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GRANITE DIAPIRISM IN THE RUM JUNGLE AREA,

NORTHERN AUSTRALIA.

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ABSTRACT

Early studies in the Rum Jungle area suggested an intrusive relationship between the Rum Jungle and Waterhouse 'Granites', and the overlying sediments. It was later shown that the granitic 'intrusions' were Archaean basement complexes on which Lower Proterozoic sediments had been deposited. Polyphase folding was postulated as being responsible for doming of the basement and cover rocks.

This paper proposes to show that the domed structures in the Rum Jungle area, and the emplacement of Middle Proterozoic granites in the Pine Creek Geosyncline were related, and caused by diapiric intrusion of granites, in a solid state, into basement complexes and cover rocks.

Structural and metamorphic evidence in support of diapiric intrusion in the Rum Jungle area includes: pebble deformation within steeply dipping beds of quartz conglomerate, disappearance of polyphase fold structures away from the basement complexes, bending of folded country rock strata into concordance with the complex-sediment contact, and metamorphic and metasomatic alteration of sediments in contact with the basement complexes. Gravity data show mass deficiencies in the Archaean complexes which possibly coincide with young granite diapirs.

INTRODUCTION

The distribution of steeply dipping Lower Proterozoic sediments around the Rum Jungle and Waterhouse igneous masses led Sullivan and Matheson (1952), and later Malone (1962 a,b) to postulate an intrusive relationship between the 'granites' and overlying sediments. However, subsequent work by Rhodes (1965) and Johnson (1974 a,b) has shown that both the Rum Jungle and Waterhouse 'Granites' are 'complexes' which contain basement metamorphic rocks. Age determinations by Richards et al. (1966) on zircons from the Rum Jungle Complex showed that at least part of it was Archaean, with an age of 2550 m.y. The Waterhouse Complex has a reported age of 2450 m.y. (Compston and Arriens, 1968). In addition, several non-conformities between the complexes and sediments have been described by French (1970) and Johnson (1974a). The Rum Jungle and Waterhouse rocks are therefore considered to be Archaean basement complexes on which Lower Proterozoic sediments were deposited.

Williams (1963) believed that the Rum Jungle area was subjected to four generations of deformation which were responsible for folding the basement into dome and basin structures. Rhodes (1965) supported Williams' idea that the sediments had not been intruded by any of the Rum Jungle granites, and that the doming was produced by polyphase folding.

In this paper we will use structural, metamorphic, and gravity data to show that the Archaean basement complexes and the Lower Proterozoic sediments were domed by diapiric intrusion of granite into the basement rocks.

STRATIGRAPHY

Pine Creek Geosyncline

The stratigraphy of the Pine Creek Geosyncline has been described by Walpole et al. (1968). Major Lower Proterozoic rock units in the geosyncline are shown in Fig. 1, and those relevant to this paper are the Batchelor, Goodparla, and Finniss River Groups.

Rocks of the Batchelor Group are exposed only around the Rum Jungle and Waterhouse Complexes, and are the oldest sediments in the Pine Creek Geosyncline. These sediments represent a shelf-type facies deposited on Archaean basement, and consist of dolomite, algal reefs, arkose, hematitic sandstone, quartz greywacke, sandstone, pebble and boulder conglomerate, and siltstone.

Overlying the Batchelor Group are the Goodparla and Finniss River Groups, which are lateral facies equivalents. The Goodparla Group is essentially a siltstone-mudstone sequence deposited in basins surrounding the shelf margins of the geosyncline. Flysch-type greywacke and siltstone of the Finniss River Group were deposited in troughs adjacent to the basin and shelf areas.

Rum Jungle Area

Rhodes (1965) mapped the Rum Jungle 'Granite' (Malone, 1962) as a complex of metsediment, schist, gneiss, and several varieties of granite, and he renamed it the Rum Jungle Complex. Johnson (1974b) found that the Waterhouse 'Granite' is a similar complex of metasediments (including banded iron formations), volcanics, amphibolite, schist, gneiss, migmatite, granite gneiss, and several types of granite, and renamed it the Waterhouse Complex.

The Batchelor Group is made up of alternating clastic and chemical sediments of the Beestons Formation, Celia Dolomite, Crater Formation, and Coomalie Dolomite. The stratigraphy and estimated sediment thickness of the Batchelor Group around the Rum Jungle Complex and the Waterhouse Complex are shown in Fig. 2. The quartz pebble conglomerates within the Crater and Beestons Formations, and the quartz-hematite boulder conglomerate in the Crater Formation are extensively deformed, and form excellent strain-marker beds around the two complexes.

The Goodparla Group consists of black shale siltstone, quartzite, ironstone, and amphibolite of the Golden Dyke Formation, and massive pyritic quartzite and quartz sandstone of the Acacia Gap Tongue. Bryan (1962) has described both para-and ortho-amphibolites in the Golden Dyke Formation. Rhodes (1965) considered that the amphibolites of the Golden Dyke Formation were originally tholeiitic dolerite sills emplaced in the sediments before folding and metamorphism. The concordance and folding of the amphibolites in the Golden Dyke Formation are shown in Fig. 3. A similar stratigraphic succession intruded by dolerite sills is found in the Golden Dyke Formation around the Burnside Granite, 65 km south of Rum Jungle.

Upper Proterozoic sedimentation formed ripple-marked sandstone and basal hematite-quartzite breccia of the Depot Creek Sandstone Member. The sandstone was deposited on a very irregular Lower Proterozoic erosion surface, and has been preserved in a rim syncline structure around the Waterhouse Complex.

METAMORPHISM

Archaean metamorphism of the basement complexes reached almandine-amphibolite facies (Rhodes, 1965). Retrogressive metamorphism of the complexes associated with regional low-grade metamorphism of the Lower Proterozoic sediments caused alteration of feldspar to sericite, and biotite to chlorite. Granitic rocks of the complexes commonly show a preferred orientation of quartz, feldspar, and biotite, which parallels the complex-sediment contact. The recrystallization event producing this mineral alignment is believed to coincide with the intrusion of younger granite into the basement.

Lower Proterozoic sediments were regionally metamorphosed to low-grade greenschist facies. Petrographic examination of the sediments shows extensive quartz recrystallization; the quartz grains commonly exhibit strain twinning. However, in places (e.g., Brown's deposit, White's mine, and the eastern side of the Waterhouse Complex) the Celia and Coomalie Dolomites, and accompanying shale of the Golden Dyke Formation have apparently reached a higher metamorphic grade characterized by members of the tremolite-actinolite series, together with biotite, phlogopite, and andulusite.

W.M.B. Roberts(pers. comm., 1974) described specimens of Celia Dolomite, taken from the eastern flank of the Waterhouse Complex, as consisting of coarsely crystalline biotite with some phlogopite and tremolite set in a matrix of fine-grained dolomite and quartz. Tremolite crystals have been corroded by the matrix to the extent that only residual crystals remain. The matrix is also characterized by the presence of strongly altered orthoclase which has been replaced by biotite, phlogopite, tremolite, and coarse-grained dolomite, and is recrystallized. Roberts stated that it is significant that the areas where apparently higher-grade metamorphism has been reached are associated with shaly or quartz-rich dolomite. He believes that the shearing of the sediments is associated with the doming of the Waterhouse Complex, and that the development of biotite, phlogopite, and tremolite is controlled by accessibility of aqueous solutions which moved into suitable structures, rather than by a higher grade of metamorphism.

Quartz-tourmaline veins and tourmalinization of sediments affect the Rum Jungle Complex, Waterhouse Complex, Batchelor Group, and lower members of the Golden Dyke Formation. The quartz-tourmaline veins radiate from both basement complexes, and the tourmaline commonly occurs as radiating groups of crystals within quartz, and these crystals may extend into the surrounding country rock. Extensive replacement by quartz and tourmaline of sandstone beds of the Crater Formation occurs on the eastern side of the Waterhouse Complex. Marjoribanks (1967) reported that at Mount Fitch, 14.5 km northwest of Batchelor, scapolitization of impure dolomite rocks is associated with quartz-tourmaline veins. Scapolitization and brecciation of diorite and granodiorite occur on the eastern contact margin of the Waterhouse Complex. The tourmaline and scapolite are believed to have been derived from the igneous masses which intruded the basement complexes.

Table 1 summarizes the metamorphic events and their relationship to major deformational events in the Rum Jungle Area. The effects of low-grade regional metamorphism are recognized in the Lower Proterozoic sediments and the Archaean basement complexes. The apparent development of a higher metamorphic grade within dolomitic shales is associated with the Giants Reef Fault, (Fig. 3). However, the preferred orientation of minerals within the complexes, the extensive distribution of quartz-tourmaline veins, the apparent higher grade of metamorphism of the Celia Dolomite on the eastern side of the Waterhouse Complex, and the brecciation and scapolitization of granitic rocks on the eastern edge of the Waterhouse Complex are all alteration effects which are believed to have originated from an igneous reactivation of the Archaean basement. The mechanism for this reactivation is postulated to be diapiric intrusion of granite into the basement rocks.

