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Cambrian palaeomagnetic data confirm a Natal Embayment location for the Ellsworth–Whitmore Mountains, Antarctica, in Gondwana reconstructions

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SUMMARY

The Ellsworth–Whitmore Mountains (EWM) are one of five terranes that form West Antarctica. Constraining the positions of these terranes in pre-break up Gondwana is crucial to understanding the history of the palaeo-Pacific Gondwana margin. We report the results of a detailed palaeomagnetic investigation of the EWM, which comprises some 150 sites in six formations, ranging in age from Cambrian to Permian. Five of the studied units yield only viscous remnant magnetizations of recent age, or unstable natural remanent magnetizations. The remaining unit, the mid-late Cambrian Frazier Ridge Formation, yielded stable magnetizations at 16 of 35 sites. This component passes a fold test at the 95 per cent confidence level, indicating that it pre-dates Permian deformation, and we argue that it is of primary origin. The resulting palaeopole (9°N; 293°E; $A_{95} = 5.1°$) is in good agreement with two previously published palaeopoles from similarly aged rocks in the EWM. Collectively these data indicate that the EWM were located in the Natal Embayment prior to Gondwana break-up, and underwent 90° of anticlockwise rotation during break-up. All three studies, however, yield inclinations that are slightly too shallow when compared with coeval Gondwana reference poles.

Key words: Antarctica, Cambrian, Ellsworth Mountains, Gondwana, palaeogeography, palaeomagnetism.

INTRODUCTION

The Ellsworth Mountains are part of a geologically (Dalziel *et al.* 1987) and geophysically (Maslanjy & Storey 1990) defined crustal block: the Ellsworth–Whitmore Mountains (EWM) (Fig. 1A). This crustal block is one of five allochthonous terranes that form West Antarctica (Dalziel & Elliot 1982; Storey *et al.* 1988; Dalziel 1997). Constraining the pre-break-up positions of these terranes is crucial to establishing the geological history of the palaeo-Pacific Gondwana margin.

Several pre-break-up positions have been suggested for the EWM in Gondwana during the early Palaeozoic and these fall into three groups. Schmidt & Rowley (1986) proposed that the EWM originally lay outboard and to the west of the Pensacola Mountains and rotated clockwise to its present position through dextral strike-slip faulting along the Transantarctic Mountains during Gondwana break-up (Fig. 1B). Alternatively, Duebendorfer & Rees (1998) suggested that the EWM might have been part of the Queen Maud Terrane (QMT) (Rowell *et al.* 1992) (Fig. 1C). The collage of terranes that constitute the QMT are thought to have been accreted on to East Antarctica during the Middle Cambrian and almost certainly by the end of the Ross Orogeny at ∼500 Ma (Encarnación & Grunow 1996). Duebendorfer & Rees (1998) suggest that the QMT lay within the belt of Ross deformation throughout its existence. One interpretation of recent palaeomagnetic data from the palaeo-Pacific margin of East Antarctica (Grunow & Encarnación 2000) offers support for the existence of the QMT, but does not provide further evidence of its relationship to the EWM. The most significant problem with associating the EWM with the QMT is the lack of evidence for deformation in the EWM during the Cambro-Ordovician Ross Orogeny. Some workers have advocated a polyphase deformation history for the EWM (e.g. Yoshida 1982; Thorstenson *et al.* 1994; Duebendorfer & Rees 1998), and Duebendorfer & Rees (1998), in particular, have suggested that the EWM were also deformed by a pre-Gondwana event that they suggest may be related to the Ross Orogeny. There are localized erosional disconformities present along the basal Palaeozoic Crashsite Group (Spörli & Craddock 1992; Goldstrand *et al.* 1994), and a slight angular unconformity at Webers peaks (Duebendorfer & Rees 1998). The lower Palaeozoic succession, however, generally conformably overlies, and is in structural continuity with, the Cambrian sequence (Curtis & Lomas 1999). Geochemical analysis of volcanic and subvolcanic rocks exposed at five igneous centres in the Heritage Range indicate that deposition occurred in a continental rift setting (Curtis *et al.* 1999). The weight of structural, stratigraphic and geochemical evidence, therefore, does not support the presence of an early Palaeozoic contractional/orogenic phase (Webers *et al.* 1992a; Goldstrand *et al.* 1994; Curtis 1998; Curtis *et al.* 1999; Curtis & Lomas 1999). In our

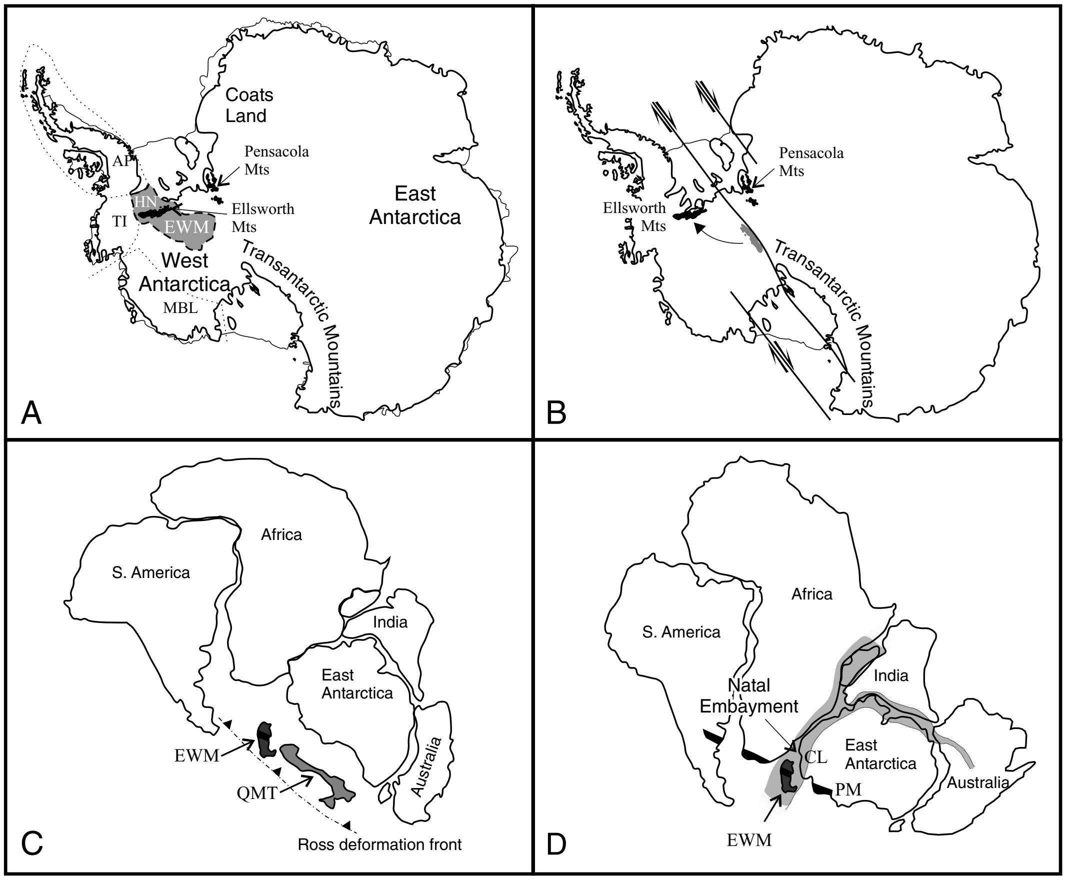

Figure 1. (A) The position of the Ellsworth Mountains within the Ellsworth–Whitmore Mountains block (EWM) and the position of the EWM within Antarctica. For the purposes of this paper, the EWM includes the small adjoining Haag Nunataks block (HN). Positions of the other major West Antarctic continental terranes are also shown: AP. Antarctic Peninsula; TI, Thurston Island; MBL, Marie Byrd Land; modified from Storey *et al.* (1988). (B)–(D) Cartoons depicting reconstructed early Palaeozoic positions for the EWM: (B) along the East Antarctic margin (Schmidt & Rowley 1986); (C) as part of the Queen Maud Terrane (QMT) (Duebendorfer & Rees 1998); (D) within the Natal Embayment between southern Africa and Coats Land (e.g. Dalziel & Grunow 1992; Curtis & Storey 1996). The shaded area shows the extent of the Grenvillian basement (Moores 1991; Storey *et al.* 1994). The black area shows the structural trend of the Permo-Triassic Gondwanan orogeny (CL, Coats Land; PM, Pensacola Mountains).

