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Tensile and compressive growth structures: relationships between sedimentation, deformation and granite intrusion in the Archaean Coppin Gap greenstone belt, Eastern Pilbara, Western Australia

Wouter Nijman *, Bart J.A. Willigers [1], Albert Krikke

Vening Meinesz Research School of Geodynamics, Institute of Earth Sciences, Utrecht University, Postbus 80021, 3508TA Utrecht, The Netherlands

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Tensile and compressive growth structures: relationships between sedimentation, deformation and granite intrusion in the Archaean Coppin Gap greenstone belt, Eastern Pilbara, Western Australia

Wouter Nijman *, Bart J.A. Willigers [1], Albert Krikke

Vening Meinesz Research School of Geodynamics, Institute of Earth Sciences, Utrecht University, Postbus 80021, 3508TA Utrecht, The Netherlands

Abstract

The Coppin Gap greenstone belt is composed of an east–west striking asymmetric synclinorium between the Muccan and Mount Edgar batholiths. Along the contact with the Muccan batholith, the vertical to overturned northern limb is intensely sheared, folded and tectonically reduced. The southern limb is relatively undisturbed and irregularly intruded by the Mount Edgar batholith. Progressive unconformities and sedimentary infilling of growth structures in the Gorge Creek Group record the deformation history. The unconformities constrain which of the now steeply dipping shear zones have to be rotated with their cover sequence before they can be interpreted kinematically. Four mid-Archaean clastic systems have been recognized: the first and third are transgressive littoral quartzose and feldspathic arenites; the second and fourth comprise conglomeratic and ferruginous alluvial fan-related deposystems. East-verging thrust tectonics affected the belt after unconformable deposition of the first deposystem, on the early Archaean Warrawoona Group. In the western extremity of the belt, primary tectonic relief was filled with the second deposystem. Thrust folds were overprinted at right angles by folding sub-parallel to the developing belt. After truncation, the belt was covered by the third and fourth systems. In the eastern part of the belt, relief created by belt-parallel folds affecting the first deposystem, was filled by conglomerate overlain by basalts; a sequence also assigned to the Whim Creek Group. We relate systematic depocentre shifts, as observed in the Bamboo Creek Syncline, to differential doming of the adjacent batholiths. Buried thrusts and shear zones may have caused km-scale repetition of the underlying sequences. The observed relationships place uncertainty on the validity of the existing stratigraphic correlations, which now need geochronologic work to resolve. Part of the thrusting appears to have taken place by inversion on pre-existing detachment shear zones in the underlying Warrawoona basalts and ultramafic rocks. The shear zones descend from a high stratigraphic level in the east towards deeper levels in the west. The first motion has been west-block down, listric normal growth faulting, in places accompanied by synsedimentary, explosive intrusion of black chert veins, mega-brecciation and back tilt of fault blocks. Geometrically, these early structures cannot be related to the geometry of batholith doming and are interpreted as the result of either regional tensile stress, local caldera collapse or both mechanisms acting synchronously. The mid-Archaean influx of siliciclastic sediments in the Coppin Gap Belt coincides with this change from a tensile to a complex compressive deformation, the latter caused by regional thrusting and interbatholith folding. Late deformation of the belt includes further steepening of the strata and eastward oblique dextral and 060° sinistral strike–slip. © 1998 Elsevier Science B.V.

Keywords: Archaean; Pilbara, Western Australia; Growth structures; Sedimentation and tectonics; Greenstone belt

* Corresponding author. e-mail: wnijman@earth.ruu.nl.

[1]Present address: Geological Museum, Copenhagen, Denmark.

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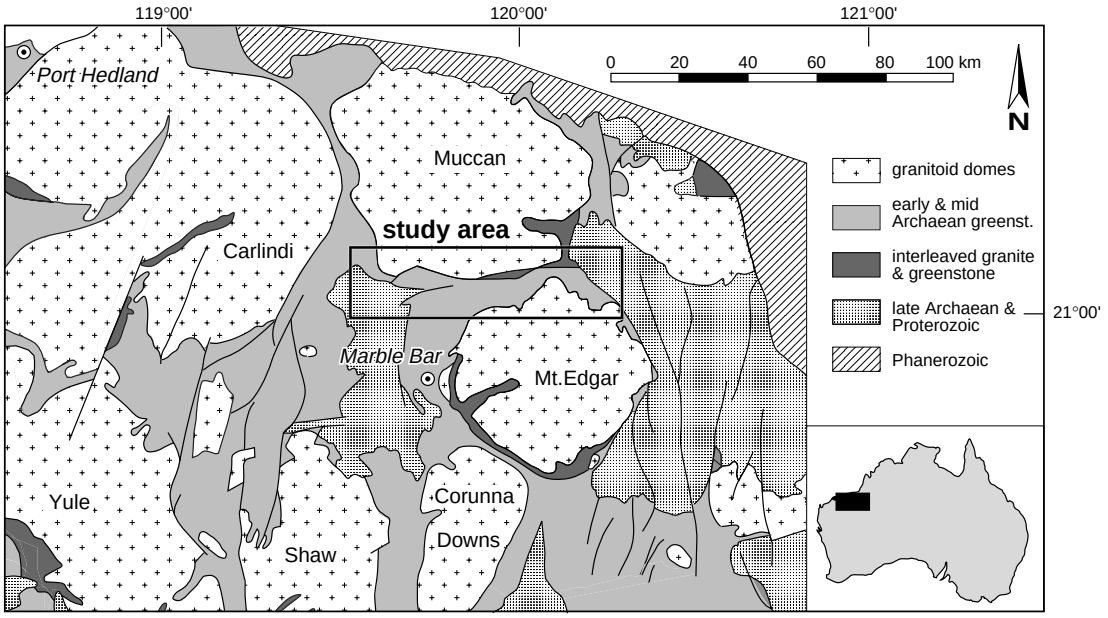


Fig. 1. Position of study area and Coppin Gap Belt in Pilbara Block.

1. Introduction

Sedimentation patterns and structural styles change drastically in the east Pilbara greenstone belts at 3.3 Ga (Barley, 1993; Krapez, 1993; Eriksson et al., 1994). Whereas the Early Archaean was characterized by basaltic and subordinate felsic volcanism and only minor deposition of quartzose elastic sediments, the latter are abundant after 3.3 Ga. This transition is marked by unconformities. For the first time, deformation shows the important effects of crustal shortening.

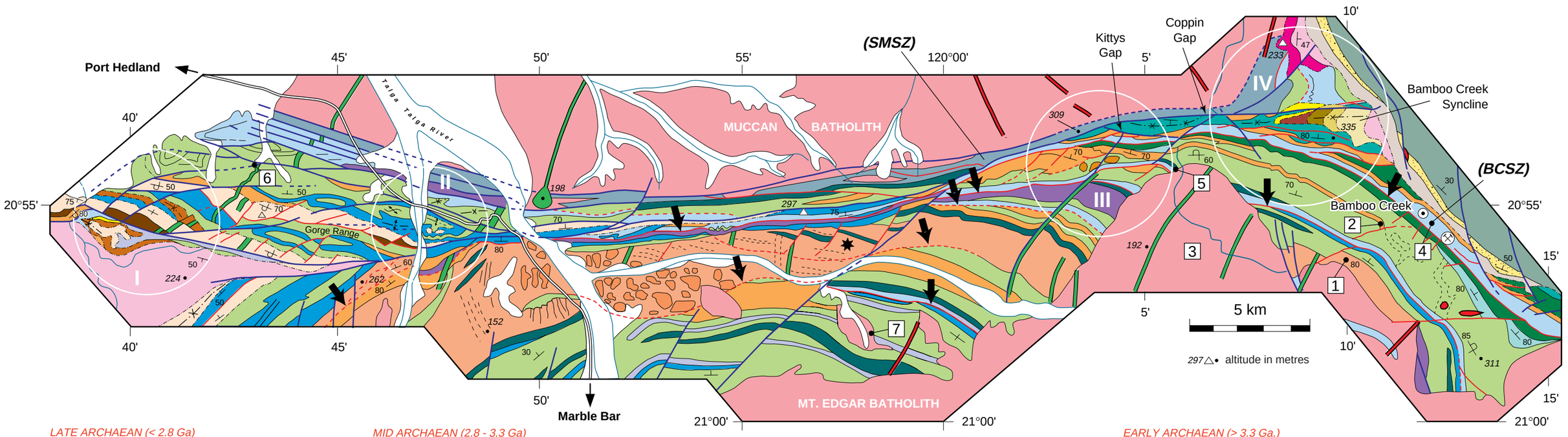
Part of the deformation history is recorded in the sedimentary sequence, particularly in growth structures and unconformities. The Coppin Gap greenstone belt[2] provides an excellent example of relationships between sedimentation and deformation. The belt strikes eastwards between the Mount Edgar and Muccan batholiths (Fig. 1). Its dumbbell shape in map view (Fig. 2) reflects a strain gradient from open synclinoria at both ends to a central, tight interbatholith syncline. In the oppositely plunging synclinoria, elastic sediments correlated with the Gorge Creek and Whim Creek Groups (Megasequences of Krapez, 1993; Eriksson et al., 1994), overlie the volcano-sedimentary rock suite of the Warrawoona Group. These clastic sedimentary systems were unconformably deposited on a supracrustal substrate during brittle deformation. The investigation of the latter relationship complements structural analysis of deeper crustal levels exposed in adjacent belts (Zegers, 1996). In this paper, we present results from studies in four key areas in the belt (I–IV in Fig. 2), where progressive unconformities and growth structures play an important role in unravelling the deformation history.

2. General structure of the Coppin Cap belt

2.1. Stratigraphy and age relationships

On the 1:250 000 geologic maps Port Hedland (Hickman and Gibson, 1981) and Yarrie

[2]We include in the Coppin Gap greenstone belt the entire east-west oriented belt along the southside of the Muccan batholith from Bamboo Creek in the east to Pear Creek in the west. Other authors indicate the western part (Gorge Range) of the belt as Northern Marble Bar Belt.



LATE ARCHAEAN (< 2.8 Ga)

Fortescue Group

porphyry
basalts
sandstone
agglomerate

MID ARCHAEAN (2.8 - 3.3 Ga)

Whim Creek Group (?): ***fill of Bamboo Creek Syncline***

conglomerate
vesicular basalts

Gorge Creek Group: ***siliciclastic systems***

IV black-and white chert + conglomerate
III quartz / feldspathic arenite
II FU fanglomerate and Fe-sandstone
I quartz arenite

MID or EARLY ARCHAEAN

Gorge Creek Group or Warrawoona Group

(silicified) basalt
BIF and equivalent tuff and shale
chert in basalt, sst. & minor felsic volc.
felsic volc., qtz-porphyry, & minor sst.
"P(anorama)" -unit

EARLY ARCHAEAN (> 3.3 Ga.)

