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Jurassic titaniferous ironstone in a Devonian host: Pivot Coal Measures expunged

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Abstract: The Devonian, Pivot Coal Measures in southern Victoria Land are non-carbonaceous. The sequence contains bedding parallel, titaniferous ironstones up to 50 cm thick, but no coal or carbonaceous shale, the unit is consequently renamed Pivot Member of the Arena Sandstone. The more Fe-Ti oxide-rich (up to 40 modal %) beds appear black and coal-like with conchoidal fracture and closely spaced cleat-like fractures. The coal-like beds grade laterally and vertically into less altered sedimentary rocks in which fine bedding-parallel concentrations of Fe-Ti oxide pick-out parting surfaces on ripples and other sedimentary structures. Thin section petrography shows that the Fe-Ti oxide is replacive, and outcrop relationships show that the replacement was related to dolerite intrusion 200 million years after the sedimentary host was deposited. Replacement of muscovite, biotite and chlorite by Fe-Ti oxide occurred at 179 ± 3 Ma, at pressures of 0.3–0.4 kbar and at temperatures as low as 380°C.

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Introduction

A 200 m-thick sequence of Devonian "coal measures" was reported by Sherwood *et al.* (1989) from the upper part of the Arena Sandstone, Beacon Supergroup at Pivot Peak and Rotunda in the Ferrar Névé of southern Victoria Land, Antarctica (Fig. 1). At the time, this discovery was significant for two reasons: 1) the unit represented the oldest known coal-bearing sequence in Antarctica, and 2) the discovery of coal promised to add a valuable new insight into the then controversial debate over the marine or non-marine depositional environment of the Taylor Group (e.g. Bradshaw 1981, Sherwood *et al.* 1989, Woolfe 1990, Bradshaw *et al.* 1990, Woolfe 1993).

Initial petrographic descriptions of thin sections, polished blocks and hand specimens concluded that the rocks were carbonaceous with organic carbon contents of between 15 and 40%· However, the coal petrologist noted the absence of "recognizable macerals". These reports supported the original field description of "coal measures, with siltstones, shales, sandstones and coal seams" made by Sherwood *et al.* (1989, p. 124) who informally applied the name Pivot Coal Measures. The unit was subsequently formally named Pivot Coal Measures Member (Arena Sandstone) and described as interbedded "sandstone, gritstone and pebble conglomerate with less abundant grey, carbonaceous, shaly mudstone, maroon mudstone and thin coal seams" by Woolfe *et al.*. (1989, p. 23). However, it is now evident that in each case disseminated Fe-Ti oxide was mistaken for carbonaceous matter.

In view of the importance of this member to the palaeoenvironmental debate, the exposures at Pivot Peak were revisited during the 1989–90 Antarctic field season to undertake further sampling and field description· Subsequent chemical analysis of the "carbonaceous" shale has shown that the unit contains no organic carbon (Arnot & Woolfe 1990, Arnot 1991). More surprisingly, it was found that the dark carbonaceous- and coal-like beds contain high concentrations (up to 40%) of very fine-grained opaque iron oxides, mainly Fe-Ti oxide, and are more appropriately described as titaniferous ironstone.

This paper presents the results of additional petrographical and geochemical work on the Pivot Coal Measures· Given the non-carbonaceous character of the unit its existing name is inappropriate. It is proposed that unit be renamed Pivot Member and that its stratigraphical status as a member within the Arena Sandstone be retained (Fig.2). It is concluded that the Pivot Member was deposited by fluvial and lacustrine processes during the late Middle Devonian, and that the strata-bound Fe-Ti oxide was introduced during a Jurassic magmatic event that caused a low-temperature replacement of detrital mica and interstitial phyllosilicates by Fe-Ti oxide.

Regional geology and stratigraphy

Flat-lying Late Palaeozoic and Mesozoic sedimentary rocks of the Beacon Supergroup (Barrett *et al.* 1972) crop out along almost 4000 km of the Transantarctic Mountains and are well exposed throughout southern Victoria Land. These sedimentary rocks overlie a basement complex of igneous and metamorphic rocks which were metamorphosed and

