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Structure of the Early Palaeozoic Cape River Metamorphics, Tasmanides of north Queensland: evaluation of the roles of convergent and extensional tectonics

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Abstract

The Early Palaeozoic Cape River Metamorphics consist mainly of psammitic gneiss and schist and occur as an extensive linear belt at the western margin of the Charters Towers Province 200 km southwest of Townsville in the northern Tasmanides. A prominent foliation (S_2) is the main structure in the belt and is associated with tight to isoclinal folds, subparallel mineral and intersection lineations, and boudinaged pods of vein quartz and pegmatite. In the southwest, the main foliation is a crenulation cleavage (S_2) related to D_2 deformation. It overprints steeply dipping foliation (S_1) formed in a D_1 deformation but no associated folds have been found. Gently plunging, upright, open folds (D_3 deformation) with axial planar S_3 crenulation cleavage have affected the main foliation (S_2). These deformations were associated with upper greenschist to lower amphibolite facies metamorphism. Amphibolite-grade orthogneiss containing S_2 and S_3, deformed granite and migmatite of the Fat Hen Creek Complex occurs in the northeast. In the southwest, the main foliation (S_2) is folded around a map-scale, gently plunging synclinorium indicating that S_2 formed with a subhorizontal orientation. In metamorphic rocks, the origin of widespread, intense subhorizontal foliation, usually associated with recumbent folds, has been considered problematic and in many cases is attributed to crustal extension. We relate the origin of D_2 structures to subvertical shortening (i.e. extension) resulting in orientations that are strikingly divergent to those of upright D_1 and D_3 structures that were induced by compression. The proposed extensional event is poorly constrained in timing but it affected much of the Fat Hen Creek Complex, the oldest known phase of which is 493 Ma, and occurred prior to $^{40}Ar/^{39}Ar$ cooling ages at 423 – 409 Ma that also post-dated the D_3 deformation.

Keywords

Structure, Early, Palaeozoic, Cape, River, Metamorphics, Tasmanides, north, Queensland, evaluation, roles, convergent, extensional, tectonics, GeoQUEST

Disciplines

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Structure of the Early Palaeozoic Cape River Metamorphics, Tasmanides of north Queensland: evaluation of the roles of convergent and extensional tectonics

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Running Title: Convergent and extensional tectonics in Queensland

The Early Palaeozoic Cape River Metamorphics consist mainly of psammitic gneiss and schist and occur as an extensive linear belt at the western margin of the Charters Towers Province 200 km southwest of Townsville in the northern Tasmanides. A prominent foliation (S_2) is the main structure in the belt and is associated with tight to isoclinal folds, subparallel mineral and intersection lineations, and boudinaged pods of vein quartz and pegmatite. In the southwest, the main foliation is a crenulation cleavage (S_2) related to D_2 deformation. It overprints steeply dipping foliation (S_1) formed in a D_1 deformation but no associated folds have been found. Gently plunging, upright, open folds (D_3 deformation) with axial planar S_3 crenulation cleavage have affected the main foliation (S_2). These deformations were associated with upper greenschist to lower amphibolite facies metamorphism. Amphibolite grade orthogneiss containing S_2 and S_3, deformed granite and migmatite of the Fat Hen Creek Complex occurs in the northeast. In the southwest, the main foliation (S_2) is folded around a map-scale, gently plunging synclinorium indicating that S_2 formed with a subhorizontal orientation. In metamorphic rocks, the origin of widespread, intense subhorizontal foliation, usually associated with recumbent folds, has been considered problematic and in many cases is attributed to crustal extension. We relate the origin of D_2 structures to subvertical shortening (i.e. extension) resulting in orientations that are strikingly divergent to those of upright D_1 and D_3 structures that were induced by compression. The proposed extensional event is poorly constrained in timing but it affected much of the Fat Hen Creek Complex, the oldest known phase of which is 493 Ma, and occurred prior to $^{40}Ar/^{39}Ar$ cooling ages at 423–409 Ma that also postdated the D_3 deformation.

KEY WORDS: $^{40}Ar/^{39}Ar$ ages, Early Palaeozoic, contractional deformation, extensional tectonics, foliation, metamorphic rocks, north Queensland, Tasmanides.

INTRODUCTION

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The Early Palaeozoic Cape River Metamorphics consist of multiply deformed greenschist to amphibolite grade rocks in the northern Tasmanides and are located 200 km southwest of Townsville (Figure 1; Hutton *et al.* 1997). These rocks are unusual in that they are affected by an intense foliation (S_2) that has formed in a subhorizontal orientation and throughout the northeastern part of the unit has been folded to a steeper dip (Withnall *et al.* 1997). A similar phenomenon has also been recognised in the Anakie Metamorphic Group of the southern Anakie Inlier 350 km to the southeast where an intense foliation (S_2) has a gently dipping orientation over large areas (Withnall *et al.* 1995). In contrast, other parts of the Tasmanides are characterised by widespread sub-greenschist grade rocks that have steeply dipping folds, faults and cleavage/foliation and are attributed to horizontal contractional deformation (e.g. Withnall & Lang 1993).

We have re-examined the structure of the Cape River Metamorphics and have also obtained several $^{40}Ar/^{39}Ar$ cooling ages that provide an upper limit on the timing of the main structural events. Our aim is to interpret the structure of the Cape River Metamorphics in a regional context and in particular to assess the significance of the initially flat-lying S_2 foliation. For the Anakie Metamorphic Group, the intense flat-lying S_2 foliation has been related to a ductile, contractional thrust-style of deformation (Green *et al.* 1998). Much literature exists to support an alternative interpretation that subhorizontal foliation in regional metamorphic rocks can be attributed to extensional tectonics (Gibson 1991; Pavlis & Sisson 1993).

GEOLOGICAL SETTING

The Charters Towers Province of the northern Tasmanides (Henderson, 1980) has widespread Early Palaeozoic rocks including metamorphic rocks (Cape River Metamorphics and similar units), plutonic rocks (Reedy Springs, Lolworth and Ravenswood Batholiths) and a volcanic and sedimentary succession (Seventy Mile Range Group, Figure 1). The Cape River Metamorphics and similar units (Anakie Metamorphic Group, Argentine, Charters Towers and Running River Metamorphics) consist of a metamorphosed protolith of Neoproterozoic to Cambrian sedimentary and igneous rocks that are temporally correlated with the upper part of the succession in the Adelaide Fold Belt in southeastern South Australia (Withnall *et al.* 1995, 1996; Fergusson *et al.* 2001). No Palaeoproterozoic to Mesoproterozoic basement has been found in the metamorphic units of the northern Tasmanides in contrast to the Adelaide Fold Belt.

The Cape River Metamorphics have an east-southeast-trending strike length of some 100 km with an across strike width of up to 50 km. Cambrian to Devonian plutons intruded the metamorphics in their northwestern and northeastern parts. At the northern end of the belt, the Clarke River Fault juxtaposes them against the Ordovician to Carboniferous sedimentary succession of the Graveyard Creek Subprovince of the Broken River Province (Withnall & Lang 1993). Elsewhere the metamorphics are unconformably overlain by Permian and younger units.

Regional deformation and metamorphism in the Cape River Metamorphics and similar units has been attributed to the Middle Cambrian to earliest Ordovician Delamerian Orogeny (*ca* 500 Ma; Hutton *et al.* 1997; Withnall *et al.* 1997). Older deformed granites of the Lolworth Batholith (Fat Hen Creek Complex) intrude the Cape River Metamorphics and have isotopic ages in the range 493–455 Ma (Hutton *et al.* 1997) indicating significant Middle to

Late Ordovician deformation, which post-dated the Delamerian event. The Seventy Mile Range Group south of Charters Towers (Figure 1) contains Lancefieldian to Chewtonian fossils (Henderson 1984) indicating absolute ages of *ca* 488–472 Ma according to the timescale of the International Commission on Stratigraphy (2004). Thus this supracrustal assemblage overlaps substantially with the timing of granite intrusion in the metamorphic units of the Charters Towers Province. The Seventy Mile Range Group is weakly to locally strongly deformed by contractional deformation with a dominant east-west trending upright cleavage and folding event considered by Berry *et al.* (1992) as probably of Late Ordovician or younger age as it affected Middle Ordovician plutons of the region. Late Silurian to Early Devonian plutons that are structurally controlled by northeasterly trending lineaments/faults postdates these east-west trending structures. These lineaments/faults and associated late northeast-trending cleavage in the Seventy Mile Range Group are therefore of probable Silurian to Early Devonian age (Berry *et al.* 1992; Hutton *et al.* 1997).

LITHOSTRATIGRAPHY AND SEDIMENTARY STRUCTURES

The Cape River Metamorphics consist of gneiss, schist, quartzite, graphitic slate, calc-silicate rocks and amphibolite that are intruded by orthogneiss, deformed granite and migmatite of the Fat Hen Creek Complex (Hutton *et al.* 1997; Withnall *et al.* 1997). Most of the Cape River Metamorphics are undifferentiated and dominated by quartzose metasedimentary schist and gneiss that are mainly metamorphosed sandstone with less abundant pelite. Amphibolite is rare in the area studied apart from in the northeast, adjacent to the Fat Hen Creek Complex, but is abundant further east. Several mappable units are included within the Cape River Metamorphics (Withnall *et al.* 1997). The Morepork Member, with white quartzite ridge-forming horizons interlayered with mainly metasandstone and minor graphitic schist, occurs in the southwest. A thin unit with calc-silicate rock in addition to metasandstone has been mapped for over 30 km along the northeastern side of and structurally below the Morepork Member (Withnall *et al.* 1997). Northeast of the Fat Hen Creek Complex (Figure 1) the Cape River Metamorphics consists of high-grade paragneiss with strong layering and common granitic veins (Figure 2a).

In much of the Cape River Metamorphics the main primary feature is decimetre- to metre-scale lithological layering representing relict bedding (Figure 2b), with some associated planar lamination. Sedimentary structures are only rarely preserved and are best displayed in an unnamed creek 8 km southwest of 'Oak Vale' along a 1 km cross-strike section through one of the quartzite units of the Morepork Member (305084 7737145 to 305680 7738057, Lolworth (7957) 1:100 000 sheet, coordinates throughout are in metres relative to the Australian Geodetic Datum – AGD66). Here, we have identified widespread thin micro-crosslaminated and plane laminated quartzite layers (Bouma C and D layers respectively), basal scours and flute marks, and a slumped layer with dispersed intraformational fragments (Figure 2c). These structures are consistent with deepwater turbidite deposition but for most of the succession depositional environments remain unknown.

STRUCTURE

Three deformations (D_1, D_2, D_3) have affected the Cape River Metamorphics with the main deformation (D_2) forming a well-developed, ubiquitous foliation and associated structures

(Figure 3; Withnall *et al.* 1997). We describe the structure of the Cape River Metamorphics incorporating new data we have collected from detailed mapping in three areas (Oxley Creek, Black Mount, Gorge Creek).

D_1 deformation

Evidence for the D_1 deformation is largely restricted to lower grade rocks in the lower Oxley Creek area (Figures 4, 5, 6) where the main foliation has been labelled 'S_2' on the basis that microlithons are well developed along the S_2 differentiated layering and preserve a finer scale S_1 differentiated foliation (Figure 3c; Withnall *et al.* 1997). In the hinges of F_2 folds, the orientation of S_1 is steeply dipping with a strike to the southeast. No associated F_1 folds were found so that overall little can be deduced about the style of the D_1 deformation.

D_2 deformation

D_2 deformation is evident in most of the Cape River Metamorphics and is characterised by a laminar to platy foliation (S_2) defined by aligned biotite, muscovite, and quartz. F_2 mesoscopic folds are scarce in lithological layering (e.g. 291300 7142900, 292772 7743674 Lolworth (7957) 1:100 000 sheet) and more abundant in foliation and quartz-epidote veins (Figure 3a, b). They are tight to isoclinal folds with axial planes parallel to the main S_2 foliation. Isoclinal folds in foliation at 295908 7747253 Lolworth (7957) 1:100 000 sheet (Figure 3a) must have formed during D_2 after significant S_2 development and are typical of deformation in mylonite zones (Bell & Hammond 1984). In the Black Mount area (Figures 7, 8, 9), quartzite units in the Morepork Member outline map-scale fold couples and we regard these as most likely representing F_2 hinges. Terminations of the quartzite units to the northwest could also represent F_2 hinges. All F_2 folds have high amplitude-to-wavelength ratios and indicate that significant shortening developed perpendicular to the plane of the main foliation. Abundant boudinaged pods of vein quartz and/or pegmatite veins with long axes lying within the foliation plane indicate that stretching has occurred within it. Given the intensity of deformation associated with the D_2 deformation, and the lack of way-up indicators, we consider that no original stratigraphy can be determined from outcrop patterns.

