

Centre for Ore Deposit and Exploration Studies



## Proterozoic sediment-hosted base metal deposits

### P384 - Sponsors Field Meeting

AMIRA/ARC Project P384  
Report No. 6

June 1994

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# P384 - Sponsors Field Meeting

LEADERS: Stuart Bull, Richard Keele, David Cooke and Jamie Rogers

## Itinerary

### Day 1 (Friday 17th June) - Northwest Batten Fault Zone

8.00 AM	Butterfly Springs
9.00 AM	Drive to Four Archers Fault
9.30 AM	Four Archers Fault Traverse
11.00 AM	Drive to Lorella Springs
12.30 PM	Lunch
1.30 PM	Lorella Fault Traverse
3.00 PM	Drive to Coppermine Creek
3.30 PM	Coppermine Creek Traverse
5.00 PM	Drive to Heartbreak Hotel

### Day 2 (Saturday 18th June) - Mallapunyah Dome and Top Crossing

8.00 AM	Drive to Kilgour Waterhole
9.00 AM	Kilgour Waterhole Traverse
12.00 PM	Kilgour Copper Mine
12.30 PM	Drive to Top Crossing
1.30 PM	Lunch
2.00 PM	Top Crossing Traverse
5.00 PM	Return to Heartbreak Hotel

### Day 3 (Sunday 19th June) - Batten Range

8.00 AM	Drive to Eastern Batten Range
10.00 AM	Tawallah Group - McArthur Group transition
2.00 PM	Lunch
2.30 PM	Tawallah Fault Traverse
4.30 PM	Return to Heartbreak Hotel

### Day 4 (Monday 20th June) - HYC Mine Visit (Led by Ross Logan, MIM)

8.00 AM	Drive to HYC
9.00 AM	HYC Mine visit
4.30 PM	Drive to Daly Waters



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## Acknowledgements

This field trip could not have been run without the close cooperation and assistance of the Northern Territory Geological Survey, and we thank Paul Le Messurier and staff for their continuing support. MIMEX are thanked for permission to visit HYC, and Doogie Wilson and Ross Logan for organising and leading that part of the trip. Peter Haines is thanked for the use (and abuse) of his printer. BHP exploration are thanked for logistical assistance in the field.



## Day 1 - Structures in the NW Batten Fault Zone, Southern McArthur Basin

Richard A. Keele

### INTRODUCTION

The purpose of this short report, together with the accompanying field guide, is to present the results of structural mapping from three areas: the Four Archers Fault near Nathan River homestead (Stops 1 & 2), the Lorella Fault at Lorella Springs (Stop 3) and the Coppermine Creek Fault at the Coppermine Creek prospect (Stop 4; Fig. 1). The NW part of the Batten Trough was originally mapped by Plumb & Paine (1964) but has recently been remapped by Rawlings et al. (1993) and Haines et al. (1993). This excellent data base has enabled the project to focus in on areas of special structural and sedimentological interest in the Tawallah Group. Our research has concentrated on the basal rather than middle or upper sequences, because the processes and evolution recorded here have important ramifications for the McArthur basin as a whole. A detailed description of one of the localities (ie., Lorella Springs) has been already been given in report No. 4 (Keele 1993), otherwise many of the aspects of the structure discussed here are new and have not been reported before. Work is continuing in all three areas.

### FOUR ARCHERS FAULT

Considerable uplift (up to 6 or 7 km) is implied by the juxtaposition of Scrutton Volcanics against Roper Group sediments along this section of the fault (Fig. 1). Clearly, not all this uplift took place at the same time, nor did it necessarily take place along the same structure. It probably comprised a combination of processes, including:

- (1) E- & W-directed thrusting
- (2) W- (& E-) block down normal movements
- (3) block-faulting (E block-up)
- (4) dextral strike-slip faulting

### (5) arching in the basement

All of these have contributed to the development of a N-S trending fault zone some 3 km wide and 50 km long that stretches along the eastern boundary of MANTUNGULA. Evidence that the Four Archers Fault had been active during Tawallah times cannot be found in the localities we are visiting today, but exists on the TOWNS sheet to the north, where Sly Creek Sandstone (Ptl) is juxtaposed against Settlement Creek Volcanics (Pte) across the fault. Since this occurs immediately beneath the Masterton "unconformity", this implies considerable uplift towards the end of Tawallah times.

The Four Archers Fault displays many features that suggest it is a wrench fault, ie., synthetic riedel fault splays, a restraining bend, parallel forced folds and in-line graben slices (Harding et al., 1985; Fig. 1). However, the wrench analogy could easily be carried too far, particularly when applied to events prior to the Roper, because demonstrable offsets on the faults are of the order of 850-1200 metres, hardly enough for the fault to qualify as a major wrench system. No quartz fibres or striae associated with the wrenching movement have been found on the main fault itself; although the Lorella Fault, with a demonstrated 2.5 km dextral offset, has some insignificant fault striae associated with this movement. Most of the evidence points to late-stage dextral reactivation at high crustal levels of a system of reverse faults or thrusts that formed during several inversion events.

The marine and fluvial parts of the Yiyintyi Sandstone are faulted against each other at Butterfly Springs in spectacular fashion. In this section of the Four Archers Fault, the Yiyintyi comprises at least two distinct tectono-stratigraphic blocks - the upper and lower sandstone units. Intense silicification has occurred in the tip zone of the slice of the basal fluvial sandstone. Such fluid focussing is probably the result of mechanical processes controlling fluid flow during faulting.



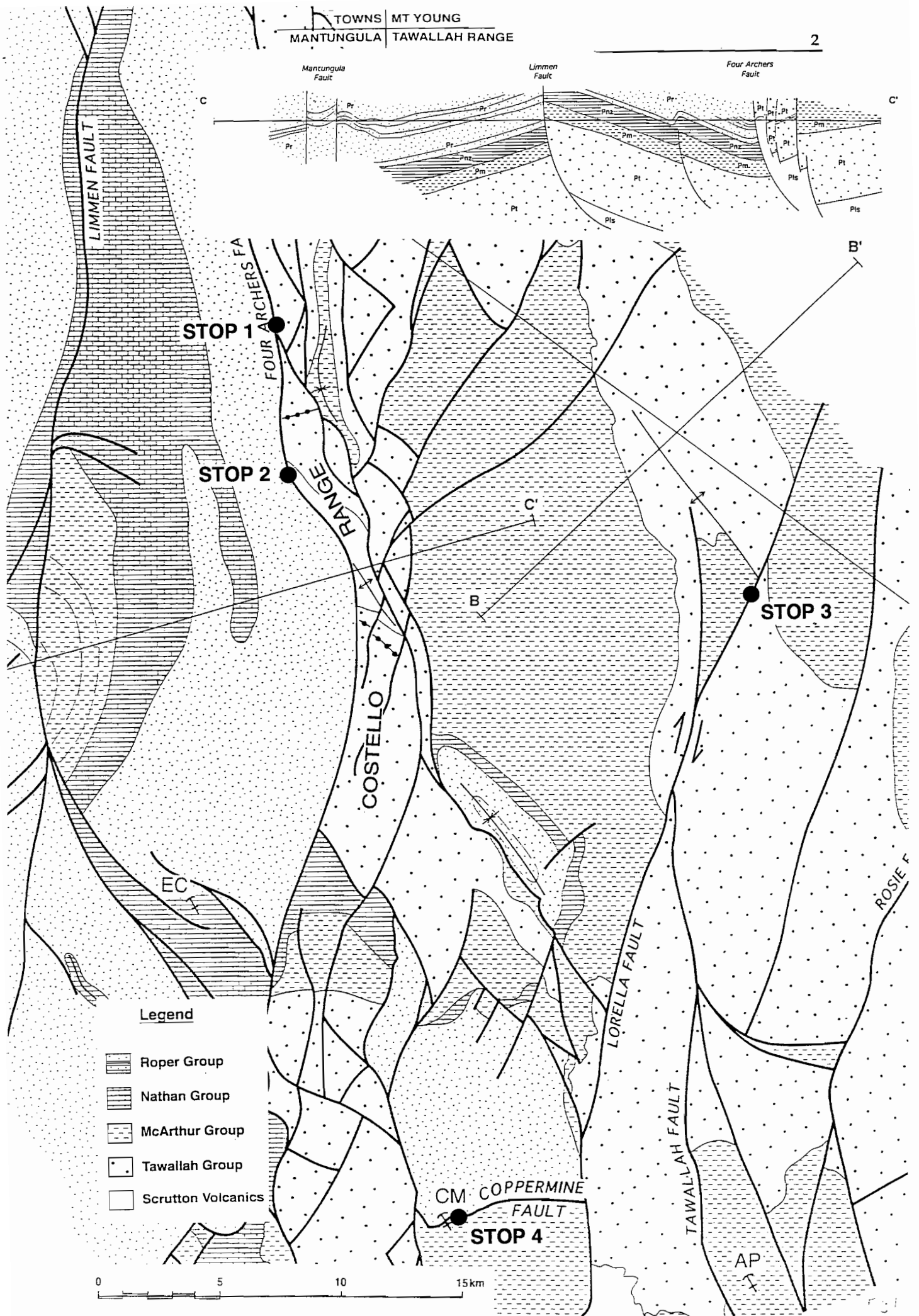


Figure 1 - Geology of the NW Batten Fault zone showing stops for Day 1

## SCRUTTON VOLCANICS

The Scrutton inlier is folded and faulted and has a considerable sedimentary and volcanic stratigraphy associated with it (Rawlings, pers. comm. 1994; Fig. 2). The greater part of the fault in this region contains a thin screen of sediment or volcanics along it; in fact, nowhere was Roper actually seen to be faulted against Yiyintyi! All the best cleavages seen to date in the McArthur Basin have come from the Scrutton rocks adjacent to the Four Archers Fault, suggesting that the rocks have reached low metamorphic grade (prehnite-pumpellyite facies?). The existence of a probable syn-volcanic growth fault at the western end of the Scrutton inlier is significant because it confirms the kinds of structure that Leaman (1992) had predicted for the basement rocks in the vicinity of the Tawallah Range; its NE-SW trend agrees with the general trend of the formative rift as deduced from the magnetics on MOUNT YOUNG.

## WARRAPIRRMANTILA DOME

This remarkable structure was a zone of uplift during the late Tawallah, showing a maximum erosion level for the Southern McArthur Basin down to at least the Sly Creek Sandstone (Fig. 3). The Masterton Sandstone is mapped as being thicker on the SW flank of the dome, thus the present NNW-trending domal axis marks a hinge line that must have controlled sedimentation during Masterton times.

The cross-section of the Lorella Fault shows Tawallah age (possible Sly Creek Sandstone age) hematite breccias, that controlled late-Tawallah to early McArthur Group sedimentation in the district (Fig. 4). This is generally supported by their NW to NNW trend and their clear overprinting by younger structures.

Recent work on the Sly Creek Sandstone, 1.5 km west of Lorella Springs, indicates that soft sediment deformational processes accompanied breccia development. These structures equate to those on the Lorella Fault, and are a possible avenue for future research.

## CORRELATING DEFORMATION EVENTS WITH THE MT ISA INLIER

Controversy surrounds early deformation in the Mt Isa Inlier. Detailed mapping by Nyman et al. (1992) failed to substantiate Bell's (1983) hypothesis that the inlier had suffered considerable crustal shortening (ie. thrusting) prior to the upright folding event. Stewart (1992) recognised an early E-W cleavage in the Horse's Head which was overprinted by a N-S cleavage; however, he pointed out that the E-W faults which were the basis for Bell's (1983) postulated stacked sequence, actually cut the D2 antiforms. The purpose of bringing such a discussion into a report on the McArthur Basin, is to draw attention to the fact that some of the events or styles recognised by Nyman et al. (1992) and Stewart (1992), may have their counterparts in the Batten Fault Zone. The sequence of events recognised at Coppermine Creek (Fig. 5), although different in style to the Mt Isa structures, may represent stress states that existed across a wider cross section of the North Australian Proterozoic Craton than has hitherto been recognised.

The existence of E-W folds in the McArthur Group, that are not present in the younger Roper sediments, forms the basis for postulating a crustal deformation that preceded the Roper basin, with the main basin inversion taking place after this. The sequence of events at Coppermine Creek has an uncanny resemblance to the sequence of events at the Horse's Head, particularly D3, D4 and D5. It is these events in the Batten Trough that may correlate with the Mt Isa orogen. The 50-60 Ma that separated Mt Isa D1 and D2 in the Page and Bell (1986) model, leaves plenty of time for a sedimentary basin to form.





## DAY 1 - NORTHWEST BATTEN FAULT ZONE

The main reason for coming here is to view the spectacular exposures of the Four Archers Fault along the Costello Range. The fault marks the most western exposure of basement in the NW part of the Batten Fault Zone.

*At the start, take the left turn onto the old road, about 2 km south of the Nathan River homestead, and follow this track for 4-5 km. Stop and park vehicle at the waterhole.*

### STOP 1 - BUTTERFLY SPRINGS

An excellent view of a splay off the Four Archers Fault can be obtained by climbing the cliffs on the N side of the pool where, from a suitable vantage point (about two-thirds of the way up) it may be seen in the cliffs towards the south. A 25 m wide, slightly recessive zone with enhanced vegetation, marks the actual position of the fault. To the left, the steeply dipping beds of the upper Yiyintyi Sandstones can be seen; whilst to the right, strongly silicified and jointed, paler looking sandstones belonging to the lower Yiyintyi Sandstone dip parallel with the fault, ie. steeply towards to the E.

Notice the different bedding characteristics of the essentially fluvial beds on the right and the marine beds on the left. The intense silicification of the lower beds is due to the preferential flow of fluids through the tip zone of a fault-bound wedge of sediment in a strike slip system.

The kinematics of the fault splay are not especially clear at this locality; however, a number of small-scale faults along strike show evidence for an E-W compression and an E-W extension that affected both Roper and Tawallah rocks. The best evidence is to be found on the western side of the fault (about 2 km to the south along the scarp) where E block up and W-directed thrust movements are clearly recorded in quartz fibres on the fault.

*Retrace your tracks to the main road and continue S for several km until you meet the old road coming in on your left. Park at the junction and walk up the creek. This traverse is the shorter of two options presented as stop 2, which are both designed to cross the fault. For the second option take the next creek to the south.*

### STOP 2 (OPTION 1) - FOUR ARCHERS FAULT TRAVERSE

The Roper Group (Crawford Formation) beds dip (& face) at a flat angle to the E at the start of this

traverse. Moving a short distance up the creek, the dip can be seen to steepen until the beds are vertical and facing to the W. This asymmetric syncline is due to compression across the fault and its effects are particularly well displayed on the N side of the creek in the burnt out area of bush. This point marks the western limit of the Four Archers Fault, and the change to the Abner Sandstone.

The silicification becomes more intense and striae appear on bedding surfaces at this locality. A particularly good example of lunate riedel flakes, giving a reverse sense of movement, can be seen on an E-dipping bedding surface; this indicates W-directed thrusting during post-Roper times.

Continue on up the creek for a further short distance to the open ground which marks the site of the main fault. The faulted contact between Roper Group and Scrutton basement is not exposed here; however, to the north it is seen as a thin screen of cleaved mafic rock sitting between the Roper and Yiyintyi sandstones. The fine-grained, laminated sandstones that crop out in the flat area are actually a slice of lower Scrutton Volcanics stratigraphy that have been faulted in during thrusting. Note some outcrops of sediment have a down-dip extension lineation and, therefore, qualify as true low-grade metamorphic rocks.

The faulted Yiyintyi-Scrutton contact may be seen on the other side of the valley.

### STOP 2 (OPTION 2) - NEAR KINGKIRRA WATERHOLE, SCRUTTON INLIER (Time away from the vehicle - 1 1/2 to 2 hours)

This traverse, initially along the creek beds, provides a good opportunity to see the Four Archers Fault and walk some of the Scrutton Volcanics stratigraphy.

#### Stop 2A

This stop is intended to be a pause on the way up the creek bed to observe the gentle folding in the Roper Sandstones. The fold plunges  $13^\circ \rightarrow 120$  and is typical of a style developed during the post-Roper inversion, especially adjacent to a major fault. Its orientation is consistent with the NE-SW compression generally associated with this event.





*Stop 2B*

Two important features to see at this locality are:

- the extent of **silicification** in the Roper sandstones. What appears initially to be complete silicification is found, on closer inspection, to be merely a surface coating around cores of normal sandstone; silicification is controlled largely by the bedding plane and a set of 065 trending joints. Compare this with the adjacent Scrutton Volcanics sandstone horizons.
- **overturning** of the Roper sandstones against the fault. The Roper sandstones dip to the NE but face SW (the facing is easily obtained from current cross-bedding). This overturning of the beds on the SW side of the fault implies a transport direction in that direction. On the other side of the fault, the sandstones dip & face to the NE, implying transport the other way.

*Stop 2C*

The beds here are also overturned and dip steeply to the SW, facing to the NE. In conjunction with the last outcrop, this indicates that the Four Archers Fault is an anticline whose hinge has largely been removed by faulting. The fault striae data indicate a strong component of N-S compression in the area. This is due to the inlier being located at a restraining bend within a dextral strike slip fault system.

*Stop 2D*

A NW-trending spaced fracture cleavage may be seen here in siltstones of the Scrutton Volcanics and is (for the McArthur Basin, at least) unusually well developed.

*Stop 2E*

The **quartz fibres** at this locality show a N-directed movement followed by S-directed movement on small-scale flat dipping thrusts in silicified sandstones. Such random and inconsistent senses of vergence are typical of wrench faults. The fibres due to the second movement can be seen as coatings of blue-green sericite (?chlorite) on the quartz fibres. This alteration probably derives from the volcanics which are only a few metres away.

*Stop 2F*

This rock is a friable, massive spherulitic rhyolite-dacite from the Scrutton Volcanics. This unit has a faulted contact with the siltstones/shales to the

west. The fault is a **syn-volcanic** or **growth fault** because (1) it separates massive rhyolites and dacites to the east from thinner basalts and sediments to the west, and (2) the displacement decreases markedly in the overlying conformable Yiyintyi Sandstones. Note the abundant **quartz amygdales** in the basalts at *Stop 2G*

*Return to the vehicles and drive southwards along the main road until you reach the turn off to Lorella Springs (35-40 km). This turn off is well signposted*

## STOP 3 - LORELLA SPRINGS, LORELLA FAULT

The outcrop at Lorella Springs displays cross-section, side elevation and plan views of the fault. The vertically dipping NNE trending Lorella Fault juxtaposes Sly Creek sandstones (Ptl) against Masterton sandstone (Pms). It is a good place to compare the style, age and development of fault-related silica-hematite brecciation and quartz veining in sandstones units from the Tawallah and McArthur Groups.