Warrawoona Group

felsic agglomerate *(Duffer Fm) (*) megabrecciated*
(ferruginous) chert
basalt (predominant)
gabbro / dolerite sills
peridotite / serpentinite sills
ultramafics, komatiite
intensily sheared, folded, and chemically altered (ultra)mafics: *e.g. Bamboo Creek shear zone* ***(BCSZ)***

Sources:

(a) detailed mapping in key areas I-IV (present project:1992-'96),
(b) aerial photo analysis and field checks over the entire belt (present project:1992-'96)
(c) geologic mapping of the Bamboo Creek Mine district, (Utrecht University 1983-84)
(d) 1:250 000 Aust. geol. map sheets Port Hedland and Yarrie
(e) unpublished satellite imagery (AGSO, Canberra, 1995)

batholiths

Muccan and Mt. Edgar batholiths
South Muccan shear zone ***(SMSZ)***

dykes

2.8 Ga dolerite dykes
< 2.8 Ga hornblende porphyry

fault systems

pre 2.8 Ga
syn to post 2.8 Ga

unconformities

tectonic discontinuities
normal fault array
I - IV key areas
1 dating sites

referred to in text

Fig. 2. Geologic map of Coppin Gap Belt. Indicated are the four key areas of investigation; there is a further description in text.

(Hickman et al., 1982) and on the geologic map of the Pilbara by Hickman (1983), the volcano-sedimentary suite of the Coppin Gap Belt is assigned to Warrawoona, Gorge Creek and Fortescue Groups. The thickest rock sequence of the Warrawoona Group is exposed southeast of Kittys Gap (Fig. 2, area III). It is composed of about 13 km of alternating ultramafic, basaltic, felsic rock and minor clastic sediment. The felsic volcanic rocks, prominently represented by the Duffer agglomerate (DiMarco and Lowe, 1989), are important because of their potential for U–Pb dating of zircons. At the Bamboo air strip, south of Bamboo Creek (Fig. 2, site 1), it is dated at 3471 ± 5 Ma (Thorpe et al., 1992a).

At Kittys Gap, stratigraphically higher in the sequence of the Warrawoona Group, a felsic volcanic rock unit ('P'-unit, see below) along the southern side of the Bamboo Creek shear zone (BCSZ) has been assigned to the Wyman Formation (geologic map and plate 2 in Hickman, 1983). It consists of quartz porphyry and rhyolites, overlain by bedded chert, silicious sandstone and Fe-rich mudstones. U–Pb zircon ages of this unit are 3454 ± 1 and 3470 ± 2 Ma (Fig. 2, site 2; Thorpe et al., 1992a) confirming its position in the Warrawoona Group and definitely below the Wyman Formation. Throughout the entire belt, this felsic unit and associated chert are found close to, or immediately below, the Gorge Creek Group unconformity. The felsic volcanic component decreases westwards along the belt. For reasons given below in this paper, the stratigraphic position of this rock assemblage cannot be accurately established, but compares with the Panorama Formation (Hickman, 1983, 1990). We therefore informably assign the unit with the prefix 'P(anorama)'.

All zircon ages fall within the age range given for the Duffer Subgroup, of which the Duffer agglomerate only forms part (McNaughton et al., 1993). Since the sample sites of the 'P'-unit and of the Duffer felsic volcanic rock at Bamboo air strip are stratigraphically 2.8 km apart and are separated by important bedding-parallel shear zones (Fig. 2), the overlapping ages suggest a tectonic repetition within the Warrawoona sequence. Emplacement of gold in the BCSZ is dated at 3.4 Ga (Zegers, 1996), well within the time range of deposition of the Warrawoona Group, establishing an early age of generation of this major shear zone.

Imbricated felsic volcanic rocks and sandstone, north of the BCSZ in area IV, have been assigned to the Gorge Creek Group by Hickman (1983). In the established stratigraphy, this unit also would fit in with the Wyman and Corboy Formations since overlying BIF generally is considered to belong to the Cleaverville or Paddy Market Formations. Horwitz (1990) incorporates an unconformably overlying sequence of coarse clastic sediments and basalts below the Mount Roe Basalt of the Fortescue Group with the Whim Creek Group.

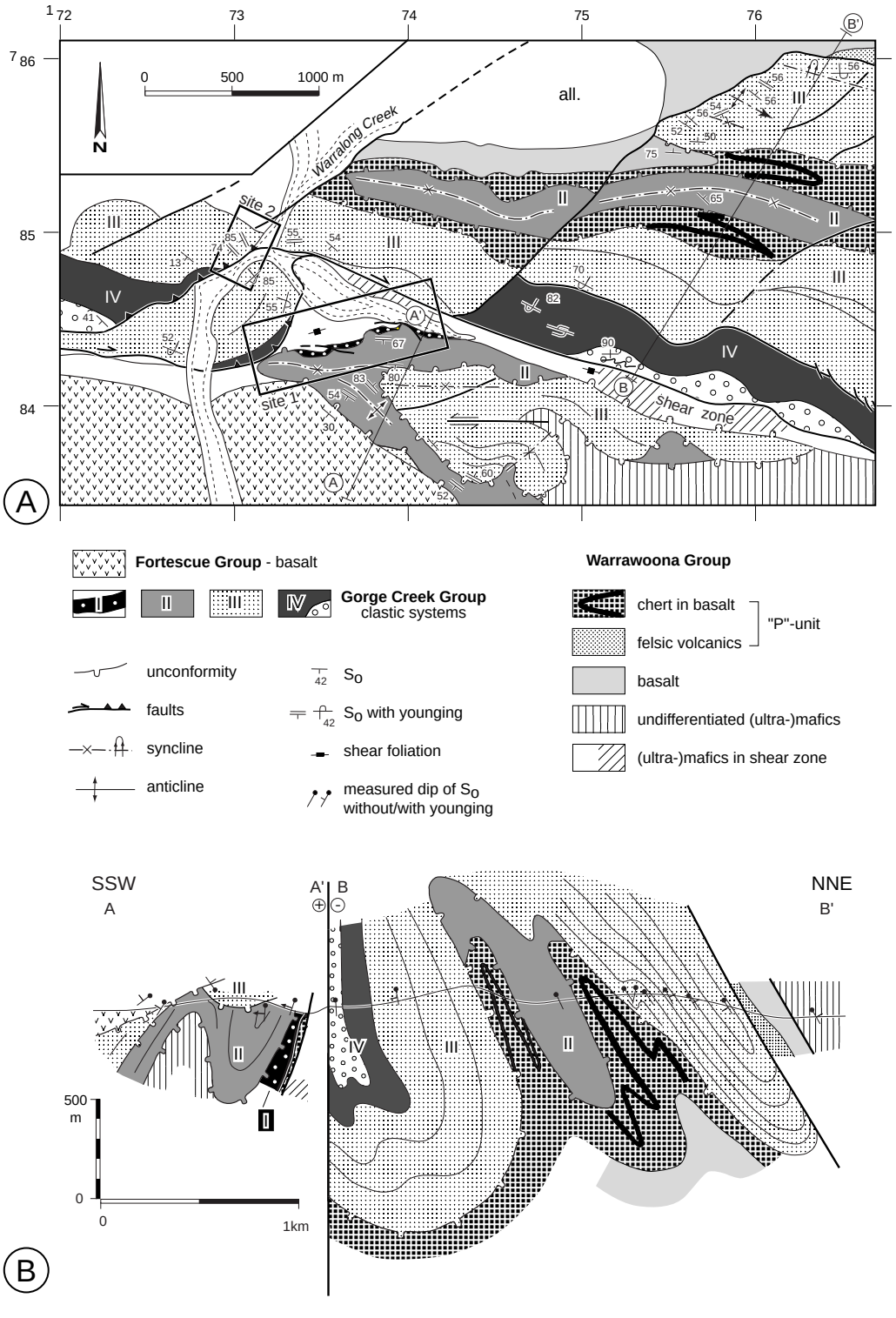
The Gorge Creek Group is generally accepted to have been deposited between 3325 Ma and the age of the base of the Fortescue Group, i.e. 2775 Ma (Eriksson et al., 1994). The dolerite dykes correspond to an event dated at circa 2.8 Ga (Black Range: Zegers, 1996).

South of Coppin Gap (Fig. 2, site 3), a lobe of the Mount Edgar batholith named Coppin Gap Suite granodiorite by Williams and Collins (1990), intruded the Warrawoona Group and early shear zones. The authors assign an age of 3314 ± 26 Ma to the granodiorite.

Galena from quartz veins at Bamboo Creek (Fig. 2, site 4), south of Coppin Gap (Fig. 2, site 5) and west of Doolena Gap (Fig. 2, site 6) produces model lead ages of, respectively, 3416, 3326 and 3329 Ma (Thorpe et al., 1992b, partly recalculated from Richards et al., 1981). This places an upper age to the major shear zones which are intersected by the veins. Younger lead ages of 2918/2926 Ma are derived from quartz veins at Nimerry Creek (Fig. 2, site 7), cutting through an apophyse of the Mount Edgar granodiorite.

2.2. Deformation

The asymmetry and southerly vergence of the Coppin Gap Belt synclinorium is determined by a vertical to overturned northern flank, intensely sheared and tectonically reduced against the Muccan batholith, a faulted core, and a well-



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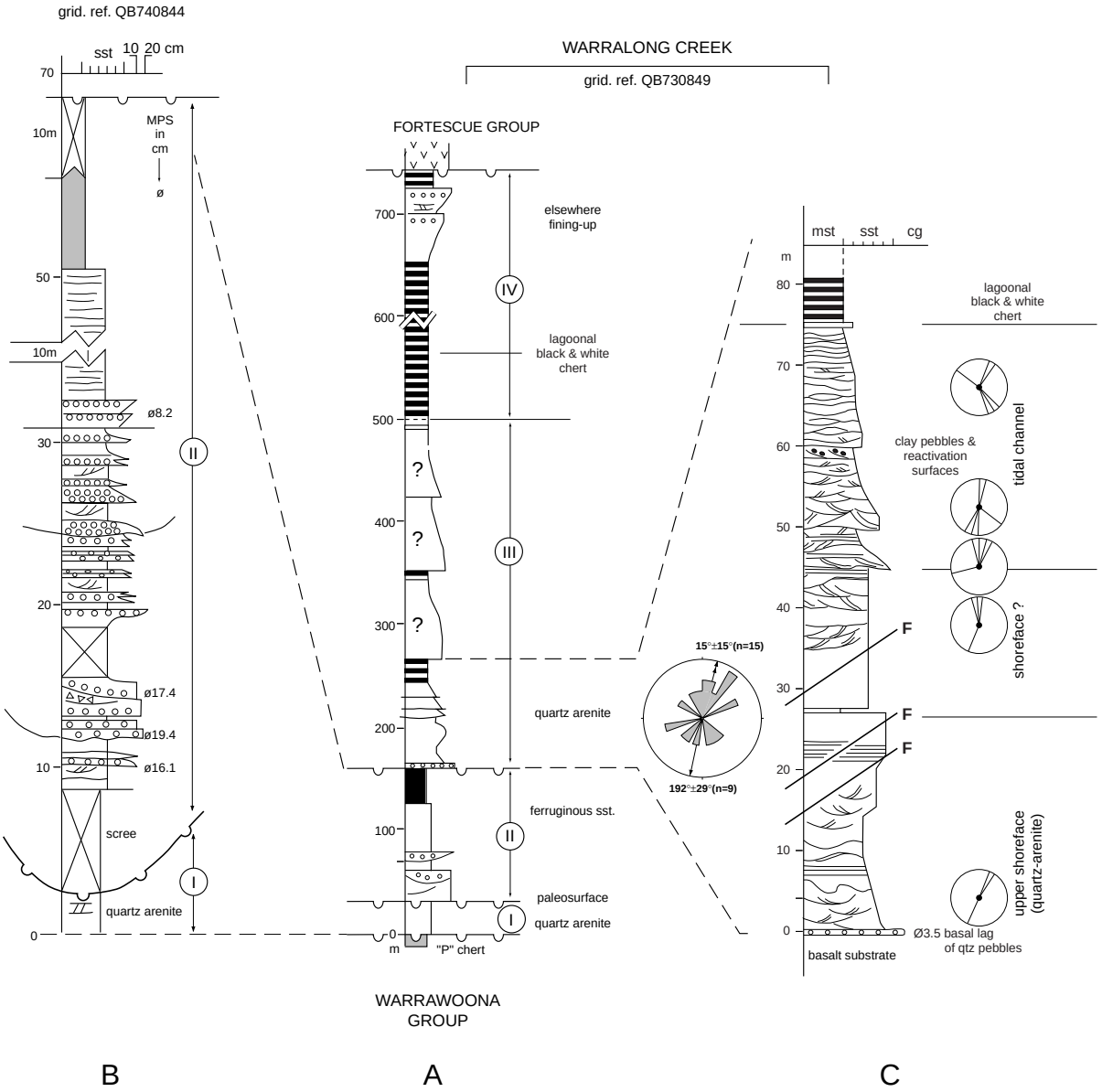

