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

Christopher L. Fergusson
University of Wollongong, cferguss@uow.edu.au

R A Henderson
James Cook University

K. J. Lewthwaite
James Cook University

D. Phillips
University of Melbourne

I. W. Withnall
Dept. of Natural Resources and Mines, Qld.

Follow this and additional works at: https://ro.uow.edu.au/scipapers

Part of the Life Sciences Commons, Physical Sciences and Mathematics Commons, and the Social and Behavioral Sciences Commons

Recommended Citation

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
Structure of the Early Palaeozoic Cape River Metamorphics, Tasmanides of north Queensland: evaluation of the roles of convergent and extensional tectonics

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
Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

This journal article is available at Research Online: https://ro.uow.edu.au/scipapers/1148
Structure of the Early Palaeozoic Cape River Metamorphics, Tasmanides of north Queensland: evaluation of the roles of convergent and extensional tectonics

C. L. FERGUSSON1*, R. A. HENDERSON2, K. J. LEWTHWAITE2, D. PHILLIPS3 and I. W. WITHNALL4

1School of Earth and Environmental Sciences, University of Wollongong, NSW 2522, Australia.
2School of Earth Sciences, James Cook University, Townsville, QLD 4811, Australia.
3School of Earth Sciences, University of Melbourne, Vic. 3010, Australia.
4Geological Survey of Queensland, Natural Resource Sciences, Department of Natural Resources and Mines, 80 Meiers Road, Indooroopilly QLD 4068, Australia.

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 (S2) 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 (S2) related to D2 deformation. It overprints steeply dipping foliation (S1) formed in a D1 deformation but no associated folds have been found. Gently plunging, upright, open folds (D3 deformation) with axial planar S3 crenulation cleavage have affected the main foliation (S2). These deformations were associated with upper greenschist to lower amphibolite facies metamorphism. Amphibolite grade orthogneiss containing S2 and S3, deformed granite and migmatite of the Fat Hen Creek Complex occurs in the northeast. In the southwest, the main foliation (S2) is folded around a map-scale, gently plunging synclinorium indicating that S2 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 D2 structures to subvertical shortening (i.e. extension) resulting in orientations that are strikingly divergent to those of upright D1 and D3 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 40Ar/39Ar cooling ages at 423–409 Ma that also postdated the D3 deformation.

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

INTRODUCTION

*Corresponding author: cferguss@uow.edu.au
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 (S2) 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 (S2) 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 ⁴⁰Ar/³⁹Ar 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 S₂ foliation. For the Anakie Metamorphic Group, the intense flat-lying S₂ 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 postdate 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-cross laminated and plane laminated quartzite layers (Bouma C and D layers respectively), basal scour 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 (D1, D2, D3) have affected the Cape River Metamorphics with the main deformation (D2) forming a well-developed, ubiquitous foliation and associated structures.
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 30°–40° 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).

**D3 deformation**

The D3 deformation in the Cape River Metamorphics consists of open to locally tight folds in
the S2 foliation with an S3 axial planar crenulation cleavage (Withnall *et al.* 1997). Our
mapping in the Oxley Creek area confirms the observation of these authors that the S2
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 (F3) plunge gently to the northwest and southeast.
They are subparallel to a widely developed intersection lineation (L3) between the
differentiated layering (S2) and the axial planar crenulation cleavage/foliation (S3). On the flat
lying to gently dipping southwest limb, large areas with flat to gentle planar S2 are
interspersed with smaller areas with abundant F3 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 S2 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 F3 folds are scarce but S3 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 F3 folding. In some exposures in the Fat Hen Creek Complex, S2
foliation is tightly folded (F3) 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 S2 foliation is not represented. Bedding
in this marker dips steeply and youngs consistently to the northeast with rare southwest-
vergent F3 fold couples. A continuous cleavage is developed at a low angle but steeper than
bedding (Figure 14) and has an orientation consistent with S3, but is not a crenulation
cleavage as S3 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
F3 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 D1 and D2
deformations and shows D3 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 S3 (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 (S1, S2, S3) 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 40Ar/39Ar 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 (S2) is gently dipping to the northeast with F3 folds developed with metre long wavelengths. Both S1 and S2 are defined by aligned muscovite and some biotite. Some biotite porphyroblasts also cross-cut the S2 foliation, whereas occasional muscovite grains are randomly oriented. Thus metamorphism was both synchronous with fabric development (S1 and S2 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 plagioclas, 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 (S2) with alternating mica- and quartz-rich domains, delineating axial
planar crenulations associated with open F3 folds. Some biotite grains cross-cut the S3 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%. 40Ar/39Ar 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. K2SO4 salts were included in the irradiation package to determine correction factors for K-produced 40Ar. After irradiation, weighed aliquots of each sample were loaded into tin foil packets and step-heated in a tantalum resistance furnace. 40Ar/39Ar 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: (36Ar/37Ar)Ca = 2.54 (±0.09) x 10^-4; (39Ar/37Ar)Ca = 6.51 (±0.31) x 10^-4 (Bottomley & York 1976); (40Ar/39Ar)K = 0.028 ± 0.002. Decay constants are those reported by Steiger and Jager (1977). The 40Ar/39Ar plots were generated using K. Ludwig’s ISOPLOT software package (1999).