At this locality we shall see three types of quartz veining and brecciation: the first is present in the Sly Creek only, the second and third are present in both Sly and Masterton; overprinting of the third onto the second will be demonstrated.

Evidence for at least **one** movement pre-the Masterton unconformity and **two** movements post-early McArthur Group times (the so-called Post-Roper Inversion) will be presented and the implications discussed at the outcrop.

*Stop 3A - western side of fault*

The first outcrop on the western side of the fault shows **brecciation** due to fluids leaking out into the flat-dipping Mallapunyah Formation. Relict bedding is clearly visible in the pale silicified clasts, which were originally siltstones or fine-grained sandstones; the dark red-brown areas are silicified and ferruginised muddy dolomitic layers in the sediment. Note the extent of the hydraulic fracturing developed this far from the fault (plus 100 m), which is unusual in this formation; the breccias are matrix to clast supported.

*Stop 3B - Masterton Sandstone*

Two generations of quartz veins can be observed in the Masterton Sandstone. The earliest veins are irregular to planar quartz veins formed during a post-McArthur **silica-hematite brecciation** event (Batten sub-group inversion?). The later veins are **epithermal-style** quartz veins formed during the post-Roper compression (NE-SW).





The later veins are white, pink or grey and show **colloform banding**. The presence of mutually intersecting veins with two dominant directions (NNE & ENE) suggests that they formed as **conjugates** in a NE-SW directed compressional stress field. This generation forms a good **stockwork** in the Masterton on the western side of the fault; they are also developed in the Sly Creek on the other side of the fault, however, here they only form along the set that parallels the fault.

A **stylolitic cleavage**, in which quartz has been removed by pressure solution, can be seen in silicified and hematized Masterton Sandstone at this locality. Note that the individual hematitic shears are sharply truncated on the surfaces and it is not possible to correlate them across the stylolite surface. The orientation of the stylolites is consistent with the Post-Roper compression event.

#### *Stop 3C - the main fault and the Sly Creek Sandstone*

Looking S along the main fault, it is represented by a 2-3 m wide slightly recessive zone that separates Ptl (left) from Pms (right). The Sly dips shallowly to the east (left), whereas the Masterton dips steeply to the west (right). Note the ripples on the Sly bedding surface and how the silicification in the main fault terminates abruptly, with bedding disappearing over the length of a pencil or so as it becomes a joint surface. Rare dextral strike-slip fibres can be picked up along the main fault.

As you move across into the Sly Creek Sandstone, note the **silica-hematite breccias**. These NW-trending faults not only have sharp boundaries with parallel quartz veins, but also distinct offsets along bedding planes. Can you see any consistent sense of movement on these structures? Nearby, 1.5 km to the W in the large outcrop of Sly sandstone, evidence is emerging that these breccias may have formed early (ie., pre-lithification) because they are closely associated with soft sediment deformation in the Sly Creek Sandstone.

There are some quite intensely deformed quartz veins exposed on the rock pavement beneath the end of the cliff. They are cut by later shears and quartz veins of the post-Roper event.

*Retrace your wheel tracks until you reach the junction with the main road to Heartbreak again. Copper Mine Creek is approximately 6 km south of this junction; but beware, the signpost on the road refers to another tributary of this creek system and is not the "Coppermine Creek" marked on the 100,000 TAWALLAH topographic map. The site of the gossan is immediately W of the road, several hundred metres south of the creek; at this point a*

*track also goes off to the E, and follows the Coppermine Fault for several kilometres.*

#### STOP 4 - COPPERMINE CREEK.

This stop provides an opportunity to see two styles and orientations of folding in Amelia Dolomite and a spectacular **fault-related breccia** in silicified dolomite. There is also **copper mineralisation** associated with an E-W fault that juxtaposes Roper Group sandstones (Pri) against McArthur Group carbonates (Pma).

#### *Stop 4A - Folds in Amelia Dolomite*

Two types of folding are present in Amelia Dolomite just south of the main E-trending Coppermine Creek Fault (Fig. 6). The best examples are about 150 m apart:

- (1) An ?early, **gentle E-W folding** event with a very weak axial plane fracture cleavage. The fold plunges to the E and has a parasitic fold with the wrong sense of vergence.
- (2) A ?later **close NW-SE folding** event that has a better developed axial plane fracture cleavage, plunging to the NW.

The first fold is equated with the same broad E-W folding in the Batten Trough, W of the HYC deposit, which pre-dates the Post-Roper compression. The gentle folding here is ascribed to that event.

The outcrop pattern here is dominated by large-scale folds whose axes are moderately to steeply plunging to the NW. Sinistral strike-slip movement on the main fault is sufficient to explain the orientation of these folds; this movement pre-dates the regionally developed N-S dextral wrenching event.

Some 100 m north of these outcrops, overturned Tatoola Sandstone beds (Pmt) dip towards the SW.

#### *Stop 4B - Fault-related breccias.*

*(The track continues eastwards following the ridge of silicified Pri. The breccia horizon is about 600 m along this track and 100 m to the S).*

Most of the good quartz fibres in the main fault at this locality are only present in the oblique cross-cutting fractures, rather than in the fault itself. This is because the fault here is a normal fault and the fibres would be less likely to have survived due to later silicification. This movement is due to N-S



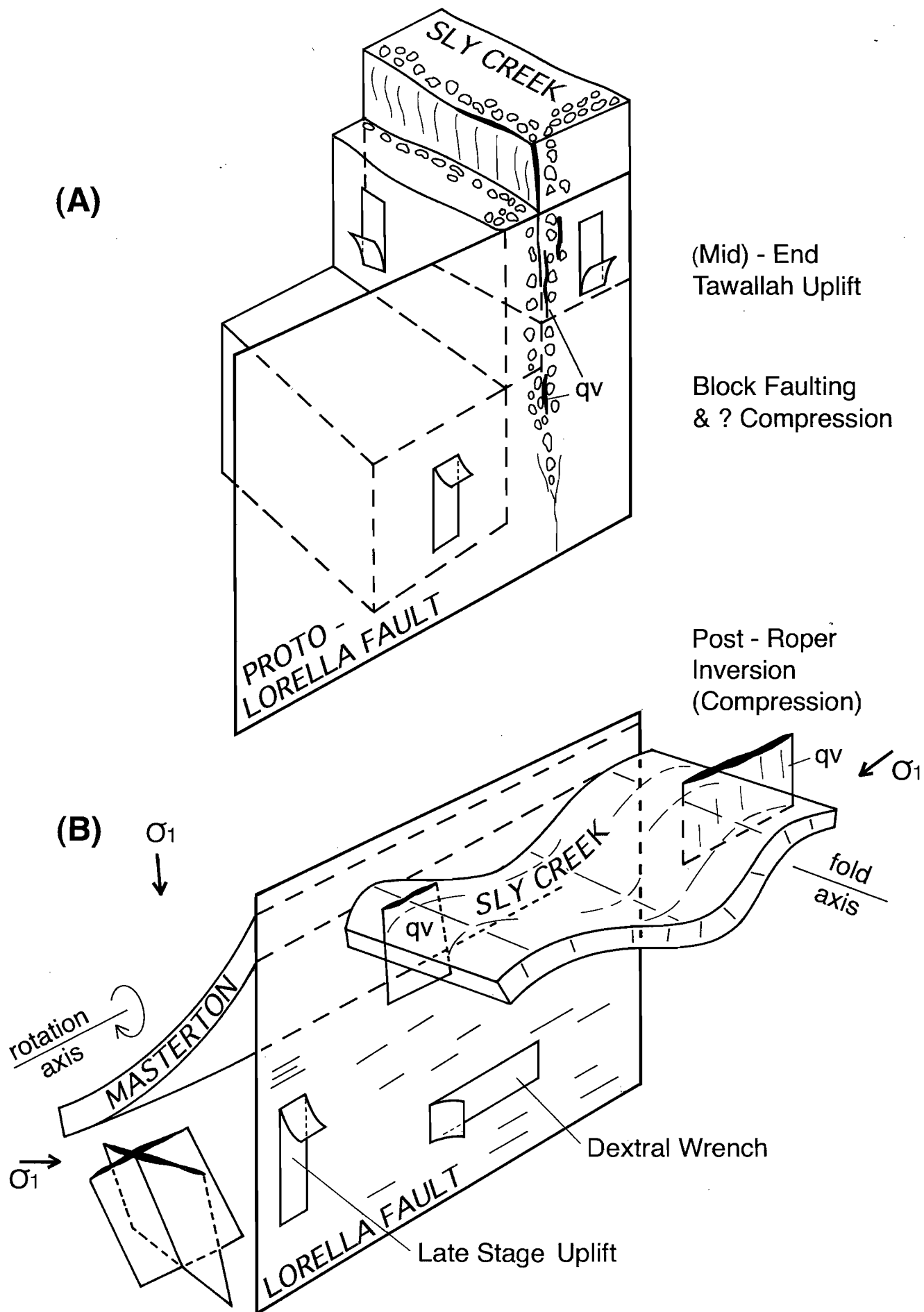


Figure 5 - Block diagram showing the Tawallah-age hematite breccia zones and post-Roper movements on the Lorella Fault.

extension and is the second of several movements recorded at the prospect.

The fault-related breccias contain strongly banded chert clasts (after dolomite) and form a spectacular looking rock. Make your own mind up as to its genesis; bear in mind, though, that as we shall see, the Cu mineralisation at the gossan also lies a short distance S of the fault in a similar position.

**Overprinting relationships** in the faults indicate the following sequence: reverse -> normal (sinistral) -> sinistral -> dextral. This sequence has a similar style and orientation to the D1, D3, D4 & D5 events in the Horse's Head structure of the Paroo Range in the Mt. Isa Inlier (Stewart 1992).

We shall be having a much closer look at the Amelia Dolomite on DAY 2.

#### *Stop 4C - Copper gossan*

The massive gossan occurs 100 m west of the road. It forms a line of sub E-W gossanous outcrops about 200 metres long that die out where the lode intersects the main NE-trending fault.

The gossans are derived from sulphidic zones in siderite-altered dolomitic beds. Fine malachite veins may be seen in a small pit at the western end of the gossan zone. A number of 2-5 mm thick, flatly dipping quartz veins, with delicate growth bands in their centres and limonite-manganese oxide halos, indicate a high level, near epithermal, origin for the mineralisation.

Copper mineralisation in similar rocks from Kilgour copper prospect will be presented and discussed at length during DAY 2.

*(Heartbreak is now exactly 100 km to your south!. Safe drive)*



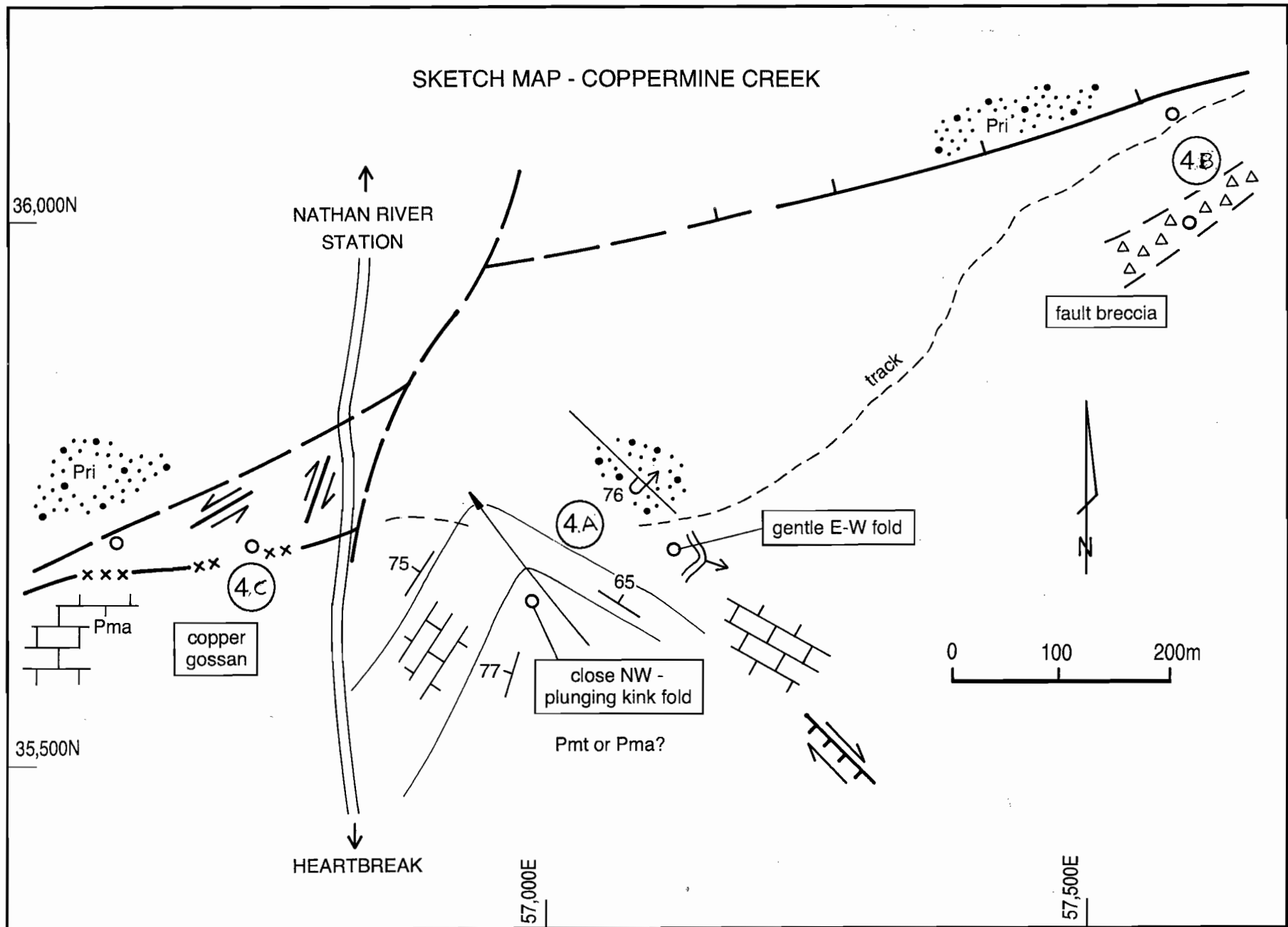


Figure 6 - Geological sketch map of the Coppermine Creek area.

## Day 2 - Geology and Geochemistry of the Upper Tawallah and Lower McArthur Groups, Kilgour Waterhole, Mallapunyah Dome

Stuart W. Bull, David R. Cooke and Serena Donovan

### INTRODUCTION

Mallapunyah Dome is a roughly circular feature with a diameter of approximately 10 km (Fig. 7) which occurs 65 km SSW of McArthur River. It consists of a core of upper Tawallah Group sedimentary and volcanic units flanked by McArthur Group sediments. The mechanism and timing of dome formation is undetermined. In the area of Kilgour Waterhole, the transition from upper Tawallah Group to lowermost McArthur Group is exposed on the western edge of the Dome. The units to be examined are the Settlement Creek Volcanics, Wollogorang Formation and Gold Creek Volcanics of the Tawallah Group and the Masterton Sandstone of the McArthur Group.

The general aims of the traverse are:

- (1) To demonstrate the nature of the Settlement Creek Volcanics which forms the basis of the largely intrusive emplacement model presented in Report No. 4 (Bull, 1993).
- (2) To examine selectively pervasive and vein-controlled potassic alteration in the Settlement Creek Volcanics, consider possible modes of formation, and discuss implications for metal transport and deposition.
- (3) To examine the unit mapped as the Gold Creek Volcanics at this locality and other areas on the flanks of Mallapunyah Dome and to assess its implications for the timing and genesis of Mallapunyah Dome.
- (4) To examine the general sedimentological characteristics of the Masterton Sandstone in the Mallapunyah Dome area for comparison with the section to be examined in the Batten Ranges on Day 3.

A summary of previous interpretations of the units exposed in the Kilgour Waterhole section (eg Jackson et al., 1987; Pietsch et al., 1991), and of revisions to these interpretations (Bull, 1993) is outlined below. This is followed by a description of the geological and geochemical characteristics of hydrothermal alteration in the Settlement Creek Volcanics around Mallapunyah Dome.

### STRATIGRAPHY

#### *Settlement Creek Volcanics*

The Settlement Creek Volcanics have been described as basic to intermediate intrusives, extrusive lavas, pyroclastics and minor intercalated sedimentary rocks (Jackson et al., 1987). The type section nominated for the unit is in the Mallapunyah Dome area, where its total thickness is between 100 and 150 m. The formation was originally considered to be present in all areas of Tawallah Group outcrop (with the possible exception of the Masterton Horst), but was interpreted to be sediment-dominated north of 16°40'S (Jackson et al., 1987). A depositional model was proposed in which the volcanic-dominated southern area represented subaerial extrusive volcanic activity associated with sedimentation in shallow lakes and lagoons. The sediment-dominated northern area was interpreted to represent marine deposition in a seaway.

More recent geological mapping and interpretation indicates that the proposed sediment-dominated northern portions of the Settlement Creek Volcanics belong to the Aquarium Formation (Pietsch et al., 1991). Outcrop of the Settlement Creek Volcanics to the north of Mallapunyah Dome is actually restricted to a large body in the Scrutton Range, and preserved remnants below the Masterton Sandstone in the Batten Range. In addition, the predominance of intrusive mafic units



was recognised during this study. The overall extrusive depositional model for the volcanic-dominated Settlement Creek Volcanics remained the same, however, the abundant intrusive mafic units were interpreted to represent a later phase of igneous activity associated with the emplacement of the Gold Creek Volcanics (Pietsch et al., 1991).