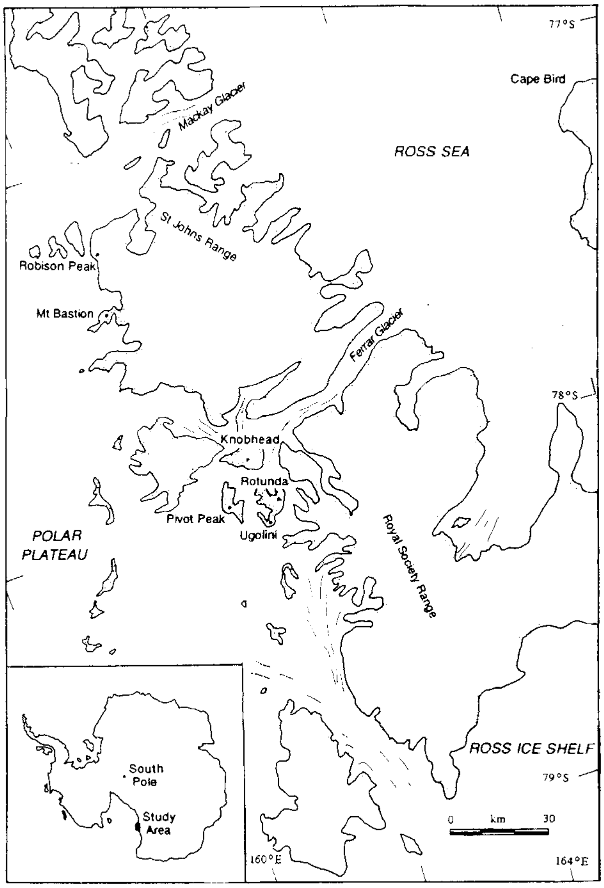

Fig 1. Locality map showing principle locations discussed in the text. Inset shows the location of the Pivot Peak area in Antarctica.

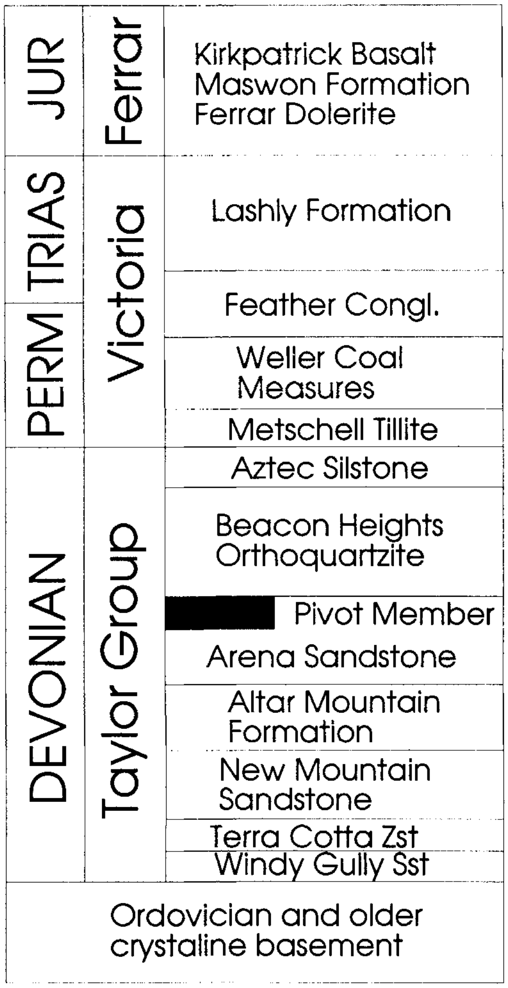

Fig 2. Generalized stratigraphical column for the Beacon Supergroup (Taylor and Victoria Groups) in southern Victoria Land.

intruded during the Ross Orogeny (Ordovician), and are in turn overlain by tholeiitic basalts (Fig. 2). The sedimentary units were intruded by dolerite sills and dykes associated with the Ferrar magmatic event during the Jurassic Period (179 ± 3 — Kyle *et al.* 1982). Beacon Supergroup rocks are separated from underlying Lower Palaeozoic and Precambrian igneous and metamorphic rocks of the East Antarctic Shield by the Kukri Erosion Surface. This generally planar surface is of great regional extent, being exposed from the Horlick Mountains (Long 1961), through the central Transantarctic Mountains to southern Victoria Land and possibly as far north as the Tucker Glacier in northern Victoria Land (Wood 1963), a distance of about 3500 km.

The Beacon Supergroup dominantly comprises quartzose or quartzo-felspathic sandstone with subordinate conglomerate, mudstone and coal, and is divided into two groups. The Taylor Group (Devonian) is dominated by clean quartz sandstone with minor mudstone and conglomerate, whereas the Victoria Group (Late Carboniferous to latest Triassic) tends to be more feldspathic and two of its formations contain laterally extensive coal seams. The combined thickness of the supergroup is about 2.5 km. The benchmark stratigraphy for the area (McElroy & Rose 1987), has been followed and supplemented by additional 1:50 000 scale geological mapping (Woolfe *et al.* 1989; Allibone *et al.* 1991, Turnbull *et al.* 1994).

The Fe-Ti oxide-bearing strata described in this paper define the Pivot Member of the Arena Sandstone, in the upper part of the Taylor Group. Early Devonian palynomorphs from the Terra Cotta Siltstone (Kyle 1977) and Late Devonian fish remains and macroflora from the Aztec Siltstone (McPherson 1978, Young 1988, Woolfe *et al.* 1990) indicate a late Middle Devonian depositional age for the Pivot Member.