A S_1–S_2 intersection lineation is found in the Oxley Creek area (Figures 4, 5, 6) where S_1 is distinguished and indicates the orientation of F_2 hinges. This intersection lineation is well developed on the southwest flat-lying limb of the main F_3 synclinorium (see below) in the Oxley Creek area and plunges gently to the east-southeast at an angle of 30º–40º to L_3 (Figures 5, 6). Rarely, a mineral stretching lineation defined by elongate biotite and quartz-chlorite pods is also subparallel to this intersection (Figure 6c, d). This is consistent with high strain being associated with the formation of this foliation.

In some exposures of pelitic rocks along Oxley Creek (277501 7758050 White Mountains (7857) 1:100 000 sheet), an earlier differentiated layering (crenulation cleavage) is developed at a high-angle to the main foliation. Thus a more complex history has affected the Cape River Metamorphics but this is not recognisable in the bulk of the dominantly psammitic rock types of which it is comprised.

In the Gorge Creek – Oak Vale area, Cape River Metamorphics occur northeast and southwest of the Fat Hen Creek Complex with the main foliation developed in both units (Figures 10, 11, 12). Here, the Cape River Metamorphics are at their highest metamorphic grade as indicated by the presence of high-grade gneiss and migmatite. The main foliation in the gneiss contains isoclinal intrafolial folds. Shear sense structures associated with the main foliation including asymmetrical boudinage, shear bands and asymmetric fold trains indicate top to the west (Figure 13) consistent with that reported by Hammond (1986).

D_3 deformation

The D_3 deformation in the Cape River Metamorphics consists of open to locally tight folds in the S_2 foliation with an S_3 axial planar crenulation cleavage (Withnall *et al.* 1997). Our mapping in the Oxley Creek area confirms the observation of these authors that the S_2 foliation is folded into a synclinorium trending east-southeast, with its core occupied by the Morepork Member (Figures 4, 5, 6). The synclinorium has an axial plane that is steeply inclined to the northeast with a steep southwest-dipping northeast limb and a gentle northeast dipping to flat-lying southwest limb. Abundant short wavelength (up to 1 m) open to close folds associated with the synclinorium (F_3) plunge gently to the northwest and southeast. They are subparallel to a widely developed intersection lineation (L_3) between the differentiated layering (S_2) and the axial planar crenulation cleavage/foliation (S_3). On the flat lying to gently dipping southwest limb, large areas with flat to gentle planar S_2 are interspersed with smaller areas with abundant F_3 folds.

Withnall *et al.* (1997) extrapolated the synclinorium of the Oxley Creek area for some 80 km to the southeast where it passes beneath younger cover. Within the Black Mount area we have mapped steeply dipping S_2 and lithological layering in the northeast whereas in the southwest these structures dip moderately to gently southwest (Figures 7, 8, 9). Thus a broad kink-like feature with an axial plane dipping to the northeast, and each limb represented by the two domains referred to above, has replaced the synclinorium in the Black Mount area (Figure 8). Note that the calc-silicate marker unit in the steeply dipping belt is not repeated as would be expected had the synclinorium extended to this area. In the southwest part of the Black Mount area, mesoscopic F_3 folds are scarce but S_3 crenulation cleavage is more widely developed (Figure 7) especially in graphitic slate layers.

The steeply dipping limb extends up to 20 km to the northeast away from the axis of the synclinorium/monocline as shown by steep southwest dip of foliation in the Cape River Metamorphics and the Fat Hen Creek Complex in Gorge Creek (Figures 10, 11, 12). Thus a deeper structural level represented by the sheet-like Fat Hen Creek Complex and its surrounds has been exposed by F_3 folding. In some exposures in the Fat Hen Creek Complex, S_2 foliation is tightly folded (F_3) with steeply dipping axial planes that strike southeast. Granitoid dykes and sills, variably deformed, are common in the undifferentiated Cape River Metamorphics immediately south of the Cape River.

In the southwest part of the Gorge Creek – Oak Vale area, a major quartzite marker is developed that contains well-preserved sedimentary structures (see above). In contrast to elsewhere in the Cape River Metamorphics, laminar S_2 foliation is not represented. Bedding in this marker dips steeply and youngs consistently to the northeast with rare southwest-vergent F_3 fold couples. A continuous cleavage is developed at a low angle but steeper than bedding (Figure 14) and has an orientation consistent with S_3, but is not a crenulation cleavage as S_3 is elsewhere. The younging, dip and bedding-cleavage vergence data are consistent with this quartzite marker occurring as part of a southwestern limb of a map-scale F_3 syncline, although this structure has not been found to the northwest in the Black Mount area. Thus this area appears to form a low-strain zone with respect to the D_1 and D_2

deformations and shows D_3 structures as dominant, in contrast to the Cape River Metamorphics elsewhere.

A late upright, very broad fold occurs in the Black Mount area (291300 7142900 Lolworth (7957) 1:100 000 sheet). Rarely a late crenulation cleavage is developed at low to moderate angles postdating the main foliation and S_3 (e.g. 291921 7749375 Lolworth (7957) 1:100 000 sheet).

Late faults

A set of faults trending northeasterly to easterly with apparent sinistral strike-slip offsets in quartzite markers of the Morepork Member is shown on the White Mountains and Lolworth Special 1:100 000 geological sheets (Hutton *et al.* 1998; Withnall *et al.* 1998). Evidence of brittle-style deformation including small sinistral vertical faults, domino offsets along brittle quartzite layers, and abundant vertical kinks in schist, occur along a section of creek from 295136 774589 to 295388 7745575 Lolworth (7957) 1:100 000 sheet (Figure 7, north of J). These features are northeasterly trending and related to a sinistral fault of similar trend in this area and therefore also inferred to be near vertical. It is clear from these exposures that these faults are late-stage features unrelated to the earlier ductile deformation history.

GEOCHRONOLOGY

Metamorphic minerals, in particular biotite and muscovite, are aligned along foliations (S_1, S_2, S_3) and indicate that metamorphism was synchronous with ductile deformation (Withnall *et al.* 1997). Additionally some samples contain biotite and muscovite grains that cross-cut all foliations, indicating that, at least locally, metamorphism continued after ductile deformation. The grade of metamorphism is upper greenschist to amphibolite facies as indicated by widely developed biotite, some andalusite, amphibole in calc-silicate rocks, and migmatites in the highest grade rocks (Yardley 1989). Given that metamorphic mineral growth continued during and after the formation of all three foliations, biotite and muscovite mineral separates might be expected to constrain the time of final metamorphic cooling in the region.

Samples CR35a, CR114a, and CR183 were selected from the Cape River Metamorphics for $^{40}Ar/^{39}Ar$ age analysis. Sample CR35a is biotite schist derived from fine quartzose sandstone located in Oxley Creek (Figure 4; 273800 7754600 White Mountains (7857) 1:100 000 sheet). Here, the main foliation (S_2) is gently dipping to the northeast with F_3 folds developed with metre long wavelengths. Both S_1 and S_2 are defined by aligned muscovite and some biotite**.** Some biotite porphyroblasts also cross-cut the S_2 foliation, whereas occasional muscovite grains are randomly oriented. Thus metamorphism was both synchronous with fabric development (S_1 and S_2 foliations) and continued after deformation.

Samples CR114a and CR183 are from the Gorge Creek – Oak Vale area. Sample CR114a is a biotite orthogneiss from the Fat Hen Creek Complex (Figure 10; 311988 7745856 Lolworth (7957) 1:100 000 sheet). Sample CR183 is biotite schist from the undivided Cape River Metamorphics (309450 7743300 Lolworth (7957) 1:100 000 sheet). The biotite orthogneiss consists of plagioclase, microcline, quartz, biotite, muscovite and chlorite. It has a weakly developed foliation with aligned biotite and weakly aligned quartz and feldspar. Quartz has widespread undulose extinction. Sample CR183 has a well-developed differentiated foliation (S_2) with alternating mica- and quartz-rich domains, delineating axial planar crenulations associated with open F_3 folds. Some biotite grains cross-cut the S_3 fabric, indicating that metamorphic mineral growth continued after deformation.

Biotite and muscovite mineral separates (180–200 μm) were prepared from all samples, using conventional crushing, magnetic and heavy liquid separation methods. Final handpicking of the separates achieved purity levels greater than 99%. $^{40}Ar/^{39}Ar$ analyses were carried out in the School of Earth Sciences, The University of Melbourne (see McDougall & Harrison 1999 for details of the technique). Samples were irradiated along with flux monitor GA1550 biotite (Renne *et al.* 1998; age = 98.8 ± 0.5 Ma) in the McMaster University reactor, Canada. K_2SO_4 salts were included in the irradiation package to determine correction factors for K-produced ^{40}Ar. After irradiation, weighed aliquots of each sample were loaded into tin foil packets and step-heated in a tantalum resistance furnace. $^{40}Ar/^{39}Ar$ step-heating analyses were conducted on a VG3600 mass spectrometer, equipped with a Daly detector. Mass discrimination values were monitored by analyses of purified air aliquots from a Dorflinger pipette system. Correction factors for interfering isotopes are: $(^{36}Ar/^{37}Ar)_{Ca}$ = 2.54 (±0.09) x 10^{-4}; $(^{39}Ar/^{37}Ar)_{Ca}$ = 6.51 (±0.31) x 10^{-4} (Bottomley & York 1976); $(^{40}Ar/^{39}Ar)_K$ = 0.028 ± 0.002. Decay constants are those reported by Steiger and Jager (1977). The $^{40}Ar/^{39}Ar$ plots were generated using K. Ludwig's ISOPLOT software package (1999).

$^{40}Ar/^{39}Ar$ analytical results are shown in Table 1 and Figure 15. Biotite and muscovite separates from sample CR35a yielded age plateaux, with indistinguishable weighted mean ages of 410.0 ± 0.8 Ma (2σ; 410.0 ± 2.1 Ma, incl. J-error) and 409.4 ± 1.0 Ma (2σ) (409.4 ± 2.2 Ma, incl. J-error), respectively. Sample CR114a produced broadly similar results, with weighted mean plateaux ages of 409.2 ± 1.2 Ma (2σ; 409.2 ± 2.3 Ma, incl. J-error) for biotite and 413.7 ± 1.6 Ma (2σ; 413.7 ± 2.5 Ma, incl. J-error) for muscovite. The biotite separate from sample CR183 is characterised by an older plateau age of 422.6 ± 0.8 Ma (2σ; 422.8 ± 2.2 Ma, incl. J-error). In contrast, muscovite from this sample produced a discordant age spectrum, with apparent ages ranging from 375 ± 5 Ma to 456 ± 1 Ma and a total-gas age of 441 ± 2 Ma.

The ages from samples CR35a and CR114a are interpreted to indicate metamorphic cooling through biotite and muscovite closure temperatures of ~350 to ~300°C at ~410 Ma. The area represented by sample CR183 may have experienced earlier, relatively slow cooling, implying that differential uplift has occurred across the region.

DISCUSSION

Tectonic History of the Cape River Metamorphics

Deposition of the Cape River Metamorphics must have postdated the youngest reported detrital zircon ages (1145 ± 21 Ma) from the unit and predated the 493 ± 10 Ma maximum age given for the Fat Hen Creek Complex (Hutton *et al.* 1997). Early deformation in the Cape River Metamorphics is strongly overprinted by the D_2 event and is therefore poorly known. S_1 is best preserved in lower Oxley Creek and has a steep dip and southeast strike, consistent with northeast-southwest contractional deformation. This deformation may well have predated intrusion of the Fat Hen Creek Complex, as it has not been recognised in these plutonic rocks implying that it is older than the maximum 493 Ma age of the complex.

The major tectonic event is the D_2 deformation, which strongly affected older plutons of the Lolworth Batholith and all of the Cape River Metamorphics apart from the small part of the Morepork Member in the unnamed creek 8 km southwest of 'Oak Vale'. It is clear from the gentle plunge of the F_3 synclinorium in the Oxley Creek area that this deformation formed with the foliation being subhorizontal. Isoclinal folds in layering and foliation, widespread boudinage, and locally subparallel intersection and mineral lineations indicate intense deformation. Much of the unit appears to have been affected by strong shortening perpendicular to the foliation rather than by a dominantly simple shearing mechanism. However this deformation also shows evidence of a localised rotational component as indicated by asymmetric shear sense criteria in the high-grade unit of upper Gorge Creek.

A change in the metamorphic grade occurs across the unit with respect to the orientation of the folded S_2 foliation. The lowest grade metamorphism occurs in the core of the F_3 synclinorium in Oxley Creek at the highest structural level, whereas a higher grade of metamorphism occurs associated with the Fat Hen Creek Complex in the lower part of the main southwest-dipping limb of the synclinorium. The implication is that metamorphism associated with D_2 is increasing downwards in the metamorphic pile, i.e. there has been no repetition of metamorphic elements in the unit by shear zones at a low-angle to the main foliation (S_2).

The D_2 deformation must have overlapped with, or followed intrusion of the Fat Hen Creek Complex, which has U-Pb zircon ages in the range 493–455 Ma (Hutton *et al.* 1997). According to these authors, a SHRIMP zircon age of 469 ± 12 Ma was determined on granite showing only minimal strain from the complex near ‘Oak Vale’. However, deformed granitoid of the Fat Hen Complex from an isolated area of outcrop near ‘Lolworth’ yielded a SHRIMP zircon age of 455 ± 10 Ma (Hutton *et al.* 1997). The relationship of these granitic phases to the deformation history we have recognised is obscure. However it is clear that D_2 predated metamorphic cooling at *ca* 420–410 Ma.