STRUCTURE

The doming of Lower Proterozoic sediments in the Rum Jungle area was thought by Sullivan and Matheson (1952) and Malone (1962 a,b) to have been due to the intrusion of the Rum Jungle and Waterhouse Granites. However, Williams (1963) recognized three and possibly four generations of deformation in the area, and explained the dome structures by superimposing two phases of folding (D_2 and D_3) perpendicular to an earlier fold structure (phase D_1) in accordance with a slip-fold model. Rhodes (1965) concluded that the sediments had not been intruded by the granites of the Rum Jungle Complex but rested unconformably on the eroded surface of the older rocks, and agreed with Williams that the doming of the basement complex and cover rocks was caused by later polyphase folding.

We consider that solid-state granites, i.e. granites intruded as a plastic crystalline mass, were emplaced diapirically within the two complexes, and consider the following structural features to be diagnostic of such a diapiric emplacement: the dying out of polyphase fold structures away from the basement complexes, the bending of the layering in the country rock into concordance with the complex-sediment contact, the tightening of pre-existing folds close to the complexes, the formation of a rim syncline around the Waterhouse Complex, the development of shear zones and mylonite and the basement-sediment contact, the preferred orientation of minerals in the igneous rocks parallel to the basement-sediment contact, the stretching of conglomerate pebbles, and the refolding of regional structures in the Golden Dyke and Burrell Creek Formations. A summary of textural and structural events after deposition of the Lower Proterozoic sediments is shown in Table II.

Structure within sediments of the Golden Dyke and Burrell Creek Formations

The regional folding in the Rum Jungle area is best seen in shale, siltstone, and greywacke of the Golden Dyke and Burrell Creek Formations. Towards the close of uranium mining in the Rum Jungle area in the mid-1960's a structural analysis was carried out by Williams (1963) in some of the open-cut mines and costeans. Today the mines are filled with water, and their sides, like those of the costeans, are strongly weathered, making the recording of new structural information difficult. The structures observed by Williams and new observations made by the authors suggest the following tectonic history:

1. Folding (F_1) along non-cylindrical north-south fold axes and subsequent development of foliation S_1 and lineation L_1. This event, referred to as the first phase of deformation, D_1, resulted from an east-west compression, and affected most parts of the Pine Creek Geosyncline, forming transposition folds and minor folds which were refolded in the late stages of the D_1 deformation period.

2. The second phase of deformation, D_2 was the doming of the two complexes. The structures recorded by Williams (1963) in the area between the basement complexes can be explained by two events. The first is a bodily rotation of the early F_1 folds, together with the formation of a new foliation, S_2, which is the dominant structure near the twin dome. The second is a rotation of S_1, and the local formation of secondary micas in the monoclinal F_3 folds, related to the late stage of the doming. This style of folding, and the formation of new micas are particularly well developed in the area between the basement complexes, where the stress field is complex and the deformation intense. The monoclinal F_3 folds with steeply plunging axes in the shales seem to be related to a postulated underlying ridge of granitic material between the domes.

Williams' recording and the new observations of structures near the twin-dome structure indicate an inconsistent distribution of the different structural elements from one area to another. There is also an inconsistent distribution of the structural elements within the whole area, which makes a dynamic model of polyphase folding open to question.

If the large-scale stuctures were formed by three or four periods of folding, as suggested by Williams (1963) and Rhodes (1965), one would expect to find evidence of the same degree of deformation in the surrounding areas. However, it is significant that at distances of about one-half to one-dome diameter from the complex-sediment contact the only structural deformation observed is D_1. This observation is explained if we associate the polyphase deformation structures with diapiric intrusion of the complexes, which has overprinted the regional D_1 deformation phase only in the immediate vicinity of the complexes.

The contact strain from the doming caused a tightening of the folds, and a warping of early axial planes and rock strata to become parallel with the sediment-complex contact, e.g., the southern part of the Waterhouse Complex (Fig. 3). Granite diapirism of the complexes is believed to be the mechanism that deflected the strata, and not polyphase folding. The different directions of fold plunges in the Burrell Creek Formation can be developed during the one folding episode, representing simultaneous cross-folding rather than polyphase folding.

Structure within the basement complexes and at their margins

The complexes have a rounded outline, and the Waterhouse Complex has a slight north-south elongation (Fig. 3). The sediments unconformably overlie the complexes, and have sharp contacts except for irregularities connected with the Giants Reef Fault and minor faults (Fig. 3). The domed sediments dip outwards from the complexes at angles ranging from 30° to 80°, an average dip being 60°. In at least four different places the sediments are overturned. Nowhere within the complexes are xenoliths of Lower Proterozoic sediments nor their ghost stratigraphy recognized, and nowhere have the sediments been intruded by granites of the complex. These facts support the idea that any granitic intrusion within the complexes took place in a solid state.

During the updoming of the complexes, particularly the Waterhouse Complex, the surrounding strata subsided, causing the formation of a rim syncline in which the Upper Proterozoic sandstone of the Tolmer Group is preserved.

At the complex-sediment contact, the parallel attitude of foliation (S_2) and mineral lineation (L_2) in both the complex and sediment suggests that the basement and cover were deformed together. This observation can be explained by the diapiric intrusion of granite which simultaneously deformed both the basement and cover rocks. The character and intensity of S_2 and L_2 differ with lithology and location. The mineral lineation in the complex rocks is expressed by quartz, hornblende, and plagioclase, and is discernible on weathered surfaces where these minerals have been exposed by differential etching. The lineation is synchronous with the foliation, and dips steeply outward along the contacts of the complexes. Stretching and reorientation of the mineral lineation is in the direction of tectonic transport which is believed to result from emplacement of granites within the complexes.

Mylonitization and chloritic shear zones along the complex-sediment contact, and locally overturned beds (Fig. 4) clearly indicate a differential vertical movement of the complex relative to the overlying sediments. These structures strongly favour a diapiric doming of the complex, which has caused local overturning and shearing at the complex-sediment contact.

Porphyroblasts of feldspar, alignment of mica in the plane of foliation, and lineation of hornblende and quartz in the basement rocks indicate that deformation occurred during the growth history of the minerals. Structural and textural relationships, discussed above, imply that the mineral alignment is a superposed structure, and not a primary alignment due to magmatic flow. These textural relationships are therefore thought to have originated by deformation in a solid state.

For the Waterhouse Complex there is a gradual change from strongly foliated granite at the contact to weakly foliated granite towards the centre of the complex. This observation is in agreement with experimental models on diapirism (Dixon, 1974) where maximum deformation in the diapiric and host igneous rocks is at the margins of the diapiric intrusion, whereas minimum deformation is in the helmet area of the intrusion.

Deformed pebbles in sediments of the Batchelor Group

The cover rocks around the complexes contain several types of conglomerate, and their appearance in the stratigraphic column is shown in Fig. 2, and their areal distribution in Fig. 3.

The first type of conglomerate (Fig. 6A) contains white quartz boulders in a quartzitic matrix, and is represented by the close-packed conglomerate of the basal Beestons Formation. The boulders are sharp-edged and rhomboidal with a maximum length of 40 cm. The planes containing the major and mean pebble axes are parallel to the fracture cleavage (S_2) in the matrix. At some locations, e.g., 2 km southwest of Rum Jungle, the fracture cleavage penetrates both the pebbles and the matrix.

The second type of conglomerate (Fig. 6B) contains deformed quartz pebbles 3-5 cm long, and is found in both the Beestons and Crater Formations. The pebbles are in a schistose matrix of quartz, feldspar, and mica. The contrast in competence between the pebbles and matrix has favoured concordance between the schistosity, S_2, in the matrix and the pebble elongation.

The third kind of conglomerate (Fig. 6C) is a hematite-quartzite boulder type, and occurs within the Crater Formation around both basement complexes. This conglomerate is well exposed, and can be traced for several kilometres, although the pebble density, size, and degree of deformation are not consistent. The quartz, banded iron formation, and quartzite pebbles of this conglomerate were derived from the basement complexes, and are contained within a hematite-quartz-mica matrix.

These three major types of deformed conglomerate are excellent marker beds for investigating the strain distribution around the twin-dome basement structure. Determination of the values of principal strain ratios, and orientation of their axes ~~was~~ were made by measuring the three axes of the stressed pebbles. Where this was not possible two of the three axes were measured within the plane containing the principal axes. The axial ratios of the strain ellipsoids, together with the shape and orientation of the strain ellipse in the plane of foliation, i.e. the plane containing the major and intermediate axes, are shown in Fig. 5. Also shown in Fig. 5 are equal-area plots of foliation, and the directions of the long axes of the deformed pebbles at various localities around both complexes.

The shapes of the deformed pebbles range~~s~~ from oblate or disc-shaped caused by flattening perpendicular to the plane of foliation, to prolate or cigar-shaped caused by stretching in the direction of tectonic transport. With few exceptions, the plane containing the major and mean axes of pebbles parallels the schistosity, and dips outwards from the dome structures. These planar and linear features are believed to have formed by the vertical emplacement of granites into the complexes. The random nature of the long axes of the strain ellipsoids in the area between the basement complexes is postulated to reflect the strain in the overburden from the upward movement of the granitic material in the saddle between the two domes.