The type section of the Pivot Member was defined by Woolfe *et al.* (1989) as the north ridge of Ugolini on the Rotunda massif from 78°01.5'S 161°35'E to 78°02'S 161°35'E and is not changed by this revision. The member is 90 m thick at the type section but is known to exceed 200 m in thickness on Pivot Peak, 15 km to the north. The lateral extent of the member is not known with confidence, but Woolfe *et al.* (1989) considered that the member may be

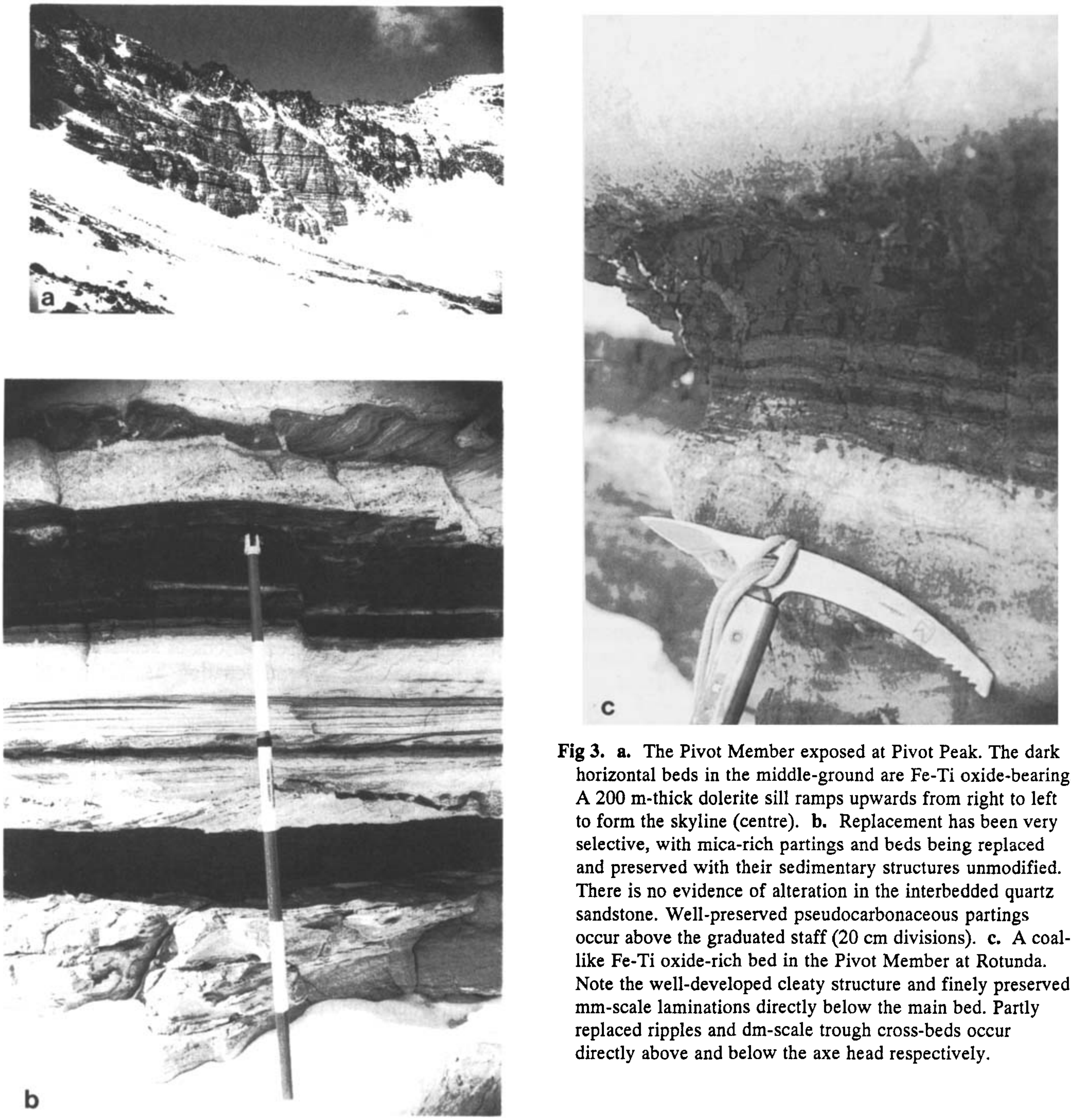

Fig 3. a. The Pivot Member exposed at Pivot Peak. The dark horizontal beds in the middle-ground are Fe-Ti oxide-bearing. A 200 m-thick dolerite sill ramps upwards from right to left to form the skyline (centre). **b.** Replacement has been very selective, with mica-rich partings and beds being replaced and preserved with their sedimentary structures unmodified. There is no evidence of alteration in the interbedded quartz sandstone. Well-preserved pseudocarbonaceous partings occur above the graduated staff (20 cm divisions). **c.** A coal-like Fe-Ti oxide-rich bed in the Pivot Member at Rotunda. Note the well-developed cleaty structure and finely preserved mm-scale laminations directly below the main bed. Partly replaced ripples and dm-scale trough cross-beds occur directly above and below the axe head respectively.

continuous with dark bands observed at the south end of Sickle Ridge 25 km to the south.

