QUARTERLY NOTES
Geological Survey of New South Wales

MINERAL RESOURCES NEW SOUTH WALES

No 107
September 1998

CONTROLS ON OPAL LOCALISATION IN THE WHITE CLIFFS AREA

Gary R. Burton and Anthony J. Mason[1]

[1]Present address: RZM Pty. Ltd., 6B Hines Street, Mildura 3500

ABSTRACT

The opal fields of the White Cliffs area are situated within the Cretaceous (Aptian) Doncaster Member of the Great Australian Basin sequence. The Doncaster Member is comprised of interbedded sandy/silty claystone and sandstone. Opal occurs mainly as thin, horizontal and, less commonly, vertical seams within the sedimentary rocks. It also occupies cracks within erratic boulders and concretions as well as forming coatings on those bodies. Opal also forms casts after fossils and minerals, and occurs within and adjacent to faults. Silica-rich fluids, believed to have been produced as the result of kaolinisation of the Cretaceous rocks, pooled within joints and other voids and — over time — precipitated opal. The opal does not appear to be related to any particular lithological horizon. Hence vertical facies changes cannot be used as an opal exploration tool in the White Cliffs area, in contrast to the opal fields of Lightning Ridge. There is some evidence that faults have assisted in siliceous fluid migration and hence opal deposition. Some opal seams occur within and adjacent to faults, as shown by old opal workings developed parallel to faults — and many opal workings in the White Cliffs area occur on or adjacent to lineaments and lineament intersections identified on aerial photographs. The interpreted photolineaments trend north-easterly, north-westerly and northerly. Interpreted Landsat lineaments in the region also trend north-easterly, north-westerly and northerly and mainly reflect drainage and the limits of Cretaceous outcrop. Basement structures, interpreted from regional aeromagnetic and gravity images, trend mainly north-easterly and north-westerly. Although a direct correlation between the location of opal fields and interpreted basement structures is equivocal, it seems likely that basement structures have influenced structures in the Cretaceous rocks and in turn those structures have influenced opal deposition. Hence, the recognition of lineaments in the Cretaceous rocks is considered to be a useful opal exploration criterion. However, as many opal deposits are not apparently associated with lineaments there may be no indirect method of locating some opal deposits within the White Cliffs area. Further work to improve the understanding of opal formation in the White Cliffs area should include detailed structural analyses and detailed stratigraphic, lithological and geochemical studies. Stratigraphic relationships indicate that opal probably formed during a Maastrichtian to Early Eocene weathering event.

Keywords: Opal, opal formation, White Cliffs, stratigraphy, geophysics, structures

INTRODUCTION

In this study the term 'White Cliffs area' is defined as that area encompassing the White Cliffs opal fields and neighbouring opal fields of Gemville, Pinnacles, Barclays Bunker, Welshes Knob, Polpah and Morambie, and the Purnanga opal field, approximately 60 km north-northeast of White Cliffs (figure 1). The town of White Cliffs is approximately 300 km north-east of Broken Hill in far western New South Wales. Opal was discovered there in either 1884 (Rodgerson 1891), or in 1889 (Jaquet 1893); and at Purnanga in 1896 (Kenny 1934). Opal mining was first reported at White Cliffs in 1890 (Relph 1961). Intensive mining continued until the First World War, when the market slumped, and the field became virtually deserted. Total production from the White Cliffs opal fields is unknown. MacNevin and Holmes (1979) gave a very conservative estimate of $2 307 000 worth of opal, of which $2 228 000 was recovered by 1911. Their estimate was simply a sum of the recorded value of production for each year, using the conversion £1 = $2 and given in 'dollars of the day' values. There has been no recorded production of opal from the White Cliffs fields since 1967.