Fig. 4. (A) schematic log of clastic system I–IV at Warralong Creek (site 2 of Fig. 3); (B) detail of clastic system II (site I); (C) one cycle of system III.

Fig. 3. (A) Geologic map of area I (West Gorge Range) with details of clastic systems I–IV, and corresponding unconformities. Cross-section A–B refers to Fig. 4. Site I (frame) refers to location of Fig. 4(B) and Figs. 5–7; site 2 (frame) to logs of Fig. 4(A and C). (B) NW–SE cross-section through West Gorge Range shows progressive folding of clastic systems I–IV, longitudinal with respect to greenstone belt, and corresponding unconformities. System III truncates folded system II and is more open-folded. It grades upwards into banded chert with lenses of polymict conglomerate of system IV. The uppermost unconformity (extreme left) forms base of late Archaean Fortescue Group.

preserved, 40°–80° north-dipping, southern flank with lobate-intrusive, undeformed, contact with the Mount Edgar batholith.

Fault systems can be subdivided as pre- and syn- to post- (2.8 Ga) dolerite dyke intrusion. Dolerite dykes and dyke-parallel 60°E-striking, sinistral faults have been dextrally offset by a generation of longitudinal faults, predating the late Archaean Fortescue Group. These faults intersect, reactivate, and associated folds refold, earlier faults and tectonic discontinuities such as the Bamboo Creek shear zone (BCSZ) and the South Muccan shear zone (SMSZ). In the Gorge Range at the western end of the belt (Fig. 2, areas I and II), outcrop relationships yield the following deformational sequence: (a) early shear zones in the Warrawoona Group affected by (b) pre-dolerite folds belonging to the Coppin Gap synclinorium; (c) dolerite dykes and pre-Fortescue Group, 60°E striking faults offset by (d) late dextral strike–slip faults. In the context of this paper, emphasis is on the early deformational structures.

The BCSZ and several similar shear zones in the southern flank of the Coppin Gap Belt descend westwards to deeper stratigraphic levels of the Warrawoona Group (bold black arrows in Fig. 2). The shear zones are characterized by intense chemical alteration (talc, chloritization, carbonatization, etc.) of mafic and ultramafic rocks showing, in places, refolding of an earlier foliation parallel to the shear zone (see Section 3.3). Ultramafic and mafic rock types include komatiite, peridotite and gabbro. In many instances, the shear zones are found just above felsic volcanic units. This defines the repetition of (ultra)mafic to felsic rock suites of the Warrawoona Group, shown on Fig. 2 (south of area III; grid SS920830[3]). Hence, tectonic slicing rather than stratigraphic continuity characterizes the thick rock sequence of the Warrawoona Group in the Coppin Gap Belt.

The earliest structures of the belt consist of arrays of listric normal faults [in the footwall of the BCSZ, grid SS965865 (area III); * in Fig. 2); these are covered by Warrawoona Group basalt and are therefore of early Archaean age. Along the northern side of the BCSZ, felsic volcanic rocks, clastic sediments and BIF, show internal imbrication and are unconformably overlain by siliciclastic sediments.

[3]Grid references relate to the 1:100 000 topographic map sheets

3. Relationships between deformation and sedimentation

3.1. Area I: Western Gorge Range

Anticlinal cores in area I expose tightly folded Warrawoona Group basalt with chert beds; synclines reveal superposition of four clastic sedimentary sequences (Fig. 3) numbered I–IV.

Clastic system I is only present as an erosional remnant below the unconformity at the base of the second clastic system [Fig. 3(A), site 1]. It is composed of very mature quartz arenite and overlies black chert of the 'P' interval of the Warrawoona Group. We relate the maturity of the quartz arenite to a littoral depositional environment by comparison with occurrences of this type of arenite in the clastic system III where primary structures have been better preserved.

Clastic system II fills up a paleorelief, Fe-oxidized with ferricrust and gossan, retaining much of its primary tectonic character (Figs. 5 and 6). The stratigraphically youngest unit involved in deformation of the substrate is clastic system I. The sequence fines upwards [see also Fig. 4(A and B)] from channel-fill conglomerate, locally of boulder size (grid QB755852 and QB737844), to ferruginous sandstone. Conglomerate shows inverted grading and other characteristics of mass flow deposition. The composition records erosion of the immediately underlying quartz arenite (system I) and black chert. The deposit is characteristic of a proximal to distal alluvial fan depositional regime.

Clastic system III forms the present topographic culminations of the Gorge Range. Its base is defined by an angular unconformity and its thickness increases rapidly and stepwise from about 240 m at Warralong Creek crossing [Fig. 3(A), site 2] to over 400 m eastwards along the range. At Warralong Creek, the cross-section shows stacking of four sedimentary cycles [Fig. 4(A)], one of which is illustrated in detail in Fig. 4(C).

A basal interval of locally pebbly, trough cross-bedded, lithic quartzose arenite grades upwards into thick-bedded, even-laminated, coarse quartz arenite and back into trough cross-bedded arenites. The upper half of the cycle consists of three fining-upwards intervals of trough and planar cross-laminated to wavy laminated feldspathic sandstone, terminating in evenly laminated black-and-white chert. In places, sets of cross-beds show reactivation surfaces, silicified clay drapes and mud pebbles. Paleocurrents are bimodal [Fig. 4(C)] both up and down dip.

The above characteristics indicate a tidally influenced littoral environment, most probably a tidal inlet system (FU units) in a barrier coast (well-washed quartz arenite). After correction for deformation, tidal currents appear to have been oriented predominantly 15°E with counter direction to 192°E (rose diagram, Fig. 4).

Clastic System IV the arenites of clastic system III give way to the black-and-white (BW) banded chert of clastic system IV [Fig. 4(A)]. Lenses of conglomerate and sandstone occur more than 100 m above the base of the upper BW-chert interval of the columnar section. These lenses are more than 20 m thick and are either fine-grained (grid QB752843) or coarsen upwards (grid QB722845), with pebble sizes of up to 13 cm. Again, the composition reflects the immediate substrate: quartz arenite and BW-chert. Ubiquitous cross-beds yield bimodal W–E paleocurrents with eastward dominance. The upper part of deposystem IV is truncated by the late Archaean Fortescue Group unconformity.

We interpret the coarse-grained members of clastic system IV as alluvial fan or fan delta sediments deposited in a low-energy environment represented by the banded chert, the latter being genetically related to the littoral sandstone of clastic system III. Whether this low-energy environment was situated offshore or inshore is difficult to assess, but the association with high-energy alluvial fan deposits favours an inshore lagoonal or coastal lake environment. If this is the case, system III probably represents a south-facing shoreface which, after initial transgressive northward onlap, prograded over the folded clastics of system II. This progradation ended with lagoonal or lacustrine, rhythmically laminated mudstone, interrupted by the advance of the high-energy fan deposits of system IV.

3.1.1. Interference of deformation and sedimentation

The north–south cross-section [Fig. 3(B)] shows isoclinal folds in the Warrawoona Group, tight folds in clastic system II with north-dipping axial planar cleavage and open folds in the more competent rocks of system III. The latter are asymmetric and south-facing, with larger wavelength. The unconformable Fortescue Group dips 30° to the south, the youngest expression of synclinorial downwarp of the Coppin Gap Belt. All folds in the cross-section are coaxial with the synclinorium [Fig. 3(B)].

Mature quartz arenite of clastic system I is exposed on the northern limb of one of the E–W trending folds (grid QB736844). At a smaller scale, the strike exposure exhibits a different sort of deformation (Figs. 5–7): 100 m-scale folds plunge at right angles to the axis of the longitudinal fold and en échelon faults make a low angle with the bedding.

The minor folds appear to have created primary tectonic relief, subsequently filled by clastic system II. This infilling provides the argument that the buried faulted fold pattern has to be rotated with the major fold limb to horizontality before the subsequent stratigraphic sequence can be interpreted. The structure turns out to be an array of west-dipping, low-angle faults with hanging wall anticlines (Fig. 7). The thrust-folded sequence has been structurally detached along a shear zone composed of foliated, intensely altered, ultramafic and mafic rock, containing lenses of basalt and chert. Vertical S-folds in the foliation of the shear zone (grid QB750841) testify to sinistral movement, which upon rotation corresponds to the eastward overthrusting as inferred for the overlying sediments (Fig. 7).

The evidence above suggests that deposition of the Gorge Creek Group was accompanied by the following series of deformational events as detailed below.