Ironstone occurrences, which are similar to those found in the Pivot Member, are now known to be present elsewhere in southern Victoria Land. Turnbull *et al.* (1994) reported iron-rich beds from several horizons in the St Johns Range area (65–70 km to the north-east of Knobhead). Similar deposits are thought to exist at the same stratigraphical level in the Convoy Range (110–130 km north of Knobhead (R. Sykes, personal communication 1991), and in the Terra Cotta Siltstone on Terra Cotta Mountain and Knobhead (A. Morrison, personal communication 1989). Titaniferous ironstone also occurs in the Hatherton Sandstone, the lateral equivalent of the Arena Sandstone in the Darwin Mountains, 500 km to the south (Woolfe *et al.* 1990, unpublished data)· Magnetite-rich cherty sedimentary rocks also occur in the lower Weller Coal Measures at Robison Peak, 85 km NNW of Knobhead (Slansky 1986).

Sedimentology

The Pivot Member consists of interbedded, medium- to coarse-grained, pale brown, cream or pale green sandstone, granule and pebble conglomerate with less abundant grey shaly mudstone and maroon massive mudstone. Thin lenses and beds of black granule conglomerate, sandstone and shaly mudstone (now known to be Fe-Ti oxide-rich) occur throughout the member. The lateral extent of these dm- to m-scale beds ranges from a few metres to hundreds of metres.

Trough cross-beds up to 40 cm high occur in all but the fine-grained strata· Many of the sandy mudstone beds, including some of the black oxide-rich beds, display well developed ripple lamination. Scour channels, up to 50 cm deep, are common and laterally truncate many beds. Fining-upwards cycles are commonly capped with thin red shale, and desiccation polygons occur throughout.

On the basis of bed geometries (facies architecture), small-scale sedimentary structures, and lithofacies associations, Woolfe *et al.* (1989) suggested that the member consisted of braid-plain sandstone, minor braided channel sandstone and lacustrine deposits. This interpretation is also supported by more recent work on equivalent strata in the Convoy Range (Sykes & Pocknall 1991a, b) that identified lake, river and deltaic associations.

Disseminated ilmenite and titanomagnetite occur in mudstone, sandstone and some granule conglomerate beds, giving a grey to black appearance. Locally, fine-grained beds with higher concentrations of oxides appear coal-like in outcrop (see Fig. 3). The upper and lower bounding surfaces of these beds are commonly gradational, and may contain well-preserved ripple-drift lamination picked out by opaque-rich partings. The darkest beds range in thickness from a few cm to 50 cm. Many such beds display subconchoidal to conchoidal fracture and have a near-orthogonal joint set. Joint spacing is typically 2–4 cm and strongly resembles cleat (see Fig. 3). However, hand specimens are significantly more dense than typical coal and are magnetic. Many beds grade laterally into dark grey or maroon shaly mudstone.

Trace fossils are common throughout the member (Woolfe 1990). *Skolithos linearis* is abundant in many of the coarser-grained sandstone and granule conglomerate beds and it is the only trace fossil observed within dark oxide-rich sediments. *Beaconites barretti* and *B. gouldi* widely occur as endostratal, back-filled miniscate trails within planar-laminated and trough cross-bedded sandstone. *Diplichnites gouldi* occurs as exostrata trackways, up to 25 cm (typically 10–15 cm) across, on large cross-bed surfaces. No medial grooves were observed associated with the trackways. *Didymaulyponomos, Didymaulichnus* and *Cruziana* are all minor but locally abundant members of the assemblage. More complete taxonomic descriptions of all of these ichnogenera are provided by Bradshaw (1981).

Depositional environment of the Pivot Member

There has been considerable local debate concerning the depositional setting of the Taylor Group over recent years (Vialov 1962, Webby 1968, Gevers *et al.* 1971, Barrett & Kohn 1975, Plume 1976, 1978, McPherson 1978, 1979, Barrett 1979, Bradshaw 1981, Gevers & Twomey 1982, Sherwood *et al.* 1989, Woolfe *et al.* 1989, Bradshaw *et al.* 1990, Woolfe 1990, Sykes & Pocknall 1991b, Woolfe 1993). The consensus among workers appears to be moving towards a non-marine setting and this is particularly true for the middle and upper formations of the group, including the Pivot Member (Arena Sandstone).