#### *Wollogorang Formation*

The Wollogorang Formation is a widespread and laterally continuous sedimentary unit with an average thickness in the order of 100 m. The nominated type section is several hundred kilometres to the east of the Mallapunyah Dome in the area of Wollogorang homestead. A reference section is defined as BMR drillhole Mount Young No. 2, which was collared over 100 km to the north of Mallapunyah Dome (Jackson et al., 1987). The formation has been the subject of an extensive sedimentological study (Jackson, 1982; Jackson et al., 1987), in which it has been subdivided into four distinct units:

Unit 1: brown-weathering shaly mudstone/siltstone with laminations, ripples and halite casts.

Unit 2: pale grey-weathering coarsely crystalline dolostone with a distinctive layer of bulbous, cherty, stromatolitic bioherms at the top.

Unit 3: light brown to dark grey-weathering, thin-bedded to laminated dolomitic siltstone to shale with distinctive ovoid bituminous dolomite nodules.

Unit 4: coarse-grained quartz sandstone.

Overall, the depositional model presented for the Wollogorang Formation involves fluvial and lacustrine deposition of the lower carbonate units, with possible marine incursion during the deposition of the uppermost sandstone unit (Jackson et al., 1987).

#### *Gold Creek Volcanics*

The Gold Creek Volcanics have been described as a complex sequence of basic to intermediate igneous rocks including trachyte or trachyandesite lava, agglomerate, tuff, dolerite, microsyenite and tuffaceous lithic sandstone and siltstone (Jackson et al., 1987). The unit has a widespread distribution, from the Scrutton Ranges in the north to the Redbank area in the south. It has been most extensively studied in the Redbank area, where copper mineralised breccia pipes occur at this stratigraphic level (eg. Knutson et al., 1979; Jackson

et al., 1987). In the Mallapunyah Dome area, the Gold Creek Volcanics are only patchily developed (Fig. 7). They were reported as four lenticular extrusive trachyte bodies, each up to 1000 m long and 50 m thick, and three intrusive bodies (Australian Geophysical Pty. Ltd., 1968; Jackson et al., 1987). Volcanic breccias that contain clasts of underlying units (eg. doleritic clasts from the Settlement Creek Volcanics and bituminous dolomite nodules from the Wollogorang Formation) were described as "agglomerates". These deposits were interpreted to indicate explosive volcanic eruptions during the emplacement of the Gold Creek Volcanics. Recent mapping and interpretation of the Bauhinia Downs 1:250,000 geological sheet indicates that outcrop of the Gold Creek Volcanics to the north of Mallapunyah Dome is restricted to the Scrutton Ranges, where the underlying Settlement Creek Volcanics are also best developed (Pietsch et al., 1991). The unit is approximately 180 m thick in this area and includes distinctive mafic peperitic deposits, indicative of high-level intrusive emplacement into wet unconsolidated sediment (Pietsch et al., 1991; Rawlings, 1993).

#### *Masterton Sandstone*

The Masterton Sandstone is a resistant ridge-forming unit which forms the base of the McArthur Group (Jackson et al., 1987). The unit occurs throughout the McArthur Basin and overlies various units of the Tawallah Group, including the Tanumbirini Rhyolite, the Warramana Sandstone, the Wununmantlyala Sandstone, the Settlement Creek Volcanics and the Gold Creek Volcanics (Pietsch et al., 1991). Regionally this contact is interpreted to represent an unconformity at the base of the McArthur Group, however, obvious unconformities have only been reported from the Redbank area, the Masterton Horst and the Batten Ranges (Jackson et al., 1987). In other areas there is no evidence of structural discordance at the basal contact of the Masterton Sandstone, suggesting that the McArthur Group is structurally conformable with the Tawallah Group.

In terms of its sedimentological characteristics, the Masterton Sandstone can be subdivided as follows:

- (1) A lower, pebble to cobble conglomerate facies which varies in thickness from 0 to 650 m. It has been interpreted to represent alluvial fan/braided fluvial deposition on a dissected palaeosurface (Jackson et al., 1987; Pietsch et al., 1991; Bull, 1993).
- (2) A middle, fine- to medium-grained, planar-laminated, cross-laminated and rippled quartz

Figure 7 (facing page) - Locality map of stops in the Mallapunyah Dome area for day 2. Geology after Jackson et al., 1984. Australia 1:100,000 Geological Special. Geology of the Abner Range Region. Abbreviations - Tawallah Group: Pty - Yiyintyi Sandstone; Pts - Seigal Volcanics; Ptl - Sly Creek Sandstone; Ptlr - Rosie Creek Sandstone; Ptq - Aquarium Formation; Ptn - Wununmantlyala Sandstone; Pte - Settlement Creek Sandstone; Pto - Wollogorang Formation; Ptg - Gold Creek Volcanics; Ptm - Warramana Sandstone; Ptt - Tanumbirini Rhyolite; McArthur Group: Pms - Masterton Sandstone; Pml - Malapunyah Formation; Pma - Amelia Sandstone; Pmd - Tatoola Sandstone.



Back of  
Fig 7

Mallapragah

Map

sandstone with minor siltstone, which has been interpreted to represent deposition in a littoral marine environment (Jackson et al., 1987).

- (3) An upper, mainly medium- to coarse-grained, ferruginous evaporitic sandstone which has been interpreted to represent a transition to intertidal and beach sedimentation (Jackson et al., 1987).

The type section of the Masterton Sandstone occurs at Kilgour Gorge on the eastern margin of Mallapunyah Dome (Jackson et al., 1987). The basal conglomerate unit is only sparsely developed in this area, where the 50 to 150 m thick Masterton Sandstone section is sandstone-dominated.

## DISCUSSION

The original emplacement model for the Settlement Creek and Gold Creek Volcanics involved largely extrusive volcanic activity (Jackson et al., 1987). Two main lines of evidence were cited:

- (1) Amygdaloidal and vesicular ropy flow tops described from the Settlement Creek Volcanics.
- (2) Volcanic breccias described as "agglomerates" associated with both volcanic units, which were interpreted to represent explosive and, therefore, extrusive volcanic activity.

With the exception of the peperitic Gold Creek Volcanics in the Scrutton Ranges and at Redbank, the exposure of the Settlement Creek Volcanics at the base of the Kilgour Waterhole traverse is typical of both the Settlement Creek and Gold Creek Volcanics observed in the Scrutton Ranges and the Mallapunyah Dome area during this study. In general, the bulk of the exposure consists of massive fine- to medium-grained dolerite (Plates 1A and B) with locally developed monolithic, pebble- to cobble- sized doleritic breccias. Although the unit occasionally displays a basaltic texture (Plates 1D and E), no evidence of extrusive volcanic activity has been observed. Since the units are generally concordant with regional stratigraphy, they have been interpreted as mafic sills with quench and/or mechanically brecciated unit margins (Bull, 1993; Fig. 8). Relatively thin, linear flow banded and autobrecciated rhyolite units are also present in both the Settlement Creek and Gold Creek Volcanics. Many of these occur at high angles to regional strike and are interpreted to have been emplaced as dykes.

In a regional sense, the mafic sills that comprise the bulk of the Settlement Creek Volcanics have clearly accumulated at the base of the Wollogorang

Formation, which therefore appears to have acted as a partial barrier to magma ascension. A possible explanation is that the basal units of the Wollogorang Formation, being carbonate-dominated, would have been susceptible to early diagenetic processes such as compaction and cementation. Evidence of such early diagenetic activity is provided by the bituminous carbonate nodules characteristic of unit 3 (Jackson, 1982; Jackson et al., 1987). Further evidence that the carbonate-dominated basal units of the Wollogorang Formation were relatively consolidated early in their burial history is provided by the upper contact of the Settlement Creek Volcanics in BMR drillhole Mt Young No. 1. This contact is apparently intrusive, comprising a breccia zone which consists primarily of apparently "baked" clasts from the overlying Wollogorang Formation.

Where mafic magma did breach the Wollogorang Formation carbonates in the Scrutton Ranges, peperitic breccias formed, providing clear evidence of high level intrusion into unconsolidated sediment (Pietsch et al., 1991; Rawlings, 1993). Whereas the bulk of the units mapped as Gold Creek Volcanics in the Mallapunyah Dome are also volcanic breccias, they are markedly different from the Scrutton Range peperites. The breccia units at this locality are markedly heterolithic, and contain clasts of dolerite similar to those of the Settlement Creek Volcanics, and dolomite clearly derived from the Wollogorang Formation (including the distinctive bituminous nodules). These are the deposits originally described as "agglomerates" and interpreted to represent explosive volcanic activity. However, in thin section these units clearly have a terrigenous muddy matrix (Plate 1G). In combination with the massive nature of the deposits, this suggests that they actually represent epiclastic debris flow deposits.

The presence of debris flow deposits immediately above the Wollogorang Formation at Mallapunyah Dome constrains the timing of development of the dome as a positive topographic feature. Dolomitic Wollogorang Formation deposits occur in the dome interior (Fig. 7). Since these deposits are interpreted to have accumulated in a low relief, predominantly lacustrine environment, the Mallapunyah Dome could not have been a topographic high during the deposition of the Wollogorang Formation. In contrast, the distribution of the Gold Creek Volcanics breccia deposits around the flanks of the dome (Fig. 7), and the fact that these debris flow units indicate the active erosion of consolidated Settlement Creek Volcanics and Wollogorang Formation deposits, indicate that the Mallapunyah Dome had developed as a positive topographic feature by this time.



The Masterton Sandstone section at the top of the Kilgour Waterhole traverse is a typical exposure of the unit in the Mallapunyah Dome area. The basal conglomeratic unit is only sparsely developed in the region, and only the middle and upper sandstone-dominated units are present in the area (Fig. 9). These deposits have previously been interpreted to represent littoral marine conditions, transitional at the top to intertidal and beach deposits (Jackson et al., 1987). An alternative explanation is that they are genetically related to the underlying alluvial conglomeratic deposits, and represent more distal deposition in a braided fluvial or braidplain system (Bull, 1993). Evidence cited in support of this model was:

- (1) The relatively high-energy nature of the predominant suite of sedimentary structures comprising planar and low-angle truncating lamination associated with scattered to abundant trough and planar cross-bed sets.
- (2) The essentially unidirectional palaeocurrent pattern indicated by measurements from the cross-bed sets at any given locality.
- (3) The lack of wave associated sedimentary structures (eg. swash stratification indicative of beach face or hummocky stratification indicative of deeper water storm wave-associated reworking), other than symmetrical wave ripples.

All of these features of the sandy units of the Masterton Sandstone are present in the Kilgour Waterhole section. The conglomeratic basal unit will be viewed in the Batten Ranges on Day 3 allowing for a fuller discussion of the palaeoenvironmental significance of the unit as a whole.

## ALTERATION

### Introduction

A variety of alteration styles are recognised in the Upper Tawallah and Lower McArthur groups in the Mallapunyah Dome region. Silicification and hematisation occurs in sandstone units adjacent to faults (eg. Masterton and Wununmantlyala Sandstone), commonly associated with hydraulic brecciation. The alteration halos are interpreted to be the result of late (post-Roper?) cross-stratal fluid flow during high-level brittle failure events (Rogers, 1994). Intense hematite alteration recognised around vertical fractures in the Gold Creek Volcanics at Kilgour Waterhole is interpreted to be a weathering feature, possibly reflecting an original

erosional surface at the top of the Tawallah Group. Massive hematite alteration in the Wollongorang Formation at West Mallapunyah Dome is also interpreted as an erosional surface (Donovan, 1993). In the Settlement Creek and Gold Creek Volcanics, widespread and pervasive potassic alteration has imparted a pink colouration that is characteristic of these units. Patchy green chloritic alteration is also recognised locally. The following sections outline the characteristics of these last two alteration styles in more detail.

### POTASSIC ALTERATION

Potassic alteration of the Settlement Creek Volcanics at Mallapunyah Dome is characterised by the assemblage orthoclase + quartz  $\pm$  sericite  $\pm$  adularia  $\pm$  anatase  $\pm$  hematite. Some local development of minor hematite and kaolinite may be related to recent weathering. Three varieties of potassic alteration are recognised: (1) regional scale, incipient to moderate to intense, texturally preserving to texturally destructive, *selectively pervasive* potassic alteration; (2) intense, pervasive, texturally destructive *vein-related* potassic alteration halos that enclose quartz-hematite and dolomite-chlorite veins and hydraulic breccias; (3) intense, pervasive, texturally destructive potassic alteration that surrounds *amygdules*.

*Selectively pervasive* potassic alteration has resulted in the preferential replacement of plagioclase by pink orthoclase ( $\pm$  minor hematite), and augite by sericite. Original doleritic textures have commonly been preserved or even enhanced (Plates 1A and 1C). The groundmass has been partially replaced by secondary quartz  $\pm$  orthoclase  $\pm$  sericite  $\pm$  anatase (Plate 1C). This variety of potassic alteration is the most widespread in the Settlement Creek Volcanics, and shows no systematic relationship with fractures or permeable horizons such as volcanic breccias.

Intense *vein-related* potassic alteration halos up to 0.5 m wide enclose thin quartz-hematite and dolomite-chlorite veins that cross-cut dolerites at several localities in Mallapunyah Dome (Fig. 7). This texturally destructive variety of potassic alteration commonly results in a fine grained massive rock comprised solely of quartz and orthoclase. The timing relationships between pervasive vein-related potassic alteration and selectively pervasive potassic alteration are ambiguous. Cross-cutting relationships suggest that vein-related potassic alteration post-dates the selectively pervasive variety. However, some selectively pervasive alteration may have formed as an outer halo to vein-related alteration.

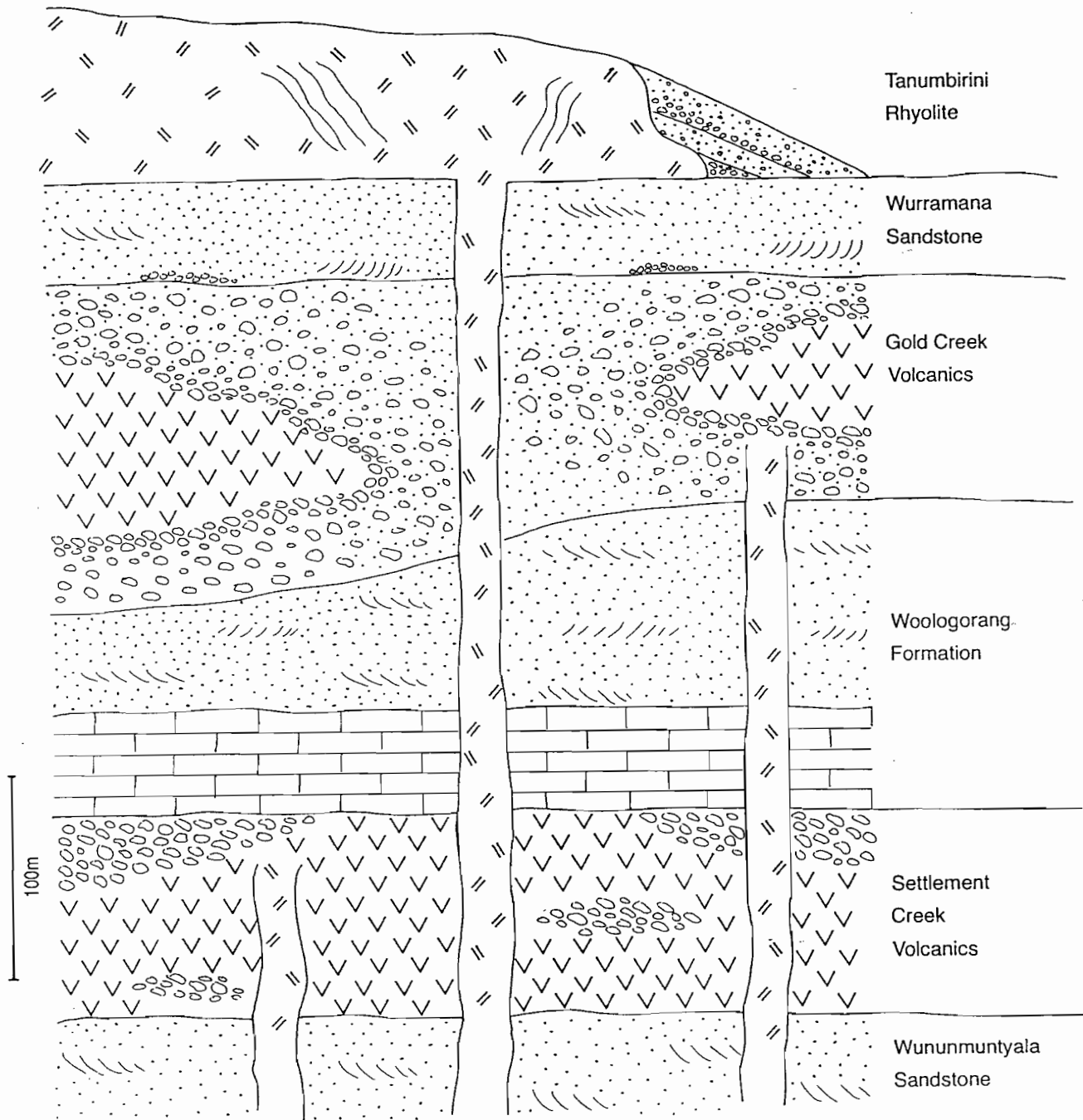


Figure 8 - Schematic model for the accumulation of the upper part of the Tawallah Group in which the Settlement Creek and Gold Creek Volcanics represent mafic sills intruded at different stratigraphic levels. These mafic units are subsequently cut by rhyolite sills/dykes (after Bull, 1993).



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Plate 1: SETTLEMENT CREEK VOLCANICS, GOLD CREEK VOLCANICS AND AMELIA DOLOMITE

A. Medium to coarse grained Settlement Creek dolerite from Kilgour Gorge, showing typical intrusive doleritic texture and selectively pervasive alteration of primary plagioclase crystals by orthoclase.

B. Photomicrograph of the Settlement Creek Volcanics (x 5) from northern Mallapunyah Dome showing typical intrusive (doleritic) texture and incipient chloritic alteration.

C. Photomicrograph showing intense, texturally preserving potassic alteration of Settlement Creek dolerite from Kilgour Gorge (x 2.5), with complete replacement of plagioclase by orthoclase. Chlorite has replaced primary mafic phenocrysts and part of the groundmass. Late dusting of feldspars by clay minerals is related to weathering.

D. Photomicrograph of the Settlement Creek Volcanics (x 2.5) from Kilgour Gorge showing a porphyritic (basaltic) texture.