view, the EWM were deformed solely by the Late Permian–Late Triassic Gondwanan orogenic event and that the EWM were not part of the East Antarctic sector of the Gondwana margin during the early Palaeozoic (e.g. Webers *et al.* 1992a; Spörli & Craddock 1992; Curtis 1997). They must, therefore, occupy a position outside the deformation zone of the Ross Orogen, in early Palaeozoic Gondwana reconstructions, and have generally been located in the Natal Embayment (Fig. 1D; e.g. Schopf 1969; Watts & Bramall 1981; Dalziel & Grunow 1992; Curtis & Storey 1996; Dalziel 1997). This location juxtaposes the EWM and South African geological provinces, the only two along the Gondwana palaeo-Pacific margin that preserve virtually complete Palaeozoic successions, and contain evidence for Middle to Late Cambrian continental rifting, as opposed to orogenesis (Barnett *et al.* 1997; Armstrong *et al.* 1998; Curtis *et al.* 1999). Additionally, this position satisfies isotopic evidence that the EWM is underlain by Grenvillian age crust (Storey *et al.* 1994; Curtis *et al.* 1999). Restoring the EWM to a pre-break-up position in the Natal Embayment also aligns the structural trend of the Permo-Triassic Gondwanan orogeny (Fig. 1D).

Until recently, the pre- and syn-break-up positions of the EWM have been loosely constrained by three palaeomagnetic poles. Watts & Bramall (1981) obtained data from the Late Cambrian Frazier Ridge Formation, which they interpreted as a primary remanence. The pole's position was interpreted as supporting a ∼90° anticlockwise rotation of the block during break-up and yielded a reconstruction similar to Fig. 1(D). Data obtained from undated, though likely mid to late Cambrian, red calcareous sedimentary rocks at Nash Hills carried the same palaeomagnetic direction (Grunow *et al.* 1987). The consistency of the pole positions from the two studies was taken to support the integrity of both data sets and the interpreted rotation. Grunow *et al.* (1987) also recovered primary magnetizations from Middle Jurassic granitoids that suggested the EWM underwent a 15° anticlockwise rotation since acquisition of the remanence.

During the 1996/1997 austral summer, we collected samples from 150 sites across six formations in the Ellsworth Mountains, making it the most comprehensive palaeomagnetic study carried out in the region. The first results from this campaign were reported by Randall *et al.* (2000), who presented new geochronological and palaeomagnetic data for the Middle to Late Cambrian Liberty Hills Formation. The geochronology confirms a late Middle Cambrian to early Late Cambrian age for the uppermost part of the Heritage Group, which includes the Frazier Ridge Formation studied by Watts & Bramall (1981) and likely the red sediments from Nash Hills studied by Grunow *et al.* (1987). The palaeomagnetic data obtained by Randall *et al.* (2000) were, however, significantly different from the previous two studies. The difference between the Liberty Hills result and the previous results is predominantly one of declination, with the Liberty Hills result indicating a rotation of the EWM block of only about 60°, which results in a misalignment of the geological structures when the EWM is restored to a Gondwana fit. Randall *et al.* (2000) evaluated a number of possibilities for the discrepancy, including the possibility that the difference represented apparent polar wander due to the formations having different ages; that the rocks had been affected by vertical axis rotation; and the possibility that one of the formations carried a remagnetization. There was, however, no clear explanation for the discrepancy. Furthermore, Randall *et al.* (2000) demonstrated that none of the early Palaeozoic palaeomagnetic data from the EWM were in very good agreement with Gondwana reference poles, after the EWM block was placed in a pre-break-up position in the Natal Embayment, because they all yielded inclinations that were too shallow. We present the results from all the remaining sampled units in this paper. The new results, presented here, reaffirm a Natal Embayment position for the Ellsworth Mountains, albeit with the problem of shallow inclinations still present, and indicate that aspects of the Randall *et al.* (2000) analysis require revision.

REGIONAL GEOLOGY

The Ellsworth Mountains form a NNE–SSW-trending range, centred at about 79°S, 85°W, which is split into two geographically distinct regions, the northern Sentinel Range and the southern Heritage Range (Fig. 2). A 13 km thick, uninterrupted Lower Cambrian to Permian stratigraphy is exposed in the mountains (Fig. 3; Webers *et al.* 1992a). The early Palaeozoic stratigraphy comprises the Heritage Group and the Crashsite Group. The Heritage Group (?Early to Late Cambrian) crops out almost exclusively in the Heritage Range and is composed of eight formations that total 7500 m in thickness. The lower Heritage Group comprises four formations that are exposed only in the area around Edson Hills at the head of the Union Glacier (Fig. 2). At the base is the 3000 m thick Lower(?) to Middle Cambrian Union Glacier Formation, which comprises terrestrial volcaniclastic sedimentary rocks deposited as lahars and ash-flow tuffs (Webers *et al.* 1992b). Subsidence then led to deposition of the laterally discontinuous fluvial to shallow marine deposits of the Hyde Glacier Formation and, subsequently, the black shales and carbonates of the Drake Icefall Formation during the Middle Cambrian. Uplift and emergence followed, with deposition of the laterally discontinuous fluvial to shallow marine conglomerates of the Conglomerate Ridge Formation.

Overlying the lower Heritage Group are the most extensively exposed rocks in the Heritage Range, those of the laterally equivalent Liberty Hills, Springer Peak and Frazier Ridge formations (Webers *et al.* 1992b). The Liberty Hills Formation is exposed only in the southern Heritage Range whereas the Springer Peak and Frazier Ridge formations are exposed in the central and northern Heritage Range (Fig. 2A). Trilobite faunas indicate a Middle Cambrian to earliest Late Cambrian age for the Springer Peak Formation (Jago & Webers 1992; Shergold & Webers 1992). No fossils have been recovered from the Liberty Hills or Frazier Ridge Formations, but early Late Cambrian fossils have been recovered from the units directly overlying the formations, suggesting that all three formations were deposited contemporaneously. In addition, Randall *et al.* (2000) reported a high precision U–Pb age for a granite clast incorporated in the Liberty Hill Formation of 525 ± 2 Ma, yielding a maximum age of this unit. Hence we regard the Liberty Hills, Springer Peak and Frazier Ridge Formations as being latest Middle Cambrian to earliest Late Cambrian in age.

The Liberty Hills Formation comprises a 1000 m thick sequence of conglomerates, quartzites, argillites and mafic lava. Lateral facies variations reveal a northward change in depositional environment from coarse-grained fluvial deposits, through transitional deltaic to fine-grained shallow marine units. The Springer Peak Formation is estimated to be 1000 m thick, but shearing and parasitic folding make accurate measurement difficult. The formation comprises brown argillite, buff greywacke and argillaceous limestone, which are interpreted as marine deltaic sediments (Webers *et al.* 1992a). Volcanic rocks were deposited synchronously with the sedimentary rocks of the Springer Peak Formation. Those exposed include basalt pillow lavas at Anderson Massif and Yochelson Ridge, basaltic sills at Dunbar Ridge, and basalt and rhyolite flows at Soholt Peaks. The geochemistry of the volcanic rocks from the Liberty Hills and Springer Peak formations indicates eruption in a continental rift setting (Curtis *et al.* 1999). The Frazier Ridge Formation is at least 500 m thick and is primarily composed of green, fine- to medium-grained sandstones with occasional units of green argillite and black shale. In the more northerly exposures, some beds of red medium-grained sandstone are also exposed interbedded with the green sandstones. The depositional environment was shallow marine.