The Pivot Member (and Arena Sandstone in general) contains several features that are strongly indicative of non-marine deposition. Widespread trough cross-bedding with unidirectional palaeocurrent directions (Sykes & Pocknall 1991a,b, Woolfe 1992), together with tabular to sheet-like bed geometries and small scale scour channels, suggest a low-sinuosity fluvial environment. Tabular cross-bed sets, up to 2.5 m high are common and have been interpreted as small Gilbert Deltas (Sykes & Pocknall 1991b). Desiccation polygons record numerous periods of subaerial exposure, and the presence of grain-coating haematite suggests weathering in an arid or semi-arid environment. Extensive, thin planar beds, some with well-preserved bifurcating oscillation ripples, are indicative of deposition from shallow bodies of standing water. The most recent interpretation of the trace fossil assemblage, which has provided much of the fuel for arguments in favour of a marine depositional setting, suggests that it is consistent with non-marine deposition (Woolfe 1990, 1993).

It is concluded that the Pivot Member was deposited in a semi-arid environment on a regionally extensive, low-gradient flood plain. Palaeocurrent data from coarse-grained units, both higher and lower in the sequence, suggest an area of high ground (and presumably exposed basement) was to the east, close to the present position of the Ross Embayment (Woolfe 1992). The member was deposited by low-gradient, sandy, braided plain rivers, small deltas and extensive shallow lakes. Aridity indicated by grain-coating haematite, suggests the system was probably seasonally ephemeral, an interpretation supported by the widespread occurrence of desiccation polygons.

Geochemistry and petrology

The Pivot Member is dominated by arkosic and subarkosic sediments with lesser amounts of detrital mica, opaque

Table I. Electron microprobe analyses.

Sample	6a	6d	50f	50e	50d	50c	50g	50h	50i
SiO_2	0.41	0.00	0.41	0.25	0.15	0.09	0.36	0.10	0.18
Al_2O_3	0.10	0.50	0.33	0.28	0.03	0.69	0.27	0.35	0.44
TiO_2	25.57	15.35	20.28	14.78	49.29	39.92	46.05	42.72	44.40
FeO	65.94	74.85	78.29	74.96	44.87	48.51	49.13	53.10	47.01
MnO	0.12	0.04	0.30	0.03	1.61	0.69	1.35	1.12	1.67
MgO	0.22	0.24	0.06	0.04	0.00	0.04	0.85	0.07	0.00
CaO	0.12	0.03	0.08	0.05	0.04	0.05	0.06	0.00	0.04
Na_2O	0.06	0.00	0.03	0.00	0.00	0.00	0.01	0.00	0.00
K_2O	0.05	0.04	0.15	0.11	0.05	0.11	0.12	0.09	0.08
NiO	0.00	0.00	0.02	0.00	0.00	0.00	0.04	0.06	0.00
Cr_2O_3	0.08	0.09	0.00	0.03	0.00	0.45	0.05	0.08	0.00
Cl	0.12	0.03	0.00	0.02	0.00	0.09	0.00	0.00	0.00
Total	92.80	91.18	99.97	90.54	96.04	90.65	97.51	97.68	93.82

member is due to variation in the abundance of minor mineral constituents, mainly chlorite, black opaque oxides and haematite.

Quartz overgrowths are strongly developed in some of the more quartz-rich sandstone units. Pale green sandstone and mudstone beds contain higher amounts of secondary chlorite, present as discrete flakes and aggregates. Some of the chlorite probably formed from the alteration of biotite during burial or as a result of pervasive low-grade metamorphism associated with the intrusion of Ferrar Dolerite in the Jurassic.

Organic carbon concentrations were determined using a Leco HF20 induction furnace coupled to a Leco 577–100 carbon determinator. Carbon contents of the black shale and fine-grained sandstone were all below detection limits (0.1%). Efforts were made to concentrate the black "organic" components using hydrofluoric acid (HF) but the entire samples dissolved in warm acid. Polished sections were prepared from the most "carbonaceous-looking" samples and examined using a scanning electron microscope. Results from electron microprobe analysis (Table I) identify the black opaque material as ilmenite and titanomagnetite. The oxides occur as 0.1–2 µm-sized, finely disseminated grains, discrete aggregates and most commonly as pseudomorphs after phyllosilicate grains.

In thin section the replacive character of the Fe-Ti oxide is clear. Sample suites show two distinct modes of replacement:

i) gradual replacement of fine-grained chloritic matrix (Fig. 4), and
ii) gradual replacement of detrital mica grains, with replacement initiating about grain boundaries, kinks and defoliations (Fig 5).