Subsequent to D_2, the last main ductile deformation (D_3) produced the synclinorium in the Oxley Creek area and associated structures marked by a switch back to northeast-southwest contractional deformation as for D_1. The syn-metamorphic character of the S_3 foliation indicates that the Cape River Metamorphics were still relatively deeply buried in the crust (>10–15 km). Uplift and cooling of the metamorphics occurred in the interval 423–409 Ma as shown by the $^{40}Ar/^{39}Ar$ ages. Widespread post-metamorphic sinistral strike-slip faults developed after metamorphism and are similar in trend to northeast-southwest trending faults and lineaments in Early Devonian plutons of the Lolworth Batholith (Hutton *et al.* 1998). Thus these late faults have either formed after intrusion of most of the batholith or they have been reactivated and lengthened in post-Early Devonian times.

Significance of the D_2 deformation

The S_2 foliation formed in a subhorizontal orientation and thus the D_2 deformation is clearly distinct compared to steep dips of foliations associated with the D_1 and D_3 deformations in the Cape River Metamorphics. In a wider context, the initial subhorizontal orientation of S_2 also contrasts with intense deformation generally in the Tasmanides where wide zones of strongly deformed rocks have mainly steeply to moderately dipping axial planes to folds and associated cleavage/foliation. For example, Ordovician-Devonian turbidites in the Camel Creek Subprovince of the Broken River Province are strongly deformed with tight to isoclinal folds, axial planar cleavage and abundant zones of disrupted strata, which are all typically steeply dipping (Withnall & Lang 1993).

Low-angle foliation and associated recumbent folds in metamorphic rocks have been related to convergent deformation as is particularly well illustrated by the Helvetic nappes of the Swiss Alps (Ramsay 1981). In this setting, large rotational strains have developed along the lower limbs of nappes that effectively acted as low-angle shear zones. Foliation in these low-angle shear zones has been rotated parallel to the lower limbs resulting in a flat-lying orientation.

Alternatively, subhorizontal foliation and associated recumbent folds, especially in medium to high-grade and even some low-grade metamorphic rocks, have been widely regarded as potentially related to crustal extension (Sandiford 1989; Gibson 1991). For example, it has been shown that the common association of low-angle foliation and recumbent folds in granulite terrains can be related to bulk crustal thinning (Sandiford 1989). Bulk crustal thinning (extension) has been recognised at higher crustal levels in Hercynian low-pressure amphibolite facies metamorphics of the French Pyrenees, where the D_3 deformation produced flat-lying foliation (Gibson 1991). Another example is in the Thor-Odin dome of British Columbia where amphibolite facies metamorphic rocks are also characterised by gently dipping foliation (Vanderheghe *et al.* 1999). Greenschist as well as higher-grade rocks are involved ductile thinning in the Yukon-Tanana terrane of Alaska with the most prominent characteristic of these rocks being the development of a regional subhorizontal foliation superimposed on older structures (Pavlis & Sission 1993).

Interpretation of the significance of the D_2 deformation in the Cape River Metamorphics is problematic. Definitive evidence for convergent deformation with development of D_2 in a low-angle, thrust type, ductile shear zone has not been found. The deeper crustal rocks surrounding the Fat Hen Creek Complex occur in the lower part of the steep southwest-dipping limb of the major F_3 synclinorium. Their location cannot be accounted for by ductile thrusting as the limited east-over-west shear sense criteria in the high-grade rocks, found by Hammond (1986) and confirmed by our mapping, indicates a normal oblique-slip sense of shearing motion along the steeply to moderately southwest-dipping foliation. Therefore, our preference is that the D_2 deformation of the Cape River Metamorphics is more likely to have developed in an extensional rather than a contractional setting. We are particularly struck by the contrast in orientation between D_2 and the clearly convergent D_1 and D_3 deformations.

The structural succession in the Cape River Metamorphics is very similar in style to that documented for the Anakie Metamorphic Group of the southern Anakie Inlier (Withnall *et al.* 1995; Green *et al.* 1998). Here, an early deformation (D_1) is characterised by steep S_1 foliation, with inferred map-scale F_1 folds, that are overprinted by an intense subhorizontal S_2 foliation with associated recumbent folds (D_2 deformation) and subsequently affected by upright folds and associated axial planar crenulation cleavage (D_3 deformation). This structural history is portrayed in Green *et al.* (1998, figure 10) and the same construct could be applied to the Cape River Metamorphics. For the Anakie Metamorphic Group, the D_2 deformation has been attributed to a low-angle, thrust-style, shear zone (Green *et al.* 1998). Evidence for rotational deformation exists in the Anakie Metamorphic Group with late shear bands and limited other shear sense criteria implying top to the east shearing (Green *et al.* 1998). A problem with the ductile thrust-style interpretation, not addressed by Green *et al.*, was the widespread evidence documented by these authors for significant non-rotational strain (i.e. coaxial shortening perpendicular to the foliation) indicated by symmetric pressure fringes on magnetite grains. These data indicate that the D_2 deformation formed largely by ductile vertical thinning (extension) with some imposed rotational deformation (i.e. approximately simple shearing). Although no strain data has been collected for the D_2 deformation from the Cape River Metamorphics, the style and orientation of this deformation has much in common with that of D_2 in the Anakie Metamorphic Group and thus both are considered by us to have developed by similar extensional processes.

Regional Considerations

In this section we place the structural history of the Cape River Metamorphics in a regional setting and also determine if any supporting evidence can be found in the regional context for an extensional origin of the D_2 deformation. The oldest constraints on the timing of low-pressure metamorphism in the Charters Towers Province and Anakie Inlier are provided by K-Ar ages for quartz-muscovite schists in the Anakie Metamorphic Group of *ca* 500 Ma indicating major deformation at the same time as the Delamerian Orogeny in southeastern Australia (Withnall *et al.* 1996). This deformation involved both the D_1 and D_2 deformations that we attribute to east-west convergence (D_1) closely followed by presumed extensional deformation (D_2). Although the D_2 deformations of both the Cape River Metamorphics and the Anakie Metamorphic Group have similar style and orientation, the age of the former at 493–420 Ma indicates that they developed at different times (Figure 16).

In the Charters Towers Province, sedimentation and predominantly silicic volcanic activity of the Seventy Mile Range Group occurred in the latest Cambrian to Early Ordovician (500–472 Ma; Henderson 1984) and synchronous with intrusion of the older plutonic rocks of the Lolworth and Ravenswood Batholiths (Figure 16; 510–455 Ma; Hutton *et al.* 1997). These assemblages are interpreted on the basis of geochemical affinity of igneous rocks and overall depositional environments as having formed in an extensional back-arc basinal setting (Henderson 1986; Stolz 1995). Limited extensional growth faulting, synchronous with Early Ordovician deposition, has been documented in the Seventy Mile Range Group consistent with a backarc extensional setting (Berry *et al.* 1992).

In the Broken River Province to the north of the Cape River Metamorphics, ultramafic-mafic rocks occur in the Gray Creek Complex and are overlain by the Lower Ordovician Judea Formation (*ca* 480 Ma), which contains a basal unit of submarine volcanic rocks of mafic to silicic character (Withnall & Lang 1993). Deformation is intense in the lower part of the Gray Creek Complex but decreases towards the overlying Judea Formation volcanic rocks (Arnold & Rubenach 1976). Contacts between these units have either been obscured by tonalitic intrusions or are younger contractional faults (Withnall & Lang 1993). Collectively the assemblage of the Gray Creek Complex and Judea Formation is potentially ophiolitic although the temporal relationship between the highly foliated lower part of the Gray Creek Complex and the less deformed volcanic rocks of the Judea Formation is not established. The D_2 inferred extensional event of the Cape River Metamorphics could have embraced both the episode of ophiolite generation in the Broken River Province and the extensional backarc assemblages of the Charters Towers Province (Figure 16).

Convergent deformation, uplift and erosion of the ophiolitic assemblage in the Broken River Province must have occurred in the Late Ordovician to Early Silurian interval as shown by deformation of the Judea Formation and an angular unconformity at the base of the overlying Lower Silurian, thick conglomeratic deposits containing ophiolitic debris (Arnold & Henderson 1976; Henderson 1987; Withnall & Lang 1993). A Late Ordovician to Early Silurian timing of the main north-south contractional deformation of the Seventy Mile Range Group is indicated by the deformation of mid-Ordovician granites and intrusion of mid-Silurian to Early Devonian granites of the Ravenswood Batholith that postdated the deformation (Berry *et al.* 1992; Hutton *et al.* 1997). These events are most likely related to the contractional D_3 deformation in the Cape River Metamorphics (Figure 16). In the western part of the Seventy Mile Range Group the main contraction direction associated with this deformation was north-northeast to south-southwest (Berry *et al.* 1992, figure 9) similar to that for D_3 of the Cape River Metamorphics. Continuing uplift and erosion resulted in the metamorphic cooling of the Cape River Metamorphics in the Late Silurian – Early Devonian (420–410 Ma) and may also have resulted in unroofing of the Reedy Springs Batholith that is reflected in the Graveyard Creek Subprovince by feldspathic sandstones, derived from the southwest, that characterise the Lochovian-Pragian Shield Creek Formation (Withnall & Lang 1993). Brittle northeast trending faults in the Cape River Metamorphics probably developed synchronously with similar trending structures that affect the Seventy Mile Range Group and also occur in Late Silurian to Early Devonian plutons of the Charters Towers Province (Hutton *et al.* 1997).

CONCLUSIONS

The Cape River Metamorphics have a complicated structural history with three main deformations reflecting initial northeast-southwest convergence (D_1 deformation), followed by development of a subhorizontal foliation with recumbent folds (D_2 deformation) and then a return to northeast-southwest convergence producing a major synclinorium. The initial flat-lying orientation of D_2 structures is considered a reflection of ductile crustal thinning rather than the result of low-angle shearing in a contractional setting. Early Ordovician backarc sedimentation and silicic igneous activity in the Charters Towers Province, and ophiolite generation in the Broken River Province, is thought to have accompanied the middle to lower upper crustal D_2 event in the Cape River Metamorphics. Contractional deformation in the Late Ordovician to Early Silurian has affected the Seventy Mile Range Group and the Broken River Province and is considered associated with the D_3 deformation in the Cape River Metamorphics. Final cooling of the Cape River Metamorphics occurred as a result of slow uplift and accompanying erosion in Late Silurian – Early Devonian time.