This work is based on a geological pilot study of the opal fields in the White Cliffs area, which was undertaken by the authors in 1995 with the intention

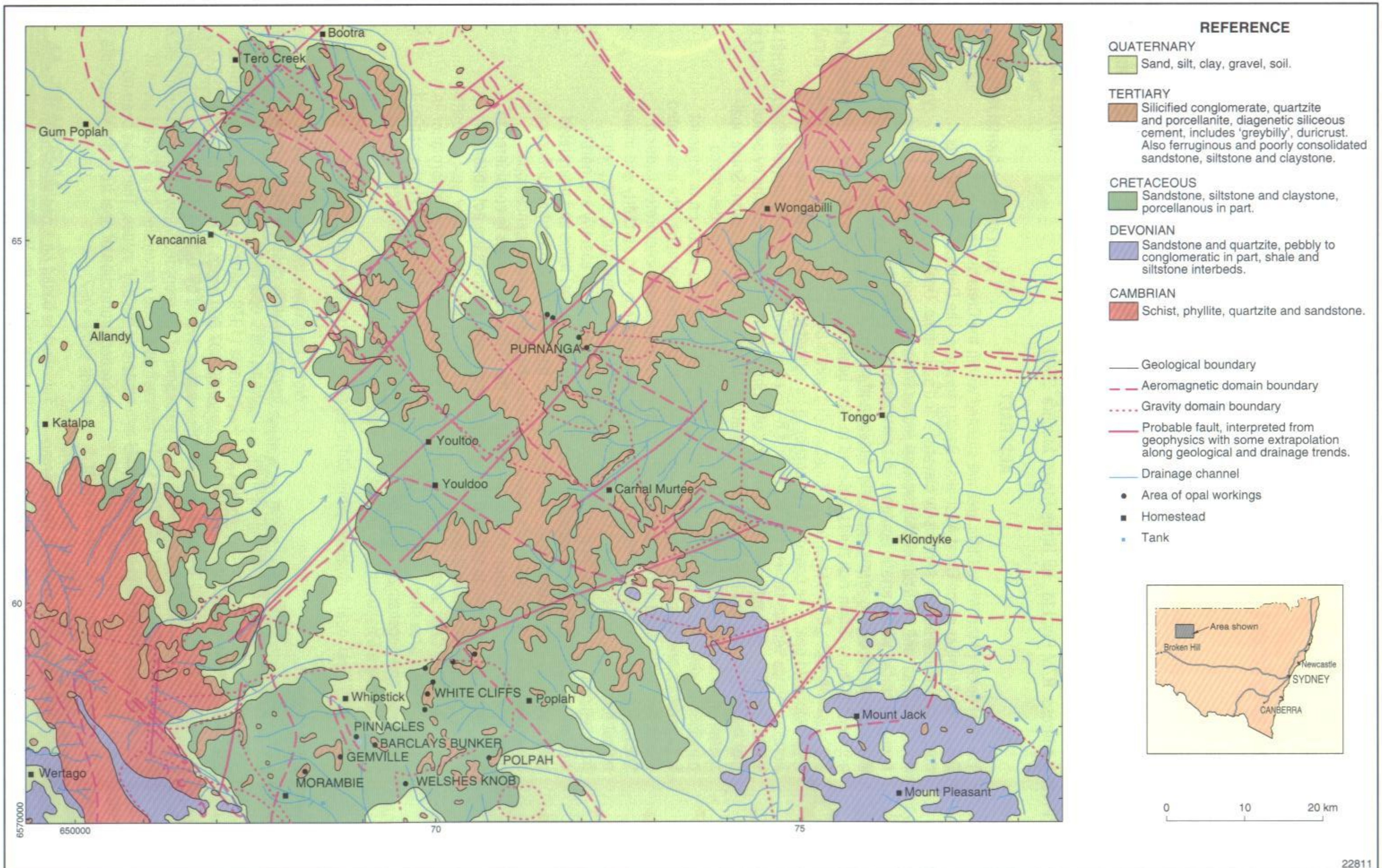


Figure 1. Geological map of the White Cliffs 1:250 000 area. Faults have been interpreted from geophysical data and extrapolated along drainage or geological trends in places. Also shown are aeromagnetic and gravity domains (also see figures 4 and 5). The major opal mining areas are also indicated (capital letters). Geology modified from Rose, Louden and O'Connell (1964)

0 1 2 3 4 5
cm

of assessing possible controls on opal deposition. The aims of this paper are to

- briefly describe the mode of occurrence of opal in the White Cliffs area;
- assess models of opal formation and their application to the White Cliffs area;
- assess opal exploration criteria on an outcrop to map scale; and
- suggest further work which could improve understanding of opal formation in the White Cliffs area.