Overlying these formations, along a sequence bounding unconformity, are the laterally discontinuous, northwards-thinning limestones of the Upper Cambrian Minaret Formation. The formation represents a change in sediment source area due to a tectonically induced reconfiguration of the basin (Curtis & Lomas 1999). The Minaret Formation is, in turn, overlain by a thin sequence of siltstones and shales that comprise the transition beds (Spörli 1992).

Stratigraphically overlying the transition beds are 3000 m of shallow marine quartzites forming the Late Cambrian to Devonian Crashsite Group (Spörli 1992). These rocks represent cessation of tectonic activity in the basin and subsequent gentle subsidence as part of a passive margin (Spörli 1992; Curtis & Lomas 1999; Curtis *et al.* 1999). The Crashsite Group has the widest exposure in the Ellsworth Mountains and comprises, from bottom to top, the Howard Nunataks, Mount Liptak and Mount Wyatt Earp formations. The Howard Nunataks Formation consists of pale green, greenish-grey and maroon sandstones with minor interbeds of argillite. The Mount Liptak Formation is a light grey to white sandstone unit estimated to be 900 m thick. These formations are more mineralogically mature than the underlying Heritage Group and become progressively more mature up-sequence. They represent deposition in a stable, shallow marine environment. At the top of the Crashsite group is the shallow marine Mount Wyatt Earp Formation. The formation is laterally variable and comprises poorly sorted, dark grey, red and brown sandstones.

Overlying the Crashsite Group is the Whiteout Conglomerate. This is a grey-black diamictite that marks the Permo-Carboniferous Gondwana glaciation in the Ellsworth Mountains (Matsch & Ojakangas 1992). The unit is dominantly exposed in the north and eastern Sentinel Range, where the formation is approximately 1000 m thick and composed of up to six massive diamictite units separated by laminated shale (Matsch & Ojakangas 1992). A truncated sequence 250 m thick with thinner diamictites is also exposed at Meyer Hills in the eastern Heritage Range (Fig. 2).

The Middle–Upper Permian Polarstar Formation is the uppermost sedimentary unit exposed in the Ellsworth Mountains and crops out only in the northern Sentinel Range (Collinson *et al.* 1992). This ~1000 m thick formation is subdivided into three units. The basal unit is dominated by argillite and gradationally, but conformably, overlies the Permo-Carboniferous Whiteout Conglomerate. Overlying the argillites is a middle unit comprising coarsening-upward

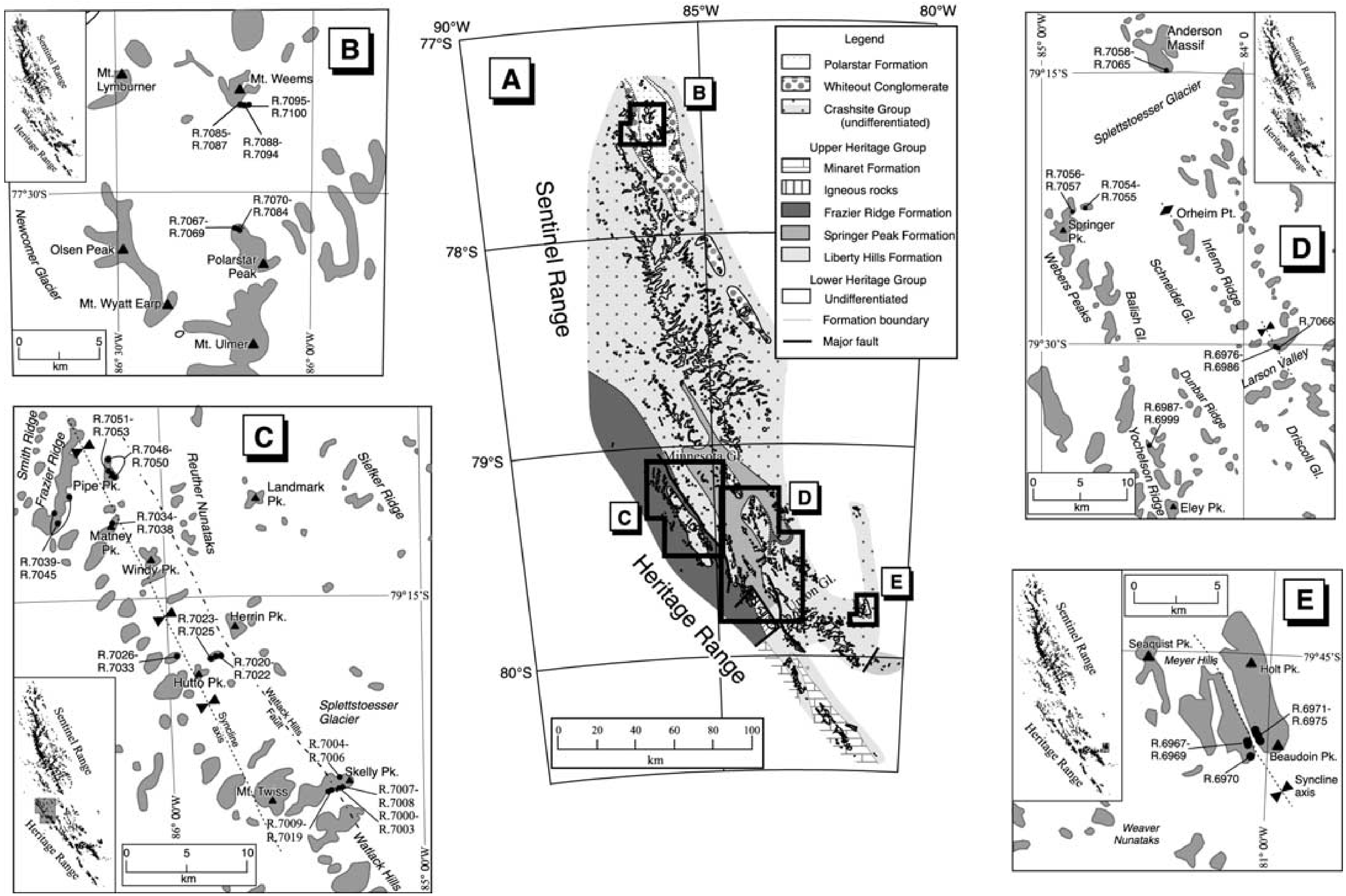

Figure 2. (A) Simplified geological map of the Ellsworth Mountains, with (B) sampling localities for the Polarstar Peak Formation in the northern Sentinel Range; (C) sampling localities for the Frazier Ridge Formation and Mount Twiss Member in the northern Heritage Range; (D) sampling localities for the Whiteout Conglomerate at Meyer Hills in the east-central Heritage Range; (E) sampling localities for the Springer Peak Formation in the central Heritage Range.