In order to determine the tectonic strains in a conglomerate where the pebbles have an initial preferred orientation, one has to know both the original fabric and the orientation of the axes of the pebbles with reference to the principal strain directions. As pointed out by Ramsay (1967, p. 218) it is generally impossible to obtain a solution to this problem as long as the matrix and the pebbles are assumed to have the same material properties. However, on the basis of experimental deformation of test models containing deformable inclusions embedded in viscous materials, Ghosh and Sengupta (1973) determined the nature of strain in the matrix in relation to deformation or rigid rotation of the inclusions. They suggested that the parallelism or concordance between the schistosity and the deformed pebbles in natural conglomerates usually develops from a combination of a certain amount of strain, a significant contrast in competence between pebble and matrix, and the spacing of pebbles. With a moderate amount of deformation in the matrix and at a viscosity contrast of more than 15, deformation of inclusions remained very small in comparison with the amount of strain in the matrix. If the inclusions are closely spaced they undergo significant deformation along with rotation even when the viscosity ratio is fairly high. The experimental results also showed that where there is a close spacing of pebbles there is a strong alignment of micas in the matrix to parallel the pebble edges.

The experimental results of Ghosh and Sengupta (1973) can be applied to explain the mechanism of deformation of conglomerates in the Rum Jungle area. A rigid rotation and a mutual interference of contact strain of close-packed boulders is a reasonable explanation for the strong alignment of the angular boulders in the basal conglomerate of the Beestons Formation. The second type of quartz conglomerate, with rounded pebbles in a quartz-feldspar-mica matrix, represents a type where all the shape-determining factors were operating, e.g., an initial preferred shape and orientation, plastic deformation, rigid rotation, and rotation due to the effect of contact strain from nearby pebbles. The bending of schistosity around the pebbles indicates a contrast in competence between the pebble and the matrix. A similar style of deformation is found in the quartzite-hematite boulder conglomerate of the Crater Formation, but locally there are highly stretched pebbles which indicate that here the conglomerate exhibits the least contrast in competence. Some of the stretched pebbles are folded with fold axes parallel to the direction of maximum extension. The great variation in direction of axial planes excludes the possibility of a later folding, and the extreme stretching of the pebbles is assumed to have been controlled by changes in the pressure on the conglomerate beds during intrusion of granite.

In summary, the different beds of conglomerate show differences in pebble deformation which are due to different degrees of deformation, pebble density, and competence contrast between pebble and matrix. The shape and orientation of the pebbles are believed to reflect the forces acting during diapiric intrusion of granite within the basement complexes. The shorter axis of the pebbles is parallel to the maximum compression, and lies in the plane of schistosity, and the long axis is parallel to the direction of tectonic transport. The random direction of orientation of the strain ellipsoids in the area between the basement complexes is believed to be a product of the strain in the sediments owing to the complex variation in stress fields caused by the intrusion of granite in this area.

GRAVITY-DRIVEN EMPLACEMENT OF GRANITES IN THE PINE CREEK GEOSYNCLINE

The gravity anomaly map over the Katherine-Darwin region (Whitworth, 1970) shows the general northwest trend corresponding to the Pine Creek Geosyncline (Fig. 7). In studies of granite diapirism gravity investigations may be used as a petrographic cum tectonic tool to determine the form of the diapirs, their density distribution, and their rock composition (Bott and Smithson, 1967; Stephansson, 1974).

With few exceptions the outcrop of Archaean basement complexes and Proterozoic granites in the Katherine-Darwin region are associated with a mass deficiency. This is of the order of 10 to 15 mGal for the rounded isolated intrusions with a shape comparable to many so-called postkinematic granite plutons. The gravity data pertaining to the Burnside (5), Margaret (6), Princes Springs (7), Soldiers Creek (13), Malone Creek (14), Mount Bundey (15), and Jim Jim Granites (17), whose locations are shown in Fig. 7, suggest that their shape is cylindrical. Using a density contrast of 0.1 $g.cm^{-3}$ between the sediments and the granites, a cover depth of 5-10 km is indicated.

The geophysical data are too limited to allow any further advance into an objective discussion of the overall shape of the different granites in the geosyncline, but we are prepared to make some predictions in order to stimulate more detailed investigations.

By inspecting the gravity map it is evident that there are several areas with strong mass deficiencies but where granites do not crop out. These areas possibly conceal basement or a granitic dome beneath the sedimentary cover. The possibility of granitic bodies in areas with mass deficiency is supported by the theory of gravity instability of multilayer systems (Ramberg, 1968; Berner et al., 1972). According to this theory, the rise of a light, horizontal, buoyant, viscous layer takes place in the form of waves with a wavelength characteristic for the particular system. Later the anticlinal parts of the waves tend to split up into individual domes which rise quasi-simultaneously as the heavier overburden tends to sink. The distance between each dome is regular and controlled by the thickness, density, and viscosity ratios of the layers. Application of this theory to a diapiric rise of granites in the Pine Creek Geosyncline gives an average distance of 24.2 km between the domes. This figure is valid for the central part of the geosyncline, assuming that a 5.5-km thick layer of light granite is overlain by a layer of sediment or basement rock of comparable thickness (Fig. 8). Theoretically we would therefore expect a hidden granitic body halfway between the Waterhouse Complex (2) and the Burnside Granite (5), as indicated in Fig. 7. This is supported by divergence in the gravity anomalies, and by unconfirmed reports of tin mineralization in the sediments east of Adelaide River.

The rate of growth of diapirs can be calculated from Ramberg's (1968) theory. When the amplitude of the interface between the metasediments and sediments is 10% of the wavelength, the velocity of amplitude growth is 0.083 cm year^{-1}. From these calculations of the average distance between granite intrusions and rate of amplitude growth, we can conclude that the buoyant rise of granitic domes from a granitic layer is a physically realistic process, and that the intrusion can take place in a solid state over 10^7 - 10^8 years.

A mechanism of solid state intrusion raises the question of the age of the granite relative to the age of intrusion. The regional structure in the Pine Creek Geosyncline is isoclinal folding with north-striking axes accompanied by low-grade regional metamorphism. Later refolding by forces generated by granite intrusions is believed to have occurred, and these intrusions are not related to any major orogeny involving crustal shortening or metamorphism. A summary of K-Ar and Rb-Sr age determinations of granites in the Katherine-Darwin area was presented by Compston and Arriens (1968). The intrusives can be divided into two major groups: one with 1830-1800 m.y. granites intruding the Archaean basement and the central part of the geosyncline (Fig. 7), the other with intrusive granites of 1750-1710 m.y. which appear along the eastern edge of the geosyncline. The K-Ar ages (Hurley et al., 1961) of the micas are 100-300 m.y. younger than the ages from total-rock Rb-Sr dates. If Hurley's dates are valid, then a possible explanation for the younger ages of the micas is that they reflect a retrograde metamorphism in connection with the solid-state intrusion of the granites. Hence, the time difference of 100-300 m.y. should correspond to the time between the formation of the granites and their intrusion.

A recent gravity survey in the Rum Jungle area shows areas of marked mass deficiency over the Rum Jungle Complex and Waterhouse Complex (J. A. Major, personal communication, 1974). The minimum in Bouguer anomalies for the Waterhouse Complex coincides with outcrop of a possibly younger fine-grained granite. Two local minima in the Rum Jungle Complex coincide with a leucocratic and a fine-grained granite. These granites are similar to those intrusive granites found in the centre of the Pine Creek Geosyncline, and in the Rum Jungle area may represent diapiric granites that have pierced the basement crust. Isotopic dating of the rocks of the complexes is in progress, and should show whether or not younger granites pierced the basement complexes.

GEOLOGICAL HISTORY

We suggest the following geological history for the Rum Jungle area (Fig. 9).

A. Deposition of Lower Proterozoic sediments of the Batchelor Group formed a marginal shelf facies on Archaean basement.

B. Sediments of Goodparla Group were deposited in basins adjacent to and onlapping the shelf areas. Base metals and uranium-rich shales were deposited during this sedimentary cycle. Then followed intrusion of basic sills and dykes, and deposition of the Finniss River Group into troughs marginal to and onlapping the basin areas.

C. Gravity instability of a granitic layer in the lower part of the Earth's crust formed gentle dome structures. Low-grade regional metamorphism and folding of the sedimentary sequence about north-trending fold axes with isoclinal folds developed in the troughs, grading into more open folds and monoclines on the shelf and marginal basin areas. The intensity and style of folding were controlled by the amount of crustal shortening, amplitude of the granitic domes, and depth of cover rocks.

D. Diapiric intrusion of Middle Proterozoic granites with consequent doming of the basement complex, Batchelor Group, and lower Goodparla Group sediments. During this period the major D_2 structures were formed, accompanied by extensive metasomatism (e.g., tourmalinization and amphibolitization). Syngenetic uranium and base metal protore were mobilized and concentrated into structural traps. The Giants Reef Fault was active during this period, and fluid movement associated with the lateral and vertical movement caused tremolitization of the Coomalie Dolomite adjacent to the fault zone. The Lower Proterozoic sediments were eroded, and then the Upper Proterozoic Depot Creek Sandstone Member was laid down. The main structural phase ended with Early Cambrian displacement along the Giants Reef Fault.