40Ar/39Ar 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 D2 event and is therefore poorly known. S1 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 D2 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 F3 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 S2 foliation. The lowest grade metamorphism occurs in the core of the F3
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 D2 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 (S2).

The D2 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 D2
predated metamorphic cooling at ca 420–410 Ma.

Subsequent to D2, the last main ductile deformation (D3) produced the synclinorium in the
Oxley Creek area and associated structures marked by a switch back to northeast-southwest
contractional deformation as for D1. The syn-metamorphic character of the S3 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
40Ar/39Ar 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 D2 deformation**

The S2 foliation formed in a subhorizontal orientation and thus the D2 deformation is clearly
distinct compared to steep dips of foliations associated with the D1 and D3 deformations in the
Cape River Metamorphics. In a wider context, the initial subhorizontal orientation of S2 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 D3 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 D2 deformation in the Cape River Metamorphics is problematic. Definitive evidence for convergent deformation with development of D2 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 F3 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 D2 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 D2 and the clearly convergent D1 and D3 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 (D1) is characterised by steep S1 foliation, with inferred map-scale F1 folds, that are overprinted by an intense subhorizontal S2 foliation with associated recumbent folds (D2 deformation) and subsequently affected by upright folds and associated axial planar crenulation cleavage (D3 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 D2 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 D2 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 D2 deformation from the Cape River Metamorphics, the style and orientation of this deformation has much in common with that of D2 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 D₂ 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 D₁ and D₂ deformations that we attribute to east-west convergence (D₁) closely followed by presumed extensional deformation (D₂). Although the D₂ 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 D₂ 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 D₁ 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 D₃ 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 (D1 deformation), followed by development of a subhorizontal foliation with recumbent folds (D2 deformation) and then a return to northeast-southwest convergence producing a major synclinorium. The initial flat-lying orientation of D2 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 D2 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 D3 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.

ACKNOWLEDGEMENTS

The Australian Research Council (grant number A00103036) funded this work with additional support from James Cook University, the University of Wollongong and the Geological Survey of Queensland. We are grateful to the landowners in the Cape River region for allowing us access to their properties. We thank Laurie Hutton for comments on a draft of the manuscript. David Carrie made many excellent thin sections. Peter Johnson computer drafted the figures. Stan Szczepanski is thanked for assistance with the $^{40}$Ar/$^{39}$Ar analyses. Major revisions suggested by Peter Cawood and an anonymous reviewer has resulted in substantial changes to the manuscript but we remain responsible for any deficiencies that remain.

