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Fault reactivation and superimposed folding in a Proterozoic sandstone–volcanic sequence, Davenport Province, central Australia

ALASTAIR J. STEWART

Division of Petrology and Geochemistry, Bureau of Mineral Resources, GPO Box 378, Canberra, ACT 2601, Australia

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Abstract—The Davenport Province is a fluvial to shallow-marine sequence of weakly metamorphosed sandstone, rhyolite and basalt deposited in an ensialic basin that was probably initiated by continental extension. Isopach ridges and cut-offs suggest that synsedimentary normal and transfer faults controlled deposition. These faults were reactivated as reverse faults and strike–slip faults during deformation. Upright concentric folding took place in two episodes, initially about NW-trending axes and subsequently about generally NE-trending axes. Balanced cross-sections suggest that the folds die out downwards above the base of the sequence. However, units from well below the concentrically folded part of the sequence crop out in anticlinal cores, indicating that there is no through-going detachment horizon in the sequence. This is consistent with the rarity of clayey, silty and evaporitic sediments suitable for detachment. Hence, the faults probably cut the entire sequence and enter the basement. Interference of the folds formed dome-and-saddle and crescentic patterns. Thrust sheets, imbricate stacks and duplexes are not recognized in the province, and layer-parallel shortening is moderate (about 28%). These suggest a correspondingly low degree of earlier regional extension (about 40%). The folding may have been due to a sudden change in lithospheric plate velocity.

INTRODUCTION

DEFORMATION histories beginning with the emplacement of fold nappes or thrust sheets and followed by one or more episodes of upright folding have been described from many Phanerozoic and some Proterozoic terranes, whereas a history consisting wholly of upright folding in one or more episodes is less common. Fold nappes and thrust sheets are promoted either by gravity sliding or by subduction attendant upon collisional or Cordilleran plate tectonics (Dewey & Bird 1970); their absence in a deformed terrane suggests a different tectonic regime – one of limited horizontal displacement and limited subduction (Kroner 1979; Etheridge *et al.* 1987).

The early Proterozoic Davenport Province in central Australia (1870–1640 Ma; Blake *et al.* 1987) is an ensialic sandstone–rhyolite–basalt sequence which accumulated in an extensional basin of the type discussed by McKenzie (1978), Royden *et al.* (1980) and Dewey (1982), and was then deformed by two episodes of concentric upright folding. In places, the folds are superimposed and form Type 1 and 2 interference patterns (Ramsay 1967). Reverse faults associated with the folds probably cut the entire Davenport sequence and enter the underlying basement. Isopachs suggest that the reverse faults began as synsedimentary normal faults, which were later reactivated. Balanced cross-sections indicate that layer-parallel shortening was about 28%, and that no bedding-parallel thrust sheets or duplexes formed.

GEOLOGICAL SETTING

The Davenport Province is located in the Northern Territory of Australia, and is the southern part of the Early Proterozoic Tennant Creek Inlier of the Australian Precambrian shield (Figs. 1a & b). The Tennant Creek Inlier comprises a turbidite–rhyolite sequence, the Warramunga Group, which is tightly folded, weakly metamorphosed and intruded by granite. A well-exposed sandstone–rhyolite–basalt sequence, the Hatches Creek Group, unconformably overlies the Warramunga Group, and makes up the bulk of the Davenport Province. The Proterozoic Arunta Inlier crops out south of the Davenport Province, but their relationship is concealed by Phanerozoic cover; the Hatches Creek Group is inferred to rest unconformably on the Arunta Inlier. The Davenport Province is unconformably overlain to the east and west by flat-lying Palaeozoic sediments of the Georgina and Wiso Basins, respectively (Fig. 1a). Aeromagnetic data (Tucker *et al.* 1979) indicate that the Davenport Province extends northeast for a further 400 km beneath the Georgina Basin, and west for 250 km beneath the Wiso Basin (Kennewell & Huleatt 1980).

The Hatches Creek Group is at least 10 km thick. It is divided into the Ooradidgee, Wauchope and Hanlon Subgroups, and into 20 formations (Fig. 2). Individual formations of the Ooradidgee Subgroup characteristically interfinger, whereas those of the Wauchope and Hanlon Subgroups are more regularly layered. In addition, the Ooradidgee Subgroup contains the greatest proportion of rhyolite and basalt, and its sedimentary component is fluviatile to deltaic (Blake *et al.* 1987); the subgroup represents the rift sequence (Etheridge *et al.* 1987) of an extensional basin. The Wauchope and Hanlon Subgroups have the greatest proportion of sandstone, and represent the subsidence sequence; they were deposited during three shallow-marine transgressive–regressive cycles, two forming the Wauchope Sub-

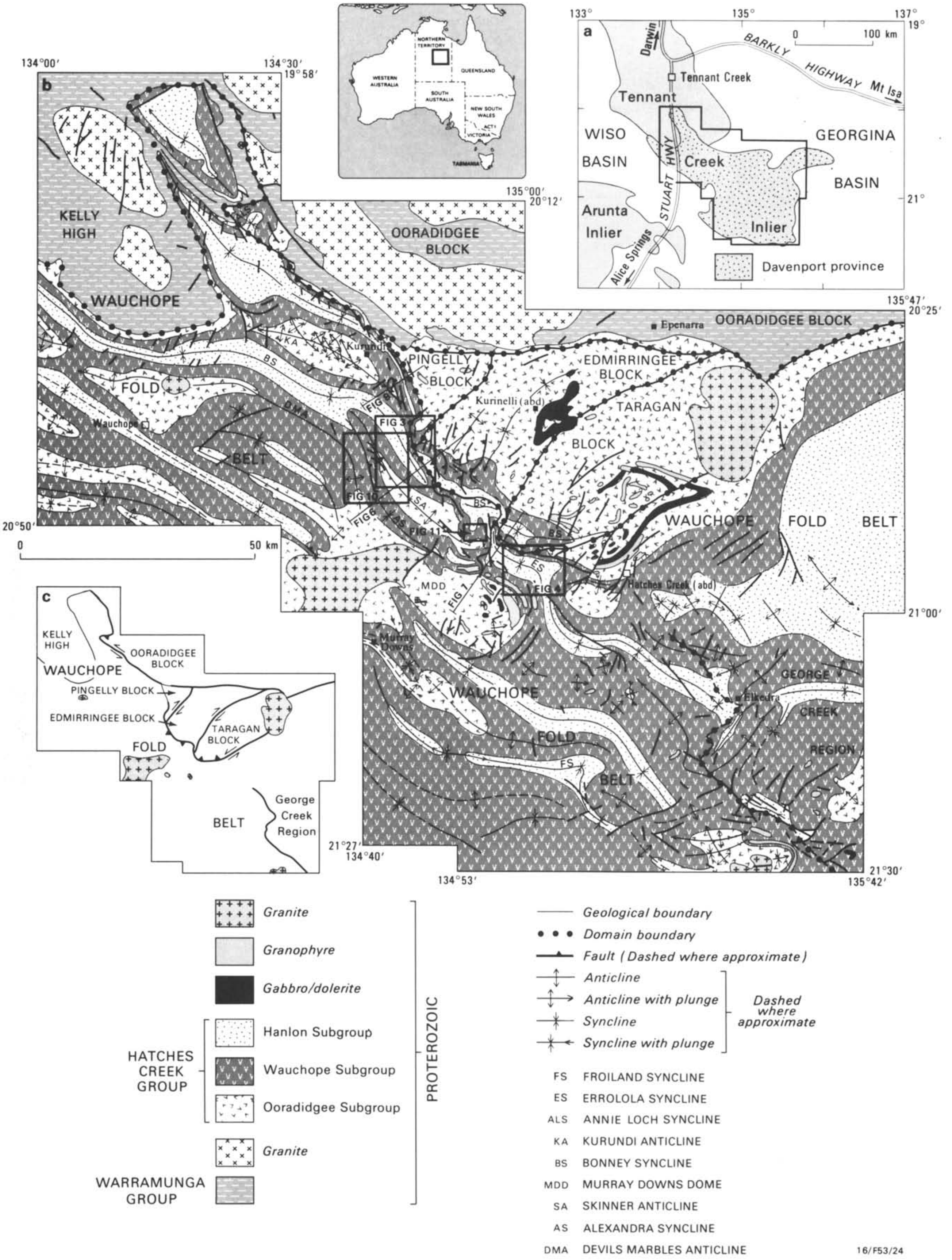

Fig. 1. Locality map (a) and geological map (b) of Davenport Province; inset (c) shows structural domains. Grey ornament in (a) indicates outcropping Proterozoic rocks.