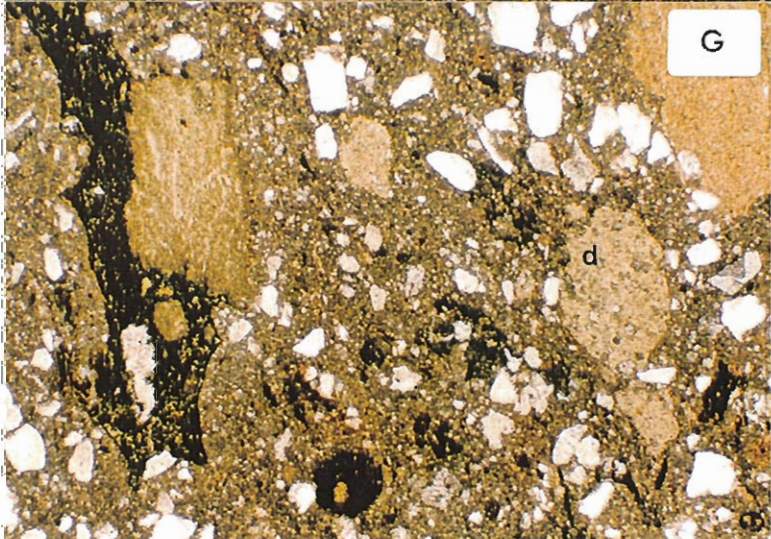
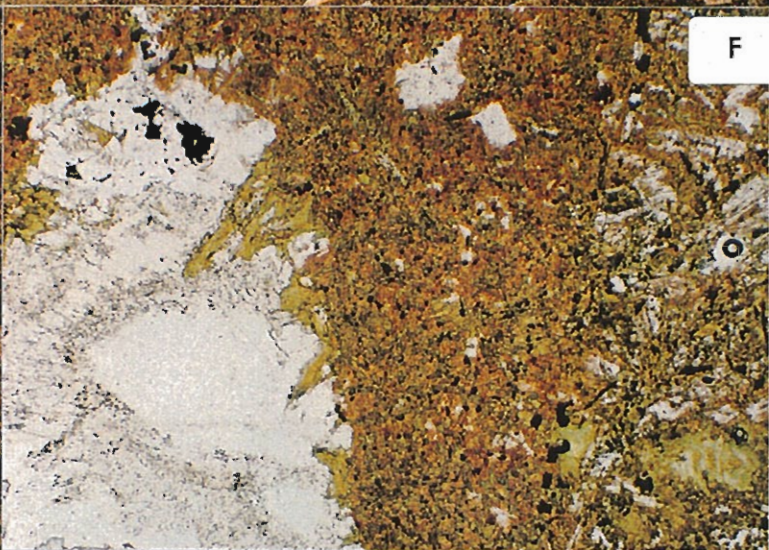
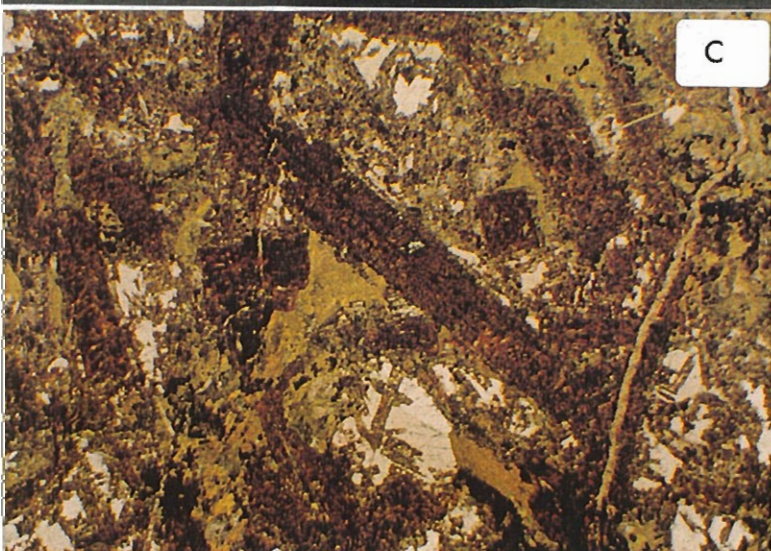
E. Photomicrograph showing a clast of porphyritic basalt in a chlorite-dolomite breccia hosted by potassic-altered medium grained dolerite (x 2.5).

F. Photomicrograph of quartz-chlorite filled amygdule in Settlement Creek dolerite surrounded by a rim of intense, texturally destructive potassic alteration that gives way outwards to texturally preserving, selectively pervasive potassic and chloritic alteration. Note the abundant primary fluid inclusions in a growth zone in the quartz crystal.

G. Photomicrograph of the Gold Creek Volcanics (x 5) from Kilgour Waterhole showing a chlorite altered volcanic fragment (dark fragment at left), dolomite lithics (eg. d) and crystal fragments in a fine-grained muddy matrix.

H. Amelia Dolomite from Kilgour Copper Mine, with a solution collapse breccia on the right hand side of the sample. Malachite occurs in the matrix of the breccia and along fractures in the dolomite. Clasts are comprised of clay-altered Amelia Dolomite. Note the bleached alteration halos around the collapse breccia and the thin fractures that occur at the top and bottom of the sample. Intraclast brecciation is recognisable at the top of the sample - no mineralisation occurs in the matrix to this breccia.

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Rare, intense, texturally destructive potassic alteration halos surround *amygdules* in chloritically altered Settlement Creek Volcanics (Plate 1F). These thin ( $\leq 1$  cm) alteration rinds are the rarest variety of potassic alteration, possibly because they can only be distinguished in samples that have not been subjected to selectively pervasive or vein-related potassic alteration. Some amygdules are filled by euhedral quartz crystals that contain primary fluid inclusions along growth zones (eg. Plate 1F); others are filled by complex bands of dolomite, quartz and/or chlorite. Rare primary fluid inclusions that contain daughter salts are testament to the involvement of hypersaline brines during amygdale formation and related potassic alteration.

#### CHLORITIC ALTERATION

Texturally preserving, incipient to moderate pervasive chloritic alteration is characterised by the assemblage chlorite - dolomite  $\pm$  sericite  $\pm$  actinolite  $\pm$  quartz  $\pm$  anatase. Hand specimens are characterised by a greenish colour due to the abundance of chlorite and the paucity of secondary orthoclase. Primary pyroxene, hornblende and the groundmass have been partially replaced by chlorite  $\pm$  actinolite  $\pm$  dolomite  $\pm$  quartz (Plate 1B and 1F). Plagioclase crystals are partially altered to dolomite  $\pm$  sericite. Anatase occurs with chlorite in the groundmass and has probably replaced magnetite. Chloritic alteration of dolerite clasts has occurred in hydraulic breccias sealed in a chlorite-dolomite matrix (Plate 1E).

Patchy development of domains of selectively pervasive potassic alteration in chloritically altered samples has led to some confusion as to the nature of alteration types in the Settlement Creek volcanics. For example, Jackson et al. (1987) did not recognise that the chloritic and potassic alteration assemblages were separate, attributing them both to a single period of late potassium metasomatism. More detailed petrographic studies of overprinting relationships in this study demonstrate that in most cases the chloritic assemblage preceded potassic alteration. However, some chloritic alteration may have formed as an outer halo synchronous with amygdale-related potassic alteration, and Donovan (1993) recognised local overprinting of potassic alteration by late-stage dolomite at West Mallapunyah Dome. Paragenetic relationships are therefore complicated and are the subject of on-going research.

#### WHOLE ROCK GEOCHEMISTRY

Donovan (1993) has presented results of whole rock geochemical analyses of altered dolerites and rhyolites from the Settlement Creek and Gold Creek Volcanics at West Mallapunyah Dome, as part of a larger program investigating these units in the Mallapunyah Dome and Scrutton Range areas. Important conclusions from her study and from the on-going research program are:

- 'Dolerites' from the Settlement Creek Volcanics contain up to 12.2 wt %  $K_2O$ , 66.5 wt %  $SiO_2$  and between 2.2 and 21.3 wt %  $Fe_2O_3$ , reflecting the dramatic chemical effects of potassic alteration
- Potassic alteration has caused enrichment of  $SiO_2$ ,  $K_2O$  and  $Fe_2O_3$ , and depletion of  $MnO$ ,  $MgO$ ,  $CaO$ ,  $Na_2O$ ,  $P_2O_5$ ,  $Cu$ ,  $Zn$ ,  $Ni$ ,  $Cr$ ,  $Ba$  and all REE except  $Eu$  compared to chloritically altered samples.
- Compared to the Settlement Creek Volcanics of Bauhinia Downs (Rawlings et al., 1993), intense potassic alteration has caused enrichment of  $K_2O$ ,  $TiO_2$ ,  $Fe_2O_3$  and  $V$ , and depletion of  $MnO$ ,  $MgO$ ,  $CaO$ ,  $Na_2O$ ,  $Cu$ ,  $Pb$ ,  $Zn$ ,  $Ni$ ,  $Sr$ ,  $Cr$ ,  $Ba$  and  $Zr$ .
- The mobility of  $TiO_2$ ,  $Zr$ ,  $Nb$ ,  $Y$  and REE during potassic alteration at West Mallapunyah Dome invalidates the use of traditional geochemically-based classification schemes (eg. Winchester and Floyd, 1977; Findlow-Bates and Stumpfl, 1981) for the Settlement Creek and Gold Creek Volcanics
- Significant base metal depletion has occurred during potassic alteration. Base metal contents are low (5-8 ppm  $Cu$ ; 11-20 ppm  $Zn$ ; 3-5 ppm  $Pb$ ) compared to chloritically altered samples (20-43 ppm  $Cu$ ; 21-29 ppm  $Zn$ ; 2-5 ppm  $Pb$ ) from West Mallapunyah Dome, Settlement Creek dolerites from Bauhinia Downs (25 ppm  $Cu$ ; 44 ppm  $Zn$ , 6 ppm  $Pb$ ; Rawlings et al., 1993) and tholeiitic dolerites from other sedimentary basins (eg. Rooi Rand, South Africa: 287 ppm  $Cu$ ; 110 ppm  $Zn$ ; Cox, 1988).

#### STABLE ISOTOPE GEOCHEMISTRY

Oxygen isotopic analyses of K-feldspar, chlorite and potassically altered whole rock samples, carbon and oxygen isotopic analyses of dolomite veins and amygdules, and oxygen isotopic analyses of quartz veins related to potassic alteration in the Settlement Creek Volcanics have been conducted to help



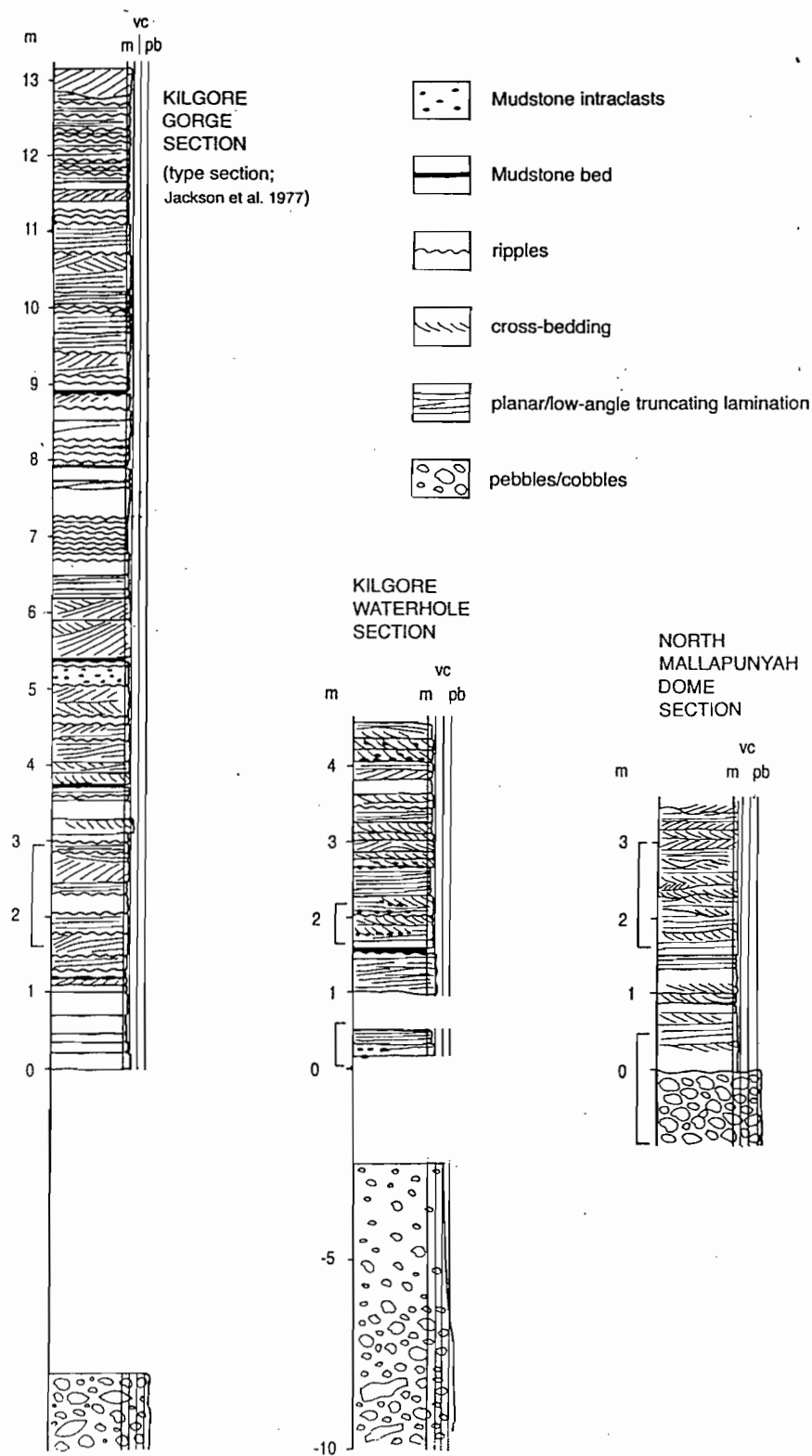


Figure 9 - Detailed sedimentological sections measured through the Masterton Sandstone at three localities in the Mallapunyah/Kiana Domes area.

Host Rock	Sample Material	$\delta^{18}\text{O}$ (SMOW)	$\delta^{13}\text{C}$ (PDB)	Reference
Pte	orthoclase - potassic alt.	+12.4 to +16.5		This study
Pte	whole rock - potassic alt.	+15.7 to +19.7		Donovan (1993)
Pte	quartz vein	+20.0 to +20.6		This study; Donovan (1993)
Pte	dol vein & bx - potassic alt.	+16.5 to +20.1	-4.3 to -2.0	This study
Pte	dolomite amygdules	+21.7 to +28.6	-3.4 to -2.6	This study
Pte	chlorite - chloritic alt.	+8.9 to +11.7		This study
Pte	chlorite vein - chloritic alt.	+8.3		This study
Pto	whole rock (dolostone)	+18.1 to +24.2	-1.3 to -0.5	This study
Pms	whole rock (sandstone)	+9.9		Donovan (1993)
Pml	whole rock (dolostone)	+17.9	-1.3	This study
Pma	whole rock (Kilgour Cu)	+25.5 to +27.4	-1.6 to -0.1	This study
Pma	breccia matrix (Kilgour Cu)	+20.7 to +25.1	-4.5 to -0.2	This study
Pma	dolomite clast (Kilgour Cu)	+20.3 to +25.7	-5.9 to -1.1	This study
Pma	dolomite vein (Kilgour Cu)	+19.3	-1.2	This study
Pmr	whole rock (Darcys Cu)	+26.0	+0.0	This study

Table 1 - Stable isotopic data for altered Settlement Creek Volcanics and representative Upper Tawallah and Lower McArthur Group lithologies in the Mallapunyah Dome region. Analyses also provided for the host dolomites, clasts and breccia matrix from Kilgour Cu and Darcys Cu mine. Pte - Settlement Creek Volcanics. Pto - Wologorang Formation. Pms - Masterton Sandstone. Pml - Mallapunyah Formation. Pma - Amelia Dolomite. Pmr - Reward Dolomite.

determine the origin(s) of potassic and chloritic alteration. Whole rock isotopic analyses of dolomitic horizons from the Wologorang and Mallapunyah Formations and the Amelia Dolomite, and of the Masterton Sandstone have been obtained for comparative purposes. The results are listed in Table 1 and illustrated on Figure 10.

Potassic alteration and related veins and amygdules in the Settlement Creek volcanics are characterised by heavy  $\delta^{18}\text{O}_{(\text{mineral})}$  values and relatively light  $\delta^{13}\text{C}_{(\text{mineral})}$  values (Table 1). The heaviest  $\delta^{18}\text{O}_{(\text{mineral})}$  values come from dolomite amygdules that have potassic alteration rinds. In contrast, chlorite from chloritically altered dolerites and related veins is characterised by lighter  $\delta^{18}\text{O}_{(\text{mineral})}$  values (+8.3 to +11.7). Although no temperature data are currently available to calculate  $\delta^{18}\text{O}_{(\text{fluid})}$  values, the fluids responsible for chloritic alteration probably were depleted in  $^{18}\text{O}$  compared to those involved in potassic alteration.

## GENESIS

Donnelly and Jackson (1988) proposed that dolomite veins in the Settlement Creek Volcanics intersected by BMR drillhole Mt. Young No. 2 are magmatic in origin due to their distinctly negative  $\delta^{13}\text{C}$  values (-4.7 to -3.6‰). They inferred a high temperature of formation for the veins, but suggested that the heavy  $\delta^{18}\text{O}$  values reflected recrystallisation of dolomite by a later low temperature (< 100°C) fluid that passed through the Wologorang Formation and Settlement Creek Volcanics. Pietsch et al. (1991)

proposed that potassium metasomatism of the Settlement Creek Volcanics in the Bauhinia Downs region occurred during the later stages of magmatic activity, due to the preservation of doleritic textures, whereas late-stage alteration by meteoric waters led to the introduction of free quartz, carbonate and chlorite.