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FIGURE CAPTIONS

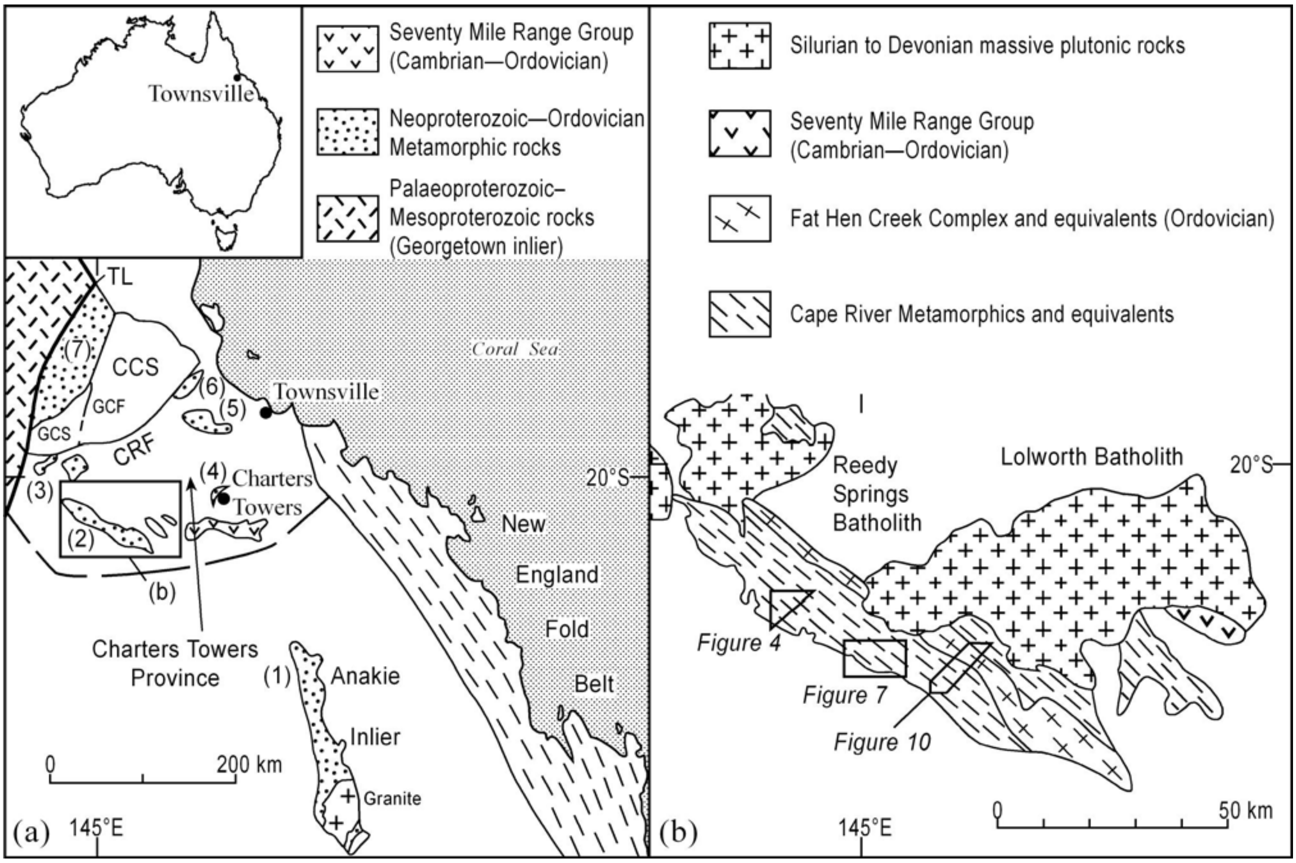


Figure 1 (a) Major Early Palaeozoic elements of the Tasmanides of the greater Townsville region (inset – map of Australia). Metamorphic units include: (1) Anakie Metamorphic Group, (2) Cape River Metamorphics, (3) metamorphics around the Reedy Springs Batholith, (4) Charters Towers Metamorphics, (5) Argentine Metamorphics, (6) Running River Metamorphics, and (7) Early Palaeozoic metamorphics of the southeast Georgetown Inlier. CCS = Camel Creek Subprovince, CRF = Cape River Fault, GCS = Graveyard Creek Subprovince, TL = Tasman Line (approximate location). (b) Detail of the Cape River Metamorphics and location of study areas.

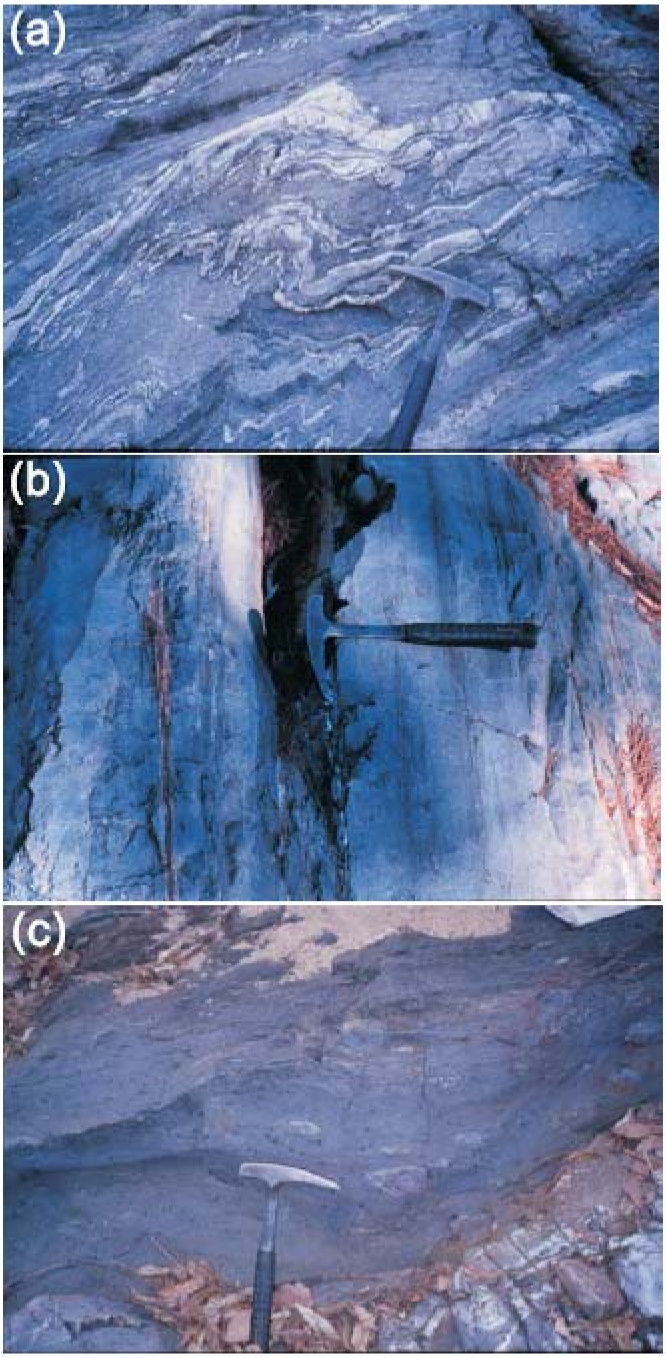


Figure 2 Photographs of units and sedimentary features in the Cape River Metamorphics. (a) High-grade gneiss in upper Gorge Creek (314768 7749979 Lolworth (7957) 1:100 000 sheet). F_3 steeply inclined folds in main foliation (S_2). (b) Thin beds of quartzite and graphitic slate, Morepork Member, Oxley Creek (277401 7757856 White Mountains (7857) 1:100 000 sheet). (c) Slumped layer (sandstone) with fragments of fine sandstone and graphitic slate, Morepork Member, creek near Bullock Paddock Bore creek (305680 7738057 Lolworth (7957) 1:100 000 sheet).

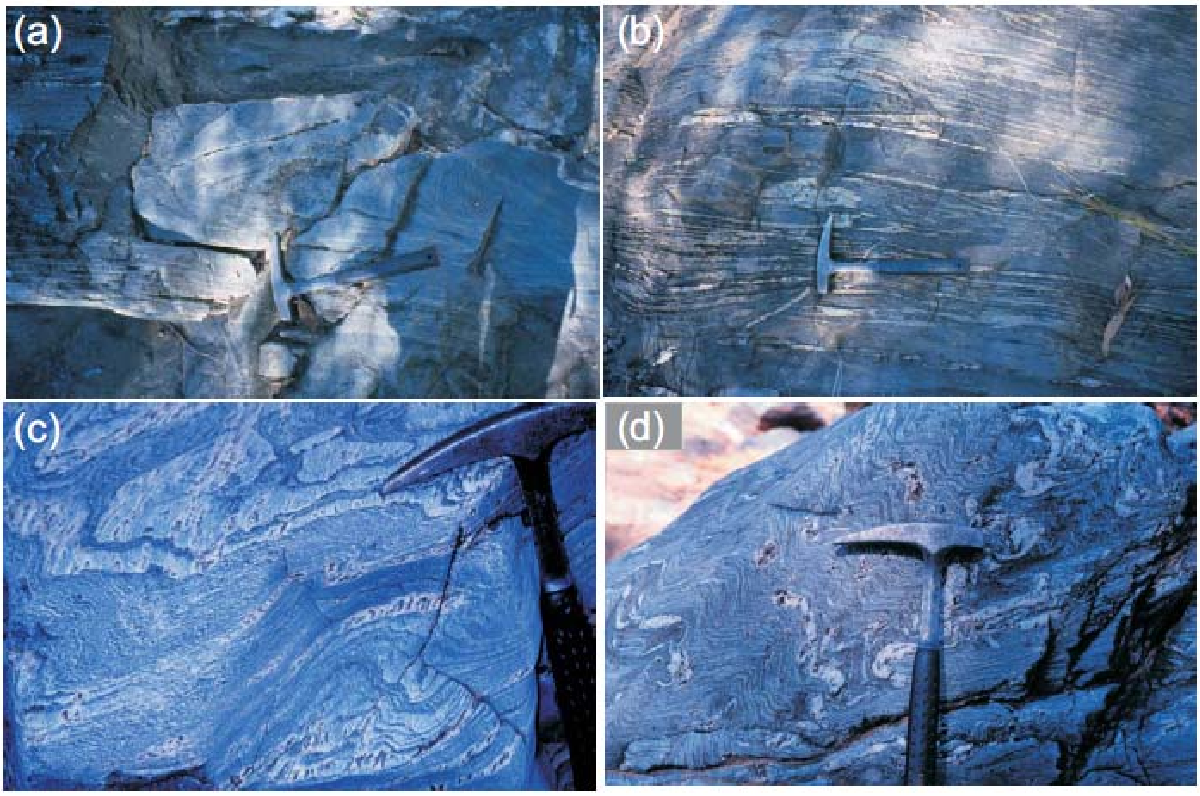


Figure 3 Photographs of structures in the Cape River Metamorphics. (a) S_2 foliation is folded in near isoclinal fold that is a late fold developed during progressive deformation associated with the D_2 deformation. Unnamed creek 4 km southeast of Black Gin Creek (295908 7747253 Lolworth (7957) 1:100 000 sheet). (b) S_2 foliation axial planar to tight folds in quartz-epidote veins. Some boudinage occurs. Same location as (a). (c) Three S-surfaces developed in schists, S_1 (fine differentiated layering), S_2 (microlithons) and S_3 (axial planar to open folds in S_2 and short wavelength folds in S_1). Oxley Creek (272032 7752604 White Mountains (7857) 1:100 000 sheet). (d) Moderately inclined, open F_3 folds in S_2 differentiated layering. Oxley Creek (272001 7752513 White Mountains (7857) 1:100 000 sheet).

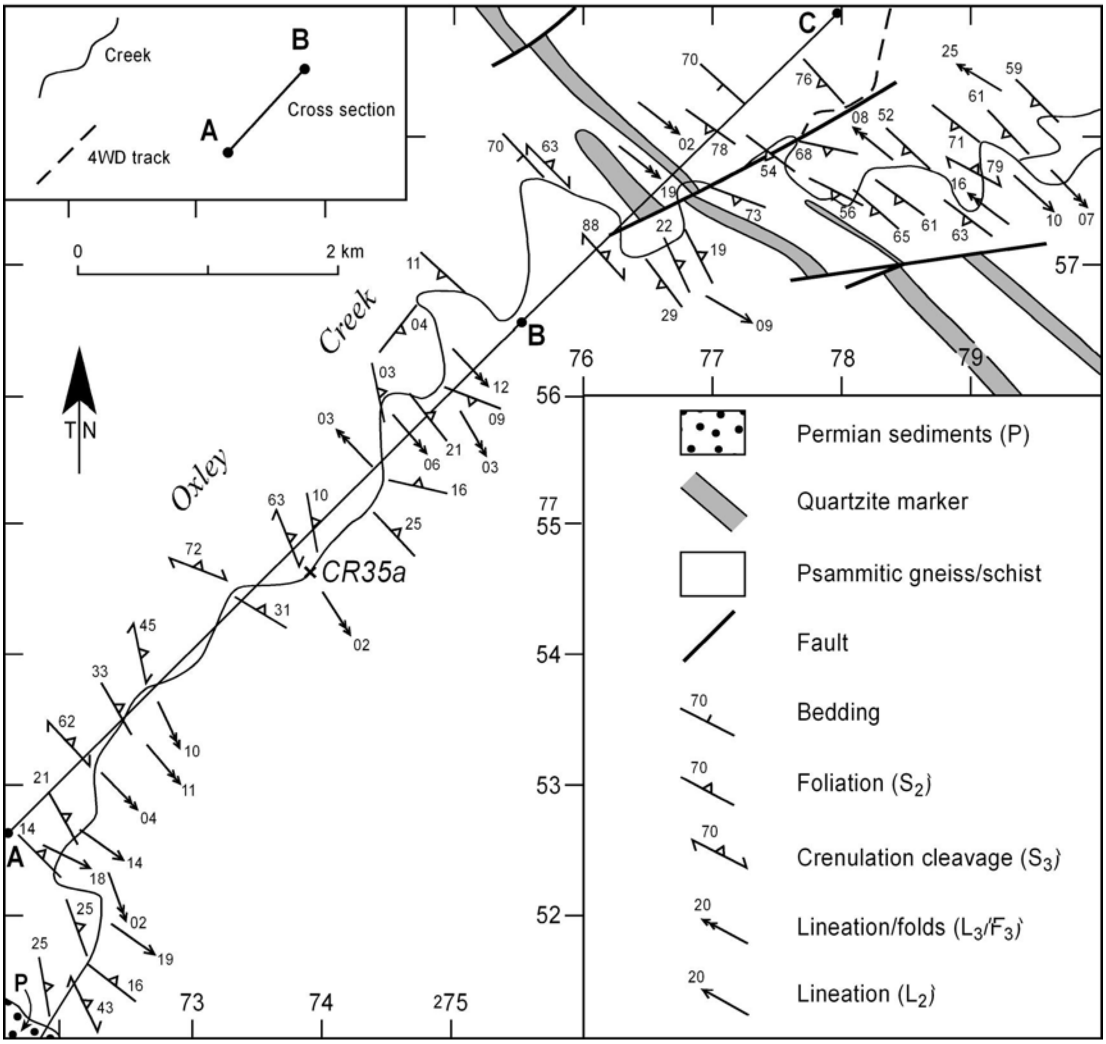


Figure 4 Map of the Cape River Metamorphics in the Oxley Creek area. See Figure 1b for location.