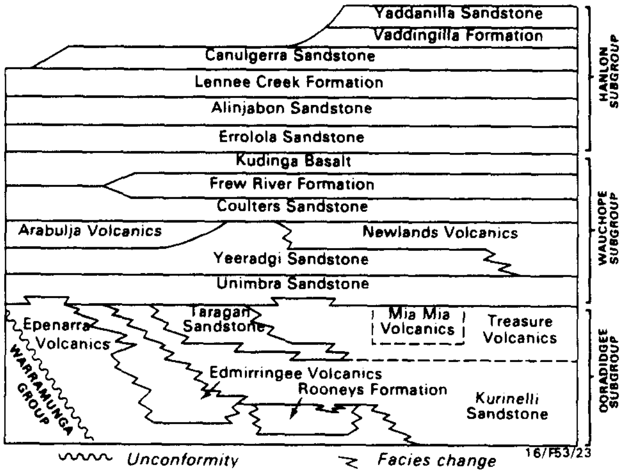

Fig. 2. Diagrammatic relationships of formations within the Hatches Creek Group. Relationship of Treasure Volcanics to Mia Mia Volcanics and Kurinelli Sandstone not known.

group, the third the lower part of the Hanlon Subgroup (Blake *et al.* 1987). The transgressive parts of each cycle are represented by three thick sandstone formations (Unimbra, Coulters and Errolola Sandstones; Fig. 2), and it is these three sandstones and their intervening units which are concentrically folded.

Sedimentary rocks of the Hatches Creek Group are mostly shallow-water lithic, feldspathic or quartz arenite, pebbly arenite and conglomerate. Siltstone, shale and carbonate are rare. Abundant pebbles and detrital clay and feldspar grains in the arenites, and widespread prolapsed cross-bedding (as described by Wood & Smith 1958) indicate rapid deposition. The volcanic rocks are almost entirely basaltic, rhyolitic or dacitic subaerial lavas and pyroclastics; andesite and trachyte are rare (Blake *et al.* 1987). The rocks form several separate volcanic centres up to 3 km thick in the Ooradidgee and Wauchope Subgroups, and interfinger with sedimentary clastic rocks on their flanks, where mixtures of tephra and terrigenous sediment are common. Volcanic rocks are rare in the Hanlon Subgroup.

Sills of gabbro/dolerite and granophyre intrude the Hatches Creek Group, and were emplaced during and/or shortly after deposition, but before folding. The gabbro/dolerites are concentrated in the centre of the province (Fig. 1b).

Folding of the Hatches Creek Group took place in two episodes, and was accompanied by high-angle reverse faulting and strike–slip faulting. Much of the Davenport Province is simply folded by regular NW-trending upright folds (Figs. 1, 3 and 4). The northeast and southeast parts of the province are likewise folded by upright but generally NE-trending folds. In places the two sets of folds occur together (Fig. 4), and overprinting shows that the NW-trending set formed first.

Two-mica granites were emplaced into the cores of anticlines and domes in the lower part of the Hatches Creek Group, up to the stratigraphic level of the Unimbra Sandstone. The granites are massive, S-type [i.e. of sedimentary parentage in the terminology of Chappell & White (1974)], cut bedding at high angles, and in places are steeply faulted and brecciated.

Major faults divide the Davenport province into five domains (Fig. 1c). They are described in the section on contractional structures, and used for reference in the section on extensional structures.

The maximum age of the Hatches Creek Group is a U–Pb zircon date of 1870 Ma on volcanic rocks in the Warramunga Group (Black 1984). The minimum age for the lower part of the group is a Rb–Sr whole-rock date of 1640 Ma (recalculated by L. P. Black, personal communication, from data in Riley 1961) on post-tectonic granite which intrudes the lower part of the group in the southeast of the province.

The Davenport Province was first mapped at the broad reconnaissance level (1:250,000 scale) by the Australian Bureau of Mineral Resources (BMR) in 1956 (Smith *et al.* 1961), and remapped at the detailed reconnaissance level (1:100,000 scale) by a joint BMR–Northern Territory Geological Survey party in 1981–83 (Blake *et al.* 1987).

EXTENSIONAL STRUCTURES

Recent studies of extensional basins have shown the importance of synsedimentary normal and transfer faulting during deposition (Bally 1981, Gibbs 1984, Etheridge *et al.* 1985, Etheridge 1986); and Jackson (1980) and Stoneley (1982) have shown that early normal or listric faults may become reverse or thrust faults during basin deformation. In an attempt to see whether these processes took place in the Davenport Province, non-palinspastic isopach maps were prepared for the Taragan, Unimbra, Yeeradgi, Coulters and Errolola Sandstones (Figs. 5a–e). Each isopach diagram also shows synsedimentary normal and transfer faults inferred to have been active during deposition of the relevant unit. Figure 5(f) is a synopsis of the faults inferred in Figs. 5(a)–(e). Scarps can form on both normal and transfer faults and thus lead to sudden changes in sediment thickness; but the assumption was made that, because the strike of the NW-striking faults is normal to the principal compressive direction, they are reverse faults that began as normal faults, when the principal stress was similarly oriented but extensional.

Transfer faults

The strongest evidence for a synsedimentary transfer fault is an abrupt cut-off of the Taragan Sandstone isopachs at the northwestern margin of the Edmirringee Block (fault 1 in Fig. 5a). The Taragan Sandstone at the cut-off consists of massive beds of quartz–pebble conglomerate, which grades into pebbly arenite away from the cut-off. In addition, a pebbly arenite subunit of the Kurinelli Sandstone (Fig. 2) below the Taragan Sandstone also terminates on the same side of the fault, and the Coulters Sandstone thickens abruptly from 300 to 1100 m southeastward across the fault. By implication,