REFERENCES


**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). F3 steeply inclined folds in main foliation (S2). (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 S3 crenulation cleavage and short bars below the topographic line show the orientation of S2 with long continuous lines showing the S2 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, $\beta$-axis 10º/125º. (b) Poles to $S_2$, $\beta$-axis 04º/134º. (c) $L_2$ – intersection lineation, mean 05º/126º. (d) $L_m$ – 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$_2$, $\beta$-axis 08$^\circ$/124$^\circ$. (b) L$_2$ – intersection lineations, mean 11$^\circ$/124$^\circ$. (c) Poles to S$_3$, mean 84$^\circ$/215$^\circ$. (d) L$_3$ – fold axes and intersection lineations, mean 11$^\circ$/128$^\circ$. 
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 S₂, β-axis 21º/125º, mean 60º/202º. Contour intervals per 1% area shown on lower right side. (c) L₂ fold axes and intersection lineations, girdle 71º/213º, mean 32º/136º. (d) Poles to S₃, mean 90º/024º. (e) L₃ – 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 S3 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.
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).
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>
<thead>
<tr>
<th>Temp (C)</th>
<th>Cum % 39Ar</th>
<th>40Ar/39Ar</th>
<th>37Ar/39Ar</th>
<th>36Ar/39Ar</th>
<th>Vol. 39Ar x10^-14 mol</th>
<th>%Rad. 40Ar</th>
<th>Ca/K</th>
<th>40Ar*/39Ar</th>
<th>Age (Ma)</th>
<th>± 1s.d. (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR35 Biotite&lt;br&gt;J-value = 0.0085511 ± 0.000021</td>
<td>600</td>
<td>1.70</td>
<td>28.22</td>
<td>0.0253</td>
<td>0.0215</td>
<td>0.296</td>
<td>77.4</td>
<td>0.048</td>
<td>21.85</td>
<td>309.1</td>
</tr>
<tr>
<td>700</td>
<td>9.90</td>
<td>30.66</td>
<td>0.0096</td>
<td>0.0039</td>
<td>1.426</td>
<td>96.2</td>
<td>0.018</td>
<td>29.49</td>
<td>405.7</td>
<td>1.3</td>
</tr>
<tr>
<td>750</td>
<td>20.05</td>
<td>30.63</td>
<td>0.0087</td>
<td>0.0019</td>
<td>1.763</td>
<td>98.0</td>
<td>0.017</td>
<td>30.02</td>
<td>412.3</td>
<td>1.4</td>
</tr>
<tr>
<td>780</td>
<td>28.78</td>
<td>30.39</td>
<td>0.0052</td>
<td>0.0021</td>
<td>1.517</td>
<td>97.9</td>
<td>0.010</td>
<td>29.74</td>
<td>408.8</td>
<td>1.7</td>
</tr>
<tr>
<td>810</td>
<td>34.47</td>
<td>30.46</td>
<td>0.0157</td>
<td>0.0021</td>
<td>0.990</td>
<td>97.8</td>
<td>0.030</td>
<td>29.80</td>
<td>409.5</td>
<td>1.6</td>
</tr>
<tr>
<td>850</td>
<td>39.19</td>
<td>30.45</td>
<td>0.0060</td>
<td>0.0023</td>
<td>0.820</td>
<td>97.6</td>
<td>0.011</td>
<td>29.77</td>
<td>409.1</td>
<td>1.4</td>
</tr>
<tr>
<td>900</td>
<td>43.94</td>
<td>30.6</td>
<td>0.0117</td>
<td>0.0027</td>
<td>0.827</td>
<td>97.5</td>
<td>0.022</td>
<td>29.77</td>
<td>409.1</td>
<td>1.3</td>
</tr>
<tr>
<td>950</td>
<td>48.99</td>
<td>30.55</td>
<td>0.0175</td>
<td>0.0029</td>
<td>0.877</td>
<td>97.3</td>
<td>0.033</td>
<td>29.68</td>
<td>408.0</td>
<td>1.7</td>
</tr>
<tr>
<td>1000</td>
<td>57.30</td>
<td>30.77</td>
<td>0.0204</td>
<td>0.0030</td>
<td>1.445</td>
<td>97.1</td>
<td>0.039</td>
<td>29.87</td>
<td>410.4</td>
<td>1.9</td>
</tr>
<tr>
<td>1050</td>
<td>72.02</td>
<td>30.47</td>
<td>0.0132</td>
<td>0.0019</td>
<td>2.559</td>
<td>98.1</td>
<td>0.025</td>
<td>29.90</td>
<td>410.7</td>
<td>1.2</td>
</tr>
<tr>
<td>1100</td>
<td>86.89</td>
<td>30.53</td>
<td>0.0265</td>
<td>0.0022</td>
<td>2.585</td>
<td>97.8</td>
<td>0.050</td>
<td>29.87</td>
<td>410.4</td>
<td>1.0</td>
</tr>
<tr>
<td>1150</td>
<td>97.99</td>
<td>30.61</td>
<td>0.0386</td>
<td>0.0024</td>
<td>1.929</td>
<td>97.6</td>
<td>0.073</td>
<td>29.88</td>
<td>410.5</td>
<td>1.2</td>
</tr>
<tr>
<td>1350</td>
<td>100.0</td>
<td>38.73</td>
<td>0.1129</td>
<td>0.0306</td>
<td>0.350</td>
<td>76.6</td>
<td>0.214</td>
<td>29.65</td>
<td>407.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Total</td>
<td>30.68</td>
<td>0.0193</td>
<td>0.0033</td>
<td>17.38</td>
<td>29.68</td>
<td>408.1</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<p>| CR35 Muscovite&lt;br&gt;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 |</p>
<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Cum % 39Ar</th>
<th>40Ar/39Ar</th>
<th>37Ar/39Ar</th>
<th>36Ar/39Ar</th>
<th>Vol. 39Ar x 10^{-14}</th>
<th>%Rad. Ca/K</th>
<th>Ca/K</th>
<th>40Ar*/39Ar</th>
<th>Age (Ma)</th>
<th>± 1s.d. (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0.62</td>
<td>160.26</td>
<td>0.1709</td>
<td>0.4425</td>
<td>0.129</td>
<td>18.4</td>
<td>0.325</td>
<td>29.53</td>
<td>407.5</td>
<td>25.2</td>
</tr>
<tr>
<td>700</td>
<td>1.90</td>
<td>45.06</td>
<td>0.1737</td>
<td>0.0506</td>
<td>0.263</td>
<td>66.8</td>
<td>0.330</td>
<td>30.11</td>
<td>414.8</td>
<td>4.7</td>
</tr>
<tr>
<td>800</td>
<td>3.40</td>
<td>43.18</td>
<td>0.0718</td>
<td>0.0453</td>
<td>0.310</td>
<td>68.9</td>
<td>0.137</td>
<td>29.76</td>
<td>410.4</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**CR114a Muscovite**