(1) *Low-angle thrusting due to east–west shortening*. The east–west shortening involving low-angle

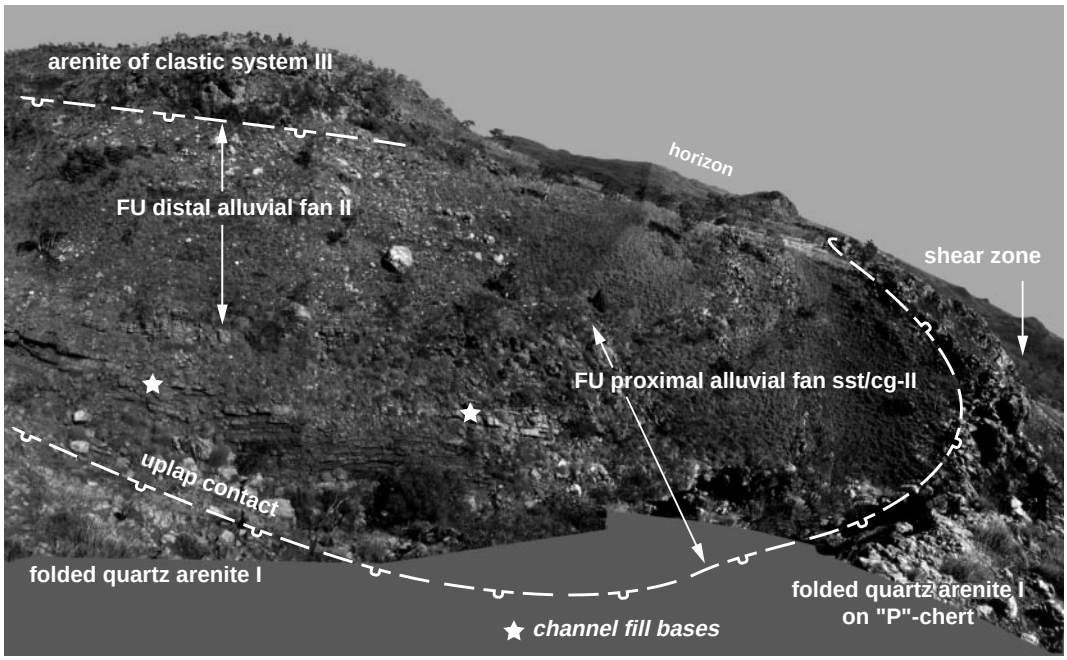

Fig. 5. Photo composite of part of structure outlined as site 1 on map of Fig. 3 and located in Fig. 7.

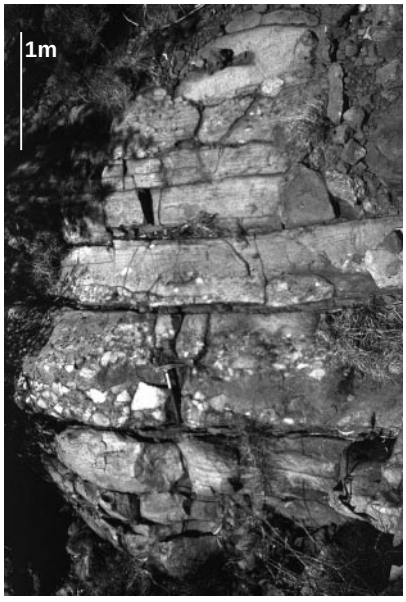

Fig. 6. Detail of FU channel fill of sedimentary log of Fig. 4(B).

thrusting occurred between deposition of system I and the lower part of system II.

(2) *Longitudinal folding due to north–south compressive shortening*. The geometry described for the longitudinal folds may be partly due to differences in rock strength. In particular, the tight folding of the thin chert beds between Warrawoona Group basalts relative to that of the unconformable clastic system II may be explained this way. The nature of early deformation prior to development of the unconformity at the base of system II is therefore difficult to interpret. The angle of unconformity must have been low because the 'P'-rock assemblage is never far below the truncation surface (Fig. 2).

The base-system III unconformity truncates anticlines of a previously formed longitudinal fold pattern deforming system II. Retaining the same asymmetry, system III has been folded in a more open style before formation of the base-Fortescue unconformity. Such relationships correspond to progressive north–south shortening, possibly starting prior to the base-system II unconformity, but certainly before the base-system III unconformity

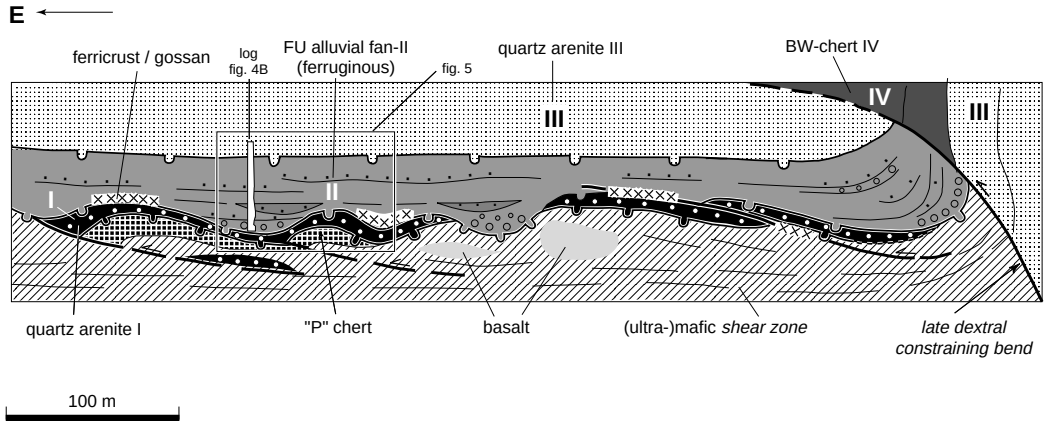

Fig. 7. Schematic W–E section parallel to dominant fold axis [site 1 on Fig. 3(A)] showing relationships between deformation and distribution of clastic systems I–III. System II (FU fan sequence) fills out relief (with ferricrust) caused by minor thrust slices that involved quartz arenite I. System III arenites unconformably cover this suite. The upthrust on the right is caused by late, constraining bend deformation along a longitudinal dextral strike–slipe fault.

and lasting into the period of deposition of the lower Fortescue Group.

(3) *Syn-clastic system III strike–slip faults and east-facing normal faults*. Late, though pre-Fortescue Group, deformation comprises 60°E-trending sinistral strike–slip faults parallel to dolerite dykes. Eastward stepwise thickening of system III over these faults probably indicates original synsedimentary normal growth faulting, prior to reactivation in a strike–slip system. Subsequently, the faults have been truncated by east-oriented, dextral strike–slip faults parallel to the Gorge Range. At Warralong Creek, a left-stepping double bend in such a fault caused local transpression generating an east-verging antiformal stack of system III/IV over the ensemble of sheared Warrawoona substrate and clastic systems I/II [Fig. 3(A), Fig. 7); grid QB732843).

3.2. Area II: Doolena Gap

Two clastic systems can be identified in an intensely deformed segment of the Coppin Gap Belt at Doolena Gap (Fig. 8).

Truncated by the unconformity at the base of the upper clastic unit, the lower system is only discontinuously exposed. It fines upwards from conglomerate to quartzose sandstone, with Fe-oxide-coated grains. The conglomerate contains pebbles of quartz and clean-washed quartz arenite. It overlies a 'P'-assemblage with lateral transition of chert into silicified volcaniclastic sandstone (Fig. 9), east of Doolena Gap. The chert contains domal stromatoloid structures (grid QB921826), in places encrusting silicified barite (grid QB892827).

The upper system is a thick suite of quartzose arenite with variable feldspar content, continuous with clastic system III of the west Gorge Range. Grainsize is generally finer, crossbedding is dominated by dm-scale tabular sets of planar crossbedding and thicker even-laminated sets; bimodal paleocurrents point to NW–SE. Compared with the western part of the range, tidal channel facies are less abundant in favour of typical shoreface facies. At the very top, an upward transition to BW-chert is observed via flaser-linsen type of tidal facies (grid QB885820), again suggesting shoreline progradation. The two clastic systems can be identified as clastic systems II and III, the former containing reworked pebbles of clastic system I quartz arenite.

In the central segment of the greenstone belt, east of the Talga Talga River (Fig. 2, grid QB950833), ferruginous chert of the 'P'-assemblage resembles typical BIF facies as exposed at

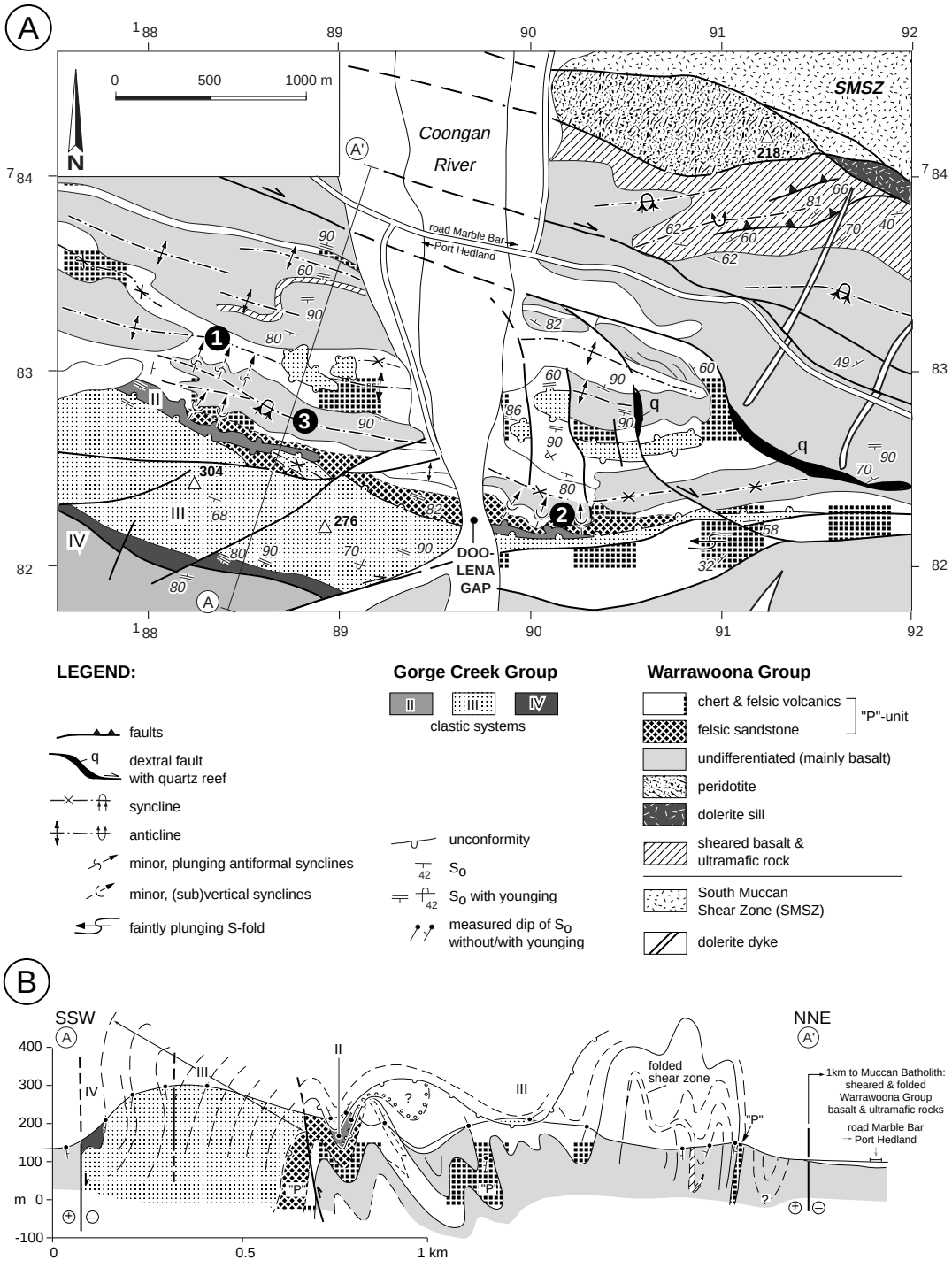

Fig. 8. (A) Geologic map of area II: Doolena Gap. Numbers 1–3 correspond to sites on photograph of Fig. 9; (B) cross-section A–B of Doolena Gap area showing the unconformable relationship of clastic systems II and III with folded chert and arenite of the 'P'-unit and basalts of the Warrawoona Group.