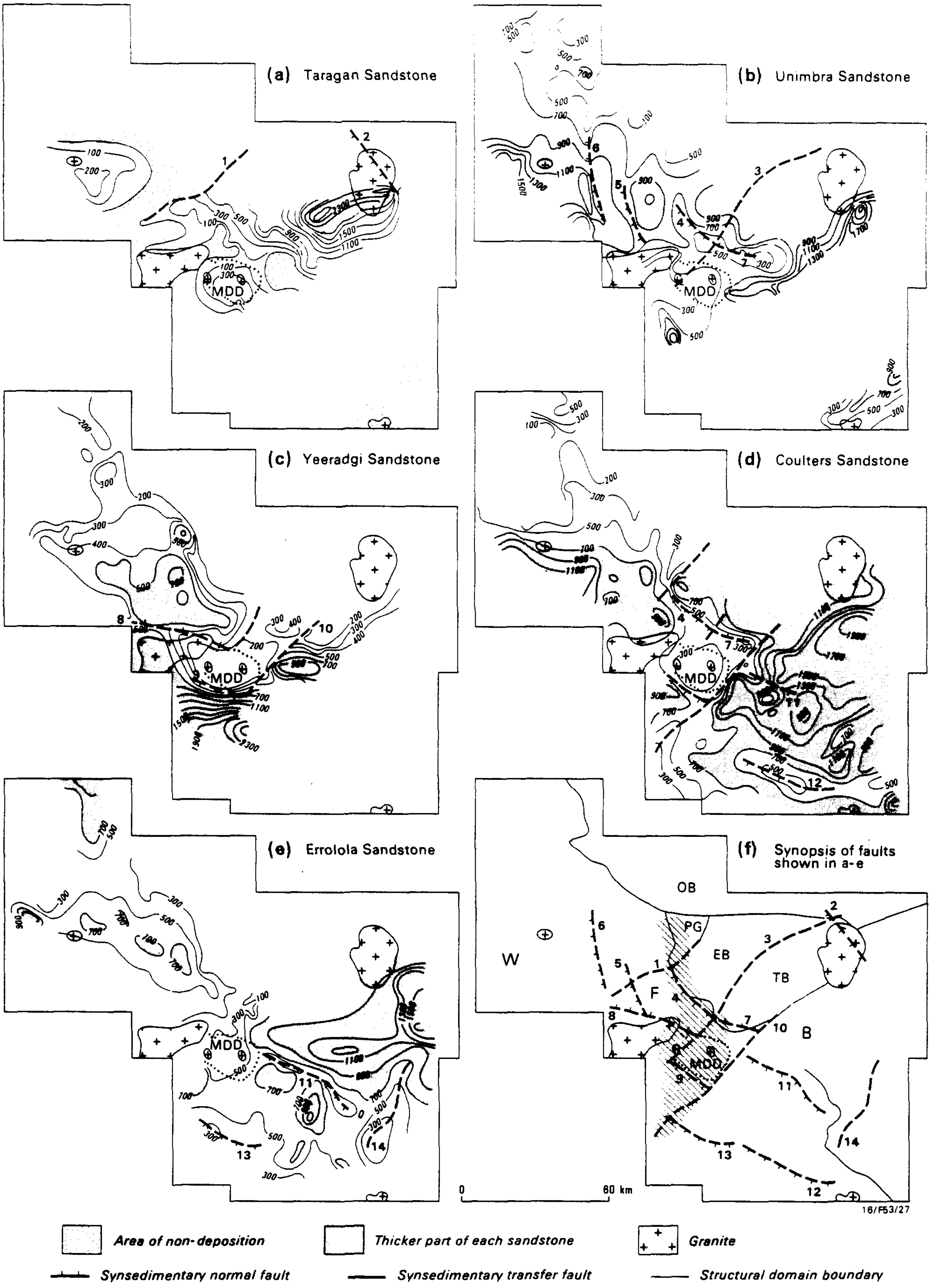

Fig. 5. Isopach maps on (a) Taragan, (b) Unimbra, (c) Yeeradgi, (d) Coulters and (e) Errolola Sandstones, showing inferred synsedimentary normal and transfer faults. Thicknesses were determined, at points 5–10 km apart, from measurements of exposed outcrop width at localities where true stratigraphic tops and bottoms were mapped on BMR 1:100,000 scale geological maps (Devils Marbles, Kurundi, Hatches Creek, and Elkedra Regions), together with field measurements of dip combined into a single average value at each point of determination. Because of folding, the sandstones are extensively exposed, and it was not necessary to estimate thicknesses of buried units. Contours are 200 m apart except where otherwise indicated, and are drawn by interpolation between points of thickness determination. (f) Synopsis of inferred normal and transfer faults from (a)–(e) and structural domain boundaries from Fig. 1(c); diagonal lines indicate inferred 'high'. Numbers beside faults are for reference in text. E.B. = Edmirringee Block, M.D.D. = Murray Downs Dome, O.B. = Ooradidgee Block, P.B. = Pingelly Block, T.B. = Taragan Block, W.F.B. = Wauchope Fold Belt.

Fig. 3. Aerial photograph of central part of Davenport Province, showing NW-trending Bonney Syncline and Skinner Anticline of first folding episode, and NE-trending anticlines (upper and lower right) of second folding episode. Location of photo shown in Fig. 1(b). Width of field 14 km. Part of Bonney Well CAG 4112, Run 6, photo 0024, 1971. Crown copyright reserved.

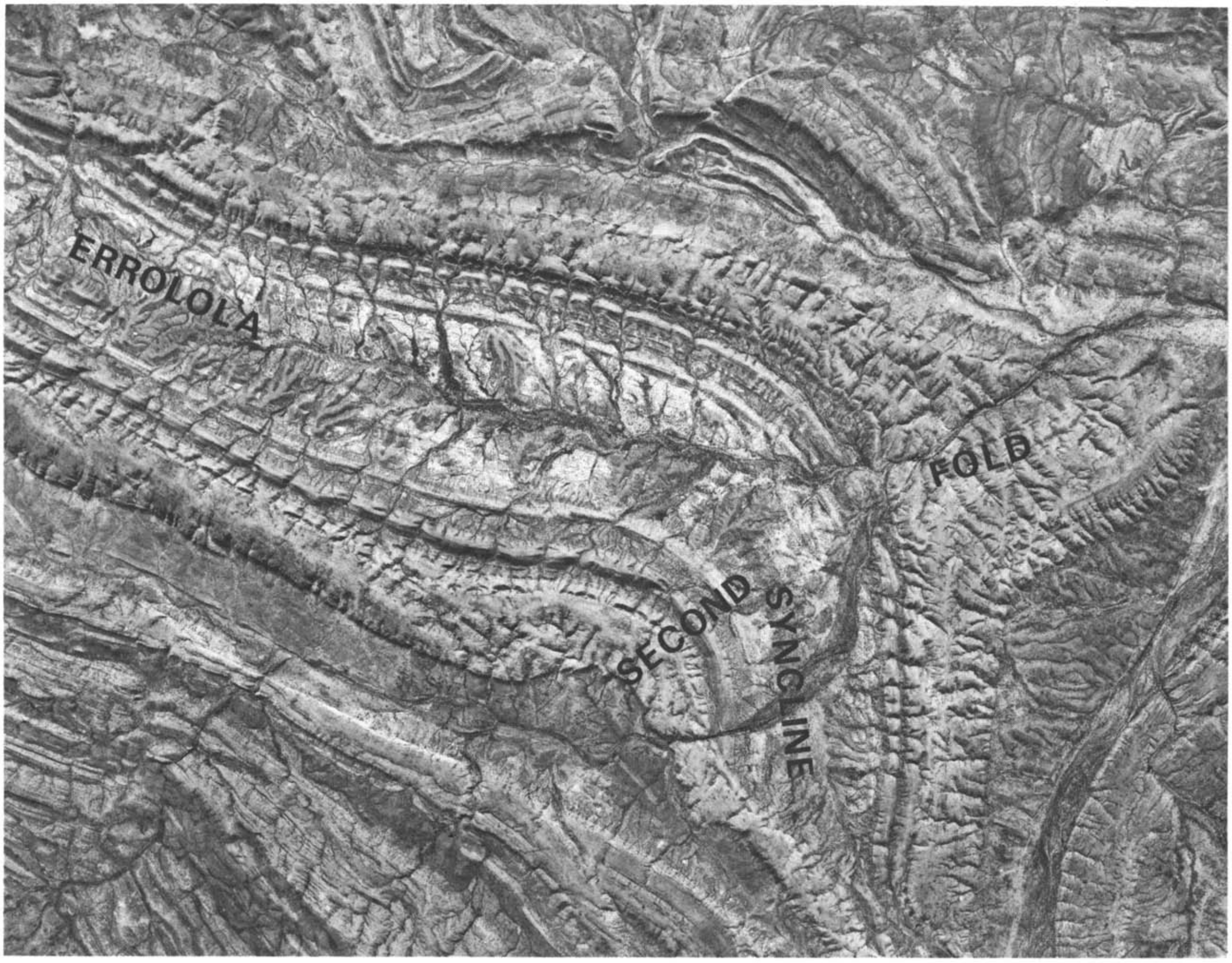

Fig. 4. Aerial photograph of central part of Davenport Province showing NW-trending Errolola Syncline of first folding episode bent by NE-trending fold of second folding episode. Location of photo shown in Fig. 1(b). Length of field 14 km. Part of Bonney Well CAG 4118, Run 8, photo 0108, 1971. Crown copyright reserved.

other faults parallel to this one (e.g. fault 3 in Fig. 5b and fault 10 in Fig. 5c) are also interpreted as having begun as synsedimentary transfer faults, and this is supported by crowding of the Unimbra, Yeeradgi and Coulters isopachs in those areas (Figs. 5b–d). A separate basin of Taragan Sandstone existed to the west, but there is no evidence that it was bounded by faults, and it probably filled a low between volcanic piles (cf. Fig. 2). A small equidimensional basin of Taragan Sandstone in the centre of Fig. 5(a) was later to be the site of the Murray Downs Dome.