J-value = 0.0085772 ± 0.000021

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Cum % 39Ar</th>
<th>40Ar/39Ar</th>
<th>37Ar/39Ar</th>
<th>36Ar/39Ar</th>
<th>Vol. 39Ar x 10^{-14}</th>
<th>%Rad. Ca/K</th>
<th>Ca/K</th>
<th>40Ar*/39Ar</th>
<th>Age (Ma)</th>
<th>± 1s.d. (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0.62</td>
<td>160.26</td>
<td>0.1709</td>
<td>0.4425</td>
<td>0.129</td>
<td>18.4</td>
<td>0.325</td>
<td>29.53</td>
<td>407.5</td>
<td>25.2</td>
</tr>
<tr>
<td>700</td>
<td>1.90</td>
<td>45.06</td>
<td>0.1737</td>
<td>0.0506</td>
<td>0.263</td>
<td>66.8</td>
<td>0.330</td>
<td>30.11</td>
<td>414.8</td>
<td>4.7</td>
</tr>
<tr>
<td>800</td>
<td>3.40</td>
<td>43.18</td>
<td>0.0718</td>
<td>0.0453</td>
<td>0.310</td>
<td>68.9</td>
<td>0.137</td>
<td>29.76</td>
<td>410.4</td>
<td>4.0</td>
</tr>
<tr>
<td>CR183 Biotite</td>
<td>J-value = 0.0085291 ± 0.000022</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600 5.63</td>
<td>23.67</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 17.02</td>
<td>31.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>750 28.02</td>
<td>31.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>780 32.76</td>
<td>31.68</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>810 36.18</td>
<td>32.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>840 39.30</td>
<td>31.83</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>870 42.97</td>
<td>31.54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>900 46.61</td>
<td>31.77</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>950 55.51</td>
<td>31.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 59.49</td>
<td>31.78</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1050 74.66</td>
<td>31.46</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1075 84.65</td>
<td>31.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1100 92.08</td>
<td>31.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1150 97.74</td>
<td>31.97</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1350 99.93</td>
<td>34.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1450 100.00</td>
<td>301.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>33.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CR183 Muscovite</th>
<th>J-value = 0.0085291 ± 0.000022</th>
</tr>
</thead>
<tbody>
<tr>
<td>550 0.47</td>
<td>33.09</td>
</tr>
<tr>
<td>650 1.50</td>
<td>32.10</td>
</tr>
<tr>
<td>700 2.64</td>
<td>32.53</td>
</tr>
<tr>
<td>750 4.40</td>
<td>32.34</td>
</tr>
<tr>
<td>800 8.32</td>
<td>33.12</td>
</tr>
<tr>
<td>850 26.50</td>
<td>33.73</td>
</tr>
<tr>
<td>900 43.96</td>
<td>32.71</td>
</tr>
<tr>
<td>925 50.93</td>
<td>31.52</td>
</tr>
<tr>
<td>950 54.92</td>
<td>32.64</td>
</tr>
<tr>
<td>975 58.04</td>
<td>32.82</td>
</tr>
<tr>
<td>1000 60.98</td>
<td>32.75</td>
</tr>
<tr>
<td>1050 69.58</td>
<td>33.04</td>
</tr>
<tr>
<td>1100 86.12</td>
<td>33.13</td>
</tr>
<tr>
<td>1150 99.01</td>
<td>33.30</td>
</tr>
<tr>
<td>Total</td>
<td>31.43</td>
</tr>
</tbody>
</table>
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: \((^{36}\text{Ar}/^{37}\text{Ar})_{Ca} = 2.54E-4; \quad (^{39}\text{Ar}/^{37}\text{Ar})_{Ca} = 6.51E-4; \quad (^{40}\text{Ar}/^{39}\text{Ar})_{K} = 3.0E-2\)
iv) J-value is based on an age of 98.8 Ma for GA-1550 biotite.