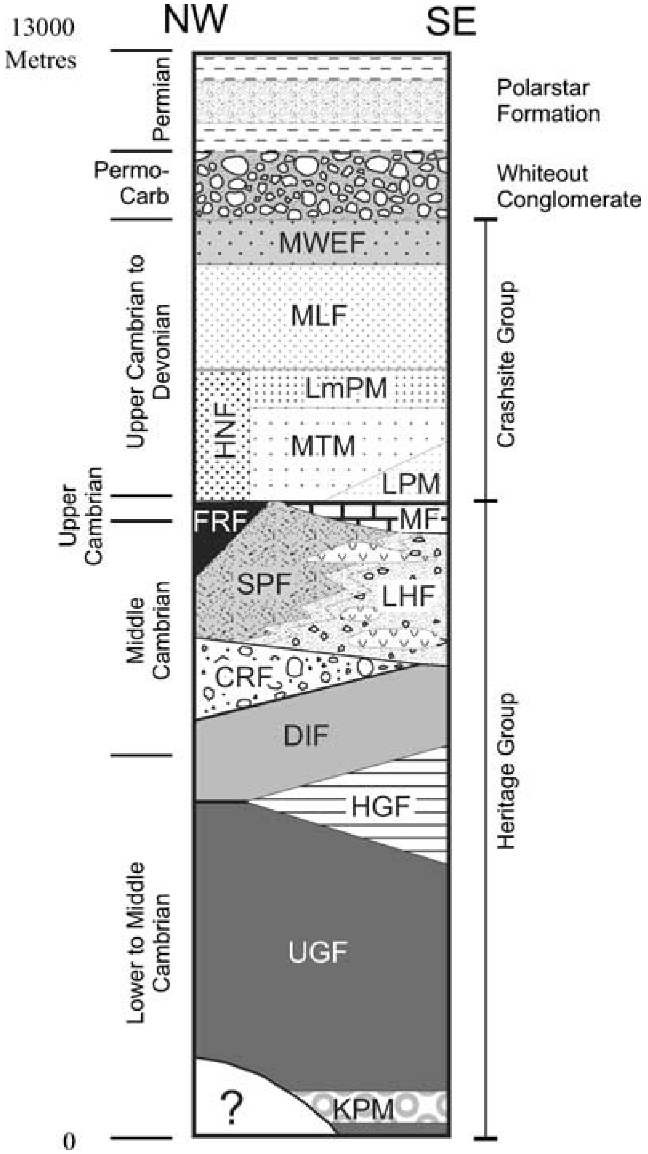

Figure 3. Stratigraphic column for the Ellsworth Mountains (after Webers *et al.* 1992a). KPM, Kosco Peak Member; UGF, Union Glacier Formation; HGF, Hyde Glacier Formation; DIF, Drake Icefall Formation; CRF, Conglomerate Ridge Formation; LHF, Liberty Hills Formation; SPF, Springer Peak Formation; FRF, Frazier Ridge Formation; HNF, Howard Nunataks Formation; LPM, Linder Peak Member; MTM, Mount Twiss Member; LmPM, Landmark Peak Member; MLF, Mount Liptak Formation; MWEF, Mount Wyatt Earp Formation.

cycles of argillite to sandstone. These are succeeded by an upper unit of fining-upward cycles of sandstone, *Glossopteris*-bearing siltstone, argillite and coal. Collinson *et al.* (1992), 1994) interpret the depositional environment as fluviodeltaic in a backarc basin setting.

The tectonic history of the Ellsworth Mountains is contentious, as discussed above. At this stage, however, the weight of evidence supports the interpretation that the Ellsworth Mountains were deformed only by the Permian–Late Triassic Gondwanan Orogeny, which produced NNW–SSE-trending folds as a result of dextral transpression (Curtis 1997).

SAMPLING

Samples were dominantly collected as drilled cores, and 10 cores were typically collected at each site. In some cases, orientated hand samples were collected. Whenever possible, samples were oriented using both solar and magnetic compasses. The fact that the southern faces of ridges were often the best exposed meant that many were orientated with a magnetic compass only. Comparison of the magnetic readings with the solar compass revealed that bearings were generally within 3°, supporting the integrity of the magnetic orientations. Where possible, localities were chosen so that field tests could be carried out to constrain the age of magnetization.

Springer Peak Formation (Middle Cambrian)

The sedimentary sequence of the Springer Peak Formation was sampled at two localities in the central Heritage Range (Fig. 2E). At Larson Valley, the sequence comprises buff-weathered greywackes (dominantly) interbedded with argillites. The major structure exposed is a first-order syncline with second-order anticline in the eastern limb. There is also a large amount of minor folding present and, while the greywackes tend to retain their thickness around the folds, the argillaceous units are thickened in the hinges. Pervasive cleavage in the argillites restricted sampling to the fine-grained sandstone beds. Samples were collected from 12 sites throughout the syncline–anticline structure (R.6976–R.6986 and R.7066: Fig. 2E). A further four sites were sampled at a near-vertical dipping section at Webers Peaks (R.7054–R.7057: Fig. 2E). Here, there is a much larger proportion of argillite relative to the greywacke beds and sampling was restricted to thin (typically less than 40 mm), fine-grained sandstone beds. At both sampling localities, sedimentary structures, in particular de-watering structures, allowed confirmation of way up in the units.

At the southeast corner of Anderson Massif, the exposure consists predominantly of tightly folded pillow lavas, typically 1–2 m in diameter, with intercalated argillites. Samples were collected from eight sites, one site per pillow (R.7058–R.7065: Fig. 2E). The pillows exposed at Yochelson Ridge, at the northern end of Soholt Peaks, are smaller than those at Anderson Massif, typically 0.2–1 m in diameter, and are much more fractured. When drilled, many of the cores broke and most of the 12 sites therefore comprise samples from several adjacent pillows. In addition to the samples from the pillows (R.6987–R.6998), 12 samples were collected from four clasts in a lahar that overlies the pillow lavas in the hope that these would provide a conglomerate test (R.6999).

Frazier Ridge Formation (Middle to Late Cambrian)

The Frazier Ridge Formation provided the samples for the palaeomagnetic data obtained by Watts & Bramall (1981). They published site mean directions from five sites sampled in haematitic argillites in the area around Pipe Peak and Reuther Nunataks in the northern Heritage range (Fig. 2C).

During this study, the formation was observed and samples collected from three areas that transect the axis of the Windy Peak Syncline in the northern Heritage Range. From south to north these are: northern Watlack Hills, Hutto Peak/Herrin Peak and Matney Peak/Pipe Peak/Frazier Ridge (Fig. 2C). Generally, the Frazier Ridge Formation comprises green or grey-green, fine- to medium-grained quartzites, interbedded with argillites, and the number and thickness of the quartzite units increases up-sequence. In most places, the argillite units are cleaved and samples were collected from the fine-grained quartzite beds.

At Watlack Hills, only the eastern limb of the syncline is exposed, the other limb being cut out by the Watlack Hills Fault. Samples were collected from nine sites distributed through approximately 600 m of near constant, southwest-dipping quartzites (R.7009–R.7019: Fig. 2C). Samples from 14 sites were collected around Hutto/Herrin peaks, R.7020–R.7025 in the eastern limb, and R.7026–R.7033 in the western limb of the syncline (Fig. 2C). Abundant sedimentary structures provided good control on stratigraphic younging and minor folding could be recognized in both limbs, with some beds overturned. At the northernmost locality, the dips are generally shallower than further south and the rocks are less cleaved. Also observed at Matney and Pipe peaks were beds of red, haematitic argillite. These had not been seen elsewhere in the Frazier Ridge Formation but here were interbedded with the more typical grey and green quartzites and argillites. Presumably, these were the units sampled by Watts & Bramall (1981). Samples were collected from 20 sites in total. These were from the western limb of the fold (R.7039–R.7045) and from the area close to the hinge at Matney Peak (R.7034–R.7038) and Pipe Peak (R.7046–R.7053). At the latter two localities, sites were collected from both the green quartzites and red argillites.

Howard Nunataks Formation (Upper Cambrian(?) to Devonian(?))