Normal faults

Synsedimentary normal faults at right angles to the transfer faults are inferred from elongate areas of thin (draped) sediment, which show as ridges in the isopach maps. Apparently abrupt thinning (based on two thickness determinations) in the extreme northeast of the Taragan Sandstone suggests the existence there of a normal fault (2 in Fig. 5a) dipping SW at about 30°. The Unimbra isopach map is crossed by three NW/NNW-trending ridges interpreted to be normal faults (4, 5, 6 and 7 in Fig. 5b); one of these (fault 4) is located near the southwestern margin of the Edmirringee Block, whence it curves to a SE and eventually an E trend, coincident with the southwestern margin (fault 7) of the Taragan Block. The Unimbra isopachs give no information on the dip directions of the normal faults, and the dip directions are assumed to have been the same as on the presently existing reverse faults—that is, SW at the southwestern margin of the Edmirringee Block (fault 4) and NE at the southwestern margin of the Taragan Block (fault 7). The Coulters isopachs show a similar ridge representing thin sediment at the southwestern margins of the Edmirringee and Taragan Blocks, and two isopach ridges trending NW suggest normal faults (11 and 12 in Fig. 5d) in the southeast. The Errolola isopachs show two NW-trending ridges (faults 11 and 13 in Fig. 5e) and a NNE-trending ridge (14) in the southeast also.

In summary, three NE-striking synsedimentary transfer faults are equated with the NE-striking strike–slip fault margins of the Pingelly, Edmirringee, and Taragan Blocks (Fig. 5f); NW-striking normal faults are equated with major NW-striking reverse fault margins of these blocks.

Central high

A common feature of the isopach maps of the three transgressive sandstones—Unimbra, Coulters and Errolola—is the location of the thickest parts of the sandstones in the east and west of the Davenport Province, each separated by a region of thinner sandstone in the centre of the province. From west to east, the maximum–minimum–maximum thicknesses are: Unimbra 1600–600–2400 m; Coulters 1200–300–2000 m; and Errolola 1000–100–1700 m. The figures suggest the existence of a high in the centre of the Davenport Province (Fig. 5f) coinciding approximately with the zone of extension between the Taragan E- and W-sloping troughs, and with the small equidimensional basin of Taragan Sandstone in the centre of Fig. 5(a). The low in the southeast of the province shows up as a NE-trending zone devoid of Ooradidgee Subgroup, but with extensive outcrops of Hanlon Subgroup (Fig. 1b).

Discussion

The isopach maps (Figs. 5a–e) suggest that synsedimentary faulting controlled sedimentation of the middle and upper parts of the Hatches Creek Group. The isopachs indicate the existence of a central N-trending high (Fig. 5f), flanked by troughs deepening to the east and west. On the eastern side of the high, the Taragan Sandstone (Fig. 5a) was deposited as a clastic wedge in a NE and NW-sloping trough or half-graben probably bounded to the northwest by a vertical transfer fault (1) and to the northeast by a SW-dipping normal fault (2); a separate wedge of Taragan Sandstone to the west filled a W-sloping but not fault-bounded trough on the other side of the central high. The shallow equidimensional basin which became the Murray Downs Dome was situated near the crest of the high between the two troughs; previously, during deposition of the Kurinelli Sandstone it had been an area of inland drainage and playa lake deposition (Stewart & Blake 1984). The origin of the central high and the lows to the east and west is unknown; a possibility is that they reflect a horst and graben in the basement Warramunga Group below the Hatches Creek Group.

In Unimbra time (Fig. 5b), a second transfer fault (3), parallel to but southeast of the first, split the wedge of Taragan Sandstone, and separated SW-dipping normal faults (4, 5 and 6) on its northwestern side from a NE-dipping normal fault (7) on its southeastern side. In Yeeradgi time two more normal faults (8 and 9) formed on the northern and southern flanks of the rising Murray Downs Dome, together with a transfer fault (10) on the eastern flank of the dome. These faults continued to influence deposition during the marine transgressions which deposited the Coulters and Errolola Sandstones, and were joined by additional faults, both normal (11, 12 and 13) and transfer (14) in the southeast.

The isopach maps show the area occupied by the Murray Downs Dome as a shallow basin in Taragan time. In Unimbra time it went into reverse, and formed a relative high throughout Wauchope Subgroup and Errolola time. The dome is intruded by two small granite masses, and occurrences of deformed pegmatite and tourmalinized sandstone around the dome, and of small sills of greisen (folded and faulted with their enclosing strata) in the dome (Stewart & Blake 1984) imply additional granite at no great depth below the present ground surface. It is possible that the Murray Downs Dome resulted from doming of the Ooradidgee Subgroup above a rising granite mass which found access easy in the extended centre of the Davenport basin, and began its ascent during deposition of the Unimbra Sandstone.

That granites may have begun their emplacement during deposition of the Hatches Creek Group is supported by the coincidence of the large granite body immediately west of the Murray Downs Dome with an area of non-deposition of the Taragan Sandstone (Fig. 5a). This suggests that the granite, which contains xenoliths and rafts of Kurinelli Sandstone, was in place by the end of Kurinelli time.

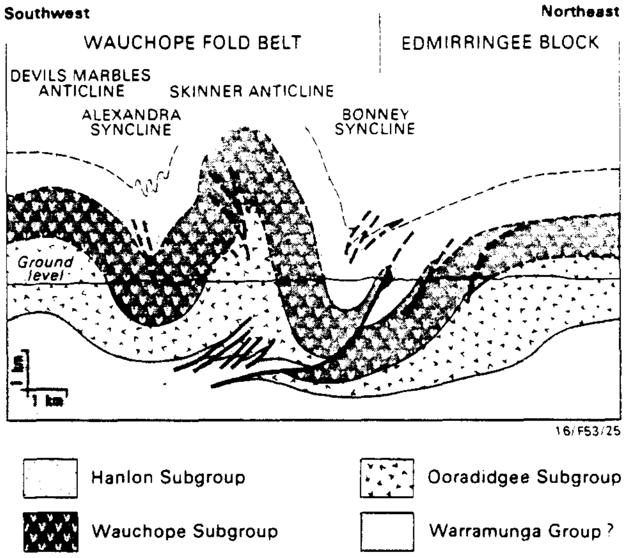

Fig. 6. Balanced cross-section through part of Wauchope Fold Belt and Edmirringee Block in centre of Davenport Province. Position of cross-section shown in Fig. 1(b).

CONTRACTIONAL STRUCTURES

Most of the Davenport Province consists of NW-trending trains of upright folds with associated reverse faults. N- to NE-trending folds and reverse faults are found in the northeast and southeast of the province. The province can be divided into five major domains—four fault blocks and a fold belt (Fig. 1c)—characterized by the two different trends and times of folding.

Domains

(1) The *Ooradidgee Block* in the north of the province is a mainly basement block comprising Warramunga Group, granite, small outcrops of the lowest formation of the Hatches Creek Group (Epenarra Volcanics, Fig. 2), and a block of Wauchope to Hanlon Subgroups on its western side folded around the NE-trending Annie Loch Syncline. The granite is observed to intrude only the Warramunga Group, and may be older than the Hatches Creek Group (Stewart & Blake 1984). The southern boundary of the block is marked by an E-striking zone of weakly foliated and quartz-veined Epenarra Volcanics. The zone is located near but not at the unconformity between the Epenarra Volcanics and Warramunga Group, and both units occur on both sides of the foliated zone. The northern boundary of the block is outside the Davenport Province. The rocks forming the Annie Loch Syncline are bounded to the southwest by a sinistral strike–slip fault, and to the northwest by a thrust or reverse fault; they form a fault block which moved 4 km northwest relative to the adjoining Wauchope Fold Belt (domain 5 below) to the southwest.

(2) The triangular *Pingelly Block* south of the Ooradidgee Block consists of moderately S-dipping felsic and mafic volcanic rocks of the Ooradidgee Subgroup. It is bounded to the southeast by a poorly exposed dextral strike–slip fault zone marked by quartz veins, and to the southwest by several steep en-échelon reverse faults in the overlying Wauchope Subgroup. The block is essentially a tilted volcanic centre which generally resisted folding except in its southernmost part, where it was squashed into a tight SW-plunging anticline between the Wauchope Fold Belt to the southwest and the Edmirringee Block to the southeast.