CONCLUSION

In a discussion of the relationship between the Rum Jungle Complex and the surrounding rocks, Rhodes (1965) suggested that the granitic rocks of the complex may (1) all be intrusive into the sediments; or (2) some intrusive, and some older than the sediments; or (3) all be uncomformably overlain by the younger sediments. Rhodes favoured the last alternative, and explained the doming of the complex and sediments by polyphase folding. We believe that the Rum Jungle Complex and the Waterhouse Complex correspond to Eskola's type of mantled gneiss domes (Eskola, 1948, Fig. 7), and that diapiric intrusions of granite caused the doming of the complexes and sediments.

The following observations support the hypothesis of diapiric intrusion of granites into the Rum Jungle and Waterhouse Complexes, which resulted in doming of the basement and cover rocks:

1. The semicircular to oval shape of the complexes.
2. Comformable structures i.e., foliation, cleavage, lineation, and schistosity in the complex and overlying metasediments.
3. No repetition of strata by folding in the metasediments of the Batchelor Group.
4. Formation of a rim syncline around the Waterhouse Complex.

5. Overturning of sediments, and development of local shear and mylonite zones, with accompanying mineral alteration, along the complex-sediment contacts.

6. Moderate to steep outward-dipping foliation and mineral lineation around the complexes, indicating that these structures were formed by granitic intrusion in the solid state.

7. Nowhere within the complexes are xenoliths of Lower Proterozoic sediments, nor is their ghost stratigraphy recognized, and nowhere have the sediments been seen to be intruded by granites of the complexes.

8. Deformation of pebbles in conglomerates of the Batchelor Group indicates a strong compression perpendicular to bedding and/or schistosity, with an extension in the plane of schistosity directed parallel to the tectonic transport caused by the proposed diapiric intrusion.

9. Bending of previously folded country rock structures into concordance with the complex-sediment contact.

10. At a distance of about one-half to one-dome diameter away from the sediment-complex contact polyphase-type fold structures disappear and only the first phase of deformation is detectable.

11. Metamorphic and metasomatic alterations at the complex-sediment contact.

12. Radial and tangential pattern of fractures and quartz-tourmaline veins, which have their origin within the complexes.

13. Gravity data show a strong mass deficiency in the centre of the Waterhouse Complex, and two local areas of mass deficiency in the Rum Jungle Complex which coincide with outcrops of a fine-grained and a leucocratic granite of possible late origin.

14. Gravity data and orientation of the axes of maximum extension in conglomerate pebbles suggest that a ridge of granitic material rose between the two complexes during the basement doming.

15. Theoretical calculations of the average distance between intrusive granites and the rate of amplitude growth from a granitic layer below the Pine Creek Geosyncline indicate that the process is theoritically possible, and can take place in a solid state over 10^7 - 10^8 years. From the theoretical results we suggest a hidden diapiric granite body halfway between the Waterhouse Complex and Burnside Granite.

The structural features listed above are in agreement with those developed in theoretical and model experimental work on diapirism as a mechanism for igneous intrusion conducted by Ramberg (1967, 1970, 1972), Stephansson (1972), and Dixon (1974).

Several of the features listed above are compatible with fold genesis of dome and basin structures, but the features 3, 4, 8, 10, 12, and 13 are characteristics that can be explained by diapiric intrusion, but not by polyphase folding.

The emplacement of granite diapirs in the Pine Creek Geosyncline provided a possible source for the introduction of hydrothermal-type metals e.g., tin, and non-metals, e.g., fluorine and boron into the country rocks. Also the diapiric emplacement of granites provided a possible energy source to mobilize and concentrate any pre-existing syngenetic base metal, copper, and uranium protore into structural traps.

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CAPTIONS

Fig. 1. Generalized geology of the Katherine-Darwin region. After Walpole and Crohn, 1965.

Fig. 2. Stratigraphic successions around the eastern margins of the Rum Jungle and Waterhouse Complexes.

Fig. 3. Solid geology map of the Rum Jungle area.

Fig. 4. Deformation at the contact between the Rum Jungle Complex and Beestons Formation, as exposed in a costean 2 km northeast of Batchelor.

Fig. 5. Generalized geology of the Rum Jungle and Waterhouse Complexes before Giants Reef faulting. Structural data on deformed pebbles. Geology of the Rum Jungle Complex simplified after Rhodes (1965). MB, Mount Burton; B, Brown's; W, White's; D, Dyson's; RJCS, Rum Jungle Creek South Mine.

Fig. 6. Deformed pebbles in the Crater Formation.

A. White quartz boulder type, 3.5 km northwest of Batchelor,

B. Quartz pebble conglomerate, 21 km northeast of Batchelor,

C. Hematite-quartzite boulder conglomerate, 5 km west of Batchelor.

Fig. 7. Gravity anomaly map of the Katherine-Darwin region showing basement complexes and granites. Gravity after Whitworth, 1970. Ages after Compston and Arriens (1968). Mineral ages shown in brackets.

1.	Rum Jungle Complex	10.	Allia Granite
2.	Waterhouse Complex	11.	Litchfield Complex
3.	Nanambu Complex	12.	Roberts Creek Granite
4.	Cullen Granite	13.	Soldiers Creek Granite
5.	Burnside Granite	14.	Malone Creek Granite
6.	Margaret Granite	15.	Mount Bundey Granite
7.	Prices Springs Granite		Mount Goyder Granite
8.	McKinlay Granite	16.	Grace Creek Granite
9.	Fenton Granite	17.	Jim Jim Granite

Fig. 8. Determination of the characteristic wavelength for granite intrusions in the Pine Creek Geosyncline.

Fig. 9. Proposed geological history of northwest-southeast section of the Pine Creek Geosyncline.

Table I. Metamorphic and structural events.

Table II. Summary of structural and textural events after deposition of Lower Proterozoic sediments.

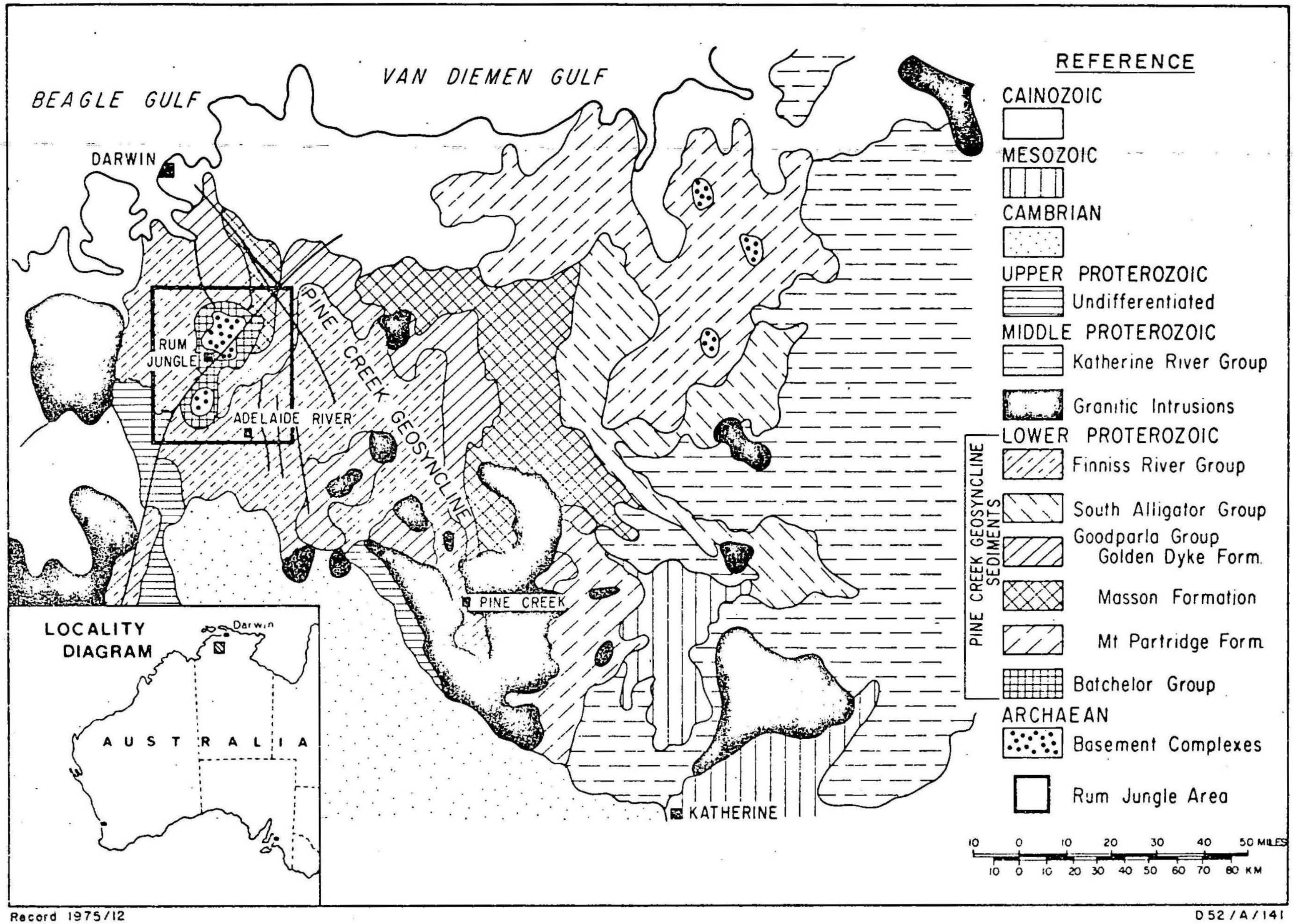

Fig. 1. Generalized geology of the Katherine-Darwin region. After Walpole and Crohn, 1965.