The Howard Nunataks Formation is subdivided, from bottom to top, into three members: Landmark Peak Member, Mount Twiss Member and Linder Peak Member (Spörli 1992). The Landmark Peak and Linder Peak members are dominantly characterized by green-grey quartzite and argillite. In contrast, the Mount Twiss Member consists of interbedded layers of maroon and white quartzite and argillite. Samples from were collected from maroon argillite and fine-grained quartzite at nine sites in the Mount Twiss Member in the Watlack Hills near Skelly Peak (R.7000–R.7008; Fig. 2C). All of the sites have an approximately consistent northeasterly dip. As the Watlack Hills Fault places Mount Twiss rocks against the Frazier Ridge Formation the other side of the fold is not exposed, so it was not possible to obtain samples for a fold test. The Mount Twiss Member was examined at other localities in the hope of obtaining sites with a range of dips, but there was often an insufficient number of maroon beds, or rocks were too fractured to sample.

Whiteout Conglomerate (Permo-Carboniferous)

The Whiteout Conglomerate was only observed at Meyer Hills (Fig. 2D). Clasts in the diamictite are poorly sorted, generally smaller than 10 mm, and lie in a dark grey matrix of siltstone and fine sandstone. The rock is pervasively cleaved and larger clasts tend to be fractured and boudinaged. The diamictite units are punctuated by laminated beds of shale, sandstone and striated boulder pavements, one of which was observed at Beaudoin Peak. The formation is exposed in two NNW–SSE ridges that correspond to opposing limbs of a syncline.

Samples of diamictite were collected at nine sites in both limbs of the syncline (R.6967–R.6975). Fracturing and penetrative cleavage made sampling difficult. Typically, 15–20 holes were drilled at each site to recover eight or nine reasonably sized specimens. Due to the massive nature of the lithology, establishing palaeohorizontal was sometimes a problem and had to be estimated for some sites. The insufficient quantity of large clasts, coupled with their pervasive fracturing, prevented sampling for a conglomerate test.

Polarstar Formation (Permian)

The Polarstar Formation was previously sampled for palaeomagnetic study by Grunow *et al.* (1987). They sampled seven sites from around a fold but failed to recover a stable remanence. Given the tectonic importance of obtaining a palaeomagnetic pole from this unit, a point noted by Grunow *et al.* (1987), it was decided to resample the formation during this study. To this end, samples were collected from the Polarstar Formation at two localities in the northern Sentinel Range (Fig. 2B). At Polarstar Peak, the top of the basal argillite unit and the middle unit of coarsening up cycles are exposed in a broad, open syncline. Samples were collected from 18 sites in siltstones and fine to medium sandstones distributed through the fold (R.7067–R.7084). The southern ridge of Mount Weems exposes the middle unit of the formation. Sandstone beds dominate and are 0.3–2 m thick and interbedded with thinner argillites. The rocks are exposed through a large, first-order syncline–anticline pair. Samples were collected from 18 sites in the fine-grained sandstone beds across both folds (R.7085–R.7100). At both localities, some of the sandstone units preserve sedimentary structures that indicate the beds are the correct way up.

PALAEOMAGNETIC ANALYSIS

Measurements of the natural remanent magnetization (NRM) were made using a two-axis CCL cryogenic magnetometer at the University of Oxford palaeomagnetic laboratory. Specimens were stepwise demagnetized using two-axis tumbling alternating field (AF) or thermal methods through at least 12 steps until they became unstable, or to 100 mT or 700 °C respectively. Where pilot samples indicated that the NRM consisted of multiple components, the number of demagnetization steps was increased, in some cases up to 25 steps. During thermal demagnetization, bulk susceptibility was measured after each step to detect heat-induced mineralogical changes.

Demagnetization results were visually inspected in orthogonal and stereographic projections. Whenever possible, remanence directions were determined from stable endpoints using principal-component analysis (Kirschvink 1980). Magnetic components were considered stable where they were defined by at least three points on vector end-point diagrams and had a maximum angular deviation not exceeding 15°. The demagnetization behaviour observed was variable and many specimens displayed multicomponent NRMs, some with overlapping blocking or coercivity spectra. Consequently, it was not always possible to define linear endpoints, and we attempted to use remagnetization circles to recover the remaining high-stability directions (McFadden & McElhinny 1988). These generally yielded great circles that intersected on an overprint, directed along the present Earth's field, in geographical coordinates, indicating that magnetic overprinting had more or less obliterated the primary magnetic components in these samples. For analysis, specimen characteristic remanent magnetization (ChRM) directions were combined to site means and site means were combined for each geological unit or sampling locality using Fisher (1953) statistics.

REMANENCE COMPONENTS

Four of the units sampled during this study failed to yield any palaeomagnetically useful results. However, for completeness, a brief description of their demagnetization behaviour is included here. These units were the Springer Peak Formation, the Mount Twiss member of the Howard Nunataks Formation, the Whiteout Conglomerate and the Polarstar Formation. The rest of the results section concentrates on the data obtained from the Frazier Ridge Formation.

Springer Peak Formation (Middle Cambrian)

Pilot specimens from the sedimentary units of the Springer Peak Formation indicated that, although weakly magnetized, typical NRM intensities were 10^{-4} to 10^{-5} A m^{-1}, some specimens displayed linear components of magnetization. Further analysis was therefore carried out, and 107 specimens from Larson Valley and 32 specimens from Webers Peaks were subjected to stepwise AF or thermal treatment. This larger sample set revealed that all samples had very noisy demagnetization and although some linear components could be recognized from the Zijderveld plots, there was little consistency within or between sites. The only component recovered consistently was steeply inclined upwards and is interpreted as a viscous remanence acquired in the present Earth's field.

All demagnetized samples from the pillow lavas similarly failed to produce interpretable results. Specimens from sites at Anderson Massif were unstable to AF and thermal demagnetization and no linear components were defined. Yochelson Ridge specimens were also unstable during demagnetization, or were characterized by single, steeply upward inclined components, interpreted as present field overprints.

Howard Nunataks Formation (Upper Cambrian(?) to Devonian(?))

Samples from all the nine sites collected in the maroon argillites and quartzites of the Mount Twiss member of the Howard Nunataks Formation, have low NRM intensities, typically in the 10^{-3}–10^{-4} A m^{-1} range, and produced stable, consistent palaeomagnetic directions. On thermal demagnetization, samples have a low unblocking temperature (<100 °C) viscous remanent magnetization (VRM) that varies within and between sites. This is succeeded by a steeply upward-directed component, oriented parallel to subparallel to the present Earth's field at the sampling location. This component persists to temperatures of some 500–600 °C. At higher demagnetization levels, the data track out along great circle paths away from the present-day direction. We attempted to fit remagnetization circles to these higher temperature components, but the fitted great circles intersected on the opposite polarity of the present-day overprint, indicating that they marked random noise, and that the present day overprint is the least dispersed component present in these samples.

Whiteout Conglomerate (Permo-Carboniferous)

Seventy-seven specimens from the Whiteout Conglomerate were measured and stepwise demagnetized using either thermal or AF methods. Specimens were weakly magnetized, having NRM intensities of 10^{-4} to 10^{-5} A m^{-1} that decayed rapidly on demagnetization to 200 °C or 10 mT. Neither method of treatment revealed stable components of magnetization.