(3) The *Edmirringee Block* east and southeast of the Pingelly Block is characterized by NE-trending folds and reverse faults. In the southwest the NE-striking reverse faults bend into or end abruptly at NW-striking strike–slip faults, partly segmenting the Edmirringee Block into smaller blocks. The southwestern margin of the block is a SW-dipping reverse fault, 28 km long, which follows the relatively incompetent Frew River Formation (the only carbonate-bearing unit in the Hatches Creek Group, Fig. 2) for much of its length. The fault places Wauchope Subgroup northeastward over Hanlon Subgroup (Fig. 6). Dip–slip movement on the fault was about 2 km. The northwestern margin of the Edmirringee Block is the poorly exposed dextral strike–slip fault zone adjacent to the Pingelly Block, and the southeastern margin is another dextral strike–slip fault marked by schistose rock and quartz veins.

(4) The *Taragan Block* is an oval NE-trending block southeast of the Edmirringee Block. It measures 65 × 25 km, and except in the southwest is characterized by low to horizontal dips. Estimates from outcrop width and dip information indicate that the Taragan Sandstone (Fig. 2) is about 2600 m thick in the Taragan Block, which is about four times as thick as in the adjoining Edmirringee Block. The greater thickness of Taragan Sandstone may explain the relative lack of deformation in much of the block. In the southwest, the Hatches Creek Group is tightly folded around the Bonney Syncline.

The Taragan Block is bounded on three sides by a single curved fault with a U-shaped trace 120 km long. In the northwest, the fault is a dextral strike–slip fault with subhorizontally-striated and slickensided fault breccia. From there it curves to the south, southeast, and east as a dip–slip high-angle fault, and thence northeasterly as a sinistral strike–slip fault. A cross-section through the southwest of the block is shown in Fig. 7; the bounding high-angle fault is folded, and changes from a NE-dipping high-angle reverse fault at its bottom to a 'normal' fault at ground level where the strata and fault are inverted, and then back to a high-angle reverse fault above the present ground level. The fault trace is colinear at the present ground level with the fault trace of the SW-dipping reverse fault at the southwestern

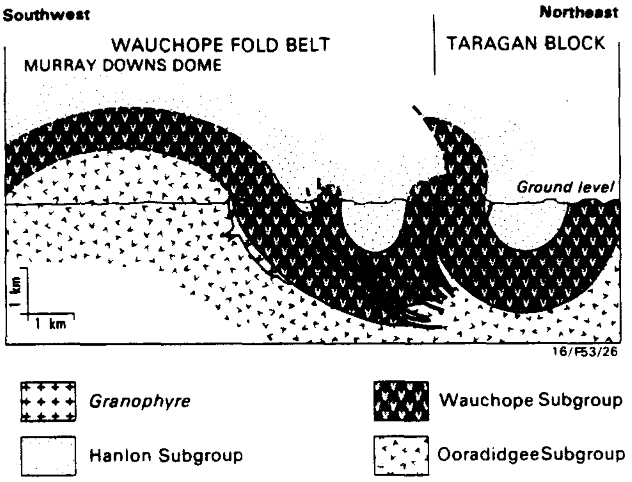

Fig. 7. Balanced cross-section through southwestern part of Taragan Block and adjoining part of Wauchope Fold Belt. Position of cross-section shown in Fig. 1(b).

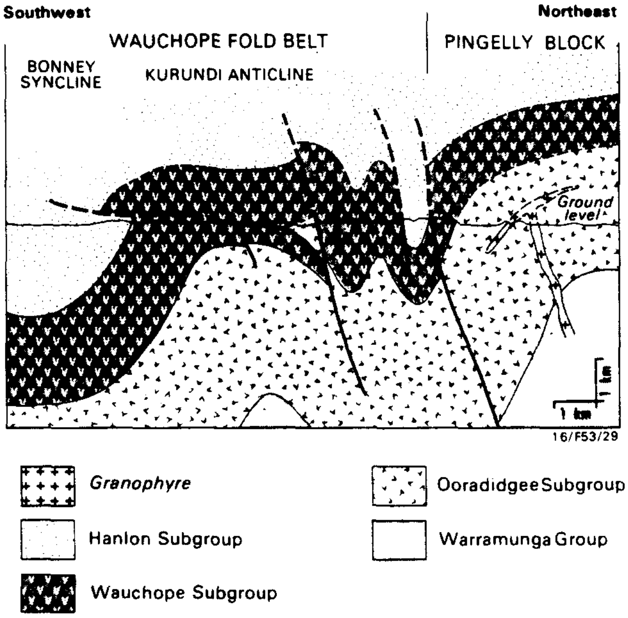

Fig. 8. Balanced cross-section through low-angle thrust fault in Kurundi Anticline and adjoining parts of Wauchope Fold Belt and Pingelly Block. Position of cross-section shown in Fig. 1(b).

margin of the Edmirringee Block, and the two faults are separated by the strike–slip fault between the Edmirringee and Taragan Blocks. Because of the single enormous curved fault bounding the Taragan Block on three sides, Stewart (1985) regarded the block as a thrust sheet or surge block similar to those described by Coward (1983) in the Assynt region of the Moine Thrust of Scotland, entirely underlain by a postulated décollement surface of which the single curved fault was the outcropping trace. There is no evidence in the Davenport Province for regional décollement however; evaporites are absent from the Hatches Creek Group, clayey and silty beds are rare, and stratigraphic units well below the concentrically folded part of the group (see section on fold style below) crop out in the cores of the concentric anticlines (e.g. the Edmirringee Volcanics in the Kurundi and Skinner Anticlines). It would be special pleading to postulate a concealed major décollement below the Taragan Block when its existence is contra-indicated everywhere else in the province. The Taragan Block is therefore best interpreted as a relatively immobile buttress. Northeastward translation of the Edmirringee Block and the Wauchope Fold Belt relative to the Taragan Block is 1–2 km, as indicated by lateral offsets in the Bonney Syncline and in a dolerite sill (Fig. 1b). The offset in the syncline indicates that translation occurred after the NW-trending folds had formed.

(5) The *Wauchope Fold Belt* south of the four blocks described above makes up most of the Davenport Province. It is characterized by NW-trending folds (Fig. 1b) and associated reverse faults (Figs. 6, 7 and 8). The folds range from open to isoclinal, and have vertical axial surfaces which are commonly sinuous in plan. Two N-trending folds are present about 5 km west of the Taragan Block.

The *George Creek Region* is a subsidiary part of the Wauchope Fold Belt in the southeast of the Davenport Province, and is characterized by open to close NE-trending folds. The area is separated from the main part of the Wauchope Fold Belt to the southwest by two major NW-striking faults linked by a NE-striking fault, but to the north it merges into the Wauchope Fold Belt, and folds in that area are oriented WNW.

The *Kelly High* is a poorly exposed area of Warramunga Group and intrusive granite in the northwest of the Wauchope Fold Belt, and is bounded by the unconformity with the overlying Hatches Creek Group.

Folds

In the Davenport Province as a whole, anticlines are doubly plunging, and cleaved volcanic rocks of the Ooradidgee and Wauchope Subgroups crop out in the cores of those less than 20 km long (brachyanticlines) (Fig. 1b). Sedimentary rocks crop out in the cores of longer anticlines. Synclines are in general longer than anticlines. The volcanics in the cores of the shorter anticlines and domes in the central part of the province represent separate volcanic edifices (Stewart & Blake 1984) which appear to have acted as nuclei during folding. The nucleating effect may have resulted from the non-bedded and relatively rigid nature of the volcanic rocks, and from the greater thickness of the volcanic edifices compared to the sedimentary rocks, and so the volcanics were thickened, domed and cleaved instead of being buckled when shortened.

Fold plunges in the Davenport Province range from horizontal to vertical, but most are between 30 and 60°. Plunges greater than 90° have been measured, i.e. the folds are downward-facing, in a small area 4–8 km west of the Taragan Block near the centre of the province (Fig. 9); the oversteepening was probably caused by the second folding episode.