GEOLOGICAL SETTING

The opal deposits of the White Cliffs area are situated within Cretaceous rocks of the Great Australian Basin. The Early Cretaceous (Aptian) Doncaster Member of the Wallumbilla Formation of the Rolling Downs Group (McMinn 1981) hosts the opal deposits. In the White Cliffs area, the Doncaster Member consists of interbedded sandy/silty claystone and fine-grained sandstone. Beds are of the order of several centimetres to several tens of centimetres thick. Drilling by Redfire Resources NL has also detected conglomerate layers within the sequence (Besley & Martin 1993a, b). The rocks are kaolinised and silicified and variably stained by iron oxides.

The claystone consists mainly of kaolinite, with lesser smectite, mixed layer clays, mica and quartz and is massive to very finely laminated. It commonly contains very fine to fine-grained (lesser medium-grained) clasts of quartz, altered feldspar, chlorite, mica and lithic fragments. The fine-grained and smaller particles are commonly angular while the medium-sized particles are rounded to sub-rounded. Lithic clasts include claystone, sandy claystone, quartzite and metamorphic (granoblastic) quartz.

Sandstones are composed of fine to very fine, angular to sub-angular grains of quartz, altered feldspar, lithic fragments, chlorite and mica. The clay minerals of the matrix are dominated by kaolinite, with lesser amounts of smectite, mixed layer clays, mica and quartz.

Spherical gypsiferous concretions several tens of centimetres to more than one metre in diameter, as well as erratic Devonian quartzite boulders, are common within the Cretaceous rocks.

The Cretaceous rocks are unconformably overlain by Tertiary rocks which are comprised of silicified colluvial gravel, locally referred to as "geyser", ranging from 0.5 m to 3 m thick (Relph 1961); sandy clay, from 0 to 3.5 m thick (Kenny 1934); and silcrete, locally referred to as "greybilly", with a maximum thickness of 6 m (Kenny 1930).

The Tertiary sequence may correlate with the Paleocene to Eocene Eyre Formation, which extends from south-western Queensland to north-eastern South Australia. Wopfner, Callen and Harris (1974) interpreted the Eyre Formation as having been fluvially deposited, initially by braided streams and later by meandering rivers. Fine-grained material was probably deposited within lacustrine environments. Tectonism occurred prior to and during its deposition.

THE OCCURRENCE OF OPAL IN THE WHITE CLIFFS AREA

MacNevin and Holmes (1979) reported that 95% of the opal in White Cliffs is common opal (potch) and that opal mostly occurs in horizontal seams (from 1 mm to 75 mm thick). Some vertical seams are present. Local miners report that horizontal seams of potch thicken and develop into precious opal. Opal has also been found as flecks filling spaces within claystone (MacNevin & Holmes 1979).

Opal is commonly found filling fossil casts. Opal "pineapples" are the result of opalisation of glauberite crystal clusters (MacNevin and Holmes 1979). Plimer (1994) reported that opal has been found replacing gypsum. Opal forms coatings on erratic boulders and in this form is referred to as a "painted lady". Opal also fills cracks and fossil casts within erratic blocks (Pittman 1901). Local miners report that concretions commonly contain fragments of opalised wood or bone. MacNevin and Holmes (1979) noted that opal also fills cracks within concretions.