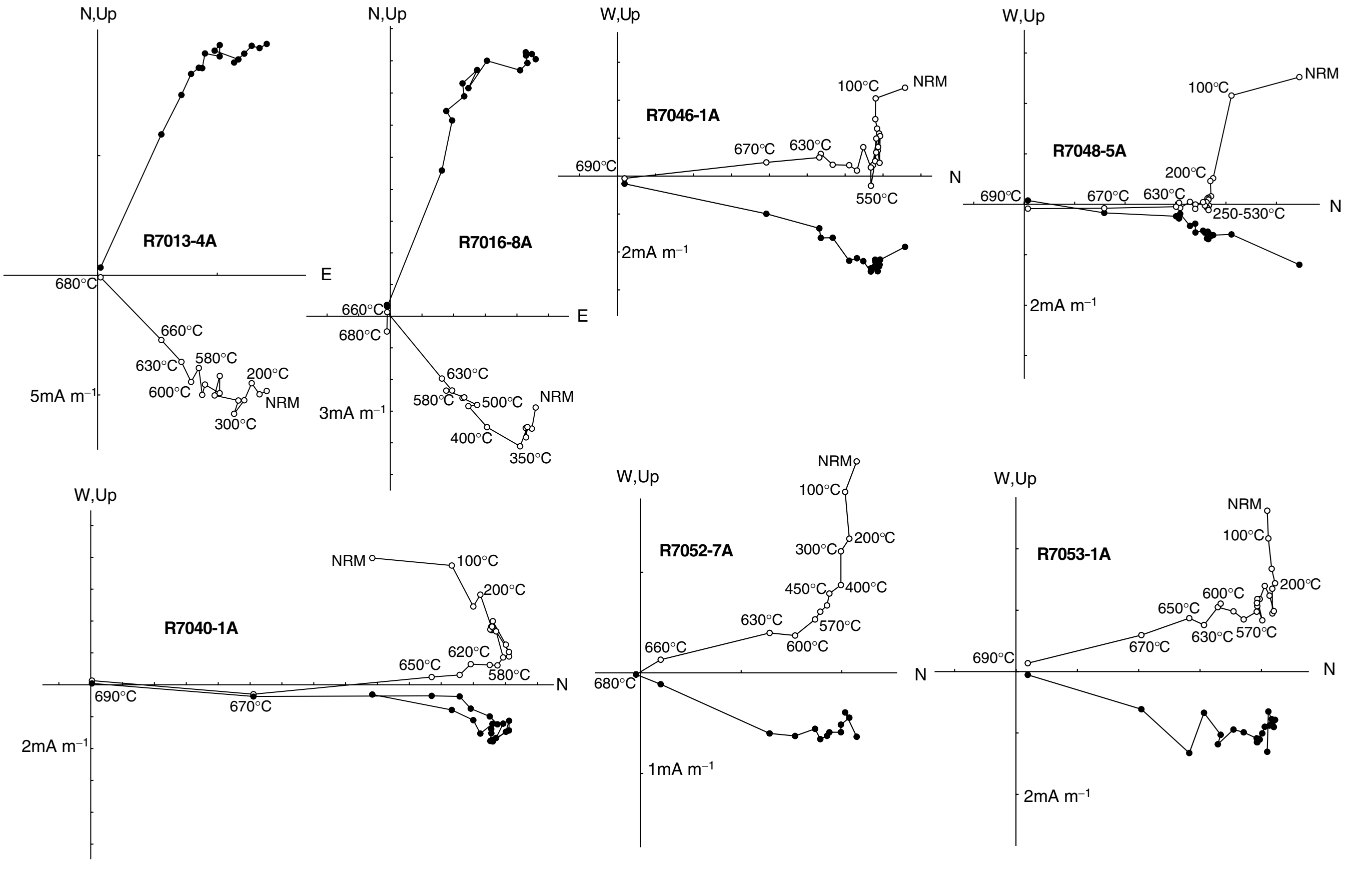

Figure 4. Examples of demagnetization behaviour observed in samples from the Frazier Ridge Formation. On orthogonal plots, solid (open) symbols are horizontal (vertical) projections. All plots are shown in geographical coordinates.

Table 1. Palaeomagnetic data from the Frazier Ridge Formation. Notation as follows: n/N, where n is the number of samples included in the site mean and N is the total number demagnetized; Dec. (Inc.) are declination (inclination) of the palaeomagnetic direction; k and α_{95} (K and A_{95}) are precision parameters and 95 per cent confidence limits on direction (pole) following Fisher (1953); VGP is virtual geomagnetic pole given for a south pole. Tilt corrections are given in dip to right of strike format.

	Location			*In situ*			Tilt corrected				VGP	
Site	Lat. °S	Long. °W	n/N	Dec.	Inc.	Tilt Correction	Dec.	Inc.	k	α_{95}(°)	Lat. °N	Long. °E
Watlack Hills												
R.7009	−79.38	−85.40		Present-day remagnetization								
R.7010	−79.38	−85.40		Present-day remagnetization								
R.7011	−79.38	−85.40		Present-day remagnetization								
R.7012	−79.38	−85.40		Present-day remagnetization								
R.7013	−79.38	−85.40	8/8	26.3	−24.2	155/60	26.2	24.3	37.6	9.2	−3.1	300.3
R.7014	−79.38	−85.40		Present-day remagnetization								
R.7015	−79.38	−85.40		No stable direction								
R.7016	−79.38	−85.40	10/11	8.3	−29.1	151/60	15.6	12.4	23.7	10.1	4.0	290.1
R.7017	−79.38	−85.40		Present-day remagnetization								
R.7018	−79.38	−85.40		Present-day remagnetization								
R.7019	−79.38	−85.40		Present-day remagnetization								
Hutto Peak/Herrin Peak												
R.7020	−79.27	−85.82		Present-day remagnetization								
R.7021	−79.27	−85.82		Present-day remagnetization								
R.7022	−79.27	−85.82		Present-day remagnetization								
R.7023	−79.27	−85.82		No stable direction								
R.7024	−79.27	−85.82		Present-day remagnetization								
R.7025	−79.27	−85.82		No stable direction								
R.7026	−79.29	−85.99		No stable direction								
R.7027	−79.29	−85.99		Present-day remagnetization								
R.7028	−79.29	−85.99		No stable direction								
R.7029	−79.29	−85.99		Present-day remagnetization								
R.7030	−79.29	−85.99		Present-day remagnetization								
R.7031	−79.29	−85.99		Present-day remagnetization								
R.7032	−79.29	−85.99		Present-day remagnetization								
R.7033	−79.29	−85.99		No stable direction								
Matney Peak/Pipe Peak/Frazier Ridge												
R.7034	−79.16	−86.25	7/9	12.4	−2.2	010/34	10.8	−3.2	43.3	9.3	12.2	284.8
R.7035	−79.16	−86.25	9/9	2.7	41.4	358/36	28.4	29.9	48.8	7.5	−6.5	301.1
R.7036	−79.16	−86.25		Present-day remagnetization								
R.7037	−79.16	−86.25	6/9	23.6	−1.9	015/32	21.3	−6.2	50.5	9.5	13.2	295.6
R.7038	−79.16	−86.25	9/11	15.3	22.1	358/38	24.9	7.3	65.2	6.6	6.2	298.8
R.7039	−79.17	−86.36		Present-day remagnetization								
R.7040	−79.17	−86.36	9/9	353.2	39.4	303/52	3.3	−4.4	47.4	7.6	13.0	277.0
R.7041	−79.14	−86.39		Present-day remagnetization								
R.7042	−79.14	−86.39		Present-day remagnetization								
R.7043	−79.14	−86.39		Present-day remagnetization								
R.7044	−79.17	−86.44	9/9	29.3	44.0	298/30	29.0	14.0	59.4	7.0	2.4	302.3
R.7045	−79.17	−86.44		Present-day remagnetization								
R.7046	−79.14	−86.23	8/9	16.7	−5.4	118/4	16.7	−1.5	256.5	3.5	11.1	290.8
R.7047	−79.14	−86.23	8/10	7.6	3.1	104/7	7.5	10.1	40.9	9.0	5.7	281.3
R.7048	−79.14	−86.23	7/9	8.2	−6.7	119/9	8.3	1.7	32.7	11.0	9.9	282.2
R.7049	−79.12	−86.27	6/9	22.3	−33.3	070/10	18.6	−25.7	32.3	12.2	23.8	293.5
R.7050	−79.12	−86.27	9/9	31.2	−13.8	077/10	30.0	−6.5	32.3	9.2	12.7	304.5
R.7051	−79.14	−86.27	9/12	13.4	9.2	018/23	17.4	10.3	26.8	10.9	5.2	291.1
R.7052	−79.14	−86.27	9/9	21.7	−1.8	356/18	20.1	−9.4	31.1	9.5	14.9	294.5
R.7053	−79.14	−86.27	9/9	22.8	−0.9	340/20	20.8	−14.3	84.9	5.6	17.4	295.4
Mean			16/35	16.2	2.2				10.3	12.1		
							18.5	2.4	24.7	7.6		
									Mean pole		9.0	292.7
											A_{95}=	5.1

