210	0.93	17.3	0.000136	0.43	11.209	0.144	0.0620	0.0013	0.0888	0.0012						549	7			
43.1	147	91	0.62	12.8	0.000070	0.54	9.902	0.129	0.0648	0.0009	0.1004	0.0013						617	8			
44.1	177	163	0.92	14.0	0.000208	0.61	10.844	0.136	0.0639	0.0017	0.0917	0.0012						565	7			
45.1	318	217	0.68	26.9	0.000123	0.28	10.140	0.116	0.0623	0.0006	0.0983	0.0011						605	7			
46.1	227	112	0.49	97.6	0.000098	0.13	1.999	0.023	0.2220	0.0007	0.4997	0.0056	15.217	0.180	0.2209	0.0008	0.955	2612	24	2987	6	14
47.1	126	93	0.74	8.4	0.000276	0.61	12.820	0.175	0.0617	0.0010	0.0775	0.0011						481	6			
48.1	339	101	0.30	38.8	0.000015	1.65	7.522	0.088	0.0792	0.0091	0.1307	0.0022						792	13			
49.1	960	72	0.07	75.9	0.000005	0.26	10.863	0.114	0.0611	0.0003	0.0918	0.0010						566	6			
50.1	540	30	0.06	47.2	0.000022	1.45	9.823	0.106	0.0722	0.0018	0.1003	0.0011						616	7			
51.1	489	375	0.77	35.7	0.000056	0.43	11.772	0.129	0.0614	0.0007	0.0846	0.0009										