Fig. 9. N–S cross-folds (1 and 2) in both flanks of E–W syncline indicated 3. The numbers correspond to sites indicated on Fig. 8(A).

Kittys and Coppin Gap (see Section 3.3). It is unconformably overlain by clastic system II arenite in continuity with the exposure at Doolena Gap.

3.2.1. *Interference of deformation and sedimentation*

Fig. 9 illustrates cross-folding in the 'P'-chert with 100 m-scale north–south oriented folds, exposed on both limbs of an overprinting, major inclined syncline plunging 17° to 110° (grid QB884828, QB884830 and QB900823). West of Doolena Gap, these minor folds are symmetrical and clastic system II has been preserved mainly in the synclines. It contains clasts of quartz arenite inferred to be derived from clastic system I. East of Doolena Gap, the cross-folds are asymmetric and west-verging and truncated by the next unconformity at the base of system III (grid QB900822). This excludes the possibility that these minor folds because of their high axial plunge, might be interpreted as a result of later strike–slip movement.

Cross-folding is much better exposed at Doolena Gap than in the western Gorge Range and confirms the interpretation that east–west shortening affected the belt before (or during?) deposition of deposystem II. A sub-vertical intraformational S-fold exposed in clastic system II on a south facing fold limb (grid QB888825), might record the persistence of east–west shortening into the period of deposition of system II.

Late deformation includes south-block down slip, accompanied by west-plunging S-folds (grid QB910821), along a major east–west fault through the core of the Coppin Gap synclinorium. This supports the inference of post-Gorge Creek, but pre-Fortescue Group, motion along this fault system in the western Gorge Range. However, dextral offset cannot be proven in this area. Since the fault system delimits an axial graben containing Mount Roe Basalt of the Fortescue Group, it also follows that these faults have been reactivated during or after the late Archaean.

In summary, correspondence between observations in areas I and II confirms the complex relationships between deformation and sedimentation established for the western Gorge Range (Table 1).

3.3. *Area III: Kittys Gap*

In an array of fault blocks, south of Kittys Gap, the 'P'-rock assemblage consists of massive rhyolite, quartz porphyry and quartzose sedimentary rock grading upwards into similar cherts and sandstones to those found at Doolena Gap.

Apart from the abundance of felsic rock, another distinctive feature of this area is the presence of swarms of black chert veins (Fig. 10). These veins are oriented at high angles to the bedding and anastomose through the host rock [Fig. 11(A)]. They are associated with white-in-black and black-

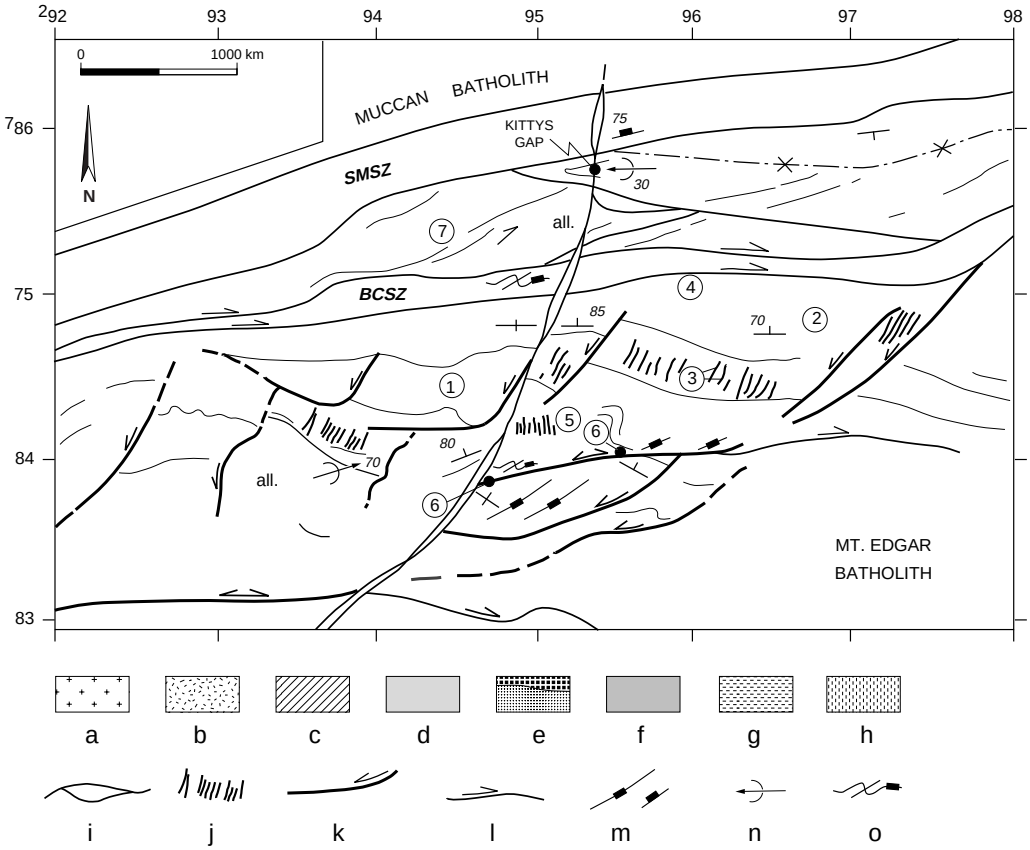

Fig. 10. Geologic map of area III: Kittys Gap. Felsic volcanic suite (1) shows array of westblock-down normal listric growth faults, with upper wedge-shaped infill of hanging wall by tuffaceous shale transitional into BIF (2). Swarms of black chert veins (3) traverse the hanging wall of normal fault blocks. Basalt (4) covers the entire structure just below the BCSZ. The sole of the array is formed of a mélange of rotated felsic volcanic blocks in deformed basalt (5). Inversion from tensile to compressive displacement is observed at (6). Above the BCSZ (7), much more deformed felsic volcanics overlain by well developed BIF seem to repeat stratigraphic sequence of BCSZ footwall. Legend: (a) batholiths; (b) South Muccan shear zone; (c) other shear zones; (d) Warrawoona Group basalt and ultramafic; (e) 'P'-assemblage: felsic volcanics, porphyries, arenite; (f) basalt with sandstone, overlying (e) and (g); (g) laminated shale and tuff transitional to BIF; (h) BIF; (i) dolerite dyke; (j) swarms of black chert veins in 'P'-unit; (k) early tensile faults; (l) subsequent low-angle thrusts and boundaries of SMSZ; (m) shear foliation and fractures; (n)minor plunging folds; (o) S_2-folded S_1-foliation.

in-white sharp-angled chert breccia in the sedimentary top of the unit [Fig. 11(B)]. The surface of the sandstone in the upper part of the 'P' unit is slightly concave and accommodates a wedge of laminated shale, volcanic tuffs and banded chert which in places obtains a characteristic BIF facies (grid SS965848). Shale wedge and sandstone are capped by pillow basalt with intercalated thin sandstone just below the BCSZ.

This 'P'-rock suite can be traced eastwards below the BCSZ to beyond the Bamboo Creek Mine district (Fig. 2) where another wedge of shale is four[illegible] 1 TS 145785), related to tensional faults below the BCSZ. In the opposite direction, 5 km west of Kittys Gap, the BCSZ descends to deeper stratigraphic levels truncating the 'P'-unit at low angles.

On the northern side of the BCSZ at Kittys Gap, similar felsic volcanic rocks overlain by jaspilitic BIF, are intensely deformed. As mentioned in

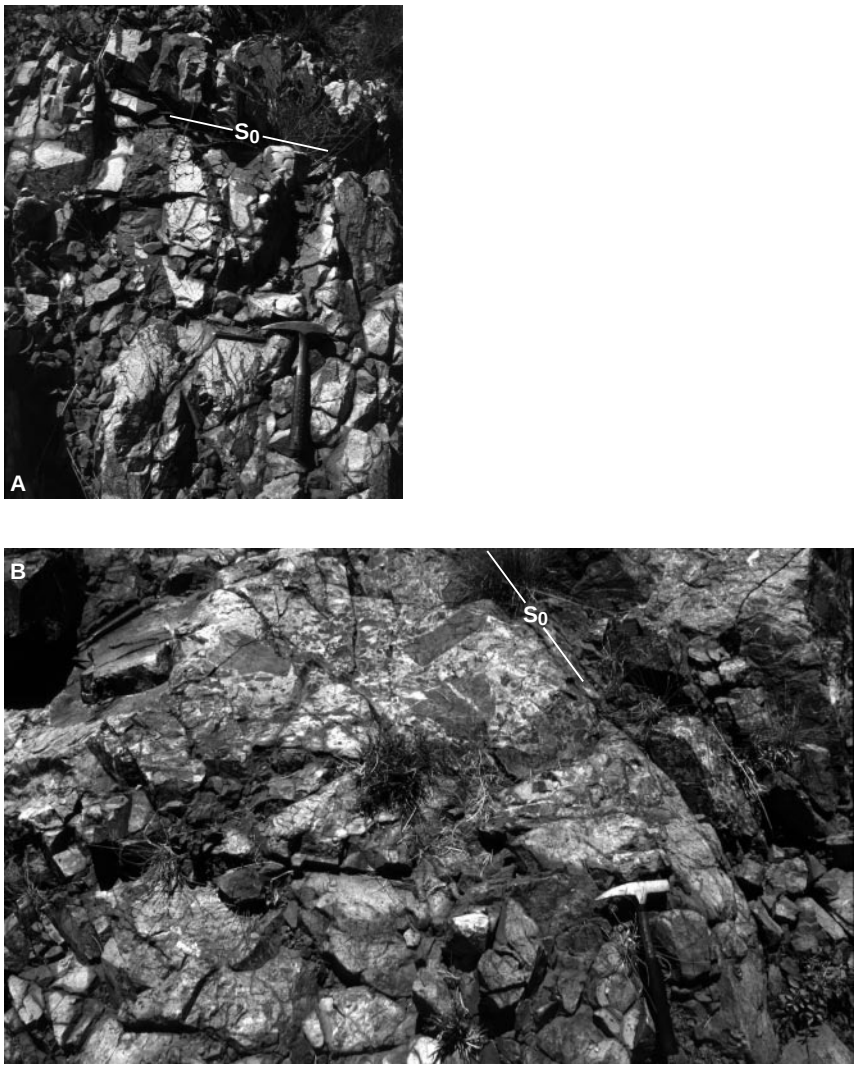

Fig. 11. (A) Anastomosing black chert veins; and (B) sedimentary chert breccia related to chert veins, in upper part of 'P' unit (locality 3 in Fig. 10).

Section 2.2, the competent felsic rock units have been internally faulted into imbricated slabs. Exposures at Coppin Gap show intense cross-folding. The entire structural unit is continuous with the eastward plunging Bamboo Creek Syncline (see Area IV, Section 3.4).