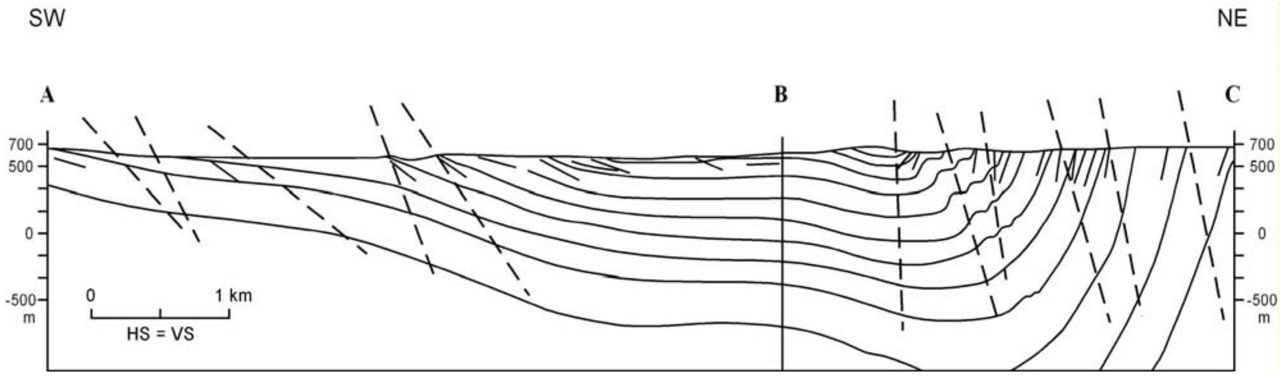


Figure 5 Cross section ABC along Oxley Creek. See Figure 4 for location. Long dashed lines show the dip of S_3 crenulation cleavage and short bars below the topographic line show the orientation of S_2 with long continuous lines showing the S_2 form-surface.

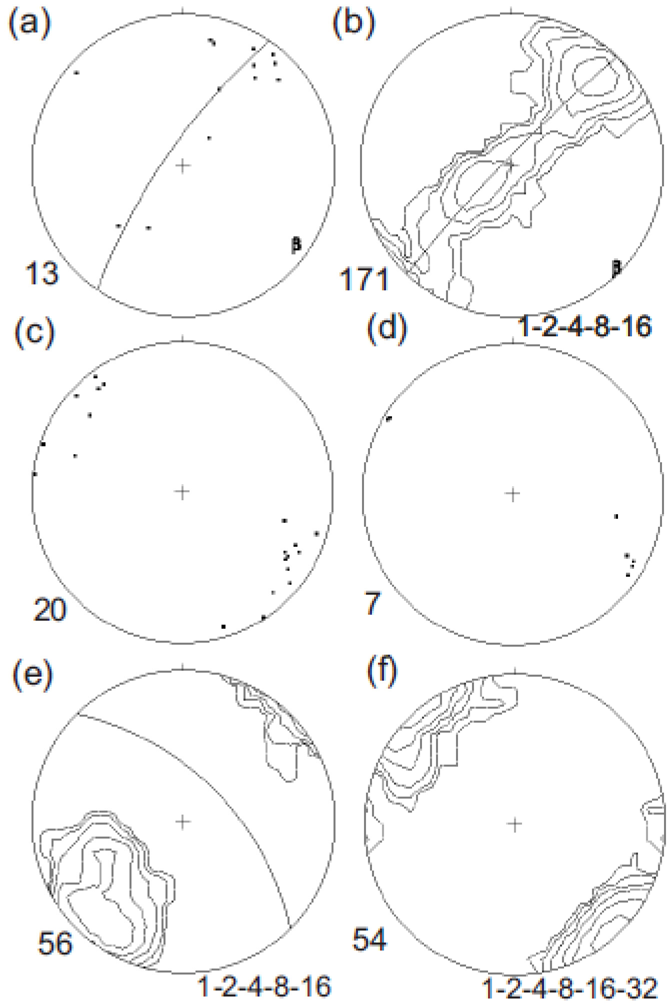


Figure 6 Lower hemisphere equal area stereographic projections of structural data from the Oxley Creek area, Cape River Metamorphics. Number of measurements shown for each stereonet on lower left side. Contour intervals per 1% area shown on lower right side for contoured plots. (a) Poles to bedding, β-axis 10º/125º. (b) Poles to S_2, β-axis 04º/134º. (c) L_2 – intersection lineation, mean 05º/126º. (d) Lm – mineral lineation, mean 09º/119º. (e) Poles to S_3, mean 66º/045º. (f) L_3 – fold axes and intersection lineations, mean 00º/317º.

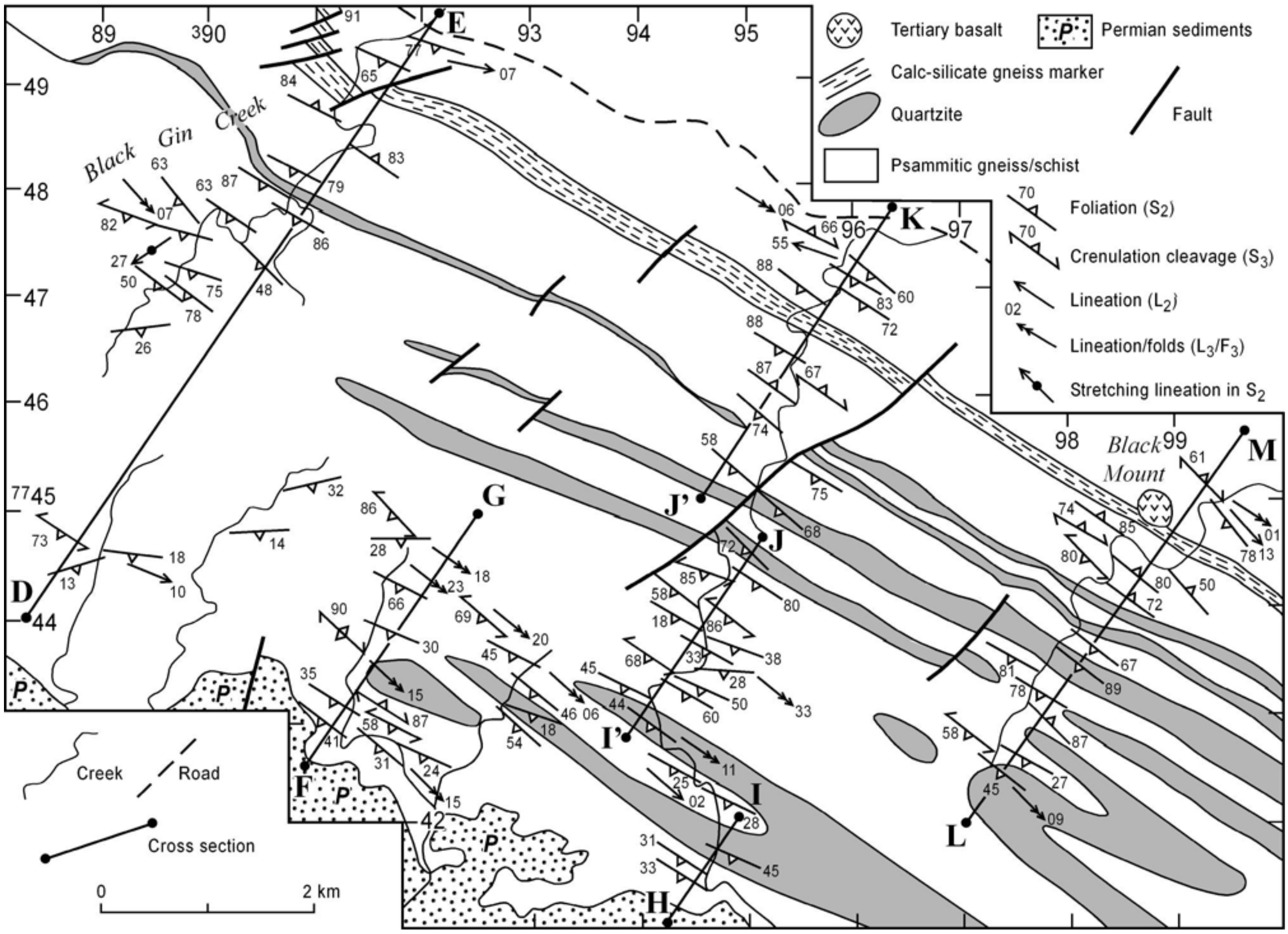


Figure 7 Map of the Cape River Metamorphics in the Black Mount area. See Figure 1b for location.

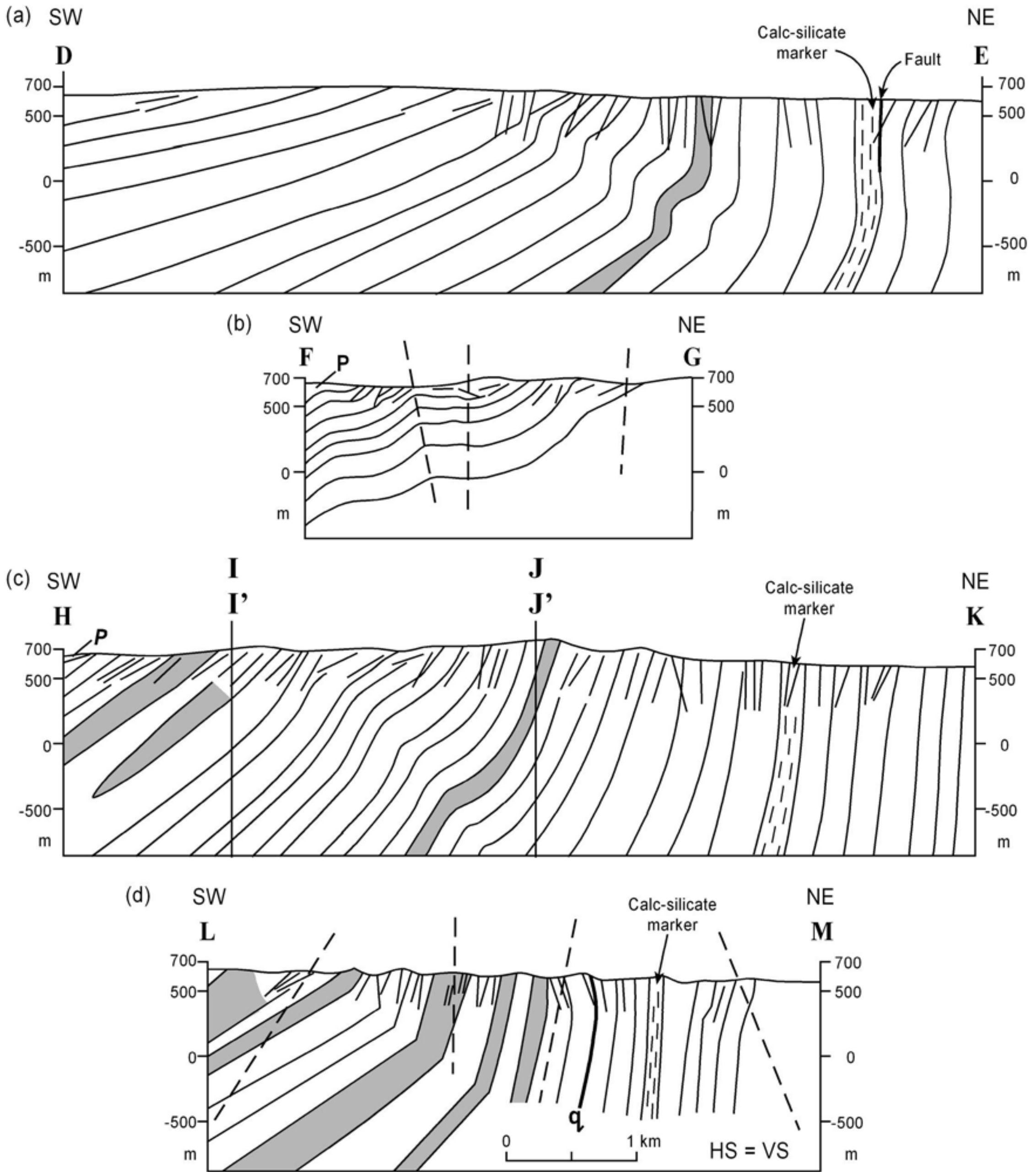


Figure 8 Cross sections for the Black Mount area. Shaded units are quartzites of the Morepork Member. Abbreviation: q = quartzite. See Figure 7 for location.