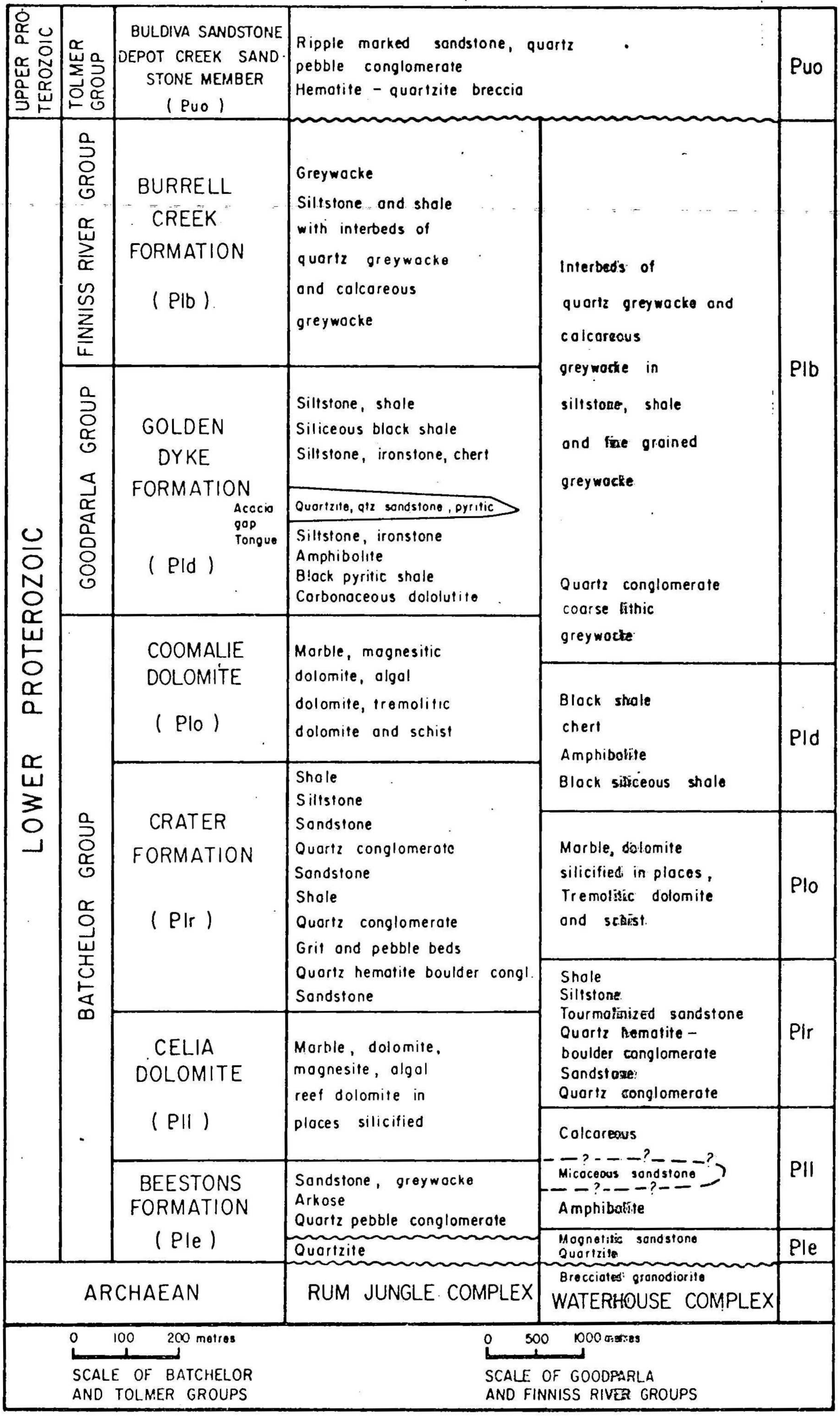

Fig. 2. Stratigrafic successions around the eastearn margins of the Rum Jungle and Waterhouse Complexes.

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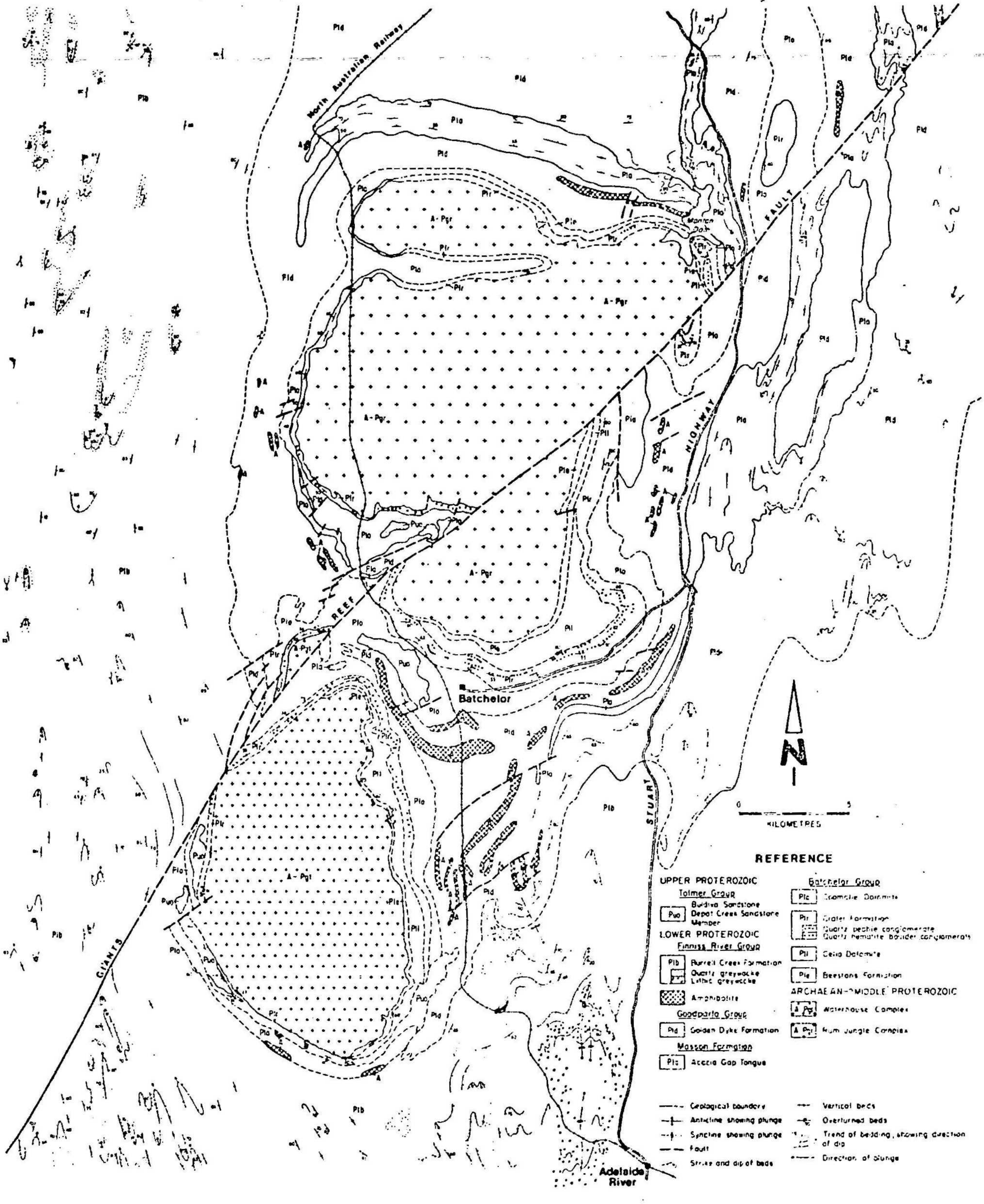

Fig 3. Solid geology map of the Rum Jungle area.