Polarstar Formation (Permian)

Forty pilot specimens were measured to assess the potential of the formation for further analysis. The specimens were weakly magnetized, with NRM intensities in the range 10^{-3} to 10^{-5} A m^{-1}. The pilot studies revealed that AF demagnetization provided better resolution of magnetic components than thermal demagnetization, where the specimens rapidly descended into noisy behaviour at ∼300–400 °C without defining linear components. A further 108 specimens were therefore subjected to stepwise AF demagnetization. Most specimens showed a rapid intensity decay with a median destructive field of approximately 30 mT. Occasionally, clear, linear, sometimes origin-bound components were recognized in some specimens, typically isolated at demagnetization levels between 20 and 80 mT. However, there was never any consistency in the directions or demagnetization behaviour within an individual sample or site, suggesting that the specimens carried only viscous remanent magnetizations.

Frazier Ridge Formation (Middle-Late Cambrian)

Samples from the Frazier Ridge Formation have a bimodal distribution of NRM intensities, with NRM intensities either falling into the 10^{-3}–10^{-4} A m^{-1} range or in a higher 10^{-1}–10^{-3} A m^{-1} range. These two groups also correspond to samples which exhibit contrasting behaviour during demagnetization, and will therefore be referred to Type I and Type II behaviour, for samples with low and high NRM intensities respectively.

For both Type I and Type II samples AF demagnetization proved to be ineffective. In the case of Type I samples AF demagnetization typically produced noisy demagnetization trends, with zig-zagging components. In the case of Type II samples AF demagnetization had very little effect on the samples, with virtually no decrease in intensity, indicating that these samples contain a high-coercivity component. Thermal demagnetization proved to be much more effective in demagnetising both Type I and Type II samples and was the preferred treatment.

Type I samples all typically carry a low-temperature VRM, which is removed by heating to 100 °C. This component is succeeded by an intermediate (typically unblocking between 100 °C and 450 °C) component with a steep upwards directed *in situ* inclination. This is interpreted as a present-field overprint. At higher temperatures the directions typically track away from this intermediate unblocking temperature component until the sample magnetizations become unstable at 520–580 °C. This behaviour indicates that a high-temperature component is present but its direction cannot be isolated. We attempted to fit remagnetization circles to these higher temperature components, but the fitted great circles intersected on the opposite polarity of the present-day overprint, indicating that they marked random noise, and that the present-day overprint is the least dispersed component present in these samples.

In isothermal remanent magnetization (IRM) acquisition experiments, Type I samples reach saturation magnetization in an applied field of approximately 300 mT. High-temperature susceptibility studies reveal Curie temperatures of approximately 580 °C. These data are consistent with the NRM being carried dominantly by magnetite.

In contrast, Type II samples exhibit a different behaviour during thermal demagnetization, being characterized by only a 20 per cent drop in NRM intensity after treatment to 580 °C, and then a rapid decay as a single component of magnetization towards the origin at 680 °C (Fig. 4). This demagnetization behaviour is much more consistent with there being a dominant haematite carrier. IRM acquisition and high-temperature susceptibility experiments support the interpretation that haematite dominates the magnetic carriers present in these Type II samples. Type II site mean directions are all characterized by a NNE directed declination and shallow inclination in tilt-corrected coordinates (Table 1; Fig. 5). A mean direction, based on all 16 sites that yield Type II behaviour and carry a stable direction, lies at Dec. = 016.2°, Inc. = 2.2° ($k = 10.3$; $\alpha_{95} = 12.1°$). Application of tectonic correction to these sites yield a mean direction of Dec. = 018.5°, Inc. = 2.4° ($k = 24.7$; $\alpha_{95} = 7.6°$). The improved grouping of site mean directions on tilt correction passes a fold test at the 95 per cent confidence level (McElhinny 1964),

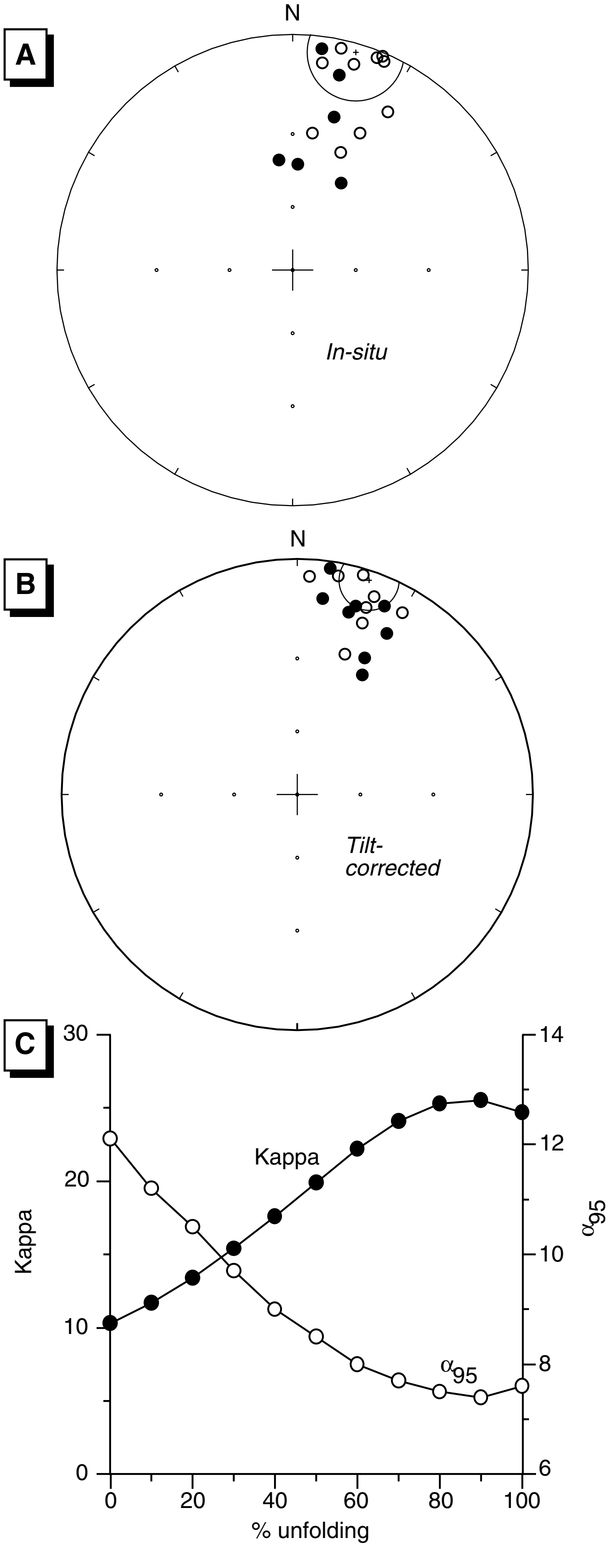

Figure 5. Equal area projections of site mean directions from the Frazier Ridge Formation in *in situ* (A) and in tilt-corrected (B) coordinates. Solid (open) symbols represent lower (upper) hemisphere projections; the mean direction in each case is marked with a cross along with the 95 per cent confidence limits. (C) Incremental fold test illustrating the substantially better grouping of the site mean directions after tectonic correction. The data pass the McElhinny (1964) fold test at the 95 per cent confidence level indicating that the characteristic remanence component pre-dates Permian folding of the sequence.