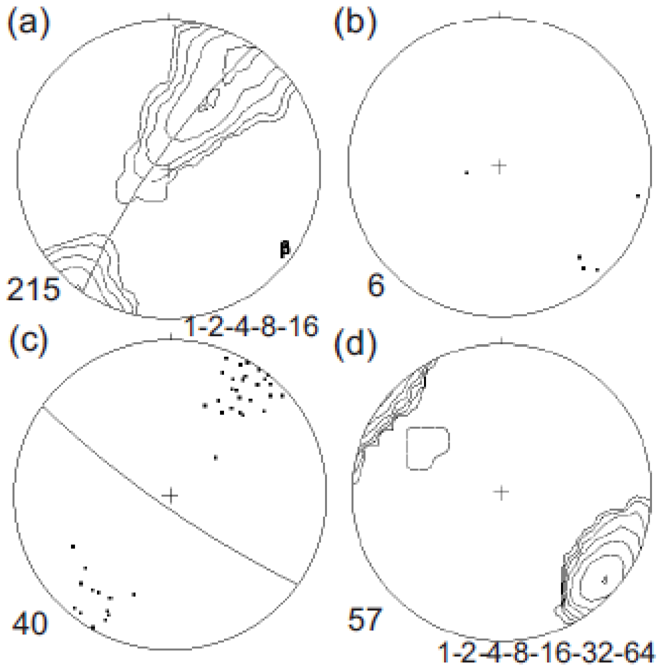


Figure 9 Lower hemisphere equal area stereographic projections of structural data from the Black Mount area. Number of measurements shown for each stereonet on lower left side. Contour intervals per 1% area shown on lower right side for contoured plots. (a) Poles to S_2, β-axis 08º/124º. (b) L_2 – intersection lineations, mean 11º/124º. (c) Poles to S_3, mean 84º/215º. (d) L_3 – fold axes and intersection lineations, mean 11º/128º.

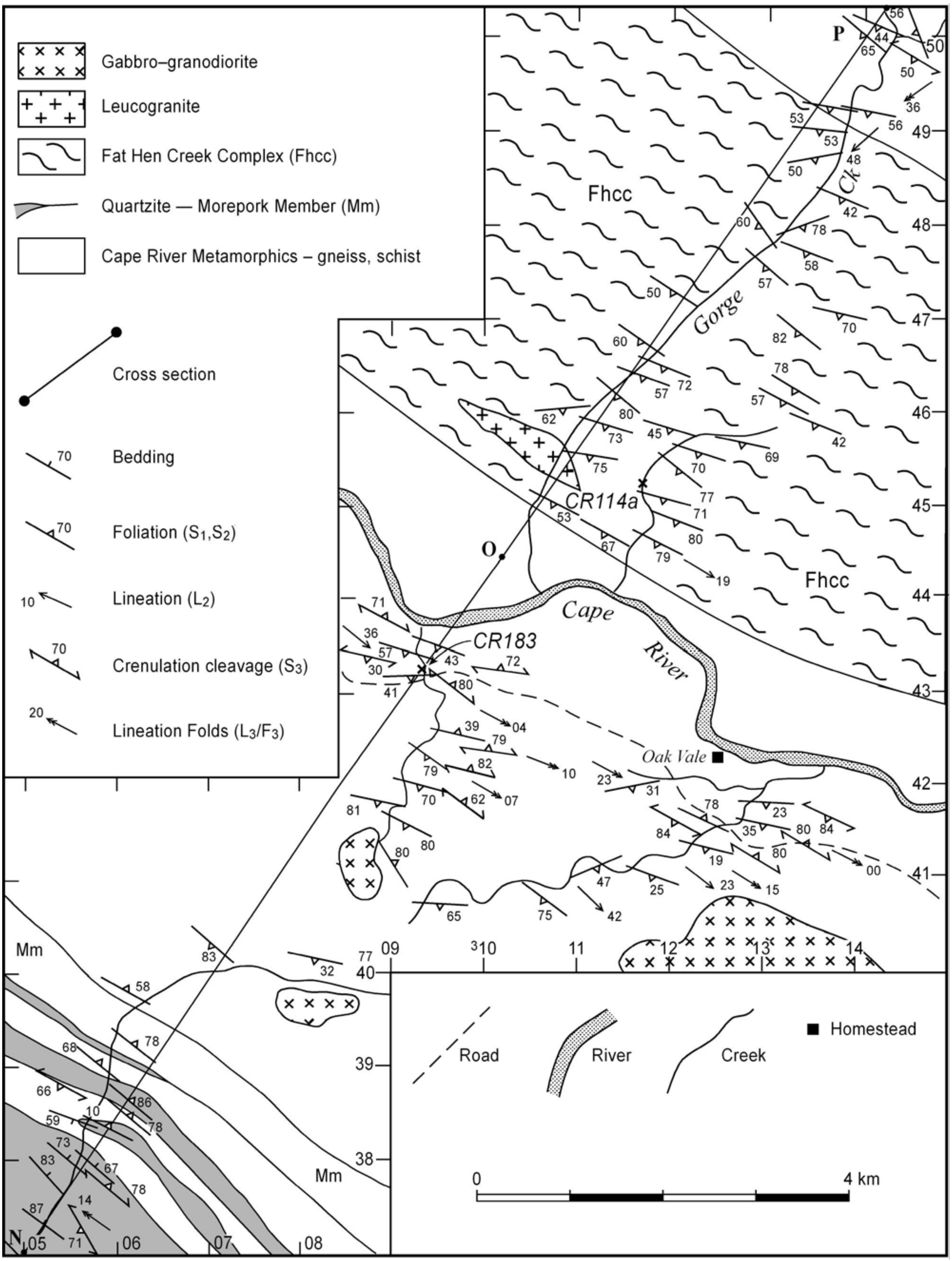


Figure 10 Map of the Gorge Creek – Oak Vale area. See Figure 1b for location.

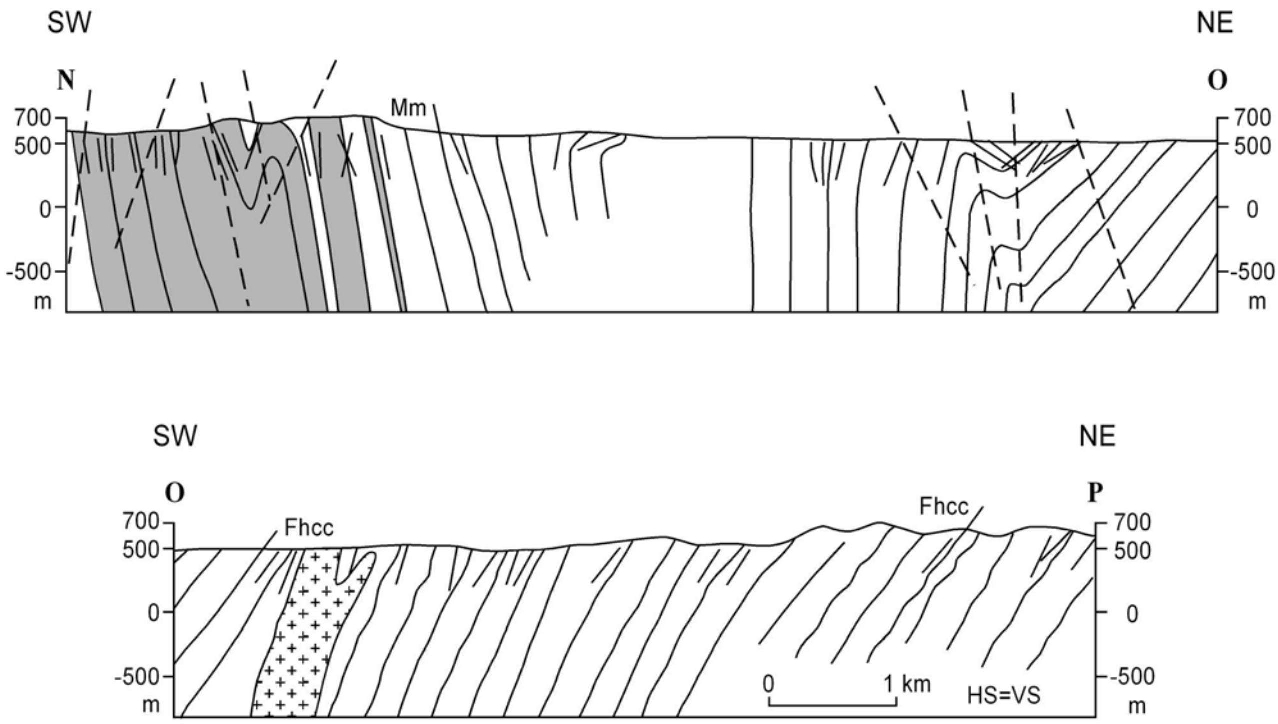


Figure 11 Cross section through the Gorge Creek – Oak Vale area. Shaded units are quartzites of the Morepork Member. Abbreviations: FHCC = Fat Hen Creek Complex. Mm = Morepork Member. See Figure 10 for location.

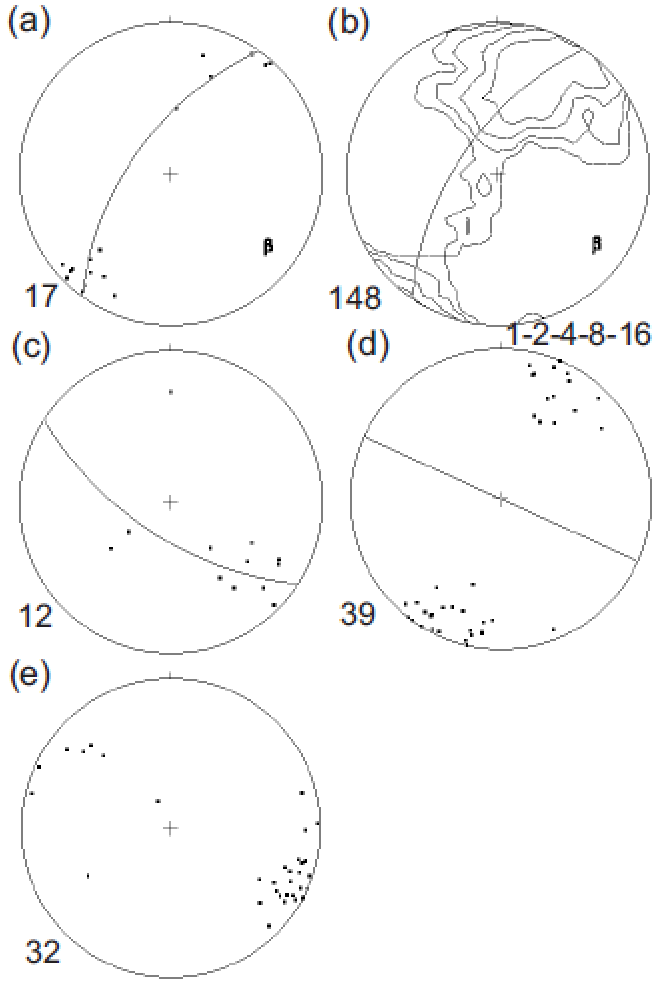


Figure 12 Lower hemisphere equal area stereographic projections of structural data from the Gorge Creek – Oak Vale area. Number of measurements shown for each stereonet on lower left side. (a) Poles to bedding, β-axis 21º/126º, mean 86º/037º. (b) Poles to S_2, β-axis 21º/125º, mean 60º/202º. Contour intervals per 1% area shown on lower right side. (c) L_2 fold axes and intersection lineations, girdle 71º/213º, mean 32º/136º. (d) Poles to S_3, mean 90º/024º. (e) L_3 – fold axes and intersection lineations, mean 06º/114º.

Figure 13 Asymmetric boudinage in granitic veins (top to right) from the high-grade unit northeast of the Fat Hen Creek Complex, upper Gorge Creek (314580 7750015 Lolworth (7957) 1:100 000 sheet).