Opal miners in the White Cliffs area generally believe that faults (or "slides") are important for localising opal. In some areas (eg, the Blocks area at White Cliffs; the Pinnacles area; and Barclays Bunker) workings have been developed along fault planes. Opal seams adjacent to fault planes have been reported by local miners (eg, in the White Cliffs area and at Gemville), and opal has been found within fault planes. Local miners have reported that some opal seams are cross-cut and brecciated by fractures, while some opal seams have been rotated into faults indicating that at least some movement has postdated opal formation. However, the presence of faults in some opal mines but not in others, and the observation that some opal-bearing ground is highly fractured while elsewhere it is not, may indicate that not all opal occurrences are controlled by faults.

The Cretaceous rocks have been variably silicified. Silica occurs within very thin veinlets, fillings within pore spaces, coatings around grains and layers parallel to bedding — and is commonly iron stained and has a very fine lamellar texture. Chalcedonic quartz is present in the centres of some veins and pore spaces. Some claystone has been largely replaced by silica. In places the rocks have been brecciated (either by collapse by weathering, or by faulting) and have been recemented by silica, which in some cases has itself been brecciated, indicating more than one event of silicification.

Some opal seams have been brecciated and recemented by opal — a texture reported by Senior et al (1977) from the opal deposits of south-western Queensland and attributed to desiccation of opal and recementing by fresh opal. This provides evidence that opal has not formed in one single event.

MODELS OF OPAL FORMATION

Most models describing opal formation within sedimentary rocks consider that the source for the silica is the host rock itself (eg, Darragh, Gaskin & Sanders (1976), Andamooka; Senior et al (1977), Queensland opal deposits; Barnes & Townsend (1982), South Australian opal fields in general; Watkins (1985), Lightning Ridge; and Robertson & Scott (1990), Coober Pedy). Those models proposed that kaolinisation of the near-surface rocks has resulted in the release of silica. The silica was dissolved in groundwater and moved downward through the rocks via permeability pathways — connected intergranular pores and/or fractures. Upon encountering an impermeable layer the silica-rich fluid was 'pooled', the fluid began to dry out and the silica concentrated into a gel. Opal then began to form as silica spheres nucleated and precipitated from the gel (Darragh et al 1965). Thiry and Milnes (1991) proposed that opal formation in the Stuart Creek field (South Australia) is an ongoing process associated with groundwater movement and silcrete formation driven by the relative lowering of the water table as the region is uplifted.

Pecover (1996) has proposed an alternative model of opal formation in which opal is considered to have formed in response to tectonism. He suggested that joints and faults have actively controlled opal deposition in a way akin to the formation of quartz veins in hydrothermal systems. This contrasts with the weathering model, which considers joints and faults to have behaved only as passive fluid pathways. Much of the evidence Pecover (1996) gave to support his model can be equally well explained by the weathering model.

It is here considered that the weathering model adequately explains the origin of opal in the White Cliffs area. The Cretaceous rocks are strongly kaolinised, suggesting that sufficient silica was released during weathering. Fossil and mineral casts, joints, and cavities within and around erratic boulders and concretions have acted as the main impermeable voids in which silica-rich fluids have pooled. The permeability pathways along which the silica-rich fluids moved were probably supplied by some intergranular porosity as well as small scale fractures. The weathering process itself can generate fractures as there is a volume increase accompanying kaolinisation (Rose, Hawkes & Webb 1979).

The occurrence of opal fragments within Tertiary gravels (Byrnes 1981) and the absence of opal veins within the Tertiary rocks, despite one unsubstantiated report by MacNevin and Holmes (1979) to the contrary, indicates that opal in the White Cliffs area formed prior to the Paleocene. Idnurm and Senior (1978) distinguished two periods of Tertiary deep weathering in south-western Queensland, which probably also occurred within the White Cliffs area. The first was Maastrichtian to Early Eocene (Morney Profile) and the second occurred during the Late Oligocene (Canaway Profile). Opal formation at White Cliffs was probably associated with the Morney Profile.

Given that the general process of opal formation in the White Cliffs area is adequately explained by the weathering model, the problem is to try to identify features on a macro (outcrop) to mega (map) scale which may have assisted in localising opal deposits and hence may be used as exploration guides.