A magmatic-hydrothermal origin for potassic alteration is considered unlikely because the pyroxene-phyric dolerites of the Settlement Creek Volcanics represent relatively dry melts that were most likely incapable of exsolving sufficient fluid to produce widespread and pervasive alteration. However, primary daughter salt-bearing fluid inclusions in amygdules provides evidence for the passage of hypersaline brines through the volcanics. The heavy  $\delta^{18}\text{O}$  values from quartz and dolomite veins and related potassic alteration halos are similar to the values recorded from dolomites in the Wologorang Formation and the Amelia Dolomite (Fig. 10). Potassic alteration is therefore interpreted to have formed during passage of low temperature brines derived from the overlying evaporitic dolomites during diagenesis. Diagenetic fluids passed along fractures, joints, flow boundaries and vesicles, forming veins, amygdules, and pervasive potassic alteration halos. Selectively pervasive potassic alteration probably formed when diagenetic brines permeated through the volcanics along grain boundary margins at lower fluid-rock ratios (thereby explaining the texturally preserving nature of this alteration style). Lighter  $\delta^{13}\text{C}$  values in the dolomite veins may reflect a meteoric component and/or bacterial oxidation of reduced C.



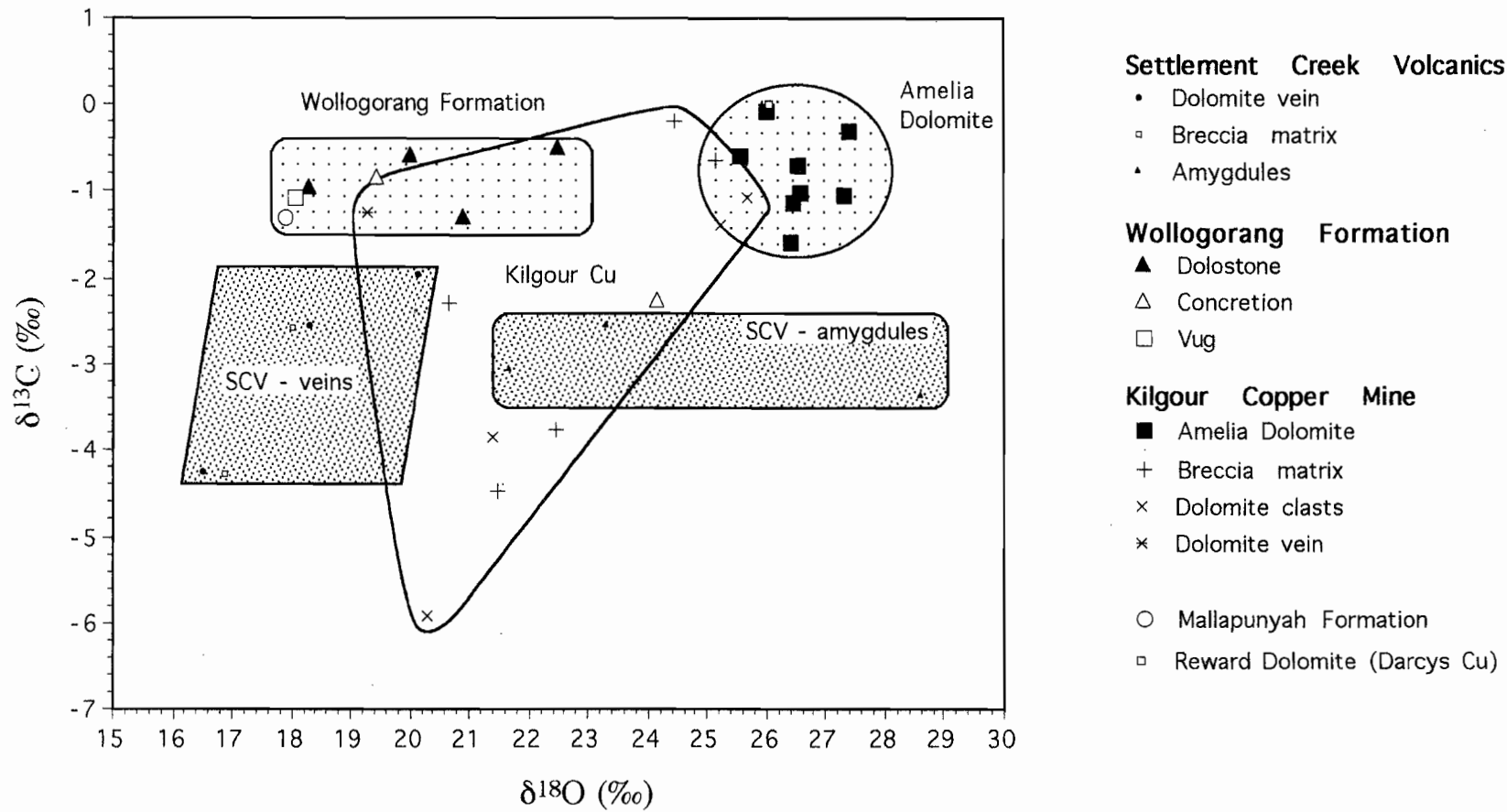


Figure 10 -  $\delta^{13}\text{C}$  vs  $\delta^{18}\text{O}$  plot for dolomite veins, breccias, amygdules and whole rock samples from the Upper Tawallah and Lower McArthur Groups, Mallapunyah Dome region. SCV = Settlement Creek Volcanics.

## STOP 1 - SETTLEMENT CREEK VOLCANICS

The Settlement Creek Volcanics crop out in the stream bed pavement at this locality. They consist of typical massive, medium-grained dolerite, and are interpreted to have been emplaced as an intrusive sill. Vein-related potassic alteration halos up to 30 cm wide enclose thin NW- to NE-trending and later E-trending quartz-hematite veins and hydraulic breccias in the dolerite. Selectively pervasive potassic alteration can be recognised away from the veins, but is partially obscured by recent weathering.

Pebble to cobble-sized breccias are present on the slope up to the small hill north of the stream pavement. Clasts consist of angular to sub-rounded, fine-grained, sparsely vesicular and amygdaloidal dolerite. In some areas, the clasts are in a jigsaw-fit arrangement, but they are clearly rotated in others. Regionally, these breccias are associated with the margins of bodies of massive intrusive dolerite, and are interpreted as pods of chilled and/or mechanically brecciated material produced during emplacement. A relatively thin, linear, flow banded rhyolite body is also present on the lower slopes of the hill. This unit is typical of the rhyolites of the Settlement Creek and Gold Creek Volcanics, which are interpreted as dykes.

## STOP 2 - WOLLOGORANG FORMATION

As outlined above, the Wologorang Formation has been the focus of extensive sedimentological studies. The unit has therefore not been examined in any detail during this project. The contact between the Settlement Creek Volcanics the Wologorang Formation in this area appears to be quite irregular, and the small Wologorang Formation section on the bank of the creek is only a few metres above the contact. It consists of thinly-bedded dolomitic siltstone with abundant planar and low-angle truncating laminae and ripples. It is interpreted to represent Unit 3 of Jackson (1982) and Jackson et al., (1987), because the bituminous dolomitic nodules characteristic of this interval are weathering out of the recessive area immediately above the section.

## STOP 3A - GOLD CREEK VOLCANICS

The Gold Creek Volcanics at this locality consist of a closely packed, open framework, heterolithic, pebble to cobble to boulder breccia. Clasts are angular to rounded, and some of the larger blocks of dolomite are slabs of original sedimentary bedding. Other clast types include fragments of fine- to medium-grained dolerite identical in appearance to the Settlement Creek Volcanics, and ovoid bituminous dolomite nodules characteristic of unit 3 of the Wologorang Formation. The unit becomes finer-grained with a more open framework towards the upper contact with the Masterton Sandstone, where a pervasive horizontal fabric (?compactional) is defined by preferential orientation of clasts. In thin section, the matrix of this breccia unit clearly consists of terrigenous muddy material (Plate 1G), and is therefore interpreted to represent a debris flow deposit. Its presence at this stratigraphic level clearly indicates that the Wologorang Formation was consolidated, uplifted and was being subjected to erosion at this time.

## STOP 3B - MASTERTON SANDSTONE

The Masterton Sandstone section exposed in the gorge west of stop 3A consists of a medium-bedded, variably hematitic, fine- to medium-grained sandstone. The major sedimentary structures are abundant planar lamination and cross-bedding indicative of tractional deposition under relatively high hydraulic energy conditions. The true thickness of the Masterton Sandstone at this locality appears to be exaggerated by structural repetition.





## Day 2 - Kilgour Copper Mine

David R. Cooke

### INTRODUCTION

Kilgour Copper mine is located 2 km west of Kilgour Waterhole (Fig. 7), and is hosted by the Amelia Dolomite of the Lower McArthur Group. This unit conformably overlies the Mallapunyah Formation, and is thought to have been deposited in a broad marginal sabkha setting (Muir, 1979).

Kilgour Cu mine yielded 125 tons of ore during sporadic production from 1913 to 1955 (Plumb and Rhodes, 1964). Malachite and minor azurite, bornite, cerussite and barite occur in solution collapse breccias, along bedding planes and in cross-cutting fractures in stromatolitic and massive Amelia Dolomite. Remnants of a steeply plunging massive copper-hematite gossan are present; the gossan dies out suddenly at a depth of 5 m (Plumb and Rhodes, 1964). Analysis of one gossan sample revealed a content of 16 % Cu (Jackson et al., 1987).

Jackson et al. (1987) claimed that extensive weathering and erosion exposed the Amelia Dolomite during the Late Proterozoic, prior to the deposition of the Cambrian Bukalara Sandstone. Erosion produced an irregular karst land surface, and the Bukalara Sandstone partially filled the solution or collapse features that now also host Cu mineralisation (Jackson et al. 1987).

### COLLAPSE BRECCIAS

Solution collapse features at Kilgour Cu are typically fracture controlled, and have sharp, well-defined contacts with the Amelia Dolomite. Some collapse breccias have been localised on the margins of large stromatolites, and terminate in a recessive, mineralised dolomitic siltstone horizon. Bleached alteration halos occur around the breccias, and around malachite-lined fractures and dolomite veins (Plate 1H). Dolomite clasts have commonly been altered to clay minerals(?) ± secondary dolomite. Coarse to fine grained crystalline

dolomite is the dominant matrix-fill, together with malachite and minor azurite and hematite.

### TIMING OF BRECCIATION

The timing of brecciation and copper mineralisation at Kilgour Cu is debatable. Jackson et al. (1987) inferred a Late Proterozoic-Cambrian timing for brecciation, based on the presence of clasts of Bukalara Sandstone in the top of the collapse breccias. However, during this study, sandstone blocks have been noted at the top of narrow, vertical, fracture-controlled mineralised breccias that terminate *within* the dolomite, indicating that collapse of overlying sandstone into a cavernous weathered doline landform is unlikely. Petrographic examinations have revealed that dolomitic sandstone horizons are present in the Amelia Dolomite at Kilgour Cu, suggesting that some of the sandstone clasts could have been derived internally from within the Amelia Dolomite.

The Amelia Dolomite is remarkably fresh for a unit that has purportedly undergone extensive weathering and erosion in the Late Proterozoic. There is no evidence of a regolith surface below the 'Bukalara Sandstone', and the contact between the Amelia Dolomite and 'Bukalara Sandstone' 500 m north of Kilgour Cu appears to be gradational. It is more likely that the small outlier of sandstone is actually the base of the Tatology Sandstone. The timing of solution and collapse are therefore indeterminate on geological grounds - breccia formation could have occurred anytime after the deposition of the Amelia Dolomite.

### BRECCIATION MECHANISMS

Since the dolomitic breccias at Kilgour Cu probably did not form at a paleoweathering horizon, an alternative mechanism of breccia formation is



required. Three hypotheses have been formulated: (1) Sub-surface cave formation and collapse brecciation was caused by descending meteoric water flushing through and dissolving the dolomite sometime after dolomitisation. Mineralisation could have formed anytime during or after initial dolomite dissolution. (2) A fault breccia that contains silicified dolomite clasts has been recognised at the north-eastern corner of the mine, suggesting that solution collapse and copper deposition could have been triggered by infiltration of Cu-bearing hydrothermal fluids into fractures during faulting. (3) Collapse brecciation may have been triggered by dissolution of halite from salt-rich beds in the underlying Mallapunyah Formation. In this model, mineralisation would postdate collapse brecciation.

#### STABLE ISOTOPE DATA

Results of oxygen and carbon isotopic analyses of dolomite from Kilgour Cu are summarised in Table 1. Compared to other dolomitic lithologies from the Upper Tawallah and Lower McArthur groups, the Amelia Dolomite has typical  $\delta^{13}\text{C}$  values ( $\approx -1$  to  $0\text{‰}$ ) but is enriched in  $\delta^{18}\text{O}$  (Fig. 10), reflecting its

evaporitic depositional environment. Dolomite clasts and secondary dolomite in the breccia matrix are depleted in  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  compared to the Amelia Dolomite, and are intriguingly similar to values from dolomitic veins and amygdules in the Settlement Creek Volcanics (Table 1; Fig. 10).

Donnelly and Jackson (1988) proposed that isotopically light carbon ( $-4.7$  to  $-3.6\text{‰}$ ) in dolomitic veins from the Settlement Creek Volcanics is magmatic in origin. However, a magmatic source of carbon is unlikely for the veins and breccias at Kilgour Cu, because the nearest volcanic unit (the Settlement Creek Volcanics) is separated from Kilgour Cu by abundant carbonate horizons (eg the Wollogorang and Mallapunyah Formations, and the Amelia Dolomite itself). Instead, meteoric fluids charged with isotopically light  $\text{CO}_2$  ( $\approx -7\text{‰}$ ) are believed to have partially dissolved the Amelia Dolomite along permeable conduits, triggering solution collapse, and causing alteration of primary dolomite and partial isotopic exchange of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  with meteoric groundwaters. Copper mineralisation probably occurred sometime after initial meteoric flushing, perhaps in association with faulting and silicification at the northern end of the mine site.

## STOP 4

Stromatolites up to 3m in diameter are exposed in the large pit at the mine site. Malachite occurs along bedding planes, in cross-cutting fractures and in collapse breccias on the margins of the stromatolites. Some collapse breccias flare upwards and terminate at the recessive mineralised bed. Others continue through the recessive horizon to the present day surface. Note the sandstone clast at the top of one of the flaring collapse breccias, and the bleached dolomite clasts.

Approximately 30 m north of the pit, silicified dolomite clasts occur in what is interpreted to be a fault breccia. Fault-related silicification of dolomite is uncommon in the Mallapunyah Dome region, although silicification halos are easily recognisable around faults in the sandstones. A small outcrop of sandstone occurs on the northern side of the fault.

Approximately 500 m north of the mine site, red dolomitic siltstones and dolomites are overlain by coarse white sandstone on a small knoll. Note the absence of weathering features in the dolomite. Intraclast breccias become more abundant towards the top of the dolomite, and a small channel conglomerate with dolomite clasts in a quartz sand matrix is present immediately below the sandstone contact. This was originally interpreted by Jackson et al. (1987) as an unconformable contact between the Amelia Dolomite and the Cambrian Bukalara Sandstone. It is now thought to represent a gradational contact between the Amelia Dolomite and the Tootola Sandstone.

## STOP 5

An apparently stratiform barite occurrence more than 2 km long has been recognised on the western flank of Mallapunyah Dome, 6 km north of Kilgour Cu (Donovan, 1993). Barite occurs in the soil profile as nodules up to 30 cm in diameter, in an area devoid of outcrop. The barite is believed to be hosted by the Amelia Dolomite, at approximately the same stratigraphic position as mineralisation at Kilgour Cu. The nodules are characterised by a central mush of syn-sedimentary breccia surrounded by radiating fibrous swallow tail crystals growing outwards to the edge of the nodules (Donovan, 1993). These textures are identical to gypsum nodules described from Nottinghamshire by Richardson (1920).

Sulfur isotopic analyses of barite yielded  $\delta^{34}\text{S}$  values between +37.7 to +50.0 (Donovan, 1993). They are interpreted to reflect sulfur fractionation due to biogenic reduction somewhere below the site of barite deposition. Biogenic reduction produced a residual  $\delta^{34}\text{S}$ -enriched, Ba-rich fluid that ascended and interacted with pre-existing gypsum nodules to produce barite (Donovan, 1993). A potential base metal trap may have existed at the site of biogenic reduction, somewhere below the barite occurrence (Donovan, 1993).





## Day 2 - Section of the Barney Creek Formation and adjacent units in the Top Crossing area

Stuart W. Bull

### INTRODUCTION

The often recessive sediments of the McArthur Group are relatively well exposed in the Top Crossing area (Fig. 11). The general aim of this traverse is to examine the sedimentological characteristics of the Barney Creek Formation in the field at some distance from the HYC deposit. No sedimentological work has been done on the unit at HYC itself in the course of this project, however, core from HYC will be viewed on Day 4 and some comparisons can therefore be made.

The contact relationships with the adjacent underlying Coxco Dolomite Member and overlying Reward Dolomite will also be examined in this traverse, as will part of the Lynott Formation which is the basal unit of the overlying Batten Sub-Group.

### STRATIGRAPHY

#### *Teena Dolomite - Coxco Dolomite Member*

The Teena Dolomite is a thick- to thin-bedded or laminated, locally stromatolitic dololomite with minor intercalated dolomitic shale, siltstone, dolarenite and intraclastic conglomerate (Jackson et al., 1987; Pietsch et al., 1991). The unit is subdivided into the lower Teena Dolomite which is approximately 60 m thick, and the overlying Coxco Dolomite Member which is 15 to 70 m thick (Jackson et al., 1987). Overall, the Coxco Dolomite Member is a thick-bedded dololomite with rare stromatolites at the base. Zones of thin-bedded dololomite are locally present with abundant interbeds of pink, buff and orange weathering potassium-rich mudstones that are generally interpreted as "tuffs". The Coxco Dolomite Member is characterised by the presence of radiating bundles of acicular crystal pseudomorphs which are up to 6 cm long and generally oriented perpendicular to bedding. These

are interpreted to be gypsum pseudomorphs (Walker et al., 1977), and their habit suggests that they represent mats of bottom nucleated crystals of the type commonly formed in shallow evaporitic brine pools. Other evaporitic features include discoidal gypsum casts and rare small cauliflower chert nodules interpreted to be after anhydrite (Pietsch et al., 1991).