P/T conditions of titaniferous ironstone formation

Lateral gradations from unaltered sandstone and shale to

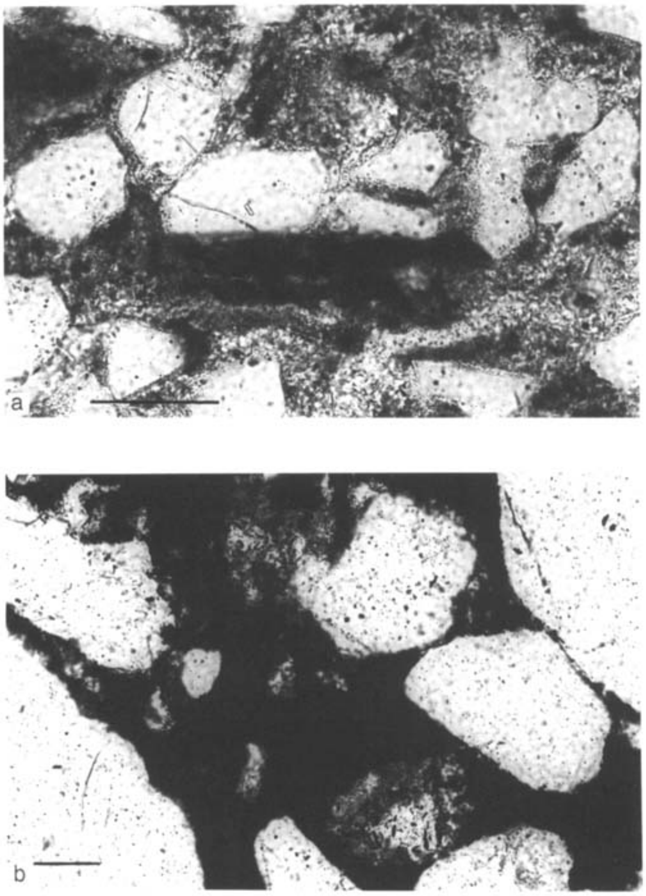

Fig 4. a. Partial replacement of chloritic matrix by Fe-Ti oxide. The dark lath-shaped area in the centre of the image is a partly replaced biotite grain (see Fig. 5). **b.** Complete replacement of matrix minerals by Fe-Ti oxide in a coarse-grained quartz sandstone. Both samples are from the type section of the Pivot Member at Rotunda. Scale bars are 100 microns.

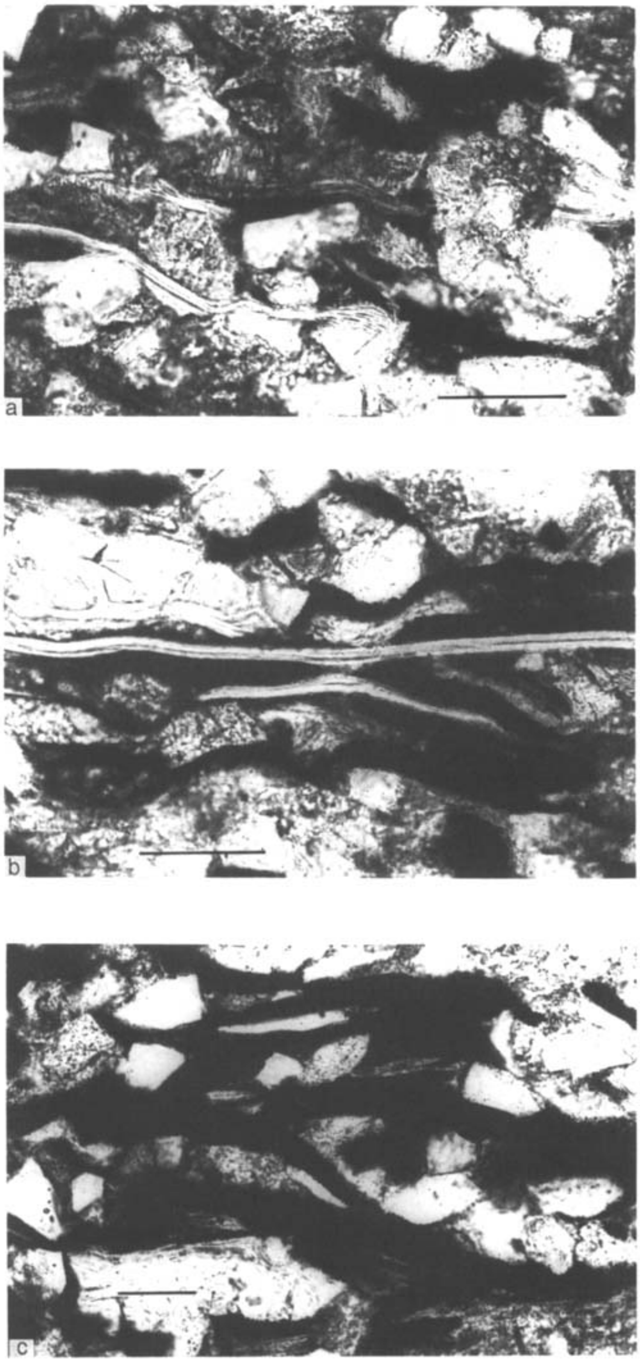

Fig 5. a. Photomicrograph under plane-polarized light. Opaque areas are Fe-Ti oxide and titaniferous magnetite. Replacement has occurred both in the matrix and in detrital biotite and muscovite grains. Biotite appears to be the preferred host. Note how replacement is preferentially occurring about the fractured areas and exfoliating margins of the kinked biotite (centre **b.**). More advanced growth of Fe-Ti oxide as it replaces mica grains in muddy sandstone. Note the ghost phyllosilicate textures preserved in some strongly replaced grains **c.** Near complete replacement of detrital phyllosilicate grains with Fe-Ti oxide, some ghost phyllosilicate textures remain. Scale bars are 100 μm.