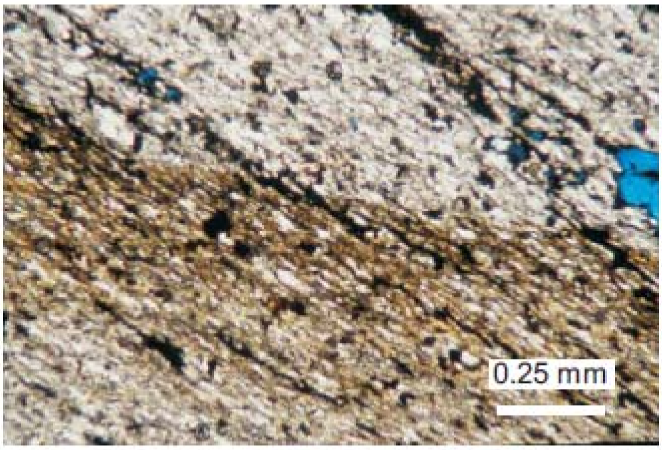
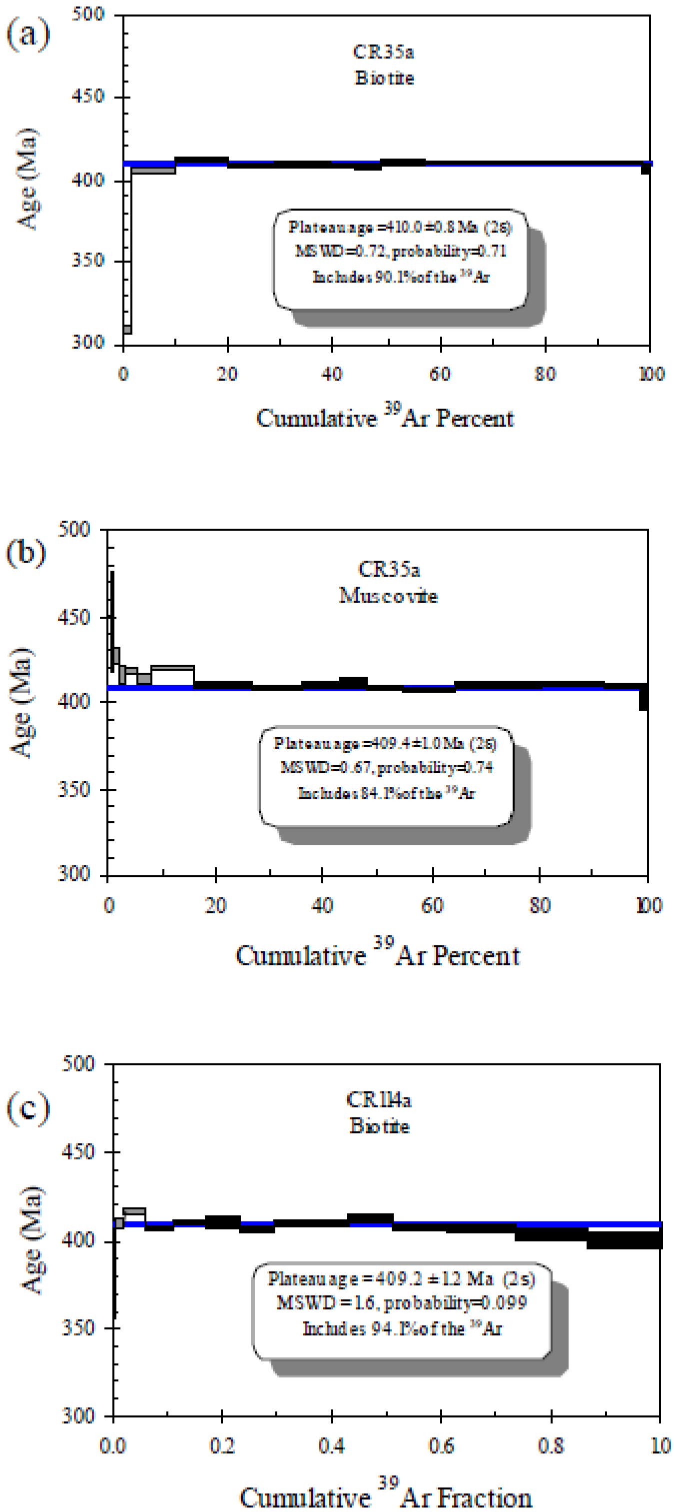


Figure 14 Continuous S_3 cleavage in graphitic slate, Morepork Member. Sample CR130 from unnamed creek, 8 km southwest of 'Oak Vale' (305656 7738376 Lolworth (7957) 1:100 000 sheet), Gorge Creek – Oak Vale area.


(a)
CR35a
Biotite
Plateau age = 410.0 ± 0.8 Ma (2s)
MSWD = 0.72, probability = 0.71
Includes 90.1% of the 39Ar
Age (Ma)
Cumulative 39Ar Percent
(b)
CR35a
Muscovite
Plateau age = 409.4 ± 1.0 Ma (2s)
MSWD = 0.67, probability = 0.74
Includes 84.1% of the 39Ar
Age (Ma)
Cumulative 39Ar Percent
(c)
CR114a
Biotite
Plateau age = 409.2 ± 1.2 Ma (2s)
MSWD = 1.6, probability = 0.099
Includes 94.1% of the 39Ar
Age (Ma)
Cumulative 39Ar Fraction

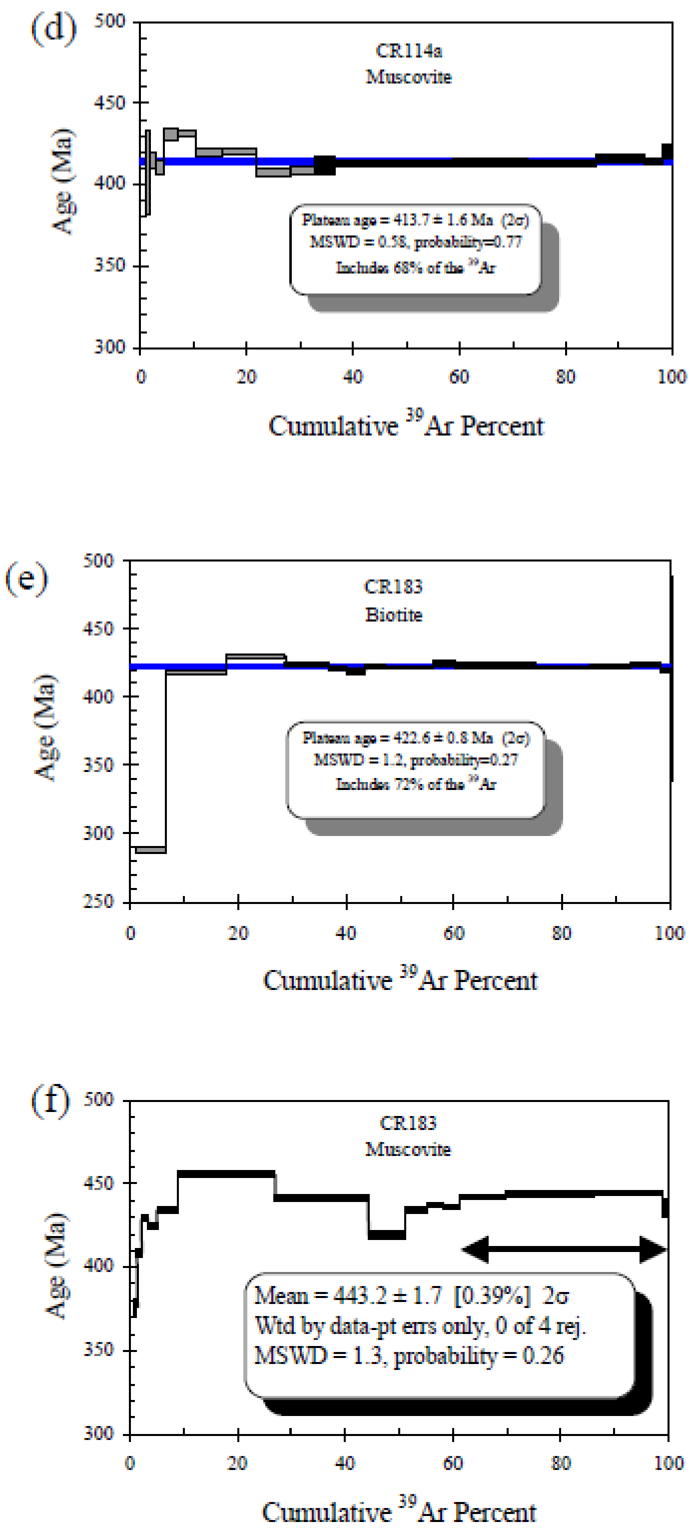
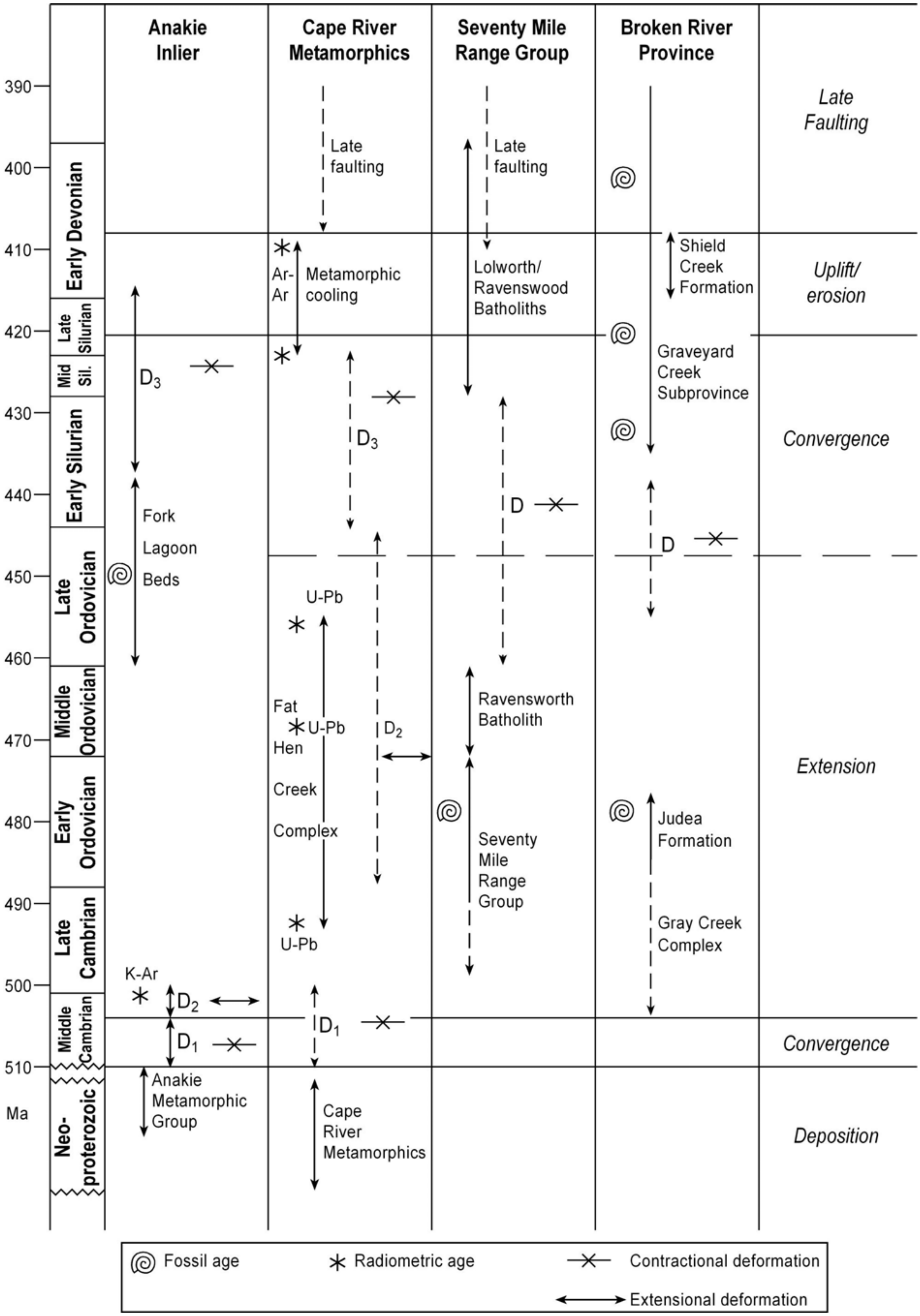


Figure 15 $^{40}Ar/^{39}Ar$ step heating spectra for muscovite and biotite separates from the Cape River Metamorphics (Error boxes are shown at the 1σ level). (a) Sample CR35a biotite separate from Oxley Creek (see Figure 4 for location). (b) Sample CR35a muscovite separate from Oxley Creek (see Figure 4 for location). (c) Sample CR114a biotite separate from near

the Cape River (see Figure 10 for location). (d) Sample CR114a muscovite separate from near the Cape River (see Figure 10 for location). (e) Sample CR183 biotite separate from Oxley Creek (see Figure 10 for location). (f) Sample CR183 muscovite separate from Oxley Creek (see Figure 10 for location).



Anakie Inlier
Cape River Metamorphics
Seventy Mile Range Group
Broken River Province
390
400
410
420
430
440
450
460
470
480
490
500
510
Ma
Early Devonian
Late Silurian
Mid Sil.
Early Silurian
Late Ordovician
Middle Ordovician
Early Ordovician
Late Cambrian
Middle Cambrian
Neo-proterozoic
Late faulting
Late faulting
Late Faulting
Ar-Ar
Metamorphic cooling
Lolworth/ Ravenswood Batholiths
Shield Creek Formation
Uplift/ erosion
Graveyard Creek Subprovince
D3
D3
Convergence
D
D
Fork Lagoon Beds
U-Pb
Fat Hen Creek Complex
U-Pb
D2
Ravensworth Batholith
Extension
Seventy Mile Range Group
Judea Formation
Gray Creek Complex
U-Pb
K-Ar
D2
D1
D1
Convergence
Anakie Metamorphic Group
Cape River Metamorphics
Deposition
Fossil age
Radiometric age
Contractional deformation
Extensional deformation

Figure 16 Time-space plot with main depositional, deformation (D), and igneous events compiled for the Anakie Inlier (Withnall *et al.* 1995, 1996, Fergusson *et al.* 2001), Cape River Metamorphics (Hutton *et al.* 1997; Withnall *et al.* 1997; data herein), Seventy Mile Range Group (Henderson 1984, 1986; Berry *et al.* 1992; Hutton *et al.* 1997) and Broken River Province (Withnall & Lang 1993). Overall tectonic regimes are shown at right. Radiometric ages are determined by K-Ar, U-Pb zircon and Ar-Ar methods and labelled on diagram. Note that the ages of the Lolworth and Ravenswood Batholiths are determined by Rb/Sr, K/Ar and U-Pb zircon methods (Hutton *et al.* 1992). Duration of events shown by continuous vertical lines are better constrained than events shown by dashed vertical lines. Numerical timescale is only shown for Middle Cambrian to Devonian interval. Neoproterozoic interval is not drawn to scale, the numerical timescale is not included and the Early Cambrian is not shown. Timescale from the International Commission on Stratigraphy (2004).