Axial-surface cleavage fans are restricted to tight fold hinges in the centre of the Wauchope Fold Belt, where they occur as sets of spaced subparallel fractures in

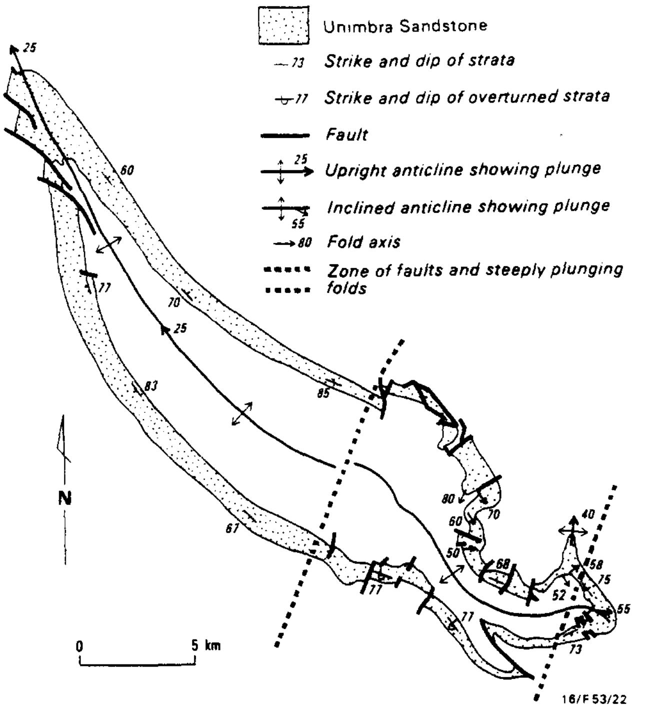

Fig. 9. Geological map of Skinner Anticline (SA in Fig. 1), showing the Unimbra Sandstone only, to illustrate the NNE-trending zone of faults and steeply plunging folds. The folds plunging 80° SSW and 52° SSE are downward-facing.

sandstone beds, and slaty cleavage in finer-grained beds. Fold mullions, formed by the intersection of spaced cleavage and small crumples in sandstone, are present in the hinges of the Alexandra and Errolola Synclines in the same area.

Fold style

Numerous concentric mesoscopic folds and the general absence of cleavage indicate that fold style is largely concentric (Figs. 6, 7 and 8), but in tight fold hinges in the centre of the province (e.g. the Skinner Anticline, Fig. 6), some flattening produced the cleavage described above. Dahlstrom (1970) discussed ideal concentric folds, the space problem encountered in concentric fold hinges and some solutions to the problem, namely crumpling, thrust or reverse faulting and minor discontinuous detachment surfaces in the top and bottom concentrically folded beds. Ideally, the concentrically folded sequence is bounded above and below by major detachment (décollement) zones, and the incompetent rocks of these zones are disharmonically folded to fill the remaining space in the fold hinges. The three transgressive sandstone formations of the Hatches Creek Group and the intervening units, i.e. Unimbra Sandstone through Errolola Sandstone, show the following features characteristic of ideal concentric folds.

(1) At the northern end of the Skinner Anticline, the upper and lower surfaces of the Unimbra Sandstone are differently folded, the lower surface being crumpled whereas the upper is a single fold (Fig. 10). Folds and strike–faults in a siltstone interval of the Unimbra Sandstone make up the minor discontinuous detachment zone which separates the two differently folded surfaces. At the southern end of the Devils Marbles Anticline (Fig. 10), the lower surface of the Unimbra Sandstone is imbricately faulted instead of crumpled.

(2) Faults approximately coincident with axial surfaces of major folds (e.g. the Alexandra Syncline in Figs. 6 and 10) are in the predicted position for reverse faults which slice up the sequence in the cores of the folds.

(3) Units of the Hatches Creek Group above and below the three transgressive sandstones are crumpled and disharmonically folded on the large and medium scales, as predicted in the major detachment zones above and below a concentrically folded sequence (Dahlstrom 1970); the southeastern corner of Fig. 10 shows crumpled bedding trends in the Kurinelli Sandstone below the Unimbra Sandstone, the lowest of the transgressive sandstones.

Hence, because of the strong evidence for concentric folding, the cross-sections shown in Figs. 6, 7 and 8 are balanced (or restorable); that is, bed length has been held constant for all formations between the axial surfaces of upright folds or between other areas of horizontal bedding. The upper detachment is achieved by disharmonic folding in synclines in the two highest units of the Hatches Creek Group. In view of the rarity of evaporite, shale and claystone in the group, the lower detachment possibly lies in or below the Warramunga Group.

Superimposed folds

Two episodes of folding affected the Hatches Creek Group. One formed the NW-trending large-scale folds of the Wauchope Fold Belt. The other formed the NE- to NNE-trending folds in the Edmirringee Block and George Creek Region, the NE-striking thrust faults and NW-striking strike–slip faults in the southwest of the Edmirringee Block, the SW-plunging anticline at the southern corner of the Pingelly Block and the SW-plunging Annie Loch Syncline in the west of the Ooradidgee Block (Fig. 1b). Interference of the two sets of folds is apparent in the north of the George Creek Region (immediately east of the abandoned Hatches Creek township, Fig. 1b), where the Hanlon Subgroup shows an outcrop pattern indicative of domes and saddles (Type 1 interference structure of Ramsay 1967), and at the southern extremity of the province, where the Ooradidgee Subgroup has a similar outcrop pattern. Elsewhere in the Wauchope Fold Belt, crescentic folds (Type 2 of Ramsay) are present, e.g. the Froiland Syncline in the south of Fig. 1(b), and the Errolola Syncline (Fig. 4). The following evidence indicates that the NW-trending folds formed first.

(1) A NNE-trending zone of faults and steeply plunging folds (some downward-facing) crosses the NW-trending Skinner Anticline near the centre of the Wauchope Fold Belt (Fig. 9). The entire anticline has shortened by buckling along its length in response to NW-directed compression. The bends in the Froiland