3.3.1. Interference of deformation and sedimentation

The map of Fig. 10 represents an east–west structural cross-section, showing listric west block-down, tensional growth faulting of the 'P'-unit, on the following evidence: (a) The intraformational character because of burial and flattening of the structure by shale and a thin sheet of basalt; (b) repeated eastward back tilt, combined with increase of thickness in the fault blocks from hanging wall towards footwall, best observed in the shale wedges; (c) mega-breccia along the sole of the fault array, consisting of rotated blocks of felsic volcanic rock set in a matrix of deformed and altered basalt, in places strongly ferruginous

at the surface, and confirming the high-crustal level of deformation; and (d) intense veining at right angles to bedding, which interfered with sedimentation, in the hanging wall of the normal faults, suggesting a synsedimentary tensile regime; similarly, growth fault-related vein swarms are reported from the North Pole Chert (Nijman et al., 1998).

The detachment plane is a shear zone, identical to the BCSZ. Foliation sub-parallel to the detachment plane has been refolded into vertical Z-folds with the development of a second axial planar cleavage (grid SS942832) at low angles to the shear zone. Also in the BCSZ, the original foliation has been refolded with the same dextral sense of displacement (Fig. 10). In all instances, the second deformation implies inversion of motion along the previous detachment planes and explains the anomalous superposition of backtilted normal fault blocks observed at grid SS960840. Whether inversion occurred at the same time as the early east–west shortening inferred for the Gorge Range, or accompanied later dextral strike slip along longitudinal faults, cannot be assessed at Kittys Gap, but only in comparison with data from area IV.

3.3.1.1. Complementary data from the central Coppin Cap Belt. Similar normal faults affect the Duffer agglomerate (* in Fig. 2, grid RB065830). Analysis of aerial photographs revealed that towards the west and at deeper stratigraphic level, the agglomerate has been completely disrupted into a megabreccia like that observed south of Kittys Gap. Because of poor outcrop of the areas between the blocks and the primary agglomeratic character of the formation, megabrecciation is difficult to confirm with field observation. West of the Talga Talga River, aerial photographs indicate an increasingly in situ arrangement of the blocks (grid QB955800). The Duffer agglomerate, moreover, is underlain by a tectonic detachment (grid RB085820).

3.4. Area IV: Bamboo Creek Syncline

The Bamboo Creek Syncline (Figs. 12 and 13) plunges 45 to the east and represents the core of the Coppin Gap synclinorium. Fold closure is observed east of Coppin Gap, whereas at Bamboo Creek an unconformity at the base of the Mount Roe Basalt truncates the syncline. The South Muccan shear zone (SMSZ) obliquely intersects the northern limb of the syncline, splaying into several branches with sinistral horizontal offset that terminate in the lower part of the Fortescue Group (Fig. 12).

3.4.1. Interference of deformation and sedimentation

In the context of this paper, two aspects of the Bamboo Creek Syncline are noteworthy: (a) repetition of stratigraphic units and deformational structures on the limbs; and (b) progressive, syntectonic infilling by a rock sequence of clastic sediment and basalt.

3.4.1.1. Repetition of stratigraphic units, folded faults and shear zones. On the southern limb of the Bamboo Creek Syncline, the stratigraphic sequence above the BCSZ comprises an over 500 m-thick sequence of: (a) silicified pillow basalt with discordant black chert veins ascending into (b) quartz/feldspar–porphyritic felsic volcanic rock with at least seven chert intervals, respectively, overlain by (c) conglomeratic, quartz-bearing, possibly volcaniclastic sandstone; (d) black-and-white chert with flat-stromatoloidal chert (grid TS025874); and (e) thick jaspilitic BIF.

To a large extent, this sequence repeats that of the 'P'-unit in the footwall of the shear zone at Kittys Gap (Area III), except for the thick and characteristic development of BIF. The latter might be explained by lateral facies change from a shale facies as observed in the 'P'-unit south of Kittys Gap and Bamboo Creek. We doubt whether the rock assemblages to the north of the BCSZ should be classified as the next younger felsic unit with respect to the 'P'-unit, i.e. as the Wyman Formation, because the contact between the two near-identical units is a major shear zone. This can be verified by future U–Pb zircon dating.

On the southern synclinal limb, structural imbrication is more pronounced than at Kittys Gap. It involves large parts of the sequence of felsic rock to BIF, in structural repetition along faults at low

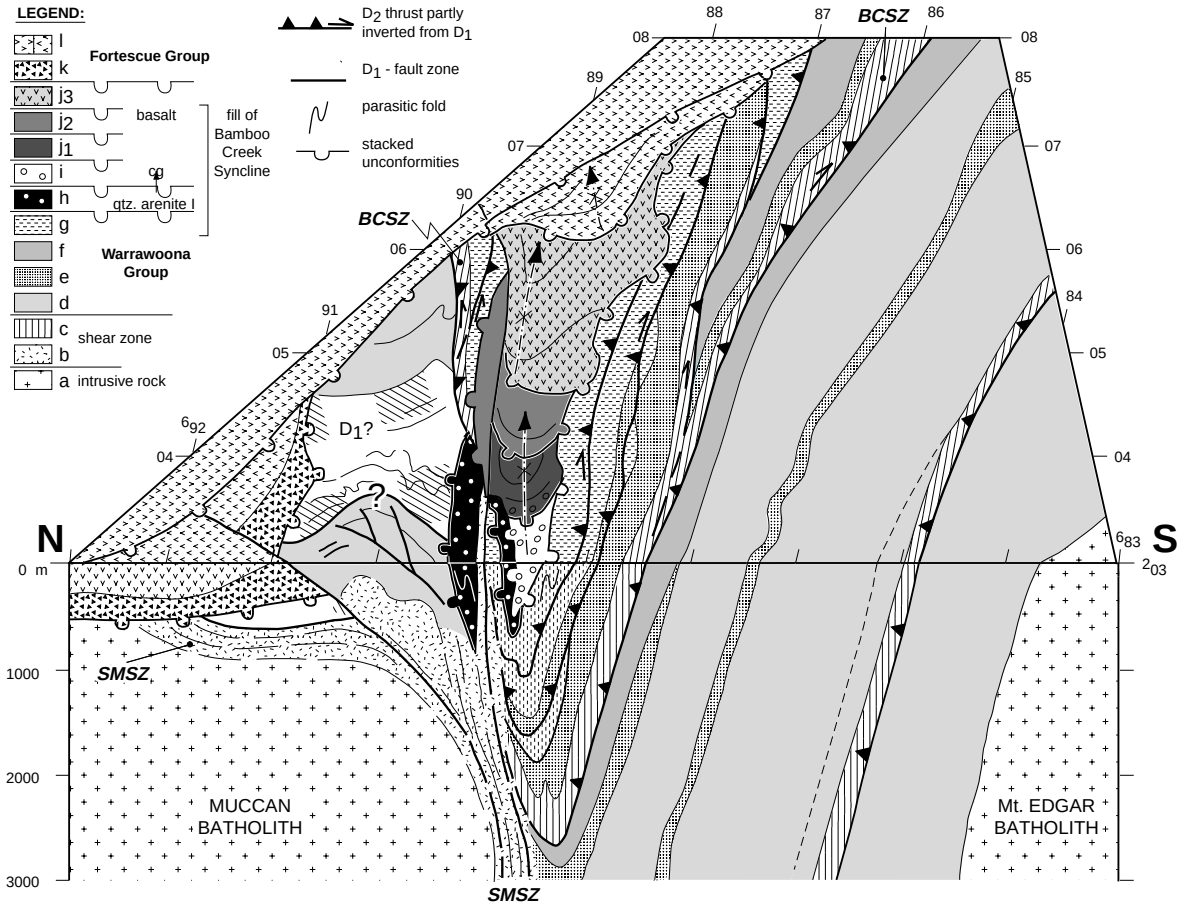

Fig. 12. Block diagram of Bamboo Creek growth syncline, area IV. View to east over N–S cross-section of Coppin Gap Belt. Along the southern limb of the Bamboo Creek Syncline, east-verging piggyback thrusts duplicate a suite of felsic volcanics-sandstone overlain by BIF, similar to the one below the main shear zone. Along faulted northern limb, unconformable contact (in Fig. 14) of quartz arenite I with sheared Warrawoona Group and BIF is preserved. Imbricated thrust structures in BIF mirror those in southflank, albeit of much smaller size. During growth, the syncline was discontinuously filled with a sequence evolving from coarse clastics (unconf. 2) into vesicular basalts (unconf. 3–6). Legend: (a) batholiths; (b) South Muccan shear zone; (c) other shear zones; (d) Warrawoona Group basalt and ultramafic rock; (e) 'P'-assemblage: felsic volcanics, porphyries, sandstone, and chert; (f) silicified (pillow) basalt; (g) BIF; (h) clastic system I qtz-arenite; (i) conglomerate; (j_{1-3}) vesicular basalts of BC synclinal fill; (k) agglomerate; and (l) basalts of the Fortescue Group.

angles to bedding (grid TS048865), which branch from the underlying BCSZ (Fig. 12). The fault imbricate is unconformably covered by the fill of the Bamboo Creek Syncline (see for details below).

On the northern limb of the Bamboo Creek Syncline (Fig. 12), late sinistral offset along branches of the SMSZ largely obscures the fact that, both stratigraphically and structurally, the northern limb mirrors the more complete southern limb.

Slices of locally intensely folded, jaspilitic BIF form en échelon structures (grid TS059888), but with opposite symmetry to those in the southern limb. The contact between BIF on the one hand and basalt and ultramafic rock of the Warrawoona Group overlain by quartz arenite on the other is

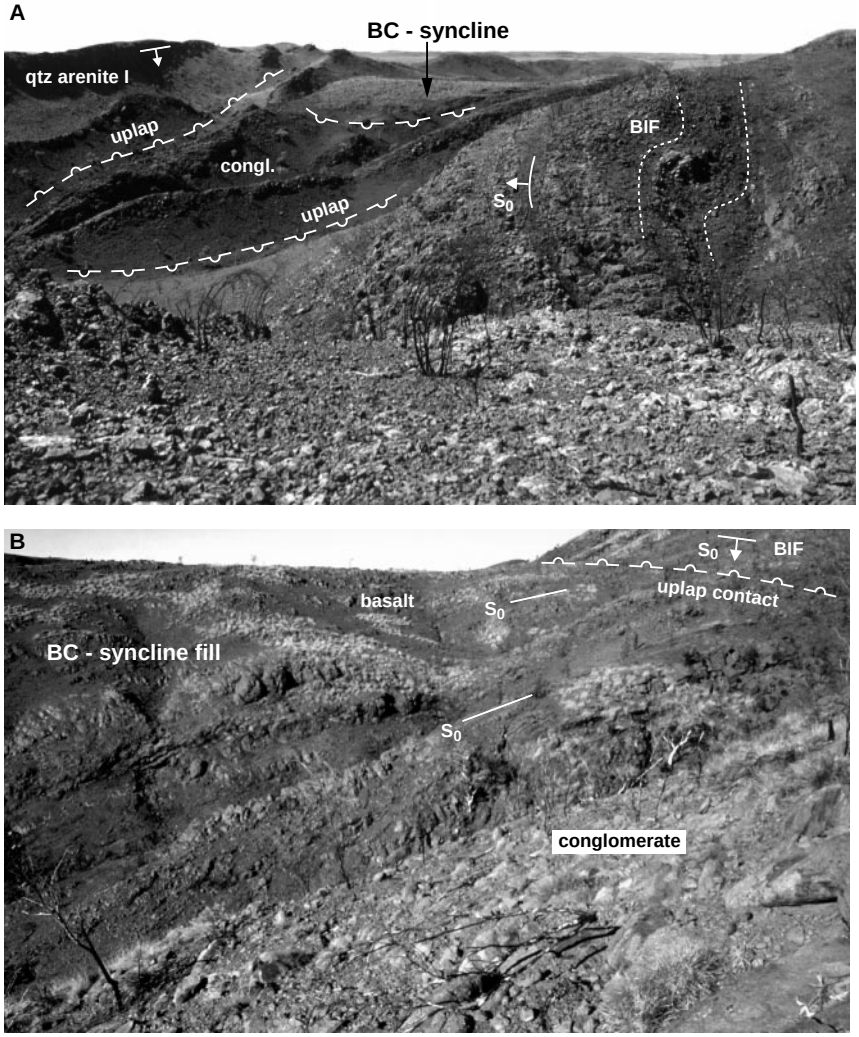

Fig. 13. (A) view to east from BIF with parasitic Z-fold in southern limb of BC syncline towards progressively flattening fill of boulder conglomerate overlain by basalt; in background, opposite limb of the syncline with quartz arenite I over BIF; (B) view to south-east of synclinal fill composed of boulder conglomerate overlain by basalt, uplapping against steeply dipping BIF of southern limb of syncline.