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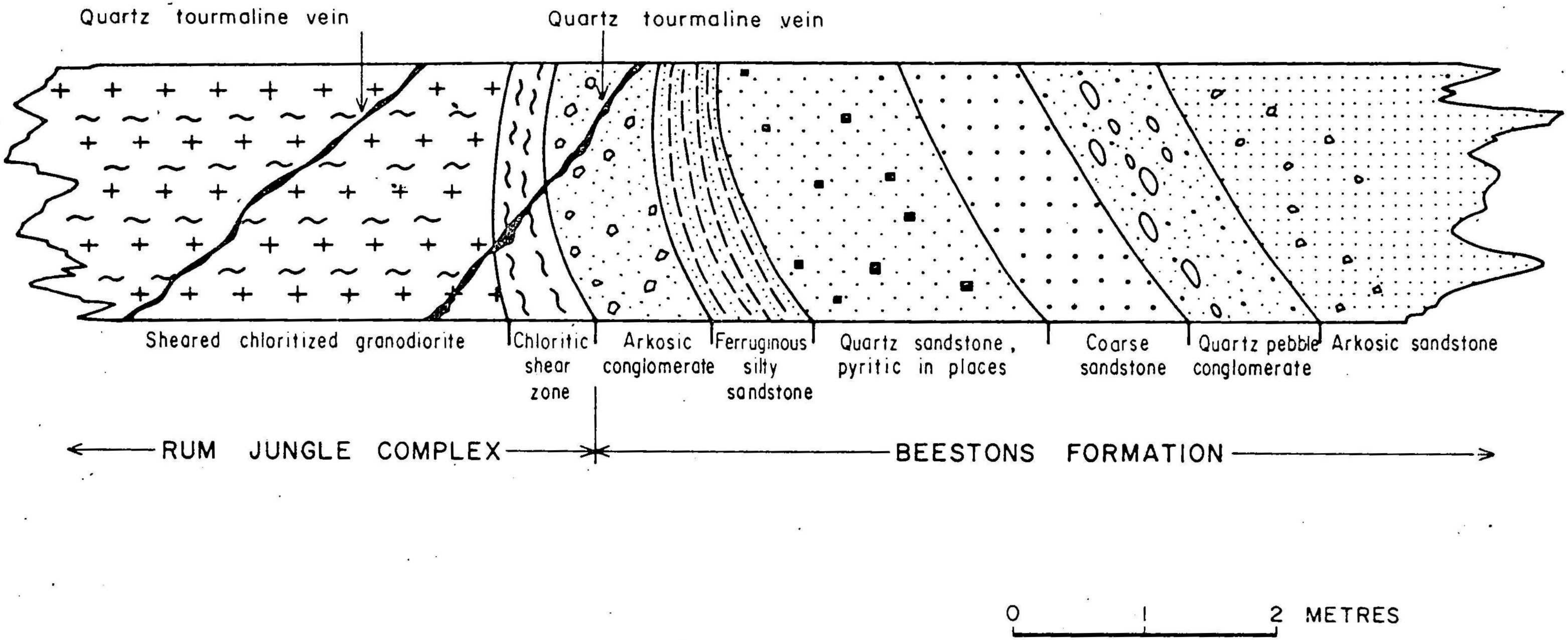

Fig. 4. Deformation at the contact betwen the Rum Jungle Complex and Beestons Formation as exposed in a costean 2 Km. northeast of Batchelor.

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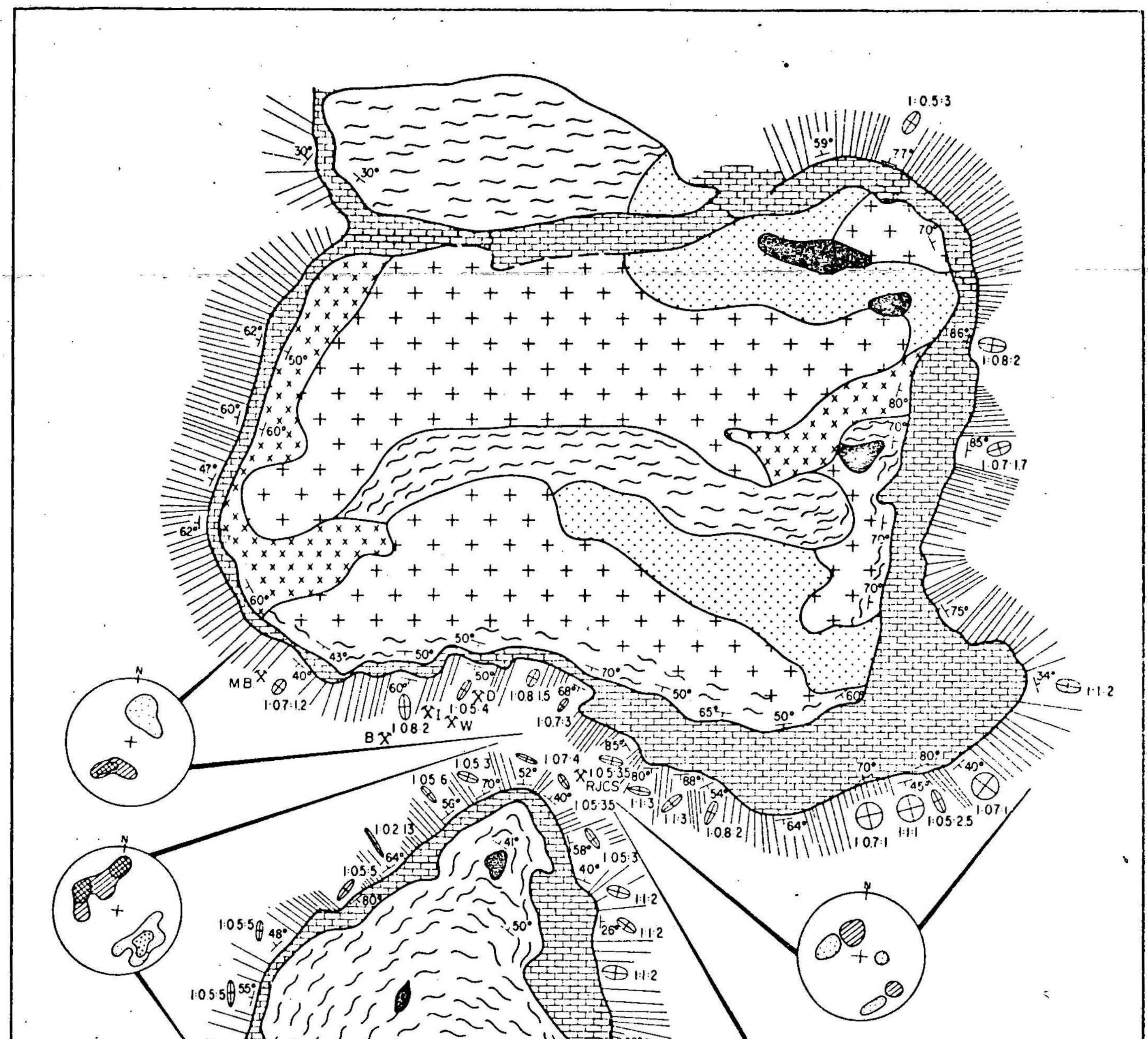

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Fig. 5. Generalized geology of the Rum Jungle and Watherhouse Complexes before Giants Reef faulting. Structural data on deformed pebbles.