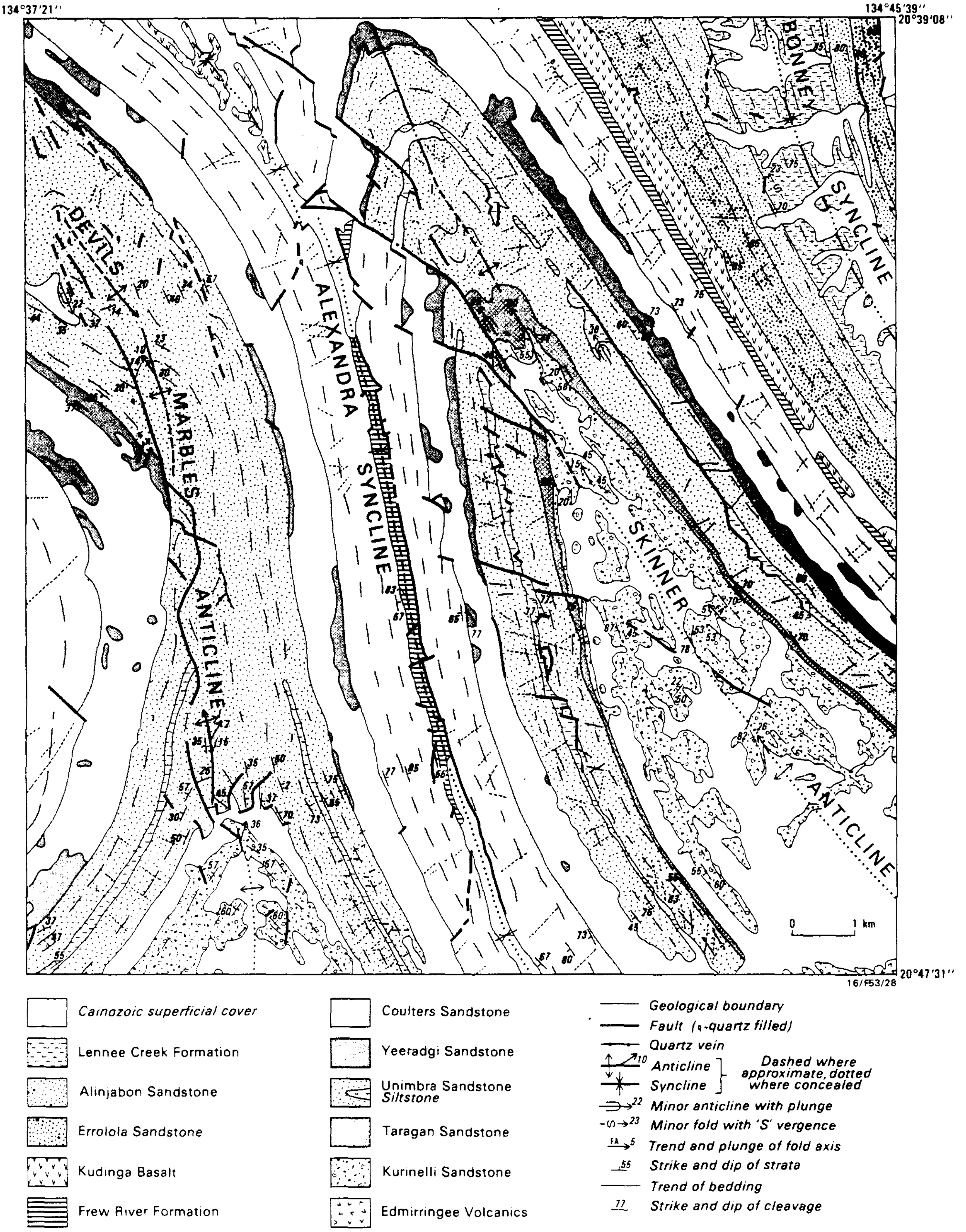

Fig. 10. Geological map of part of Wauchope Fold Belt, showing lower surface of Unimbra Sandstone crumpled (Skinner Anticline) or imbricately faulted (Devils Marbles Anticline); full explanation in text. From Kurundi Region 1 : 100,000 scale geological map published by BMR (Stewart & Blake 1984). Position of figure shown in Fig. 1(b).

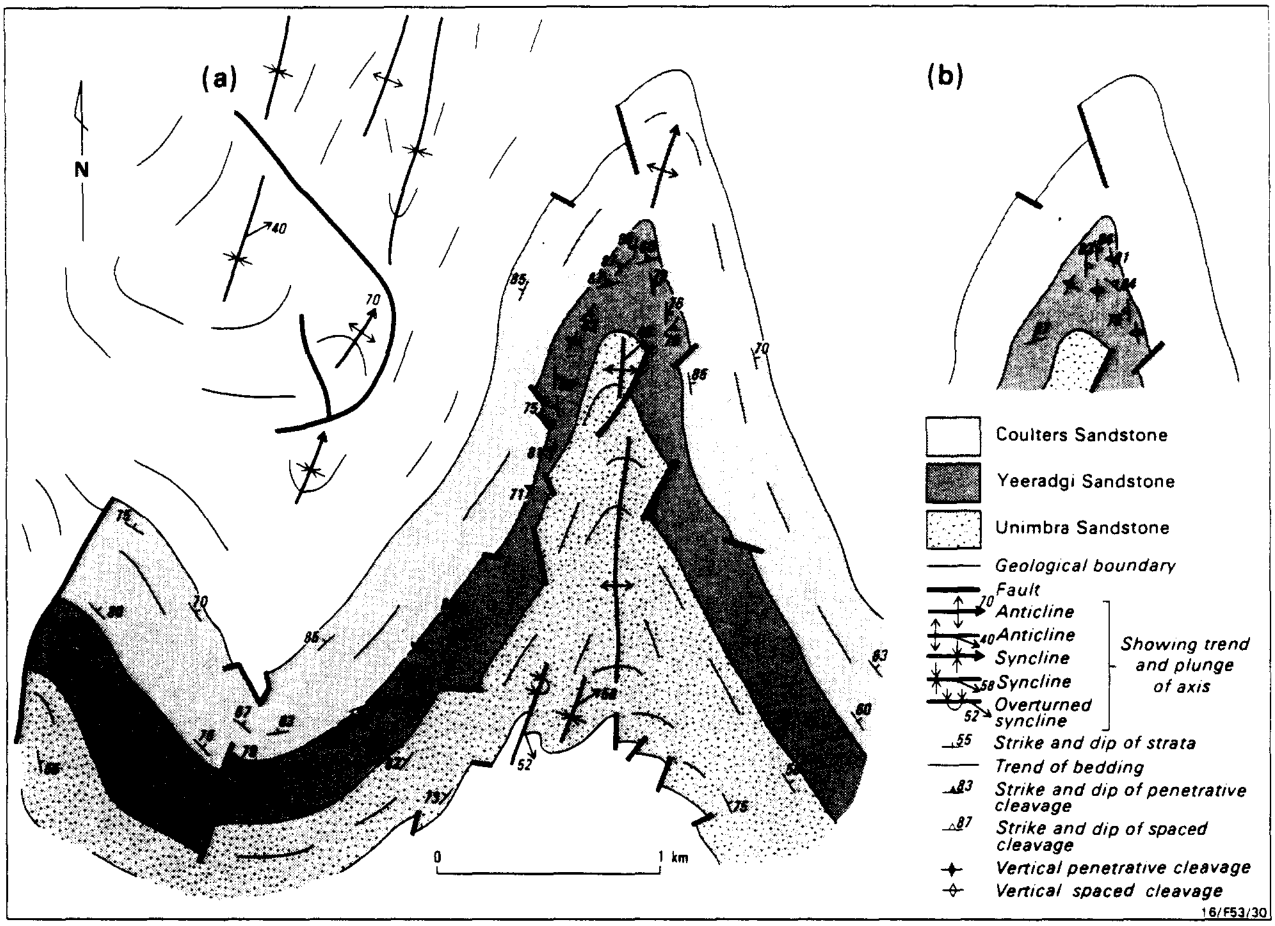

Fig. 11. Geological maps of N-trending folds on northern limb of Skinner Anticline, showing (a) folding of penetrative cleavage in slaty part of Yeeradgi Sandstone, and axial-surface cleavage in hinge zone of N-trending anticline, and (b) orientation of spaced cleavage cutting axial-surface penetrative cleavage in hinge zone of anticline. Position of figure shown in Fig. 1(b).

and Errolola Synclines are similarly caused by NE-trending folds.

(2) At two localities (one on the western flank of the Murray Downs Dome, the other at the southern end of the Alexandra Syncline) steeply plunging box-folds about 1 m in wavelength and amplitude fold NW-striking cleavage which is axial-surface to the major folds of the Wauchope Fold Belt.

(3) Penetrative cleavage parallel to the axial surface of the Skinner Anticline is folded around the two N-trending folds (Figs. 1b and 11a) 5 km west of the Taragan Block, and is overprinted by a spaced cleavage which is parallel to the axial surface of the N-trending folds; in the hinge area of the N-trending anticline, the beds are cut by both cleavages (Fig. 11b).

En-échelon folds

Sinistral en-échelon folds are present in the Ooradidgee Subgroup in the Kurundi Anticline (Fig. 1b). The folds are open, affect the overlying Wauchope Subgroup only slightly and no faulting of the hinge occurred; the folds indicate the same shear sense as the strike–slip fault at the southwestern margin of the Ooradidgee Block; and they may have formed at the same time as the fault block carrying the Annie Loch Syncline moved northwest relative to the Kurundi Anticline.

Faults

Strike faults in the Wauchope Fold Belt show no strike–slip offsets, and are likely to be reverse faults. Almost all of them dip steeply at the surface, but probably lessen in dip with increasing depth, and take on a listric shape. Only one low-angle thrust fault was seen in the belt. It forms the northwestern boundary of a triangular window at the crest of the Kurundi Anticline, and places Ooradidgee Subgroup on top of Wauchope Subgroup. The fault is marked by an extensive and spectacular white breccia about 20 m thick and dipping 20°SW subparallel to bedding. A balanced cross-section through the anticline (Fig. 8) shows the thrust fault steepening with depth, suggesting that it is a folded thrust fault that formed early; whereas neighbouring reverse faults cutting one limb of the anticline are straighter, and formed later.

Summary

The Davenport Province is cut by major faults into five major domains: a group of three fault blocks separated by NE-striking strike–slip faults in the northeast of the province; a fourth largely basement block in the north; and the Wauchope Fold Belt comprising regular NW-trending upright folds and forming the major part of the province. Anticlines are doubly plunging, mostly between 30 and 60°; brachyanticlines show volcanic rocks representing separate eruptive centres in the fold cores. Axial-surface cleavage is present only in tight folds in the centre of the province, and in general folds are concentric. NE-trending upright folds are present in the southeast and northeast of the province, and form domes and saddles (Type 1) and crescents (Type 2) where they interfere with the NW-trending folds. The NE-trending folds deform the axial-surface cleavage of, and therefore postdate, the NW-trending folds. Faults in the Wauchope Fold Belt are parallel to the axial surfaces of folds, dip steeply and are likely to be reverse faults; their dips may lessen at depth.