sheared. Like the BSCZ, the shear zone is rich in fuchsite, quartz and carbonate alteration and hosts Cu–Fe sulfides which form small gossans.

East of the Muccan batholith, the Warrawoona Group has been tilted 45° to the east, probably due to doming of the Muccan batholith and comprises a bedding-parallel shear zone with the usually observed chemical alteration. Zegers (1996) records a dextral sense of shear with 20° N-pitching lineation on the east-dipping shear foliation.

Cross-bedded quartz arenite similar to clastic system I in the western part of the belt, overlies this sequence with angular unconformity (grid TS035890: '1' in Fig. 12). Therefore, the bedding-parallel shear zone in the Warrawoona Group existed prior to formation of the unconformity

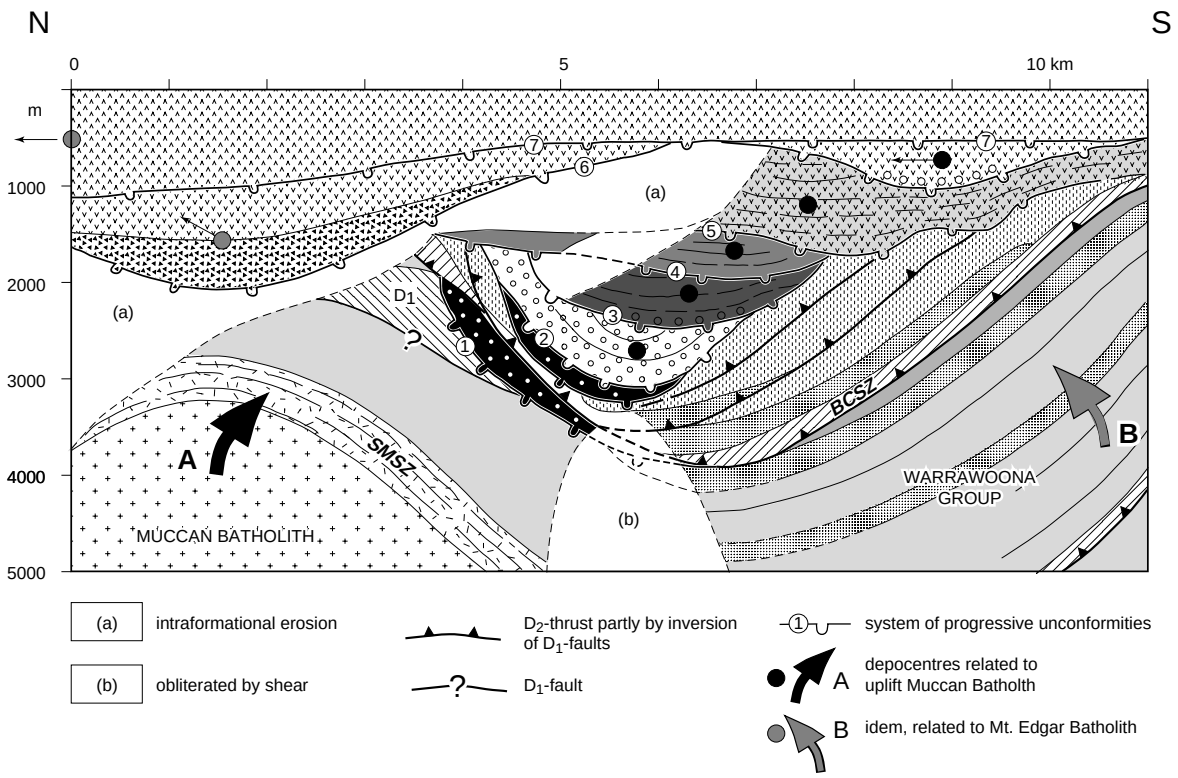

Fig. 14. Systematic depocentre shift in growth syncline is connected to successive doming of the Muccan batholith (black dots and arrow) and Mt Edgar batholith (grey dots and arrow). Low-angle thrusts with hanging walls displaced away from the viewer are shown in transverse cross-section. The unconformities are numbered 1–7. (a) Cross-sectional area lost by pre-Fortescue Group erosion; and (b) lost due to shear along SMSZ.

below the first quartz arenite in this part of the belt (Table 1). The previously mentioned mineralized shear zone, however, appears to postdate the unconformity. Its possible passage between two slices of unconformable quartz arenite is obscured by a splay of the later SMSZ. The quartz arenite is absent in the southern limb of the Bamboo Creek Syncline.

3.4.1.2. Sedimentary/volcanic fill of the Bamboo Creek Syncline. The Bamboo Creek Syncline is filled by onlapping coarse conglomerate which contains pebbles of quartz arenite, chert and BIF, succeeded by cavernous basalt (Fig. 13). It is the sequence that Horwitz (1990) correlates with the Whim Creek Group above the Shay Gap unconformity (=Roeburne Megasequence of Krapez in Eriksson et al. (1994), north of the Muccan batholith.

Unfolding of the Bamboo Creek Syncline (Fig. 14) illustrates more explicitly that the fill consists of several unconformable phases (unconformities 2–5) onlapping against the southern limb of the syncline. The onlap and progressive flattening of the increments of infill is clear evidence of the growth fold character of the syncline. Subsequently, the Bamboo Creek Syncline was truncated by unconformities 6 and 7 of lowermost Fortescue Group age. A depocentre of coarse volcanic agglomerate is situated over unconformity 6 in a shallow depression several kilometres to the north of, and parallel to, the Bamboo Creek Syncline. Fig. 14 shows that depocentres, or perhaps more precisely the synclinal bending points,

Table 1
Sedimentation and deformation in Coppin Gap belt compared with North Pole area

Stratigraphy	Age (Ma)	**Sedimentologic events and *structural events***			
		West Gorge Range	Doolena Gap	Kittys Gap and Bamboo Creek	North Pole (Nijman et al., 1998)
WARRAWOONA GROUP (= megasequence) in particular the 'Panorama'-unit	**Early Archaean** 3450–3470	Chert-basalt sequence with felsic intervals	Black and white chert-basalt sequence transitional into Fe-rich and silicified sandstone; rare stromatoloids and silicified barite	Chert-basalt sequence with felsic volcanics, hydrothermal chert veins and vein breccia; upwards transitional into BIF; rare stromatoloids	Chert-basalt sequence with silicified sandstone and stromatoloids; hydrothermal barite mounds and barite-chert veins; related to
				Listric west-block down, tensional faulting; low-angle shear zones	*listric north-block down, tensional growth faulting; low-angle shear zones; hydrothermal veins and faults*
				Basalt (Kittys Gap)	
				Eastward tilt along east-side of Muccan batholith	
unconformity	- - - - - - -	- - - - - - -	- - - ? - - -	- - - - - - -	*no data*
GORGE CREEK GROUP	3325?	Quartz arenite	Quartz arenite	Quartz arenite	
CLASTIC SYSTEM I	**Mid Archaean**	*South-trending growth synclines in hanging-wall of shear zone in basalt and UM, indicating, east-west shortening*	*South-trending folds indicating east-west shortening; low-angle shear zones in basalt and UM*	*East-verging piggyback thrusting; ramp-flat structures in Warrawoona Group; inversion of old and formation of new low-angle shear zones in basalt and UM*	*North-east-verging thrusting, indicative of unilateral shortening in the cover of the North Pole batholith*
unconformity	- - - - - - -	- - - - - - -	- - - - - - -	- - - - - - -	*no data*
CLASTIC SYSTEM II		FU coarse conglomerate and ferruginous sandstone in growth synclines	Conglomerate and ferruginous sandstone	Coarse conglomerate (*) coeval with	no data
		Folding by north-south compression	*Folding by north–south compression*	*north–south compressive folding accompanied by southward depocentre shift and stacked unconformities related to rise of Muccan batholith*	*Doming of North Pole batholith; radial faults*
unconformity	3265	- - - - - - - -	- - - - - - - -	and followed by basalt	*no data*

Table 1 (*continued*)
Sedimentation and deformation in Coppin Gap belt compared with North Pole area

Stratigraphy	Age (Ma)	**Sedimentologic events and *structural events***			
		West Gorge Range	Doolena Gap	Kittys Gap and Bamboo Creek	North Pole (Nijman et al., 1998)
CLASTIC SYSTEM III		Thick arkosic/quartz arenitic littoral (?) sheet sandstone conglomerate overlain by black-and-white banded chert grading into	Thick arkosic/quartz arenitic littoral sheet sandstone grading into heterolithic facies		no data
CLASTIC SYSTEM IV		channellized sandstone and conglomerate; (top of clastic sequence not exposed)		*(Alternative correlation: conglomerate of clastic system II)	no data
		Continued north–south shortening forming major inter-batholith syncline; dextral strike slip in east-striking dextral shear zone with constraining bend thrusts, intersected by	*Continued north-south shortening forming major inter-batholith syncline, intersected by*	*Continued north–south shortening forming major inter-batholith syncline, northward depocentre shift related to rise of Mt Edgar batholith; structural pattern intersected by*	
	±2.8 Ga	*NE–SW sinistral faults accommodating dolerite dykes*	*NE–SW sinistral faults, accomodating dolerite dykes*	*NE–SW sinistral faults*	*Block faulting with NE-SW dolerite dykes*
		East-striking dextral shear zones offsetting dolerite dykes	*East-striking dextral shear zones offsetting dolerite dykes*	*Dextral shear along contact with Muccan batholith*	
unconformity	-------	-------	-------	-------	--------
FORTESCUE GROUP Mount Roe basalt	2775–2680 **Late Archaean**	Cover basalts	Cover basalts	Cover basalts	Cover basalts

shift southward during infilling phases 1–5, but in opposite northern direction during phases 6 and 7.