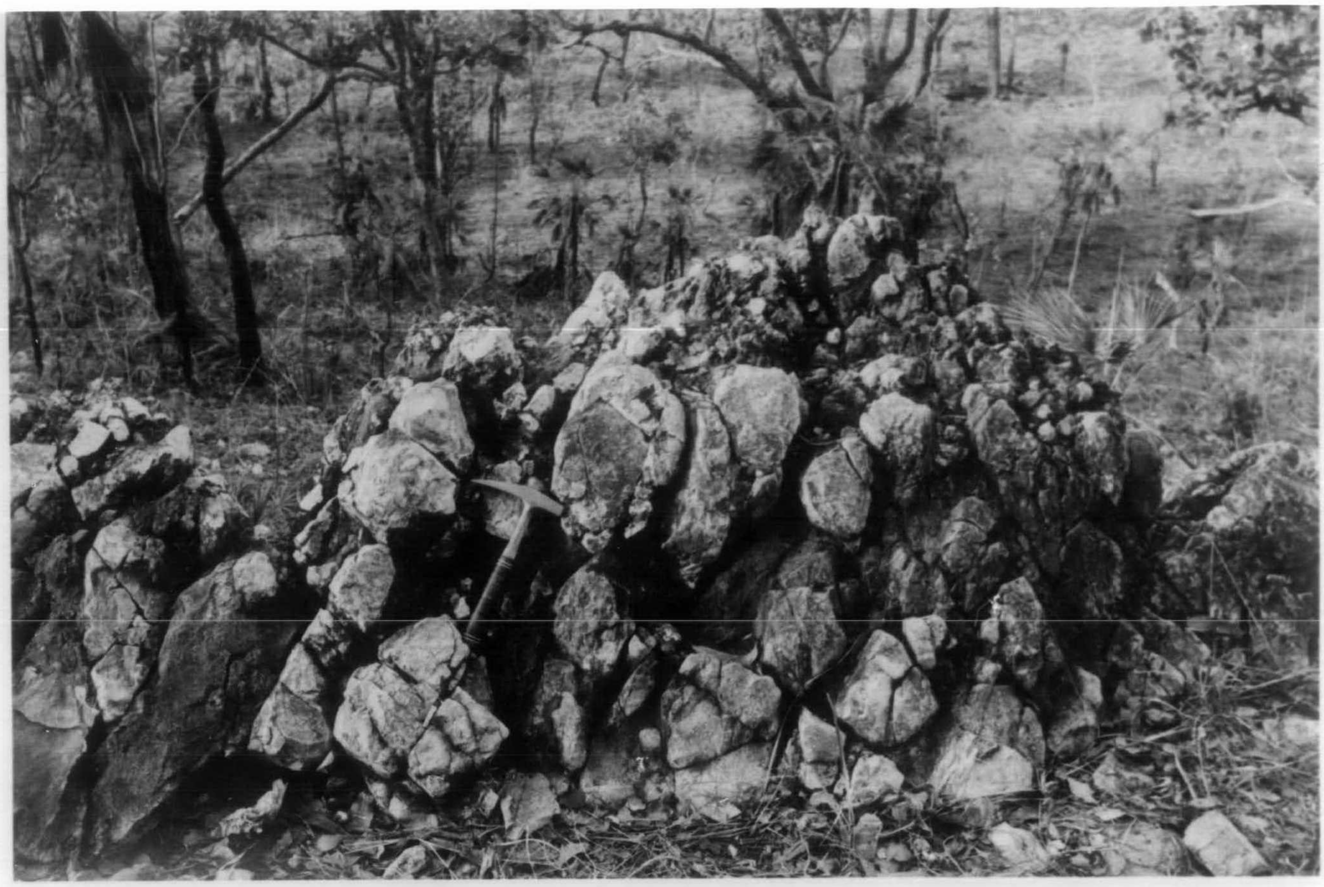


Fig 6A

Fig 6B

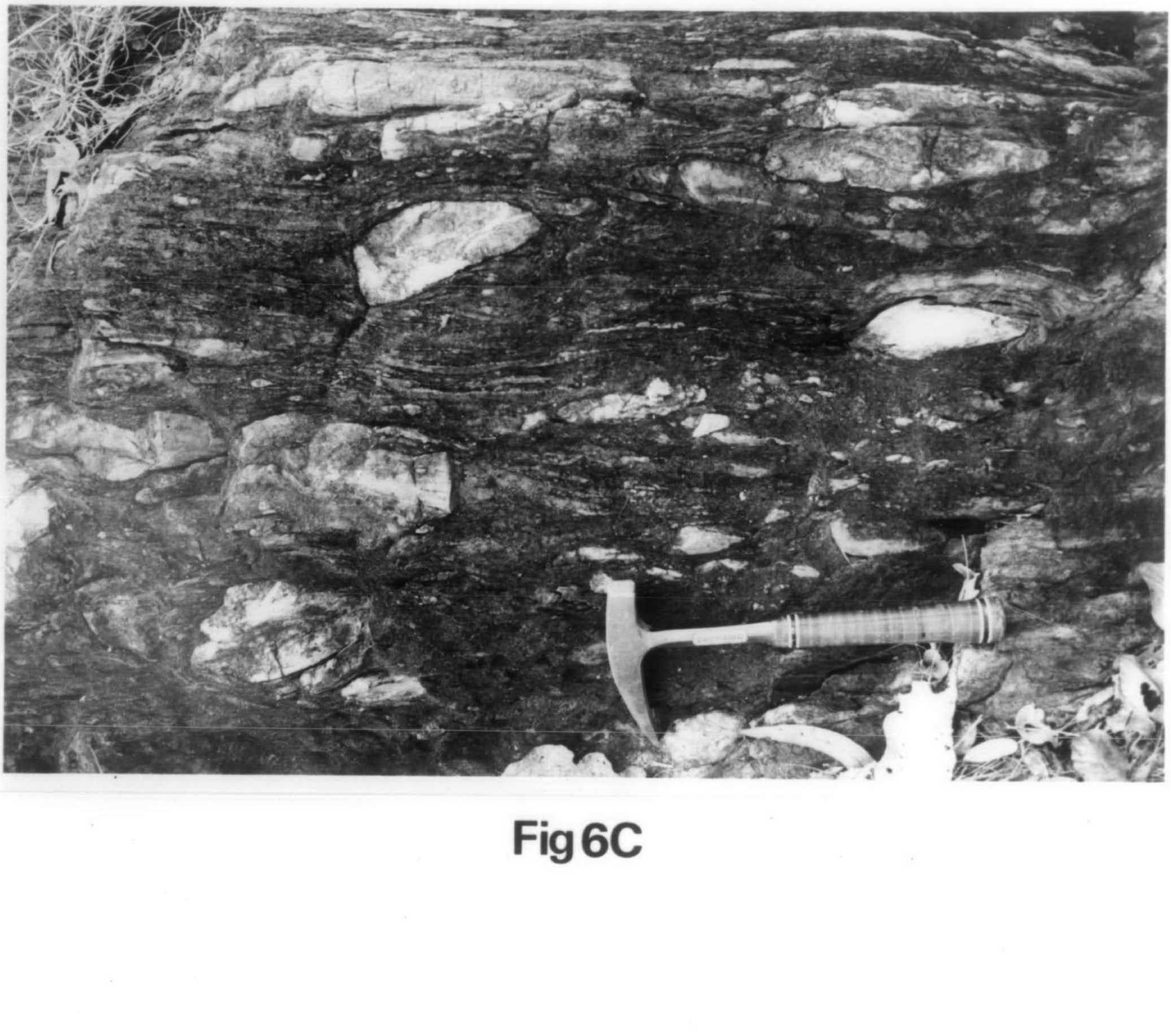
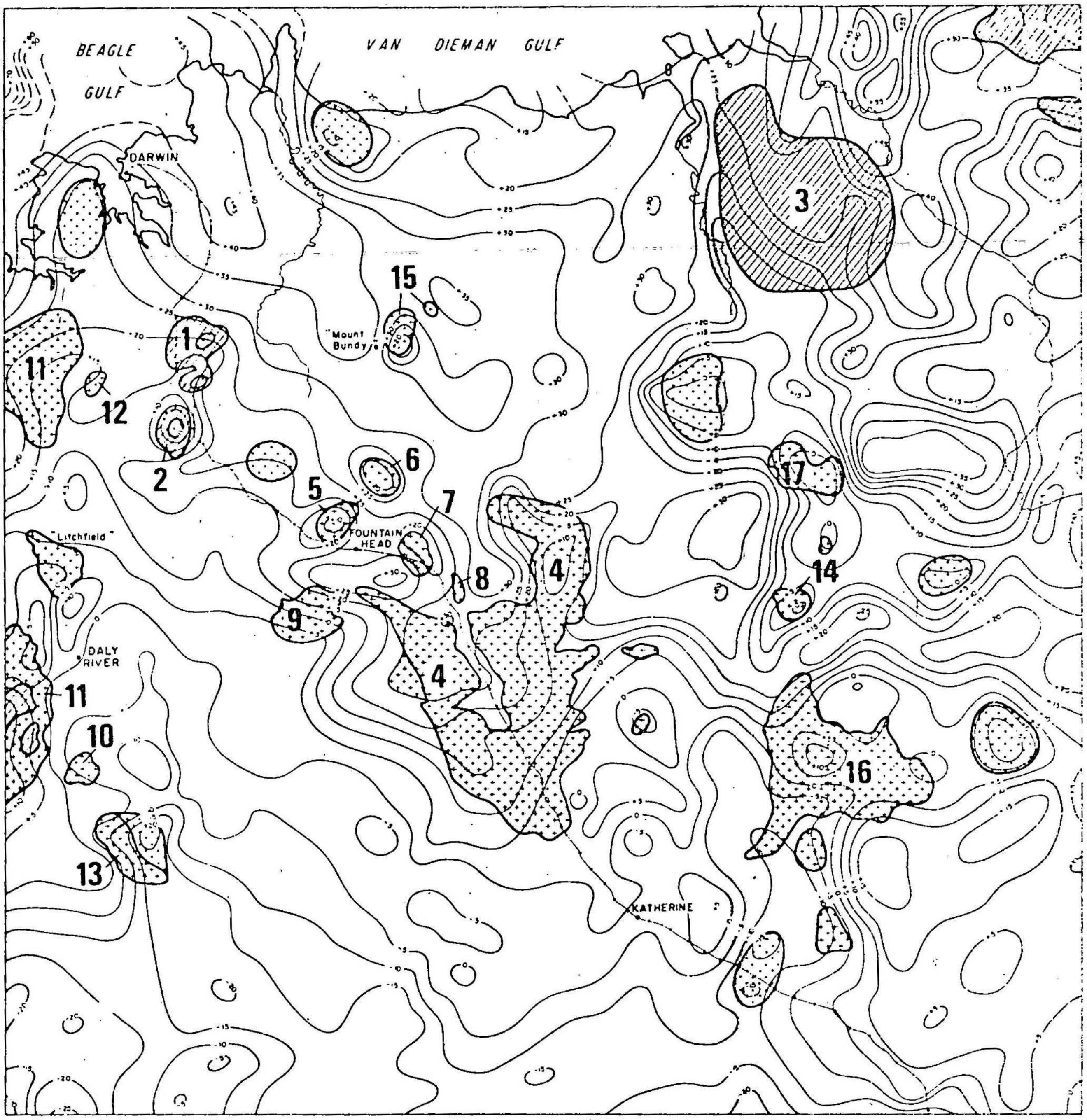


Fig 6C



0 50 km

BOUGER ANOMALY

ASSUMED ROCK DENSITY 2·2 g/cm^3

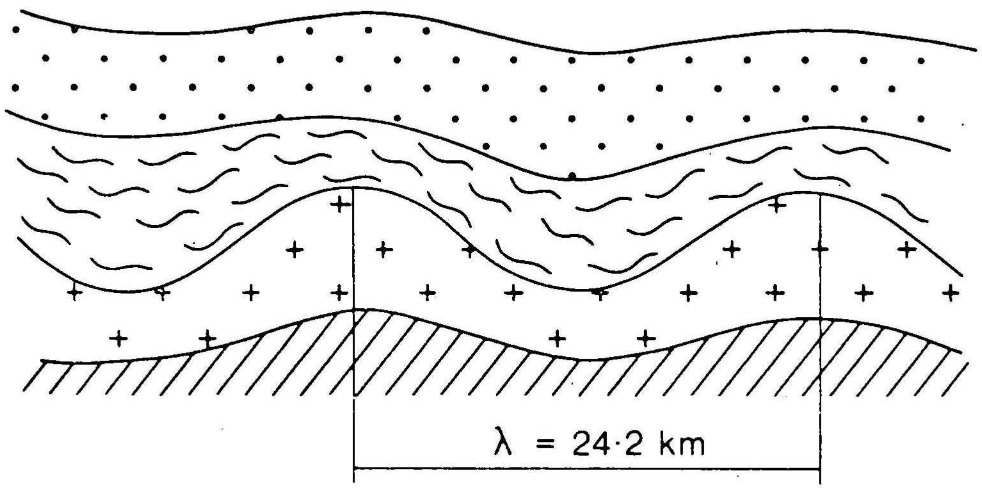
RAILWAY

ARCHAEAN BASEMENT, 1 – 3, 11 — 2500 – 2400 m.y (1750 m.y.)