Lateral gradations from unaltered sandstone and shale to titaniferous ironstone, together with textural relationships (e.g. partially replaced detrital biotite grains) revealed in thin section, provide unequivocal evidence that the titaniferous ironstone formed by replacement. Spatial relationships between the titaniferous ironstone and Ferrar Dolerite bodies (replacement extends for up to 400 m from dolerite contacts and is generally confined by bedding) show that replacement was almost certainly associated with dolerite emplacement – the only thermal event known to have effected the sedimentary column.

Beacon Supergroup strata are extensively intruded by the Ferrar Dolerite (Jurassic), although in many places the sedimentary pile appears to have been largely unaffected by this event. The limited sample suite currently available from the Pivot Member precludes characterization of fluids associated with the replacement. However, based on regional stratigraphy and studies elsewhere in the Transantarctic Mountains, it is possible to place reasonably tight constraints on the P/T conditions and fluids present at the time of Fe-Ti oxide/magnetite replacement.

The Ferrar magmatic event not only introduced huge volumes of dolerite but also led to the production of widespread flood basalts (Kirkpatrick Basalt) and basaltic lahars (Mawson Formation). These units are probably coeval with the youngest unit of the Beacon Supergroup (Member D, Lashly Formation) at Allan Hills (Gunn & Warren 1962). This enables the depth of burial at the time of Fe-Ti oxide replacement to be constrained directly on the basis of the minimum thickness of the overlying Beacon Supergroup sedimentary rocks (1400 m) and the maximum observed thickness of the overlying Beacon Supergroup plus the Jurassic volcanic pile (1800 m). This constrains the pressure during Fe-Ti oxide formation to 0.3–0.4 kbar, assuming normal geobaric gradients.

Constraining the temperature of formation is not so easy. Evidence of high-temperature contact metamorphism comes from a study of Permian coals (Schapiro & Gray 1966) and from the observation of high temperature mineral phases in the overlying Victoria Group at Robison Peak.

Schapiro & Gray (1966) found systematic increases in vitrinite reflectivity and microhardness, and a systematic decrease in resistivity with decreasing distance between samples and large dolerite sills. The most metamorphosed coal samples contain abundant microscopic gas vacuoles formed by thermal distillation, suggesting that the samples represented a form of natural coke. However, pressures had been adequate to suppress true (macroscopic) coking. Schopf & Long (1966) suggested that coal microhardnesses of between 100 and 200 kg cm^{-2} indicated coking at 700–1000°C. Samples collected 100 m from a major sill in the Robison Peak area have microhardnesses of 91–125 kg cm^{-2} and vitrinite reflectances of about 5% suggesting maximum temperatures of between 650 and 750°C.

High temperatures are also indicated by the metamorphic mineralogy of cherts in the lower Weller Coal Measures at Gibson Spur, near Mount Bastion (Bradley & Isaac 1985, Slansky 1986). The "cherts" represent mudstone beds that were metamorphosed and silicified during the emplacement of a major dolerite sill at least 120 m thick. The "cherts"commonly exhibit a silky to resinous lustre, attributed to very fine-grained sillimanite on freshly broken surfaces, (Slansky 1986). The sillimanite is associated with quartz, K-feldspar and cordierite, with or without plagioclase and minor rutile. The presence of sillimanite in muscovite-free, K-feldspar-quartz assemblages is consistent with peak metamorphic temperatures of 650–700°C for pressures less than 1 kbar (Winkler 1967). These high temperature assemblages extend for at least 30 m above the sill and are consistent with vitrinite reflectance and coal microhardness.

Relatively high, peak temperatures are also indicated by the mineralogy of calcareous bands (algal limestone beds?) within the Weller Coal Measures, 40–80 m above a major sill at Robison Peak. These rocks contain muscovite, instead of sillimanite, indicating temperatures between 500 and 600°C for pressures of less than 1 kbar (Winkler 1967). The calcareous bands, both at Robison Peak and within the heavily intruded section at Mount Bastion (where dolerite sills comprise 30–40% of the section by volume), contain the prograde metamorphic minerals hydrogrossular, vesuvianite, calcite and diopside. The calcareous bands also contain prehnite, analcime and wairakite, which are probably retrograde. Fluorite and hydroxyapophyllite are present in two specimens from Mount Bastion (Slansky 1986). The primary assemblages also indicate temperatures between 500 and 600°C: vesuvianite first occurs at temperatures of about 500°C for pressures less than 1 kbar, and the presence of quartz and calcite in the absence of wollastonite at these pressures indicates temperatures less than 500–600°C (Winkler 1967). The presence of vesuvianite, hydroxyapophyllite and fluorite all indicate a fluorine-bearing aqueous pore fluid, at least during retrograde metamorphism.