#### *Barney Creek Formation*

The Barney Creek Formation is a generally recessive unit of thinly-bedded, planar-laminated, dolomitic, carbonaceous and locally pyritic siltstones shales and dololutes (Pietsch et al., 1991). The unit is very variable in thickness, ranging up to 700 m in the area of the McArthur River mineralisation, and 900 m in the Glyde Sub-basin. In the McArthur River area the Barney Creek Formation has been subdivided into three members, mainly on the basis of subsurface data (Jackson et al., 1987; Pietsch et al., 1991). The basal W-Fold Shale Member comprises green and red dolomitic potassium rich siltstone and shale and green vitric tuff. The overlying HYC Pyritic Shale Member consists of the characteristic thinly-bedded, planar-laminated, carbonaceous, dolomitic and locally pyritic siltstone. Other sedimentary structures which have been reported in the unit are graded beds, scour structures, ripple marks, flame structures and slump related soft-sediment deformation (Jackson et al., 1987). An evaluation of the possible depositional environment of this part of the Barney Creek Formation is the focus of the discussion section below. In the area of the McArthur River mineralisation the HYC Pyritic Shale contains sedimentary breccia beds. Three types have been identified based on clast types (Walker et al., 1978), and these units have been interpreted as fault-sourced debris. The Cooley Dolomite Member is a major fault related talus slope deposit which interdigitates with the other



units of the Barney Creek Formation in the area of the HYC deposit.

#### *Reward Dolomite*

The Reward Dolomite is a locally stromatolitic dololite and pelletal or intraclastic dolarenite with minor shale, sandstone, sandy dolarenite and chaotic breccia (Pietsch et al., 1991). The unit is very variable in both lithology and thickness. The thicker intervals (up to 350 m) are generally shale-dominated and coincide with the thicker parts of the underlying Barney Creek Formation (Jackson et al., 1987). The thinner intervals generally consist of abundantly stromatolitic dolostone. The Reward Dolomite is characterised by the presence of abundant chert nodules and silica spheroids which range from a few millimetres to a few centimetres in diameter. These are interpreted as early diagenetic features (Jackson et al., 1987). Other features such as the development of "thrombolites" (grey dolomites mottled with white spar) and pisoids are interpreted to indicate weathering in the vadose zone (Jackson et al., 1987). The depositional environment of the Reward Dolomite has been interpreted as very shallow-water to emergent conditions where sediments accumulated in lakes, ponds and lagoons which were near the level of the prevailing groundwater table (Jackson et al., 1987).

#### *Lynott Formation*

The Lynott Formation, which comprises the base of the Batten Sub-Group, overlies the Reward Dolomite conformably and disconformably (Pietsch et al., 1991). In general the unit consists of dolomitic siltstone, dolarenite, chertified stromatolitic dolostone and lesser dolomitic sandstone (Pietsch et al., 1991). The Lynott Formation has been subdivided into the Caranbirini, Hot Springs and Donnegan Members (Jackson et al., 1987).

The Caranbirini Member is up to 300 m thick and consists of thinly-bedded to laminated, pyritic and carbonaceous dolomitic siltstone, shale and silty dololite (Pietsch et al., 1991). Slump structures and slump generated breccias are locally abundant, and halite casts and needle shaped gypsum pseudomorphs occur in the upper part of the unit. In outcrop and drill core the Caranbirini Member strongly resembles the Barney Creek Formation. The Hot Springs Member ranges in thickness from 50 to 350 m and is characterised by the presence of stromatolitic dolostone (usually chertified), dolarenite and sandstone beds, and abundant evaporitic pseudomorphs (Pietsch et al., 1991). The Donnegan Member is irregularly distributed and ranges up to 134 m in thickness. It consists of fine-grained dolomitic sandstone and siltstone with

basal stromatolitic dolostone, and abundant cauliflower and enterolithic chert after anhydrite.

The Lynott Formation has been the focus of a detailed sedimentological analysis (Jackson et al., 1987) in which the type section was divided into 8 members (2 in the Caranbirini Member, 4 in the Hot Springs Member and 2 in the Donnegan Member). Overall the unit was interpreted as a regressive paralic succession developed in an ephemeral lake. In this model the Caranbirini Member represents sublittoral marine or lacustrine basin sedimentation transitional at the top to lagoonal deposition, the Hot Springs Member represents intertidal and supratidal deposits, and the Donnegan Member represents sabkha conditions.

#### DISCUSSION

Two distinct depositional models have been proposed for the Barney Creek Formation. Brown et al (1978) examined the Barney Creek Formation and adjacent stratigraphy in field sections, mainly in the Top Crossing area, and in drill cores from the HYC deposit. They interpreted the Barney Creek Formation to represent "deeper water shaly carbonates" which were deposited as the result of a sea level transgression. In this model the transgressive event began after the deposition of the Myrtle Shale as a predominantly subaerial siltstone, and the transgressive sequence comprises the Mara Dolomite (intertidal deposits), the Mitchell Yard and Coxco Dolomite Members (shallow marine carbonates) and the Barney Creek Formation. Transgression was terminated by a regressive event which resulted in the return to shallower water conditions (the Reward Dolomite) and the development of local unconformities. Evidence cited in support of this model was abundant features indicative of shallow water/subaerial deposition (eg. evaporitic pseudomorphs after features such as halite casts and beds of gypsum needles, and algal structures such as oolites and stromatolites) in the adjacent units which were absent from the Barney Creek Formation.

A new depositional model for the Barney Creek Formation began to emerge with the publication of an abstract by Williams and Logan (1981). They interpreted the Barney Creek Formation to represent a mixture of shallow water/ephemeral marginal marine or lacustrine sabkha deposition and turbiditic deposition at "intermediate" water depths. Evidence cited to support shallow/ephemeral deposition of some of the sediments hosting the HYC mineralisation was the presence of distinctive dolomite nodules in a matrix of distorted carbonaceous siltstone. These were interpreted to be analogous to modern nodular

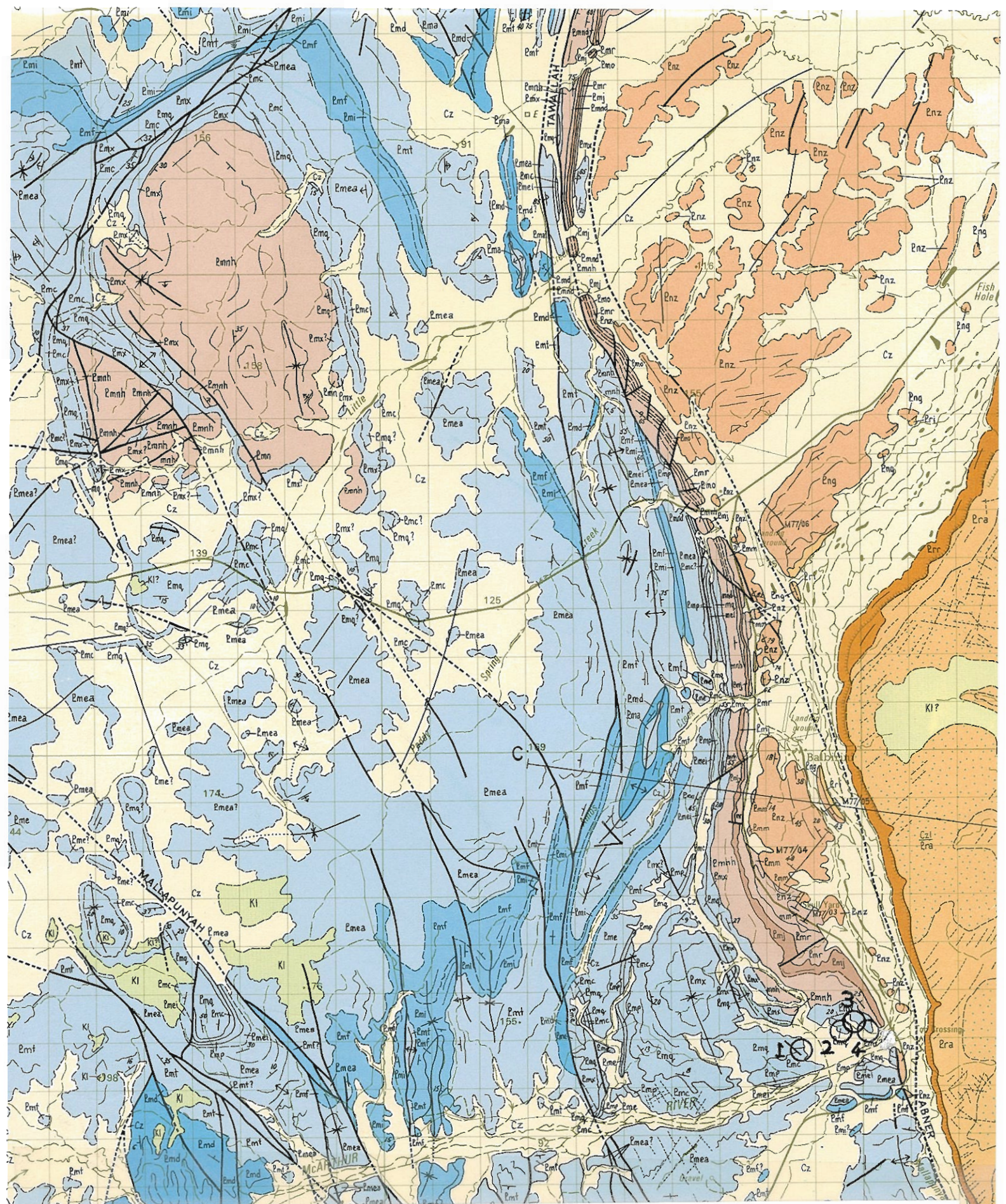


Figure 11 - Locality map for the Day 2 Top Crossing traverse. Geology after Jackson et al., 1984. Australia 1:100,000 Geological Special. Geology of the Abner Range Region. Abbreviations - McArthur Group (Umbolooga Subgroup): Pms - Masterton Sandstone; Pml - Malapunyah Formation; Pma - Amelia Sandstone; Pmd - Tootoola Sandstone; Pmt - Tooganinie Formation; Pmi - Leila Sandstone; Pmf - Myrtle Shale; Pmea - Mara Dolomite Member; Pmei - Mitchell Yard Dolomite Member; Pmp - Teena Dolomite; Pmpc - Coxco Dolomite Member; Pmq - Barney Creek Formation; Pmx - Reward Dolomite; (Batten Subgroup) Pmnc - Caranbirini Member; Pmnh - Hot Springs Member; Pmnd - Donnegan Member; Pmj - Yalco Formation; Pmr - Stretton Sandstone; Pmo - Looking Glass Formation.

carbonate- and anhydrite-bearing sediments which accumulate in shallow to emergent sabkha and saline lacustrine environments. It was noted that although both the shallow and deep water facies were mineralised, mineralisation was better developed in the deeper water deposits. This was interpreted to indicate some form of sedimentary control on the HYC mineralisation.

Muir (1983) used the evidence presented by Williams and Logan (1981), and also cited the occurrence of lithified crusts, tepee structures, intraclast conglomerates and pedogenic pisoids, to propose a purely lacustrine/sabkha depositional model for the Barney Creek Formation. This model was based on the occurrence of similar sedimentological features in the ephemeral lakes of the Coorong area in South Australia. This is also the depositional model presented in Jackson et al. (1987).

A further abstract published by Logan and Williams (1984) refined their original depositional model for the Barney Creek Formation. It was proposed that the fluctuating depositional conditions during the accumulation of the unit represented a period of instability on the Emu Fault which controlled syngenetic HYC mineralisation. In this model, the sediments below and above the HYC deposit accumulated at the eastern margin of a large lake or lagoon. This feature extended well to the west of the area of the HYC deposit, such that a shallow to emergent zone adjacent to the Cooley Dolomite talus apron graded into deeper water conditions to the west. Any hydrothermal solutions which vented at this time were dispersed in the large water body and could only form minor concentrations of mineralisation. In contrast, the sediments which host the economic mineralisation were interpreted to have accumulated in a much smaller lagoon which was similar in size to the HYC deposit itself. The deepest part of the water body was immediately adjacent to the Cooley Dolomite, and it was flanked by emergent areas where sabkha deposits accumulated. This feature was interpreted to have acted as a hydrological trap for hydrothermal solutions allowing the development of high-grade mineralisation.

In considering the possible depositional environments represented by the Barney Creek Formation it is important to be clear about the terminology used. Firstly, the term "deep water" or equivalent is often applied to graded bedded turbiditic sandstone and mudstone facies with the implication, particularly in older studies, that this indicates offshore marine conditions. In fact turbidites can accumulate in any water body, marine or continental, where low hydraulic energy

conditions prevail at the bottom such that the deposits are preserved from reworking by wave-generated and/or other current activity (eg. Muir, 1983). Turbidite sequences are, therefore, really only indicative of deposition below wave base. The depth to wave base is dependant on multiple factors such as the size and shape of the water body involved and the local climatic conditions, however, a reasonable range would be in the order of 10 to 50 m.

A second point which needs clarification is the use of the term sabkha. Although sabkha deposits are characterised by the presence of evaporite minerals or their pseudomorphs, they are not the only environment in which evaporite minerals can form. A recent definition of sabkha is "marine and continental mudflats where displacive and replacive evaporite minerals are forming in the capillary zone above a saline water table" (Warren, 1989). A facies model for sabkha deposits has been developed, largely from studies of the coastal deposits of Abu Dhabi, in which the sabkha is considered in terms of distinctive subtidal, intertidal and supratidal areas (Warren, 1989). The offshore subtidal area consists of clastic marine deposits and the intertidal area is characterised by algal mats. Both these areas typically host the subsurface growth of displacive gypsum crystals, however, the bulk of the evaporitic minerals, typically gypsum and anhydrite, occur in the capillary zone in the supratidal area where they grow displacively in a clastic framework. Abundant growth of layers of anhydrite leads to the enterolithic folding textures diagnostic of the sabkha environment.

Ultimately subsurface evaporite growth in the supratidal area raises the sabkha surface such that the uppermost deposits are elevated out of the capillary zone into the vadose zone where desiccation results in wind erosion of the sabkha cap. Overall progradation of the sabkha produces a characteristic vertical cycle which consists of subtidal, intertidal and supratidal deposits with an erosional unconformity at the top. In marine settings this cycle is typically upwards fining, however, in continental settings where sabkha deposits often occur in tectonically active grabens where alluvial/fluvial sedimentation predominates this cycle is often upwards coarsening. Importantly, because the thickness of the capillary zone is restricted to approximately 1 m and any deposits above this zone are dried up and eroded, an entire sabkha cycle is generally less than 1 m thick. Sea level and tectonic fluctuations can, however, lead to stacking of successive sabkha cycles in the rock record.



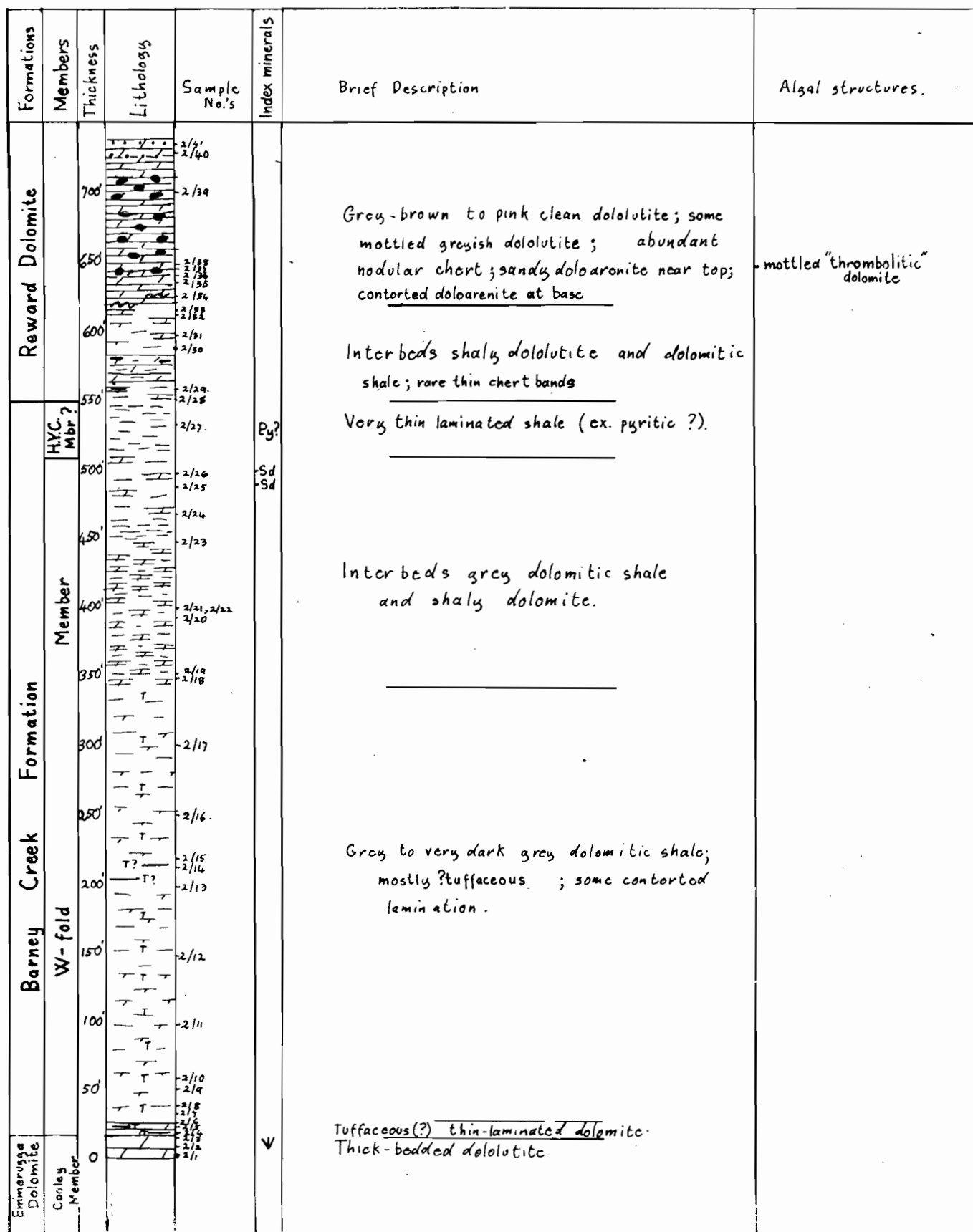


Figure 12 - Measured section of the Barney Creek Formation about 4 km west of Top Crossing (after Brown et al., 1978)

## STOP 1 - CONTACT BETWEEN THE COXCO DOLOMITE MEMBER OF THE TEENA DOLOMITE AND THE BARNEY CREEK FORMATION

*The traverse begins at the Top Crossing of the McArthur River which is 45 km north of the turnoff to Kilgour Waterhole and 8 km south of Heartbreak. Follow the north bank of the river west of the road for approximately 2 km to where a steep sided mesa of dolomite occurs on the north bank of the river. A low hill a few hundred metres to the north exposes the contact between the Coxco Dolomite Member and the Barney Creek Formation (Fig. 11).*

The Coxco Dolomite Member at this locality is a grey to buff coloured, massive and recrystallised medium- to thin-bedded dolomite which forms a low hill. Relict planar-laminated and sparsely rippled intervals are present, some of which are silicified. The "coxco needles" diagnostic of this unit are abundant. Thin units of pink to orange coloured dolomitic siltstone commonly interpreted as potassium feldspar altered tuff bands are present at several levels. In terms of the depositional environment of the Coxco Member, the "coxco needles" diagnostic of the unit, which are pseudomorphs after bottom nucleated gypsum crystals, indicate that it accumulated in shallow evaporitic brine pools.