ASSESSMENT OF OUTCROP AND MAP SCALE FEATURES WHICH MAY HAVE CONTROLLED OPAL DEPOSITION

Vertical facies changes

Vertical facies changes have been found to be a powerful control on opal localisation in the Lightning Ridge area. Opal tends to occur at the horizontal interface between permeable sandstone and impermeable claystone. The sandstone units have been interpreted to be palaeochannel sand deposits within finer estuarine muds (Watkins 1985). Opal occurs at the base of the sandstone bodies and new opal deposits have been located simply by driving along the base of the channel sand deposits (J.J. Watkins pers comm 1997). Distinct channel sands are not recognisable at White Cliffs.

The Cretaceous palaeoenvironment at White Cliffs appears to have been different to that at Lightning Ridge. While the Lightning Ridge district is interpreted to have been an estuarine setting (Watkins 1985), the White Cliffs area, while still shallow marine (glauconite is present), seems to represent a deeper water environment than at Lightning Ridge. This is indicated by the fossils which include decapods, ostracods, gastropods, bivalve molluscs, ammonites, belemnites, crinoids, brachiopods, sponges and algae, as well as spores, pollen, foraminifera, other microplankton and wood (David 1950; Exon & Senior 1976; MacNevin & Holmes 1979). In the White Cliffs opal field an opalised ichthyosaur has recently been discovered and an opalised plesiosaur was found in 1976.

Exon and Senior (1976) interpreted the Doncaster Member as having een deposited within a cold, shallow marine environment with restricted connections to the open ocean, somewhat similar to today's Baltic Sea. They considered that the sediment was derived from basement rocks and reworked sediments, but Slansky (1984) believed that it contains volcanic detritus, derived from an andesitic volcanic arc on the Queensland coast (eg, Jones & Veevers 1984 and references therein).

During this study, very little evidence was found to indicate that opal deposits at White Cliffs are strongly controlled by recognisable (on an outcrop scale) vertical facies changes. In one mine in the Sullivans Hill area (figure 2), potch seams were observed to occur both above and below a montmorillonitic claystone unit. The claystone units in that area are thin and discontinuous, so even if they have acted as a focus for opal deposition their nature precludes them from being a useful exploration tool. If vertical facies changes are important in the White Cliffs area, then they must be on a scale of centimetres rather than metres and hence they may be difficult to use as an exploration guide.

Structures

Local scale structures

As fractures and faults may focus fluid movement it has been concluded that opal deposits may form in their vicinity — particularly near fault and fracture intersections. This has led to lineament analysis being used as a tool for locating potential opal-bearing areas and has had some success in the Lightning Ridge area (Watkins 1985).

Faults in the White Cliffs area have dips commonly in the range from vertical to 45°. They consist of either a single plane or a zone of fracturing several centimetres to tens of centimetres wide. Movement on many faults is not determinable but where slickensides and displaced markers are present, normal faulting is consistently indicated. Displacements of less than one metre are common. Some are lined with gypsum and/or puggy clay. The country rock is highly fractured at fault intersections. There are no consistent orientations of the fault planes.

There is some evidence that opal deposits are associated with faults — ie, the occurrence of old drives along fault planes, as noted above, and the belief of local miners that faults are important in localising opal. However, not all opal deposits have an obvious association with faults.

Photogeological interpretations were carried out on 1:60 000 black and white aerial photographs in order to delineate any local structures which may have