MIDDLE PROTEROZOIC GRANITES — 4 — 13: 1830 – 1800 m.y. (1520 – 1720 m.y.); 14 — 17: 1750 – 1710 m.y (1650 m.y.)

HIDDEN ARCHAEAN BASEMENT AND/OR MIDDLE PROTEROZOIC GRANITES

Fig 7. Gravity anomaly map of Katherine - Darwin region, showing basement complexes and granites. Gravity after Whitworth, 1970. Ages after Compston and Arriens (1968). Mineral ages shown in brackets.



	THICKNESS km	DENSITY g/cm^3	VISCOSITY p
SEDIMENTS	5·5	2·55	10^{17}
BASEMENT COMPLEX METASEDIMENTS	5·5	2·77	10^{21}
GRANITIC LAYER	5·5	2·67	10^{20}
SUBSTRATUM	∞	3·1	10^{22}

Fig. 8. Determination of the characteristic wavelength for granite intrusions in the Pine Creek Geosyncline.

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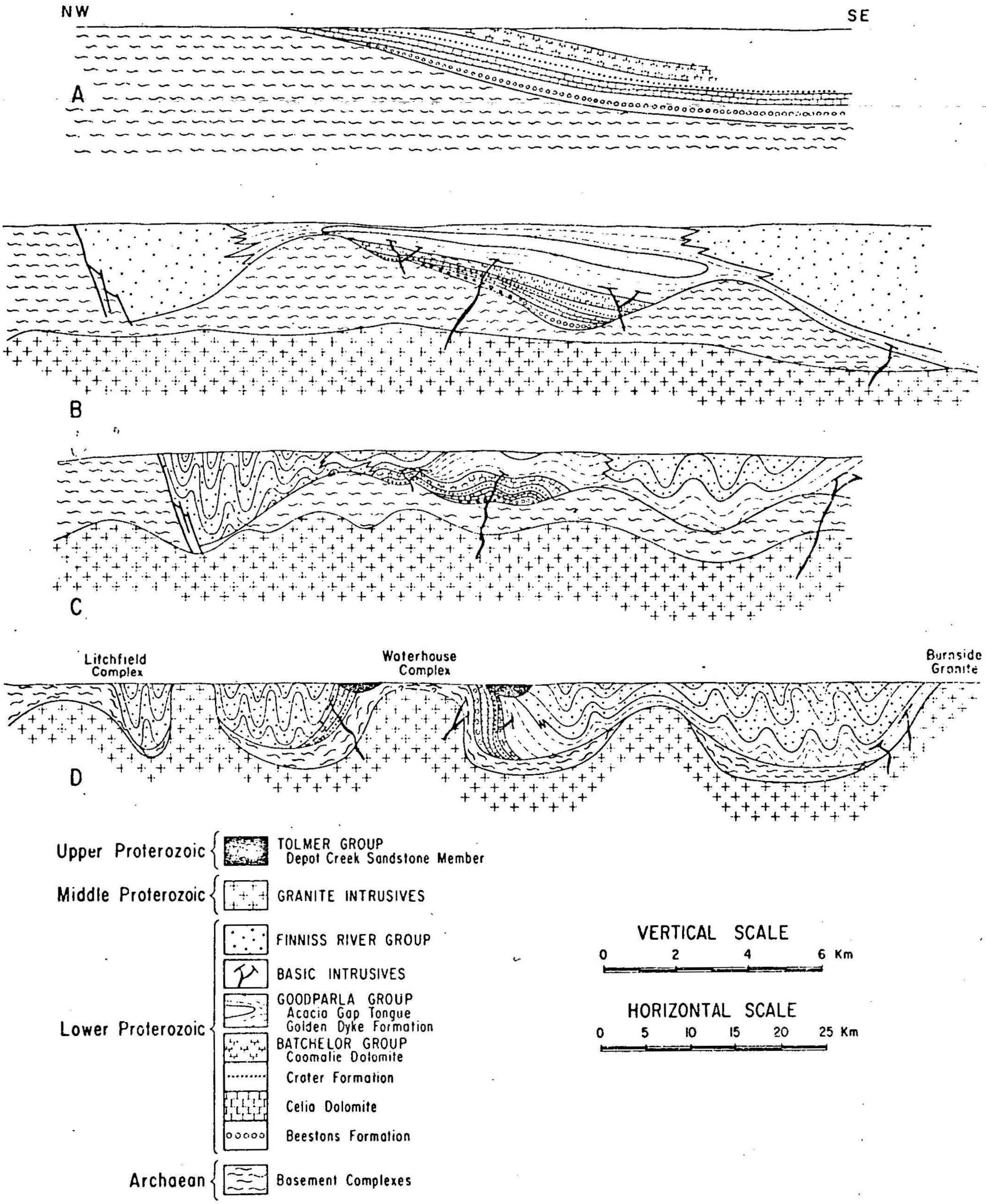

Fig. 9. Proposed geological history of northwest-southeast section of the Pine Creek Geosyncline.

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D52/A/148

TABLE I. METAMORPHIC AND STRUCTURAL EVENTS

Age	Metamorphism within: Complexes	Metamorphism within: Sediments	Structures accompanying metamorphic events
Middle Proterozoic	Preferred orientation of quartz, feldspar, and biotite paralleling the basement-sediment contact	Introduction of quartz-tourmaline veins, andalusite, scapolite	Diapiric intrusion of granite into the basement complexes, D_2. Cleavage developed within shale close to the complexes. Brecciation and mylonitization along granite-sediment margin. Giants Reef Fault zone active. Conglomerate pebbles deformed
Lower Proterozoic	Retrograde metamorphism with replacement of biotite by chlorite, and feldspar by sericite	Regional low-grade greenschist metamorphism, extensive quartz recrystallization	Northerly-trending isoclinal folds with development of slaty and fracture cleavage (D_1)
Archaean	High-grade regional almandine-amphibolite metamorphism	-	Polyphase folding and migmatitization

TABLE II. SUMMARY OF STRUCTURAL AND TEXTURAL EVENTS AFTER DEPOSITION OF LOWER PROTEROZOIC SEDIMENTS

DOMAIN	STRUCTURE	SYMBOL	TEXTURE
Granitic core of basement complex	Diapiric intrusion of granite	D_2	Fine-grained and leucocratic granite
		S_2, L_2	Weak mica foliation and quartz/feldspar lineation
			Quartz segregations, veins, pegmatites
Contact margin of basement complex with sediment	Refolding of early basement structures	D_1	
	Weak foliation north-northwest	S_1	Alignment of mica
	Diapiric intrusion of granites	D_2	
	Strong foliation and lineation dipping steeply outwards	S_2, L_2	Synchronous lineation and foliation; planar alignment of mica and feldspars
			Preferred alignment of quartz, hornblende, micas, and chlorite
	Shear zones and mylonite from localized stresses with planar structures parallel to the contact	S_2	
	Radial and tangential fracturing from latest stage of intrusion with the development of quartz-tourmaline veins		

TABLE II. (contd)

DOMAIN	STRUCTURE	SYMBOL	TEXTURE
	Transposition folds and minor folds refolded by a later stage of D_1 formation	S_1, L_1	Slaty cleavage, foliation. L_1 defined by quartzitic rods
	Diapiric intrusion of granites into the core of the complexes caused outward-dipping foliation, lineation, and pebble stretching	D_2	Fracture cleavage with alignment of mica and chlorite in arenaceous rocks
Contact margin of sediments with basement complex		S_2, L_2	Slaty cleavage in argillaceous rocks; formation of second mica
	Shear zones parallel to the contact	S_2	Alignment of micas and chlorite; crushing and stretching out of feldspars
	Monoclinal folds with steeply plunging axes from late stage of diapirism	S_3	Refolding of S_1 and S_2 structures
		D_1	Fracture cleavage in arenaceous rocks, cleavage fans about fold crests
Sediments outside basement/sediment contact	Regional folding along non-cyclindrical north-south fold axes	S_1, L_1	Slaty cleavage with mica alignment in argillaceous rocks
			L_1 defined by surface rodding and tectonic fish