The contact with the overlying Barney Creek Formation is gradational over several metres at the crest of the hill as the deposits become thinner-bedded and abundantly planar-laminated. Small (ie. up to 5 cm), scattered hematite nodules are abundant at this level, some of which have indented convex margins. That they may be pseudomorphs after nodular pyrite. Four hundred metres to the WNW is a small cliff exposure of the lower part of the Barney Creek Formation. The unit consists of thinly-bedded, abundantly planar-laminated dolomitic siltstone which is brown to buff coloured on the weathered surface but grey to black where fresh. Several very thin (< 1 cm) examples of the pink altered units are present. Overall the outcrop consists of relatively resistant dolomitic bands separated by recessive fissile layers on a scale of a few centimetres to a few tens of centimetres. This process also appears to be occurring on a much larger scale. The Barney Creek Formation above the basal cliff section is represented by a flat plain to the NE which is presumed to represent recessive fissile deposits. Scattered low hilly outcrops on the plain represent more dolomitised areas.

A section was measured and geochemical samples were taken through the Barney Creek Formation in the top crossing area by Brown et al., (1978). It is clear from the section that this lower part of the unit was interpreted to represent a correlative of the W-Fold Shale Member (Fig. 12).

## STOP 2 - UPPER BARNEY CREEK FORMATION

*A cliff exposure of the upper Barney Creek Formation occurs approximately 1 km to the NE across the flat recessive plain (Fig. 11).*

This interval is similar in appearance to the basal section, however, sparsely developed low-angle truncating laminae and ripples are present, as are shallow scour features. This part of the unit was apparently interpreted to represent a correlative of the HYC Shale Member (Brown et al., 1978; Fig. 12). In one area the characteristic planar lamination is disrupted beneath a 10 cm thick dolomitic siltstone bed. In detail, this bed appears to consist of two amalgamated turbiditic units, the lower of which is patchily altered to the pink and orange material usually considered to be characteristic of "tuff" units.

This locality completes the section through the Barney Creek Formation at Top Crossing and some comment can, therefore, be made with respect to possible depositional environments for the unit in this area. Firstly, the unit is fine-grained and contains no tractional sedimentary structures indicating that it accumulated in a quiet, low-energy environment. Secondly, the unit contains no features which could be interpreted as evidence of shallow to emergent conditions (eg. algal mats or stromatolites, flat pebble breccias, pseudomorphs after evaporite minerals etc.). The Barney Creek Formation in the Top Crossing area is, therefore, interpreted to represent sub-wave base deposition in a relatively large water body. If this water body was the same one responsible for the unit in the area of the McArthur River mineralisation, this interpretation would be consistent with the model presented by Logan and Williams (1984). However, if the Barney Creek Formation sediments are not time transgressive, the model for the HYC mineralisation presented by Logan and Williams (1984) implies that a shallow to emergent facies association is present somewhere within the unit.



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STOP 3 - CONTACT BETWEEN THE UPPER BARNEY CREEK FORMATION AND THE REWARD DOLOMITE

*Three hundred metres to the ESE of the cliff exposure of upper Barney Creek Formation, the contact with the overlying Reward Dolomite is exposed at the foot of the slope.*

The Barney Creek Formation at this locality is restricted to small scattered outcrops at the base of the slope which appear identical to those in the cliff section at the previous locality. In other areas where the Barney Creek Formation below the contact is better exposed, tepee structures and chert nodules which may be pseudomorphs after nodular anhydrite are present in the upper few metres of the unit below the contact.

The Reward Dolomite at this locality consists of massive recrystallised grey to cream coloured dolomite with abundant irregularly shaped chert nodules. These are elongate in the plane of bedding and range in size up to 20 cm thick and 1 m long. Some are internally concentrically zoned, however, others overprint original planar sedimentary lamination in the dolomite. These features do not resemble the distinctive cauliflower chert nodules considered to be anhydrite pseudomorphs and they are interpreted to be diagenetic in origin. Moving east along the base of the slope the upper part of the Reward Dolomite is intensely silicified and brecciated. This zone may represent a weathering surface developed in the interval prior to the deposition of the overlying Batten Sub-Group.

STOP 4 - LYNOTT FORMATION (HOT SPRINGS MEMBER)

*A section through the basal unit of the Batten Sub-Group, the Lynott Formation, is exposed where the prominent ridge runs down to the river flat (Fig. 11).*

The Lynott Formation at this locality consists predominantly of planar-laminated dolomitic siltstone. Scattered planar- and truncating-laminated and cross-bedded coarse-grained sandstone and gravel beds, and the occurrence of a stromatolitic bioherm which forms the ridge crest, indicate that this section represents the intertidal to supratidal deposits of the Hot Spring Member (Jackson et al., 1987). The basal Caranbirini Member is, therefore, thin and recessive or absent at this locality. At the top of the section on the eastern face of the ridge a series of resistant pink to orange coloured beds occur which are up to 1 m thick. This is the style of alteration which is generally assumed to indicate "tuffaceous" units, however, at the top of the interval the pink to orange alteration is clearly overprinting "normal" planar-laminated dolostone.

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## Day 3 - Structure and Sedimentology of the Tawallah and Lower McArthur Groups, Batten Range

Stuart W. Bull and Jamie R. Rogers

### INTRODUCTION

The Batten Range, located approximately 50 km west of the McArthur River deposit, is bounded by the Tawallah Fault along its eastern margin (Fig. 13). The Tawallah Fault has been reactivated several times during its history, so that the oldest sedimentary package (Tawallah Group) and parts of the basement (Scrutton Volcanics) are currently exposed along its western side. In the Batten Range, the lowermost units of the Tawallah Group up to and including the Settlement Creek Volcanics are exposed, which are in turn directly overlain by basal McArthur Group sediments.

The fault block that includes the Batten Range was a positive topographic feature during the early evolution of the southern McArthur Basin, being structurally emplaced by the "Mid-Tawallah" basin inversion event (Rogers, 1993). The extensional phase that followed saw the uplifted block acting as a source for clastic alluvial / fluvial sediments of the upper Tawallah Group and lower McArthur Group (Bull, 1993; Rogers, 1993), and was associated with bimodal and felsic volcanism (Settlement Creek and Gold Creek Volcanics, Tanumbirini Rhyolite). With the cessation of extension (perhaps during a NW-SE directed compressional event at some stage during McArthur Group time; Keele, 1993), suppression of relief led to continued deposition of the carbonate-

dominated McArthur and Nathan Groups in a sag-type environment (Bull, 1993). The uppermost unit of the McArthur Basin, the sandstone dominated Roper Group, may have developed in response to another, as yet unrecognised, compressional tectonic event (Bull, 1993). The major structural event to affect the southern McArthur Basin was a NE-SW directed compression post-dating all sedimentary deposition and may represent final basin closure. This event, termed the Post-Roper Inversion (Rogers, 1993), saw the reactivation of early segmented basinal structures to wrench or thrust fault geometries (depending on initial orientation), the former being the case for the Batten Range.

In summary, the Batten Range has undergone a complex structural history involving multiple periods of high level brittle deformation, with dextral wrench faulting associated with the Post-Roper Inversion particularly well recorded.

Two traverses will be completed in the Batten Range. The morning traverse provides an examination of the major structure in the area, the Tawallah Fault, and its effects on a lower Tawallah Group unit, the Sly Creek Sandstone. The aim of the afternoon traverse is to investigate the transition from Tawallah Group to McArthur Group, providing structural and sedimentological field evidence for the "Mid Tawallah" basin inversion.



## MORNING TRAVERSE - TAWALLAH FAULT

In this traverse, we will examine of the Tawallah Fault at the eastern margin of the Batten Range. Locally, the fault strikes NNE (010-020), displays a steep westerly dip between 60 and 80° and is defined by a 100 m wide silicification zone displaying several aspects of brittle deformation (hydraulic fault brecciation, fault striae and stockwork veining). These features have developed mostly in response to post-Roper dextral wrench movements on the Tawallah Fault.

The fault is hosted by the Sly Creek Sandstone, a red to white, massive to thickly bedded and intensely silicified hematitic quartz sandstone. Sedimentary structures usually present in the unit including high angle cross beds, ripples and thin (cm) sedimentary breccia beds, with the exception of bedding, are completely destroyed in the silicification zone.

Fault breccias are monomict, comprising silicified sandstone clasts in quartz-hematite matrices that under Sibson's (1989) classification represent hydraulic implosion breccias developed during seismic rupturing in a dilational environment. Brecciation associated with the Tawallah Fault is generally confined to a 150 m wide zone. Breccias that occur outside this area have developed in relation to secondary fault structures.

Late-stage quartz-hematite veins that cross-cut fault breccias at the locality may be observed up to 500 meters away from the fault zone. These show a range of orientations although vertical veins predominate. Cross cutting relationships between the late-stage veins define a complex paragenesis suggesting multiple periods of dilation adjacent to the fault zone, probably in a transtensional environment. Excellent examples of host rock controls on mineral precipitation are present, where remobilisation of primary hematite and silica from the fault breccias has resulted in local precipitation of coarse, bladed hematite and quartz in late-stage tension gashes.

*Day 3 begins with a 64 km drive north of Heartbreak Hotel to the eastern side of the Batten Range. After travelling 55 km along the Cape Crawford-Borrooloola road, turn right into a disused station track. The morning traverse commences 9 km south of this turn-off, where a 500 m flagged track leads to a creek section through the ridge forming Sly Creek Sandstone. After turning off the Cape Crawford-Borrooloola road, we essentially follow the Tawallah Fault into the Batten Range with silicified, fractured and brecciated Mallapunyah Formation exposed to the west from 4-5 km south of the turn-off. Thickly*

*bedded Cretaceous sandstone exposures can also be seen at intervals to the east.*

## STOP 1 - TAWALLAH FAULT

*Stop 1A - quartz-hematite brecciation, late-stage quartz-hematite stockwork veining*

A cliff section of massive to thickly bedded and silicified Sly Creek Sandstone enables examination of brittle deformational features approximately 20 m into the Tawallah Fault Zone. Sporadically developed throughout the section are quartz-hematite fault breccias. Breccia textures vary from clast-supported, jigsaw-fit through to matrix-supported, open framework with random clast orientation. Breccia clasts are unimodal comprising silicified Sly Creek Sandstone wall rock fragments that range from millimetres to decimetres in size. Breccia matrices are composed of quartz and hematite, with goethite, limonite and leucoxene developed in the more weathered examples.

Another feature of this locality are thin (< 5 cm) late-stage quartz-hematite tension gashes. Vein orientations are predominantly vertical, although flat, moderately dipping and bedding parallel orientations are also present. Quartz and coarse, bladed hematite veins are generally hosted in the more silicic and hematitic wall rock portions respectively suggesting remobilisation from fault breccias during late-stage dilation adjacent to the Tawallah Fault.

*Stop 1B - silicic brecciation*

Local development of a rebrecciated silicic breccia has occurred approximately 50 m along the creek section into the fault zone. Breccia clasts in this example are composed of quartz-hematite breccia contained in a milky quartz stockwork matrix. This form of brecciation is rare, and may be synchronous with late-stage quartz-hematite veining. Local variations in the quartz-hematite breccias can also be seen at this locality, with clast-supported, jigsaw-fit breccias grading laterally into more chaotic matrix-supported breccias.

*Stop 1C - fault striae*

In the cliff section 20 m to the north, original bedding can be recognised, although internal sedimentary structures are absent. Fresh surfaces show the Sly Creek Sandstone as a red/purple, medium grained and intensely silicified hematitic quartz sandstone.



P44

back of Fig 13

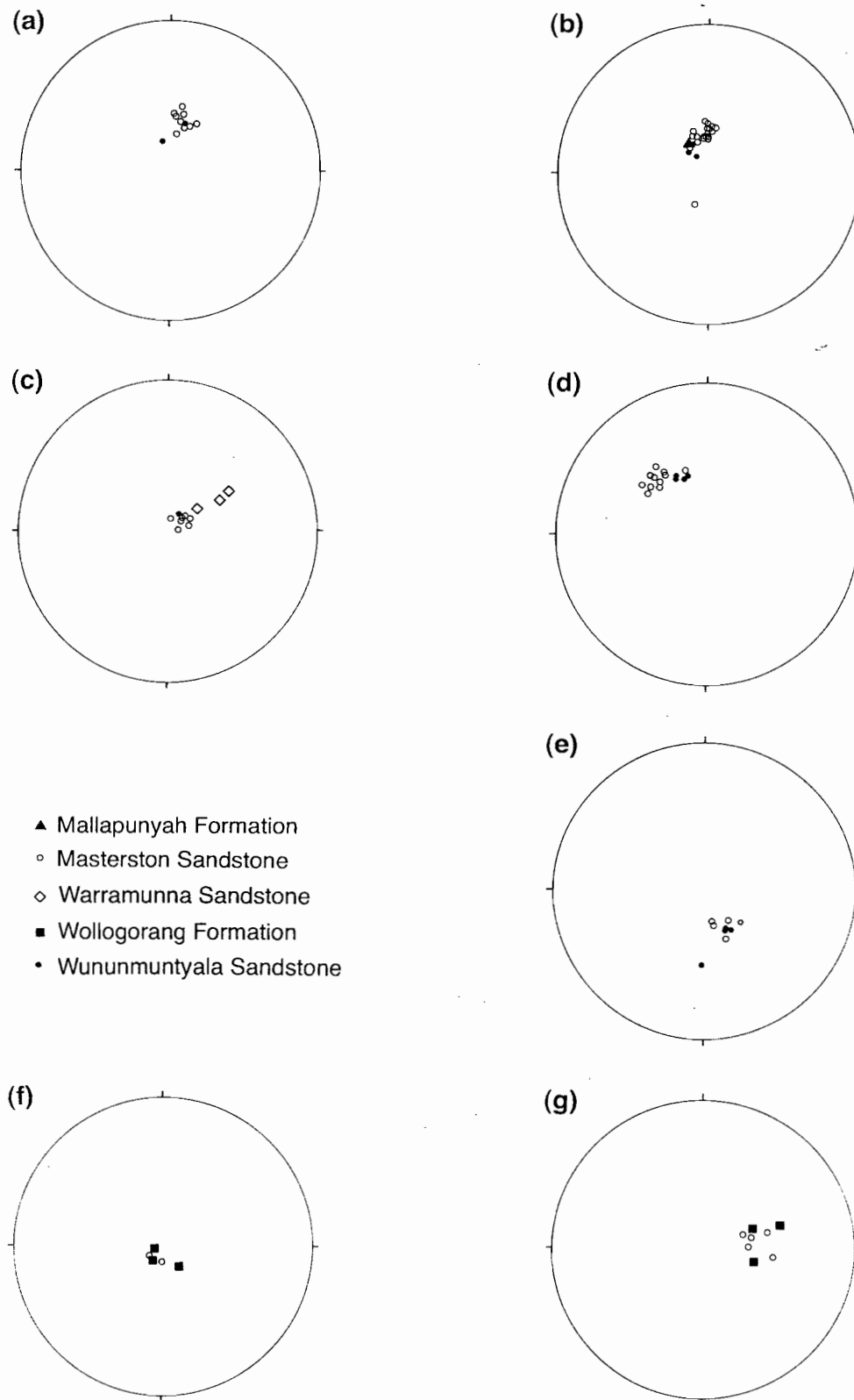


Figure 14. Plot of poles to bedding at the base of the McArthur Group at various localities; (a) southwestern Tawallah Ranges (b) southern Tawallah Ranges (c) eastern Scrutton Ranges (d) southeastern Tawallah Ranges (e) northern Batten Ranges (f) middle Mallapunyah Dome (g) western Kiana Dome.



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On a vertical surface trending approximately east-west, quartz fault striae define a reverse sense of movement. Similarly orientated surfaces at Stop 1/1 and elsewhere in the fault zone are interpreted as minor secondary movements developed during dextral wrenching on the Tawallah Fault.

*Stop 1D - edge of the Tawallah Fault Zone*

On a pavement 20 m along the creek section from Stop 1/2 and near the western edge of the Tawallah Fault Zone, granular breccia beds mark the first semblance of internal sedimentary structure. Channel lag gravels and randomly dispersed, well rounded quartz granules and pebbles are a characteristic of the Sly Creek Sandstone in the Batten-Tawallah-Scrutton Range regions of the southern McArthur Basin (Pietsch *et al.*, 1991).

*Stop 1E - outside the Tawallah Fault Zone*

Twenty metres along the creek section, the Sly Creek Sandstone, although still thickly bedded (cm to 1m) and silicified, contains internal fine laminations and rippled surfaces. The profound silicification and brecciation observed previously are less evident (although late-stage veins are abundant) suggesting that this locality is outside the Tawallah Fault Zone. Note, however, that the unit is still quite silicified particularly on comparison with the clastic units of the upper Tawallah and lower McArthur Groups. Another feature at this locality are gentle, open mesoscopic folds that are developed in some of the more thinly bedded sections.