3.4.2. Discussion

Because the system of progressive unconformities is folded with the syncline, it follows that pre- and syn-unconformity structures have to be restored for tilt until the bedding is sub-horizontal, before the deformation history can be interpreted kinematically (Fig. 14).

(1) By unfolding the Bamboo Creek Syncline and subsequent restoration for pre- to syn-unconformity-1 tilt, the older bedding-parallel shear zone in the northern limb becomes sub-

horizontal. As a consequence, the sense and orientation of the translation of the hanging wall is westward in correspondence with that of the pre-inversion tensional shear zones south of Kittys Gap and Bamboo Creek. We prefer this interpretation of tensile shear above that of east block-up, west-verging thrust motion advocated by Zegers (1996).

(2) Restoration also reveals an east-verging, low-angle piggyback-thrust system that created primary relief filled by coarse clastic sediment succeeded by basalt. The thrusting can be relatively dated to post-deposition of the first quartz arenite deposystem and pre-infilling of longitudinal fold relief by younger systems. The low-angle thrust system exposed in the southem limb of the Bamboo Creek Syncline is much more pronounced than in area I at the west end of the greenstone belt. The sole thrust is the BCSZ, a major detachment between two comparable rock suites with felsic volcanics, the lower of which certainly belongs to the Warrawoona Group. Thrust structures can be found all along the BCSZ to the east (grid TS130808) (Smits, 1985; Pieters, 1986; Marcelis, 1986) (see also Fig. 2). While piggybacks were generated at the surface, the BCSZ displayed a ductility of deformation and mineralogical alteration suggestive of a temperature beyond that expected to have prevailed at only 600–700 m below that surface (Zegers, 1996). This may be due to transport of warm fluids along the shear zone as proposed by Nijman et al. (1992) for similar surficial low-angle thrust systems in the Mount Isa Inlier, or to a relatively high thermal gradient.

(3) The mineralized shear zone in the northern limb of the Bamboo Creek Syncline that post-dates the unconformity at the base of the quartz arenite is considered equivalent to the BSCZ, at least for as far as the latter acted as a low-angle thrust. Whereas on the southern limb, inversion of normal faults to thrust faults is the rule, tensile and compressive effects have been geometrically separated in different shear zones on the northern limb of the Bamboo Creek Syncline due to tilt prior to compression.

(4) The sequence of events in the Bamboo Creek Syncline corresponds with that described for the Gorge Range, on the opposite end of the Coppin Gap Belt, i.e.: (a) unconformable deposition of quartz arenite (clastic system I?) on sheared Warrawoona Group including rocks with 'P'-unit affinity; (b) east-verging thrusting creating a tectonic relief that (c) was subsequently filled by conglomerate during north-south folding (Fig. 12 and Table 1). In this respect, the infilling conglomerate compares with either clastic system II or IV, although in the western Coppin Gap Belt no basalts are known to overly the coarse clastic sedimentary rock sequence.

(5) The observed depocentre shift within the synclinal fill might indicate that uplift of the Muccan batholith started prior to that of the Mount Edgar batholith. This would agree with the asymmetry of the entire Coppin Gap synclinorium. The asymmetry in stratigraphic development on both limbs of the Bamboo Creek Syncline, in particular the angularity of unconformity '1', indicates that doming in the area of the Muccan batholith had started prior to the formation of the unconformity and therefore also prior to low-angle thrusting. Here too, more geochronologic evidence is needed.

4. Summary and conclusions

Table 1 summarizes the data so far obtained in the Coppin Gap Belt and compares it with results of our investigation of the North Pole area (Nijman et al., 1998).

Correlation of the four clastic systems with the subdivision of the Gorge Creek Megasequence given by Krapez in Eriksson et al. (1994) is not straightforward. Rather the scale of the entire sequence of clastic systems I–IV represents a higher order of variation within the units distinguished by Krapez, such as the lowermost quartz arenite sequence in the North Lalla Rookh Basin, labelled GC la. Moreover, the coarse conglomerate and basalts of the BC synclinal fill in the eastern part of the belt have been correlated with the younger Whim Creek Group (=Roeburne Megasequence of Krapez, 1993) (Horwitz, 1990; Eriksson et al., 1994).

Correlation of the felsic units within the

Warrawoona Group and with the Wyman Formation has now also become debatable because of the recognition of low-angle shear zones in what, until now, has been described as a tectonically undisturbed stratigraphic sequence of Warrawoona Group to lower Gorge Creek Group.

Apart from confusion about the validity of the present-day stratigraphic classification and a chronic lack of sufficient chronologic data, Table 1 does show some important correspondences in the succession of deformational and sedimentary events, in both the Coppin Gap Belt and the North Pole Dome area, as follows.

(1) Syn-Warrawoona Group extension indicated by normal listric fault arrays. The arrays are mainly restricted to felsic volcanic units and oriented quite differently in the Coppin Gap Belt (W-facing), the North Pole Dome (NNW-facing; Nijman et al., 1998) and the Kelly Belt (WSW-facing; Zegers et al., 1996).

(2) Low-angle thrust structures appear to be more common than previously thought of and are in general east-verging (cf. Bickle et al., 1980; Boulter et al., 1987; Nijman et al., 1998; Van Haaften and White, 1998). At least in part, they have been generated by inversion along pre-existing extensional shear zones only where the latter were favourably oriented such as the westdipping detachments in the Coppin Gap Belt. In the North Pole Dome, the orthogonal relationship between the orientation of the two deformations prevented inversion. The thrusts may duplicate the stratigraphic sequence to an unknown degree (cf. the comments of Krapez, 1993). In the Coppin Gap Belt, an unconformable, transgressive quartz arenite (clastic system 1) is the youngest unit involved in thrust tectonics.

(3) Longitudinal folds related to the Coppin Gap synclinorium, and therefore indicative of positive movement of the areas of flanking intrusives, were being formed from deposition of clastic system II onward. In the western part of the belt, system II was immediately followed by east-trending folding, but in the eastern part appears to have been coeval with it. Although its unconformable relationship with clastic system I and the Warrawoona Group are similar in the eastern and western ends of the belt, a correlation of the conglomerate in the Bamboo Creek Syncline with clastic system IV in the west [Table 1 (*)], or with the even younger Whim Creek Group in the north (cf. Horwitz, 1990), cannot be excluded.

The Coppin Gap synclinorium is asymmetric and growth fold geometry and depocentre migration indicate that tilt affected the northern limb first. The SMSZ might represent a core complex extension with supracrustal thinning over a Muccan granitoid basement as suggested by Zegers et al. (1996) for the Shaw granite (cf. Van Kranendonk, 1995).

The much thicker stack of tectonic slices on the southern limb of the Coppin Gap synclinorium suggests it has formed in an area of downward crustal flexuring (by loading?) in balance with early uplift of granitoid basement in adjacent areas. After cessation of the thrusting, at 3.3 Ga intrusion of the Mt Edgar granitoid complex cross-cuts the thrust planes. Depocentre migration to the north, involving basal levels of the Fortescue Group, records increased influence of positive movement of the Mount Edgar domain and steepening of the southern flank of the synclinorium.

The above conjectures have to await more U–Pb zircon dating, further field investigations and more advanced integration of data obtained by our research group, but they illustrate the potential of detailed analysis of the relationship of cover sediments with the topographic expression of shallow deformation, an approach also found in studies by Lamb (1984, 1986) on the Barberton greenstone belt.

The phase of early extension is not well understood. At least as far as the surficial cover is concerned, the distribution of normal fault arrays opens other ways to interpret these structures than as the product of a unidirectional regional tensional stress field (Zegers et al., 1996). Widespread and large-scale caldera collapse of felsic cones creating hydrothermally injected, ring fault systems, many tens of kilometres wide, might be considered to have generated early normal growth faults. The Early Archaean basin form then would have been influenced by a craterlike topography. According to DiMarco and Lowe (1989) and Barley (1993), the distribution of volcanic cones,

inferred from the dispersal of volcanic facies, reflects that of the batholiths.

At the onset of the mid-Archaean, with increasing rigidity of the supracrust, regional compression inverted those extensional fault systems that were favourably oriented to accommodate the shortening in overall W→E direction. The start of siliciclastic sedimentation preceded that event indicating the availability of granitic or felsic volcanic source areas for coastal reworking and production of quartz arenite. Subsequent formation and erosion of sub-aerial relief formed by the thrust deformation is witnessed by arkosic alluvial fans of clastic system II, again subjected to coastal reworking, represented by clastic system III.

East–west shortening by low-angle thrusting may have been much greater than recognized until now. Slicing of the Warrawoona Group and repetition of felsic units showing surficial growth structures brings the discussion about the Archaean crustal built up of the Pilbara on line with the one on thrust duplication in the Onverwacht Group, South Africa (De Wit, 1982; Lamb, 1984, 1986; De Ronde and De Wit, 1994; Eriksson et al., 1994). In the Coppin Gap Belt, the deformation resulted from interference of this east–west shortening by low-angle thrusting with the development of an interbatholith synclinorium at right angles.

The structural framework of inversion of extensional growth faults into low-angle thrust imbrication compares with that suggested by Hammond and Nisbet (1990) for the 2.9–2.7 Ga $D_E \rightarrow D_1$ deformation episode of the Norseman–Wiluna Belt of the Yilgarn Block, Western Australia. They proposed an extensional mechanism of crustal delamination akin to the formation of metamorphic core complexes in an actively extending orogen and generated by pure shear in the lithospheric mantle, associated with partial melting. In the Norseman–Wiluna Belt, D_1 thrusting was thin-skinned and involved low-angle stacking of the greenstone sequence immediately after extension.

As to the Coppin Gap Belt, no positive evidence exists about an early orogenic crustal thickening and subsequent collapse causing extension (see also the discussion by Zegers, 1996). Molasse-type clastic sediments to the amount expected to have been generated by a pre-extension orogenic belt in the Early Archaean is absent in the Warrawoona Group. Rather clastic sediments, as observed in the 'P'-unit, correspond to minor source areas of mixed basaltic/felsic composition (see also Nijman et al., 1998). Supracrustal geometry and related surface expression of the tensile deformation, the stability of relatively thin (later thrust-duplicated) cooled solid basaltic crust, in places over an unknown thickness of granitoid basement, the episodically accompanying and repetitive felsic volcanism and hydrothermal activity, as well as probably raised geothermal gradients, set this Early Archaean deformation apart. According to Vlaar (1986), the special character of the Early Archaean mantle, i.e a 50 km-thick basaltic upper mantle with small density difference with respect to the thin, relatively warm and mechanically weekened crust allowed for predominantly vertical movements of subsidence and uplift, but not for the building of major relief. Episodic heating, convectivity and/or plume activity (cf. Stein and Hofmann, 1994) may account for adjacent crustal bulges, tens of km wide, serving as low-relief source areas for clastic sediments and as centres of felsic volcanism, developing radial extensional patterns upon collapse. For an alternative model of oceanic backarc extension (Krapez, 1993), where presently sub-aqueous caldera structures are known to develop (Western Pacific, Ishibashi and Urabe, 1995), the linearity of structure still has to be proven.

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