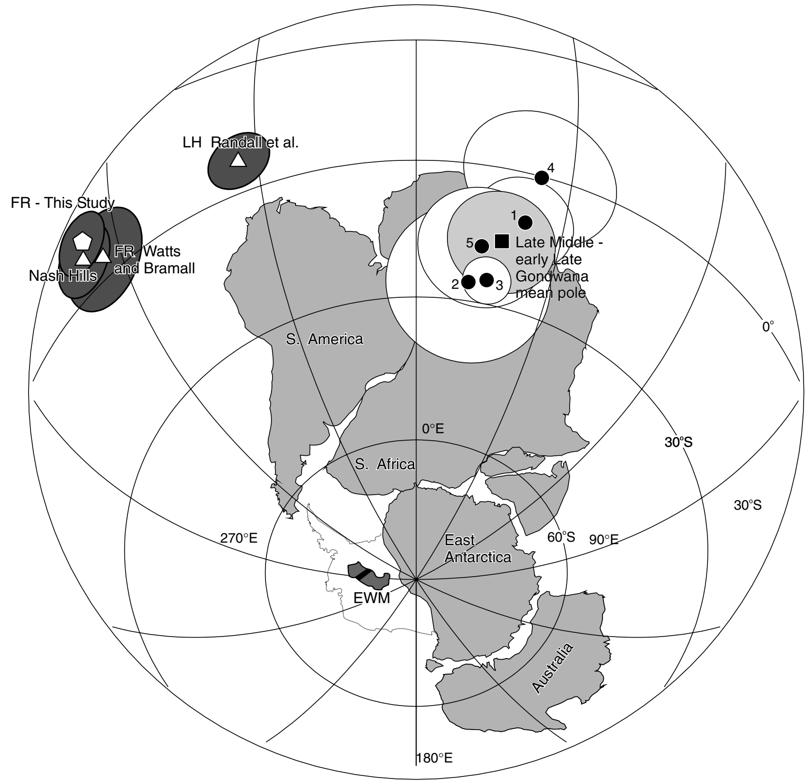

Figure 6. Early Palaeozoic palaeomagnetic poles available from the EWM. Triangles, poles from pre-existing studies (Watts & Bramall 1981; Grunow *et al.* 1987; Randall *et al.* 2000); and the new result presented in this paper is represented by a pentagon. Black circles are the late Middle to early Late Cambrian reference poles for Gondwana as follows: 1, NW Tasmanian Sediments (Li *et al.* 1997); 2, Pantapinna Frome (Klootwijk 1980); 3, Areyonga Section (Klootwijk 1980); 4, Lower Lake Frome (Embelton & Giddings 1974); 5, Basal Lake Frome (Luck 1972). All of the confidence limits shown are for 95 per cent. Poles are presented in an Antarctic reference frame, by keeping East Antarctica fixed and rotating Australian data to Antarctic coordinates using a rotation pole at 038.9°E, 2.0°S, $\Delta = -31.5°$ (Royer & Sandwell 1989). Fit of major continents is from Lawver & Scotese (1987). EWM is the present-day position of the Ellsworth–Whitmore Mountains crustal block.

and hence we interpret this component as a primary magnetization of the Frazier Ridge Formation.

INTERPRETATION AND DISCUSSION

The high-temperature component isolated in the Frazier Ridge Formation pre-dates the Permo-Triassic Gondwanide deformation event, as evidenced by the convergence of site means upon unfolding. Given this positive field test, and its high palaeomagnetic stability, when all other units in the area carry only recent VRMs, we conclude that this component likely dates to the time of deposition of the Frazier Ridge Formation: latest Middle Cambrian to earliest Late Cambrian (∼510 Ma). The associated pole (9°N 293°E) is in very good agreement with that obtained by Watts & Bramall (1981: 4°N 296°E), from five sites of the Frazier Ridge Formation at Pipe Peak and Reuther Nunataks, and that obtained from 12 samples from undated sedimentary rocks in the Nash Hills, some 250 km south of the EWM, by Grunow *et al.* (1987: 7°N 292°E). A comparison of these poles with reference data from Gondwana is presented in Fig. 6. These three studies point to a rotation of the EWM of about 90°, most likely during Gondwana break-up, and a likely position within the Natal Embayment in a pre-break-up configuration (e.g. similar to that of Fig. 1D). As we noted in the introduction, this location satisfies stratigraphic, isotopic and structural constraints.

Our new results contrast with the earlier findings of Randall *et al.* (2000) on the similarly aged rocks from the Liberty Hills Formation. The Liberty Hills Formation yielded a pole position at 7.3°N 326.3°E, which lies 30° of an arc away from the results of this study and those of Watts & Bramall (1981) and Grunow *et al.* (1987). At the time, Randall *et al.* (2000) were unable to provide a conclusive explanation for the discrepancy, but our further experience with the magnetization characteristics of these rocks leads us to conclude that aspects of the analysis of the Liberty Hills data are in error. In particular, we have noted above that several of the units we have studied failed to yield any primary magnetizations, but almost all units carried steep upward remagnetizations, close to present field values. A reanalysis of the Liberty Hills data also indicates that the vast majority of the samples also carry this overprint. The Liberty Hills mean direction was based on great circle analyses of the remaining magnetization, and our experience with the wider collection is that these remagnetization circles trend towards the opposite polarity of the overprint: in effect the great circle distribution is anchored by the overprint and the remaining magnetization is unresolved. Our re-evaluation of the Liberty Hills data set indicates that this, indeed, is also the case for the Liberty Hills Formation, and no primary magnetization is forthcoming from this unit. Randall *et al.* (2000) based their interpretation on great circle intersections in tilt-corrected coordinates, where there appeared to be two polarities and a similar inclination to previous studies. The were mislead by the unfortunate confluence of a steep overprint direction and steeply dipping beds which yield a ‘correct’ inclination, however their reported declination is some 90° away from the structural trend of the folds (roughly NNW–SSE). Structural correction about structures that trend NNW, with steep dips, of a steep upward direction (the overprint) or its opposite polarity (the intersection of the great circles *in situ*) yield directions that cluster at shallow inclinations at declinations of about 050°. Such a correction will also yield two apparent polarities. These are the characteristics of the mean direction reported from the Liberty Hills, and we think that the Liberty Hills palaeopole reported by Randall *et al.* (2000) should no longer be regarded as reliable. This analysis removes the discrepancy between the analysis of Randall *et al.* (2000) and the previously published data, and all three published studies in late Cambrian rocks from the EWM are now in agreement. There remains, however, a slight discrepancy in the observed inclinations from the EWM studies when compared with reference data from Gondwana. All three EWM studies yield inclinations that are slightly too shallow to provide an exact Natal embayment fit. We feel that this is probably due to the fact that all three studies are from sediments, which are prone to inclination-shallowing upon compaction and lithification.

CONCLUSIONS

Detailed palaeomagnetic analysis of samples from 150 sites in six formations, ranging in age from Cambrian to Permian in the Ellsworth–Whitmore Mountains indicate that most of the units present do not carry a stable magnetization. This, unfortunately, hampers our ability to elucidate the full palaeogeographical history of the EWM. Nevertheless the mid to late Cambrian Frazier Ridge Formation, does yield a stable magnetization at 16 of 35 sites, which passes a fold test at the 95 per cent confidence level, indicating that it pre-dates Permian deformation. We argue that this component is of primary origin, and the resulting palaeopole (9°N; 293°E; $A_{95} = 5.1°$) is in good agreement with two previously published palaeopoles from similarly aged rocks in the EWM. Collectively these data indicate that the EWM were located in the Natal Embayment prior to Gondwana break-up, and underwent 90° of anticlockwise rotation during break-up.

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