DISCUSSION

Fault reactivation

Evidence of fault reactivation is strongest at the northwestern margin of the Edmirringee Block. The fault margin began as a synsedimentary transfer fault, as indicated by the termination of the Taragan Sandstone isopachs at the southeastern side of the fault (Fig. 5a), by decreasing pebble abundance and bed thickness away from the fault, and by a 4-fold thickening of the Coulters Sandstone across the fault. The fault is now a mapped strike–slip fault with 4 km dextral translation; dips on each side of the fault are the same, so that the horizontal offset could not have been produced by scissor-like tilting or hinge-faulting.

Other evidence for reactivation is provided by the southwestern margins of the Edmirringee and Taragan Blocks. The margins coincide with a pronounced ridge in the isopachs for the Unimbra Sandstone, where thickness changes from 300 to 500 m at the ridge to 900–1100 m in the troughs beside the ridge (Fig. 5b), and similarly for the Coulters Sandstone: 300–500 m at the ridge, 900–1000 m in the troughs (Fig. 5d). The margins are now reverse faults, but are inferred to be reactivated synsedimentary normal faults that formed scarps over which the Unimbra and Coulters Sandstones were draped during deposition.

Relationship of extensional to contractional structures

The spatial relationship of extensional to contractional structures is shown in Fig. 5(f), which depicts all the inferred synsedimentary faults and the boundaries of the major structural domains. Initially, NE–SW oriented continental extension formed NW-striking normal faults and NE-striking transfer faults. This was followed by compression with the same orientation, and NW-trending folds formed in the area where normal faults were abundant: that is, the southwestern half of the province, forming the Wauchope Fold Belt. The normal faults were ideally oriented to become reverse faults (Jackson 1980, Stoneley 1982), and the transfer faults were ideally oriented to allow strike–slip at the sides of reverse fault blocks. The Taragan Block was not folded (except at its southwest extremity) because of its great thickness of sandstone. The block may also have been pinned in the northeast by the granite pluton southeast of Epenarra (Figs. 1b and 5f). The strata of the adjoining Wauchope Fold Belt were folded, and thrust for 1–2 km below the southwestern edge of the Taragan Block (Fig. 7). Similarly, the Edmirringee Block remained unfolded at this time, but was thrust to the southwest below the most tightly folded (and cleaved) part of the Wauchope Fold Belt (Fig. 6), which was perhaps pinned farther to the southwest by the early granite pluton northwest of Murray Downs (Figs. 1b and 5f).

It is possible that the major NE-striking strike–slip faults resulted from wrench tectonics, with the northeastern boundary of the Wauchope Fold Belt acting as a zone of over/underthrusting as the block to the east moved and fragmented into the four fault blocks now observed (Fig. 1c). This would imply that the major NW-trending folds formed as an en-échelon array, but apart from the folds in the core of the Kurundi Anticline, there is no en-échelon arrangement apparent in the pattern of the axial traces of folds (Fig. 1b). Furthermore, the NW- and NE-trending folds should have formed simultaneously if they were caused by wrenching, one set being the conjugate of the other, but the overprinting described above shows that the two sets of folds formed at different times.

Basin evolution

A working hypothesis for tectonic processes in northern Australia during the Proterozoic has recently been outlined by Etheridge *et al.* (1987). The model supposes widespread underplating and continental extension caused by small-scale mantle convection. Extension led to formation of rift basins wherein volcanics and fluviatile sediments accumulated, and was followed by thermal subsidence which allowed extensive shallow-marine sediments to accumulate. Deformation of most of the Early Proterozoic terranes of northern Australia began with 'one or more early nappe-style events, either documented or strongly implied' by mesoscopic structural evidence (Etheridge *et al.* 1987), and was followed by medium to high-grade metamorphism and abundant I-type granite emplacement. The Davenport Province, however, lacks these structures; and their absence implies only a small amount of regional shortening; that is, the 28% or so of layer-parallel shortening indicated by the cross-sections (Figs. 6, 7 and 8). This in turn implies little or no crustal thickening; and in the model of Etheridge *et al.*, the regional shortening merely restores the thinned crust to its original thickness. If this is so, the relatively small amount of shortening in the Davenport Province suggests a similarly small amount of continental extension (about 40%) in this particular area. Perhaps extension was hindered by the location of the Davenport Province deep in the interior of the northern Australian continent; this part of the continental plate did not have much room to manoeuvre. The extension was accompanied by deposition of the Ooradidgee Subgroup, and was followed by thermal subsidence, enhanced by sediment-loading, allowing deposition of the Wauchope and Hanlon Subgroups. The small amount of extension is consistent with the low metamorphic grade of the Hatches Creek Group, as the rise in the geotherms resulting from extension would have also been small.

Cause of folding

Of the two major causes of folding—vertical movement leading to downslope sliding of strata, and regional crustal shortening driven by mantle convection—only the latter is applicable to the Davenport Province, there being neither evidence of nor strata suitable for gravitational sliding. Mantle convection processes along the lines suggested by Etheridge *et al.* (1987) is strongly indicated by the evidence for continental rifting; and in this hypothesis either a sudden increase in plate velocity could push the extended plate back together, or delamination of lithospheric mantle (A-subduction) at the end of subsidence could pull the lithospheric segments on either side of the basin together. Delamination could also lead to underplating, accompanied by generation of an intense thermal anomaly under the basin and widespread intrusion of felsic I-type magma. The low grade of metamorphism and presence of only S-type granites in the Davenport Province militate against delamination, leaving a change in plate velocity as the most likely cause of folding. The change in stress pattern which led to the second episode of folding at a high angle to the first may have been caused by a change in the convection pattern below the lithospheric plate.

CONCLUSION

Reconstruction of the Davenport Province by field and isopach mapping has shown it to be a rapidly-filled fluvial to shallow-marine continental extensional basin, comprising troughs to the east and west of a central high. In many respects it supports the model proposed by Etheridge *et al.* (1987) of Proterozoic tectonism driven by small-scale mantle convection. The basin fill comprises a lower rift sequence of bimodal volcanic rocks and fluviatile sediments, and an upper subsidence sequence of fluviatile to shallow-marine sediments with fewer volcanics. Deposition was influenced by synsedimentary normal and transfer faults.

Contraction of the basin was achieved by two episodes of upright concentric folding, accompanied by reverse faulting which used the pre-existing synsedimentary normal faults, and by strike–slip faulting which used the pre-existing transfer faults. Major synsedimentary faults became the boundaries of major structural domains of different fold trend. The first folding episode formed regular NW-trending trains of folds. Because of the absence of evaporites and the rarity of clayey, silty and carbonate sediments, décollement and layer-parallel shortening were minor, and no bedding-parallel thrust-sheets or duplexes formed. Instead, faulting and folding are believed to have affected the sedimentary basement below the basin sequence, as well as the basin sequence itself. One domain (the Taragan Block) was only slightly affected during folding, possibly because of the existence there of a four times greater than normal thickness of a massive conglomerate–arenite unit, and it acted as a buttress against which surrounding strata were folded and faulted. Overall NE–SW shortening during the first folding event was 28%. The second episode formed upright generally NE-trending folds, mainly in the east of the province. Interference produced Type 1 domes and saddles in some areas, and elsewhere shortened first-formed folds along their length by bending and buckling, producing Type 2 crescents and probably the sinuous map pattern of the NW-trending folds.

The Davenport Province differs from other Proterozoic terranes in northern Australia in having no nappes, thrust sheets or thrust duplexes. Its relatively low degree of regional shortening suggests a similarly low degree of initial extension—about 40%—and supports the picture of early Proterozoic northern Australia as a large ensialic crustal plate subjected at times to tectonism from below, but not from the sides (Etheridge *et al.* 1987). The low grade of metamorphism in the Davenport province, and the absence of I-type felsic magmas militates against the subsequent folding being caused by lithospheric delamination or A-subduction, and folding was probably caused by a sudden increase in plate velocity. The change in orientation between the first and second folding episodes may indicate migration of the lithospheric plate from one convection current system to another, or alternatively a change in location of the current system relative to the plate.

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