Although, Bradshaw (1979) attributed the presence of analcime and wairakite within the Beacon Supergroup to a reaction between alkaline lake waters and volcanogenic sediments, these minerals may be the result of the pervasive low-grade metamorphism.

Hundreds of metres from the dolerite sills, most sandstone and mudstone samples contain detrital muscovite and biotite, altered feldspars and quartz. Alteration of the primary mica minerals to chlorite and other finely divided phyllosilicates (nontronite, montmorillonite etc.) is evident in nearly all thin sections. Some assemblages include minerals such as analcime, heulandite, mordenite, prehnite and wairakite that are characteristic of low temperature conditions. However, it is not clear if these minerals record a regional heat pulse associated with the Ferrar magmatic event or whether they are a retrograde assemblage.

Studies of vitrinite reflectance and coal microhardness suggest widespread low-temperature thermal alteration (Schopf & Long 1966, Kyle 1976). Kyle (1976) estimated that temperatures were raised by 350°C, 50 m away from a 100 m thick sill and by 100°C, 300 m away. Regionally, vitrinite reflectances are over mature for gas generation, suggesting that the Weller Coal Measures have been subjected to a regional temperature in excess of 200–250°C. This suggests a regional geothermal gradient of about 200°Ckm^{-1} and local temperature gradients adjacent to dolerite bodies of as much as 15°Cm^{-1}.

At Pivot Peak and Rotunda, titaniferous ironstone is observed in direct contact with dolerite bodies and extends for at least 300 m along bedding away from the contact. This, plus the observed mineralogies at Robison Peak, suggests that titaniferous ironstone formation took place at about 0.3–0.4 kbar and at temperatures ranging from as high as 600°C to as low as 380°C. Even lower temperatures may be indicated by the presence of interstitial epidote and widespread chloritic alteration in the Pivot Member· Epidote is known to form at temperatures as low as 130–235°C (Browne & Ellis 1970, Steiner 1977). However, the timing of these phases with respect to titaniferous ironstone formation is ambiguous.

Magnetite-rich cherty sediments also occur at Robison Peak, in close proximity to a major sill at least 120 m thick (Bradley & Isaac 1985, Slansky 1986). The "cherts" are black, dark olive-green to greenish grey, and occur between 6 m and 30 m above the dolerite sill. The "cherts" exhibit well-preserved mm-scale laminations, wavy bedding, graded bedding, ripples, load casts, small-scale slumps and scour-and-fills. The "chert" beds range from cm-scale to beds as thick as 2.7 m.

The magnetite-rich phases (XRD identification, Slansky 1986) are strongly magnetic and have selectively replaced phyllosilicate-rich layers and lenses in the "cherty" rocks from Robison Peak. Typically, biotite is partly pseudomorphed by interlayer mica-chlorite, or is replaced wholly by chlorite. The magnetite is partly altered to hematite and maghemite.

Discussion

The Pivot Member records unequivocal replacement of both detrital and diagenetic/metamorphic phyllosilicates by Fe-Ti oxide at temperatures as low as 380°C and pressures below 0.5 kbar. However, superb preservation of sedimentary structures including ripples with Fe-Ti oxide-rich partings and the bedding-parallel nature of titaniferous ironstone could, in the traditional sense, be used to argue for a sedimentary origin. This high-lights the ambiguity of using sedimentary structures to discriminate between sedimentary and replacive ironstone.

Whereas the P/T conditions have been fairly well constrained for the Pivot Member, little is known about the chemistry of the replacement reactions and the fluids involved. The member occurs in an undeformed terrane which has been affected by a single thermal event (Ferrar Dolerite) and the P/T conditions can be constrained by direct observation of the burial conditions at the time of dolerite emplacement and by a well-preserved, metamorphic assemblage.

Conclusions

The Pivot Member was deposited in the late Middle Devonian by unconstrained sandy, braided rivers and ephemeral lakes under semi-arid conditions. The unit was derived from a stable continental craton and was dominated by quartzose, quartzo-felspathic, and locally micaceous sandstone. The strata-bound titaniferous ironstone now contained within the member probably formed *c.* 200 M.y. after its deposition, at 179 ± 3 Ma during widespread emplacement of dolerite sills. Titaniferous ironstone developed due to a fluid-phase reaction that resulted in the replacement of biotite, muscovite and fine-grained chloritic matrix by Fe-Ti oxide. This reaction occurred at 0.3–0.4 kbar and at temperatures as low as 380°C and possibly lower.

Earlier published descriptions of these Fe-Ti oxide-bearing rocks as carbonaceous shale and coal were in error, and the name Pivot Coal Measures Member is consequently no longer appropriate. The name Pivot Member is proposed as a more acceptable alternative.

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