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## AFTERNOON TRAVERSE - MID-TAWALLAH INVERSION

The Kilgour Waterhole traverse on Day 2 examined the transition from the upper Tawallah Group to the lowermost McArthur Group in the Mallapunyah Dome area. Stratigraphic and sedimentological interpretation of the succession indicated that the Mallapunyah Dome became a significant topographic feature after the deposition of the Wollgorang Formation, but prior to the deposition of the breccias mapped as Gold Creek Volcanics. The Batten Ranges traverse also examines the Tawallah Group to McArthur Group transition, however, at this locality the upper Tawallah units examined at Kilgour Waterhole (ie. the Settlement Creek Volcanics, the Wollgorang Formation and the Gold Creek Volcanics) are not present.

In the Batten Ranges, the Wununmantlyala Sandstone of the Tawallah Group is directly overlain by the Masterton Sandstone of the McArthur Group in all except two areas where selvedges of Settlement Creek Volcanics are mapped between the two units (Fig. 13). The same relationship between the Tawallah and McArthur Groups exists in the Tawallah Range to the north. This contact has been examined in detail at five localities in the Batten and Tawallah Ranges (Bull, 1993). In all sections the contact between the Wununmantlyala Sandstone of the Tawallah Group and the Masterton Sandstone of the McArthur Group is structurally conformable (Fig. 14). In addition, sedimentological examination of the two units at these localities indicate that they comprise identical facies associations of conglomerates interpreted as alluvial fan deposits, and sandstones interpreted as braidplain or braided fluvial deposits. The palaeocurrent patterns recorded by medium- to large-scale cross-bed sets in the sandstones are also the same for both units. In each case they record derivation of sediment from the core of the Batten and Tawallah Ranges.

Initial petrological studies of the sandstones of the Tawallah and lowermost McArthur Group also indicate a genetic relationship between the Wununmantlyala and Masterton Sandstones. Examination of the Sly Creek Sandstone in thin section indicates that it consists of a quartz sandstone which has a single phase of quartz cement (Plate 2A). In contrast, the Wununmantlyala and Masterton Sandstones comprise quartz sandstones in which individual grains often have discontinuous quartz overgrowths (Plate 2B and C). These overgrowths predate the current phase of quartz, and in some cases haematite cement, although this relationship is often masked by planar grain-grain

contacts and suturing of grain boundaries (Plate 2D). The occurrence of discontinuous quartz overgrowths on grains in the Wununmantlyala and Masterton Sandstones indicates that both units were derived by erosion of older quartz-cemented sandstones.

The sedimentological similarities between the Wununmantlyala Sandstone and the Masterton Sandstone in the Batten and Tawallah Ranges indicate that they are closely genetically related. In overview, these relatively coarse-grained and high-energy clastic deposits record a major uplift event on the Tawallah Fault which occurred prior to the onset of deposition of the Wununmantlyala Sandstone. In fact they represent a sedimentological record of the "Mid Tawallah" basin inversion event recognised in the structural mapping of Rogers (1993).

The recognition of a "Mid Tawallah" basin inversion event and its effects on sedimentation in the southern McArthur Basin necessitates a re-evaluation of the lower part of the stratigraphy (ie. that of the Tawallah and McArthur Groups; Rogers, 1993). In terms of the tectono-stratigraphic model proposed, a major break in lower McArthur Group deposition occurs below the current boundary between the Tawallah and McArthur Groups, probably between the Aquarium Formation and the Wununmantlyala Sandstone. Below this level the sandstones of the "lower succession" are intensely faulted and silicified, and above it those of the "upper succession" are less silicified and have associated coarser-grained often conglomeratic facies (Rogers, 1993).

The volcanic units are the key factor in a re-interpretation of the lower McArthur Group stratigraphic package because they provided direct evidence of active extension. An example of this phenomenon is the East Africa Rift System in which rift segments where the dominant structural regime is strike slip (eg. Lake Malawi) are avolcanic, and rift segments where the dominant structural regime is extensional dip slip (eg. the Kenya Rift) are filled with volcanic deposits.

The stratigraphy of the lower McArthur Basin can be considered in terms of a rift-phase/sag-phase depositional model. This volcano-sedimentary subdivision complements the tectonic model proposed by Rogers (1993). The stratigraphic package prior to the "Mid Tawallah" inversion event accumulated during Rogers (1993) stage 1 extension (E-W?). It can be interpreted in terms of a basal rift-phase clastic and volcanic interval (ie. the Yiyintyi and Sly Creek Sandstones and the Siegal



Volcanics), overlain by a poorly-developed sag-phase carbonate package (ie. the Aquarium Formation). Sedimentation was interrupted during Rogers (1993) stage 2 Mid Tawallah Inversion (E-W compression). However, the volcano-sedimentary pattern is repeated after the inversion event during Rogers (1993) stage 3 extension (E-W?). In this case the Wununmantlyala and Masterton Sandstones, and Settlement Creek and Gold Creek Volcanics represent the rift-phase package, and the McArthur Group carbonates represent a much better-developed sag-phase package

The significance of the Wologorang Formation in terms of this provisional model is as yet unclear. However, the absence of this unit in the Batten and Tawallah Ranges is taken to indicate that these areas along the Tawallah Fault remained topographic highs after the "Mid Tawallah" inversion event.

The two major tectonically generated rift-phase/sag-phase cycles proposed in this provisional model for the Tawallah and McArthur Groups are of the same order of magnitude as the "cover sequences" defined in the Mt Isa inlier. It is probable that numerous lower order depositional cycles related to relative sea level fluctuations were superimposed on these major events. These could account for local stratigraphic variations such as the presence of the Warramanna Sandstone in the Scrutton Ranges but not in the nearby Batten Ranges. Later in the history of the basin when the rift topography was suppressed, these events could have given rise to less significant clastic units such as the Tootola and Leila Sandstones of the McArthur Group.

*The afternoon traverse in the Batten Ranges begins at Kangaroo Waterhole where a strongly faulted N-S trending block of Masterton Sandstone forms a small waterfall. Behind the waterfall is a NNW-SSE trending flat plain which is formed on recessive bedded dolostones of the Aquarium Formation, rare exposures of which can be seen in the banks of the major creek present. Approximately 1 km NW of Kangaroo Waterhole the flat plain formed on Aquarium Formation narrows into a N-S trending gully (Fig. 13).*

#### STOP 2 - SLY CREEK SANDSTONE OVERLAIN BY A BASAL CONGLOMERATE TO THE WUNUNMANTYALA SANDSTONE

It is clear that the recessive Aquarium Formation which forms the flat plain has pinched out at this locality. The eastern wall of the gully is formed by hematitic sandstones of the Wununmantlyala Sandstone which also outcrop in the creek bed. The

western wall is formed by a dip slope of massive silicified quartz sandstone of the Pty overlain by a conglomerate which forms the base of the Wununmantlyala Sandstone at this locality. The conglomeratic deposits consist of a closed to open framework arrangement of pebble- to boulder-sized clasts of silicified sandstone and minor vein quartz in a matrix of hematitic medium- to coarse-grained sandstone. These coarse-grained deposits are overlain by medium- to thin-bedded, planar laminated, rippled and cross-bedded hematitic sandstone typical of the Wununmantlyala Sandstone which outcrops in the creek bed. Intraclastic mudstone-chip breccias are locally abundant and well formed polygonal cracks occur on some bedding surfaces which could represent desiccation, synaeresis or diastasis cracks.

*To the north of the gully designated stop 2 the flat plain developed on the recessive Aquarium Formation opens out once more. Approximately 500 m across the plain to the NW is a steep ridge of Wununmantlyala Sandstone overlain by Masterton Sandstone (FIG. 13).*

#### STOP 3 - BASAL CONTACT OF THE MCARTHUR GROUP WUNUNMANTYALA SANDSTONE

The Wununmantlyala Sandstone at this locality consists of the typical bedded, laminated and cross-bedded hematitic sandstones. However, towards the top of the unit on the crest of the ridge, large-scale cross-beds are present and there are many hematitic vugs in the sandstone. In places these preserve the shape of displacive gypsum crystals up to 7 cm long.

The Masterton Sandstone at this locality is marked by a distinctive basal conglomerate which is similar to that which formed the base of the Wununmantlyala Sandstone at the previous stop. This unit is scoured into and truncates bedding in the underlying Wununmantlyala Sandstone. The conglomerate deposits are several metres to several tens of metres thick and consist of closed framework, locally imbricated, pebble- to cobble- to boulder-sized conglomerate. The clasts consist of silicified sandstone and minor vein quartz and the matrix is a fine- to coarse-grained quartz sandstone.

Approximately 500 m to the SE of the contact between the Wununmantlyala and Masterton Sandstones a ridge of Wununmantlyala Sandstone provides panoramic views back across the ranges to the south. The recessive valley in the foreground, comprising poorly exposed Aquarium Formation, separates the ridge from regionally silicified and highly fractured and brecciated Sly Creek

Sandstone. A feature to notice is the irregular thickness of the Aquarium Formation. Although structurally complicated, primary thickness variations are implied by the exposures of Stop 2 where basal Wunumantya conglomerates overlie the Sly Creek Sandstone. Rogers (1993) specified that uplift occurred in response to reverse movements on the Tawallah Fault during the Mid-

Tawallah Inversion, and Bull (1993) suggests that consequently, upper Tawallah Group clastic sedimentation developed as alluvial fan systems sourced from the uplifted block. The exposure seen at Stop 2 therefore, can be viewed as an erosional contact developed during this event and also suggests a syn to post-Aquarium timing for the Mid-Tawallah Inversion.



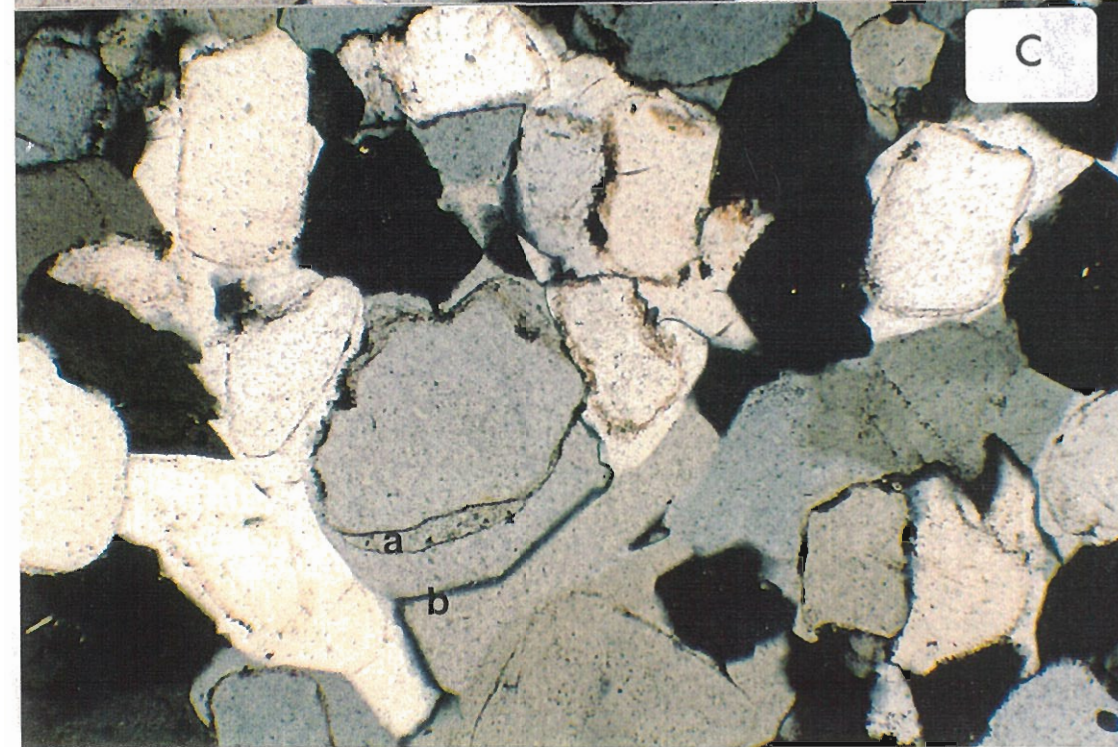
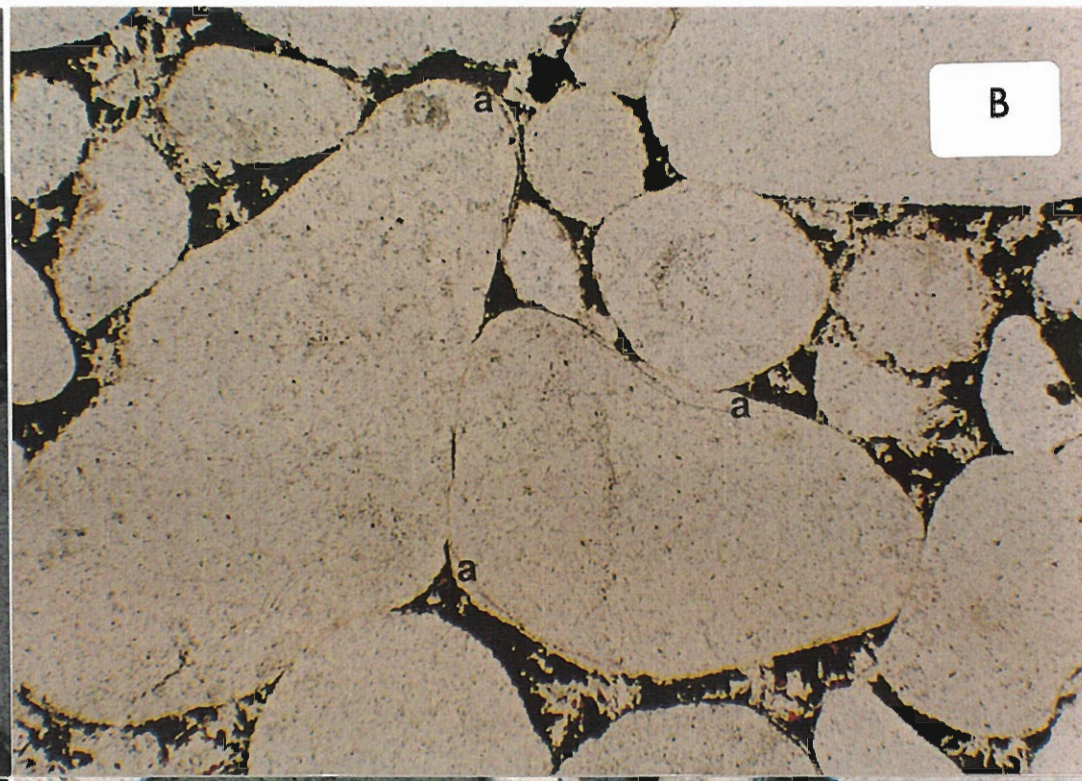
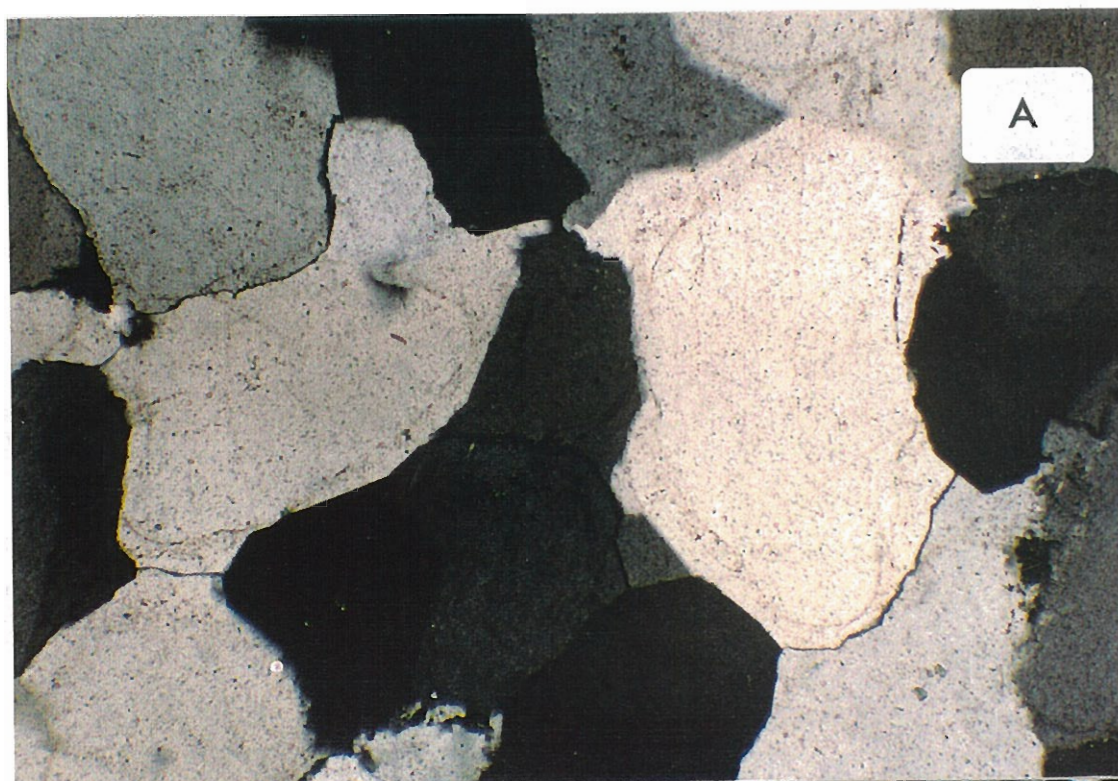
PLATE 2: SLY CREEK SANDSTONE, WUNUNMANTYALA SANDSTONE AND MASTERTON SANDSTONE

A. Photomicrograph of the Sly Creek Sandstone (x 10) from the Batten Ranges showing a single phase of quartz cement.

B. Photomicrograph of the Wununmantlyala Sandstone (x 10) from the Tawallah Ranges showing discontinuous quartz overgrowths (a) succeeded by a current phase of quartz/hematite cement.

C. Photomicrograph of the Masterton Sandstone (x 10) from the type section at Kilgour Gorge showing discontinuous quartz overgrowths (a) succeeded by a latter phase of quartz cement (b).

D. Photomicrograph of the Masterton Sandstone (x 10) from the Tawallah Ranges showing similar overgrowth/cement relationships to the previous example complicated in this case by planar and sutured grain/grain boundaries which are a common feature in this unit.





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