Table 1

Table 1 $^{40}Ar/^{39}Ar$ step-heating analytical results.The data have been corrected for mass spectrometer backgrounds, mass discrimination and radioactive decay.

Temp (C)	Cum %^{39}Ar	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Vol. ^{39}Ar x10^{-14}mol	%Rad. ^{40}Ar	Ca/K	$^{40}Ar^{*}/^{39}Ar$	Age (Ma)	± 1s.d. (Ma)
CR35 Biotite										
J-value = 0.0085511 ± 0.000021										
600	1.70	28.22	0.0253	0.0215	0.296	77.4	0.048	21.85	309.1	3.0
700	9.90	30.66	0.0096	0.0039	1.426	96.2	0.018	29.49	405.7	1.3
750	20.05	30.63	0.0087	0.0019	1.763	98.0	0.017	30.02	412.3	1.4
780	28.78	30.39	0.0052	0.0021	1.517	97.9	0.010	29.74	408.8	1.7
810	34.47	30.46	0.0157	0.0021	0.990	97.8	0.030	29.80	409.5	1.6
850	39.19	30.45	0.0060	0.0023	0.820	97.7	0.011	29.77	409.1	1.4
900	43.94	30.6	0.0117	0.0027	0.827	97.3	0.022	29.77	409.1	1.3
950	48.99	30.55	0.0175	0.0029	0.877	97.1	0.033	29.68	408.0	1.7
1000	57.30	30.77	0.0204	0.0030	1.445	97.1	0.039	29.87	410.4	1.9
1050	72.02	30.47	0.0132	0.0019	2.559	98.1	0.025	29.90	410.7	1.2
1100	86.89	30.53	0.0265	0.0022	2.585	97.8	0.050	29.87	410.4	1.0
1150	97.99	30.61	0.0386	0.0024	1.929	97.6	0.073	29.88	410.5	1.2
1350	100.0	38.73	0.1129	0.0306	0.350	76.6	0.214	29.65	407.7	2.7
Total		30.68	0.0193	0.0033	17.38			29.68	408.1	1.4
CR35 Muscovite										
J-value = 0.0085511 ± 0.000021										
600	0.68	230.30	0.0258	0.6684	0.157	14.2	0.049	32.76	446.4	29.4
700	1.86	41.15	0.0282	0.0337	0.273	75.7	0.054	31.16	427.0	4.8
750	3.14	36.99	0.0194	0.0227	0.297	81.8	0.037	30.23	415.6	5.0
800	5.11	34.53	0.0202	0.0138	0.456	88.1	0.038	30.44	418.2	2.2

825	8.19	32.07	0.0014	0.0068	0.713	93.6	0.003	30.03	413.2	2.3
850	15.86	30.82	0.0113	0.0007	1.774	99.2	0.021	30.58	419.8	1.5
875	26.88	30.46	0.0058	0.0022	2.551	97.8	0.011	29.80	410.4	1.5
900	36.23	30.37	0.0247	0.0024	2.165	97.6	0.047	29.63	408.2	1.6
925	42.95	30.80	0.0139	0.0033	1.556	96.7	0.027	29.79	410.2	1.5
950	47.86	30.92	0.0179	0.0035	1.136	96.6	0.034	29.86	411.0	2.1
1000	54.26	30.60	0.0128	0.0032	1.481	96.8	0.024	29.63	408.2	1.5
1050	63.94	30.27	0.0245	0.0023	2.241	97.7	0.047	29.58	407.6	1.3
1100	80.41	30.21	0.0123	0.0014	3.813	98.5	0.023	29.78	410.1	1.6
1125	91.93	30.33	0.0227	0.0017	2.666	98.3	0.043	29.81	410.5	1.2
1150	98.66	30.47	0.0417	0.0025	1.557	97.5	0.079	29.71	409.2	1.4
1450	100.0	49.18	0.1691	0.0675	0.311	59.4	0.321	29.23	403.3	7.5
Total		32.41	0.0197	0.0085	23.15			29.86	411.0	1.9

CR114a
Biotite
J-value = 0.0085772 ± 0.000021

600	2.44	75.68	0.0073	0.1677	0.727	34.5	0.014	26.10	364.5	8.2
700	12.17	31.45	0.0141	0.0057	2.905	94.6	0.027	29.74	409.9	2.9
750	29.42	30.66	0.0185	0.0012	5.150	98.8	0.035	30.30	416.8	1.4
780	37.99	30.32	0.0154	0.0026	2.559	97.4	0.029	29.53	407.3	1.5
810	42.76	30.88	0.0070	0.0035	1.426	96.5	0.013	29.82	410.9	1.5
840	45.32	31.21	0.0035	0.0045	0.763	95.6	0.007	29.85	411.2	3.5
870	47.13	31.88	0.0198	0.0080	0.540	92.5	0.038	29.48	406.7	2.3
900	48.79	31.78	0.0187	0.0066	0.496	93.8	0.036	29.80	410.6	1.7
950	51.70	31.50	0.0218	0.0058	0.868	94.5	0.041	29.78	410.3	1.7
1000	58.25	30.96	0.0122	0.0031	1.956	96.9	0.023	30.00	413.1	2.1
1050	75.41	32.04	0.0176	0.0083	5.122	92.3	0.033	29.56	407.7	2.1
1100	90.59	30.49	0.0001	0.0032	4.532	96.8	0.000	29.51	407.1	2.0
1150	98.76	30.66	0.0405	0.0045	2.440	95.6	0.077	29.31	404.6	3.1
1350	100.00	40.16	0.0853	0.0380	0.369	72.0	0.162	28.93	399.9	4.4
Total		32.24	0.0160	0.0087	29.85			29.64	408.7	2.2

Temp (C)	Cum $\%^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Vol. ^{39}Ar $x10^{-14}mol$	%Rad. ^{40}Ar	Ca/K	$^{40}Ar^{*}/^{39}Ar$	Age (Ma)	± 1s.d. (Ma)

CR114a Muscovite
J-value = 0.0085772 ± 0.000021

600	0.62	160.26	0.1709	0.4425	0.129	18.4	0.325	29.53	407.5	25.2
700	1.90	45.06	0.1737	0.0506	0.263	66.8	0.330	30.11	414.8	4.7
750	3.40	43.18	0.0718	0.0453	0.310	68.9	0.137	29.76	410.4	4.0

800	5.91	40.10	0.0329	0.0293	0.517	78.3	0.063	31.42	430.7	3.3
825	9.50	36.27	0.0199	0.0162	0.739	86.7	0.038	31.46	431.2	2.0
850	14.54	33.52	0.0342	0.0102	1.040	90.9	0.065	30.48	419.3	2.3
875	20.81	32.55	0.0044	0.0066	1.291	93.9	0.008	30.57	420.3	2.1
900	27.45	31.15	0.0079	0.0056	1.368	94.6	0.015	29.47	406.9	2.2
925	32.00	31.88	0.0174	0.0076	0.938	92.9	0.033	29.60	408.5	2.3
950	36.03	31.75	0.0056	0.0062	0.830	94.1	0.011	29.89	412.0	5.7
1000	43.43	32.03	0.0523	0.0071	1.525	93.4	0.099	29.92	412.4	2.0
1050	58.17	31.20	0.0151	0.0040	3.038	96.1	0.029	29.98	413.1	1.7
1075	72.47	30.94	0.0026	0.0031	2.948	97.0	0.005	30.00	413.4	2.2
1100	85.74	30.72	0.0264	0.0024	2.736	97.6	0.050	29.98	413.1	2.0
1125	94.63	31.06	0.0260	0.0029	1.832	97.2	0.049	30.20	415.8	2.2
1200	98.25	31.50	0.0615	0.0049	0.745	95.4	0.117	30.04	413.9	2.1
1450	100.00	45.92	0.2404	0.0521	0.362	66.5	0.457	30.53	419.9	4.0
Total		33.24	0.0282	0.0105	20.610			30.10	414.6	2.5

CR183 Biotite

J-value = 0.0085291 ± 0.000022

600	5.63	23.67	0.0319	0.0109	1.255	86.3	0.061	20.42	289.6	2.6
700	17.02	31.60	0.0229	0.0034	2.541	96.8	0.043	30.58	418.1	1.4
750	28.02	31.71	0.0157	0.0004	2.455	99.6	0.030	31.57	430.2	1.2
780	32.76	31.68	0.0335	0.0021	1.059	98.0	0.064	31.06	423.9	1.4
810	36.18	32.00	0.0292	0.0030	0.763	97.1	0.056	31.09	424.3	1.5
840	39.30	31.83	0.0326	0.0033	0.695	96.9	0.062	30.84	421.3	1.3
870	42.97	31.54	0.0417	0.0029	0.819	97.2	0.079	30.67	419.2	1.9
900	46.61	31.77	0.0364	0.0027	0.813	97.4	0.069	30.94	422.5	1.4
950	55.51	31.64	0.0630	0.0025	1.986	97.6	0.120	30.89	421.9	1.3
1000	59.49	31.78	0.0278	0.0021	0.888	98.0	0.053	31.13	424.9	1.6
1050	74.66	31.46	0.0352	0.0015	3.385	98.5	0.067	31.01	423.3	1.8
1075	84.65	31.37	0.0372	0.0016	2.230	98.4	0.071	30.88	421.8	1.3
1100	92.08	31.53	0.0714	0.0019	1.657	98.1	0.136	30.94	422.5	1.3
1150	97.74	31.97	0.1034	0.0029	1.263	97.3	0.196	31.09	424.4	1.3
1350	99.93	34.60	0.2052	0.0131	0.489	88.8	0.390	30.73	420.0	1.5
1450	100.00	301.25	0.0061	0.9168	0.015	10.0	0.012	30.26	414.3	73.9
Total		31.43	0.0440	0.0034	22.310			30.39	415.7	1.6

CR183 Muscovite

J-value = 0.0085291 ± 0.000022

550	0.47	33.09	0.0578	0.0203	0.173	81.8	0.110	27.08	375.3	5.3
650	1.50	32.10	0.0421	0.0079	0.375	92.6	0.080	29.73	408.1	2.2
700	2.64	32.53	0.0476	0.0035	0.418	96.7	0.090	31.47	429.4	1.5
750	4.40	32.34	0.0194	0.0043	0.644	96.0	0.037	31.04	424.2	1.6
800	8.32	33.12	0.0287	0.0043	1.434	96.1	0.055	31.82	433.6	2.0
850	26.50	33.73	0.0082	0.0003	6.649	99.7	0.016	33.64	455.5	1.4
900	43.96	32.71	0.0182	0.0009	6.389	99.1	0.035	32.44	441.1	1.5
925	50.93	31.52	0.0101	0.0030	2.550	97.1	0.019	30.61	419.0	2.5
950	54.92	32.64	0.0186	0.0026	1.460	97.6	0.035	31.85	434.0	1.6
975	58.04	32.82	0.0228	0.0024	1.139	97.7	0.043	32.08	436.8	1.3
1000	60.98	32.75	0.0260	0.0024	1.076	97.7	0.050	32.02	436.1	1.5
1050	69.58	33.04	0.0150	0.0017	3.148	98.4	0.029	32.51	442.0	1.6
1100	86.12	33.13	0.0205	0.0015	6.048	98.6	0.039	32.67	443.9	1.5
1150	99.01	33.30	0.0179	0.0019	4.715	98.2	0.034	32.71	444.4	1.5

1450	100.00	49.64	0.2335	0.0599	0.363	64.3	0.444	31.94	435.1	5.0
Total		33.16	0.0196	0.0023	36.580			32.44	441.2	1.6

I) Errors are one sigma uncertainties and exclude uncertainties in the J-value.

ii) Data are corrected for mass spectrometer backgrounds, discrimination and radioactive decay.

iii) Interference corrections: $(^{36}Ar/^{37}Ar)_{Ca}$ = 2.54E-4; $(^{39}Ar/^{37}Ar)_{Ca}$ = 6.51E-4; $(^{40}Ar/^{39}Ar)_{K}$ = 3.0E-2

iv) J-value is based on an age of 98.8 Ma for GA-1550 biotite.