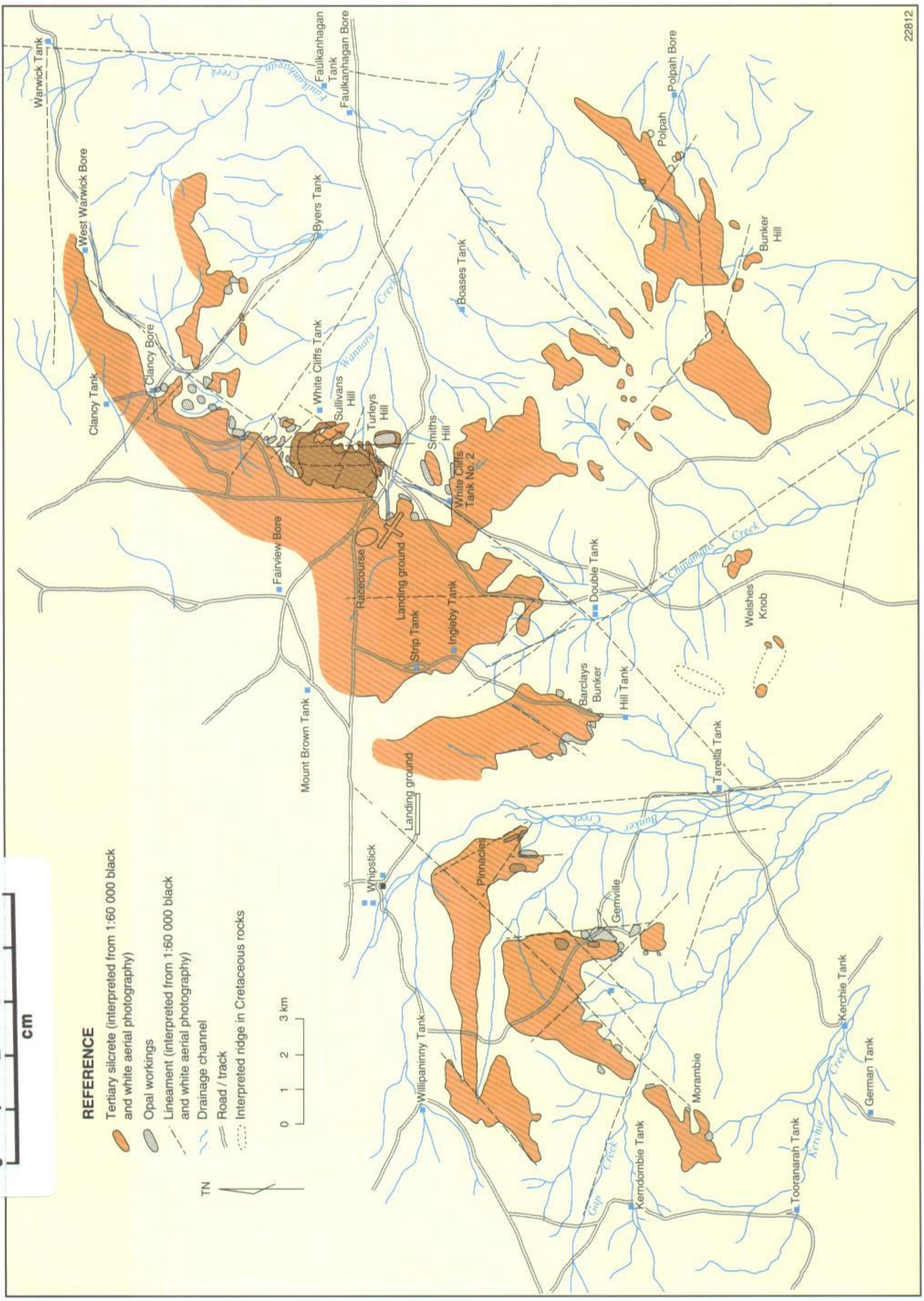


Figure 2. White Cliffs and surrounding opal mining areas, showing lineaments interpreted from aerial photographs, and Tertiary cover

localised opal deposits. In the opal fields of White Cliffs and surrounding areas (figure 2) interpreted lineaments strike northerly, north-easterly and north-westerly. Virtually all known opal mining areas occur near or immediately on interpreted lineaments. Gemville, Pinnacles and the White Cliffs fields occur at the intersections of interpreted lineaments. In some cases, joints and faults observed in the field are parallel to photolineaments (eg, Gemville, Pinnacles and, to some extent, the White Cliffs area), suggesting that the interpreted lineaments reflect real structures. In other areas there appears to be no correlation, but the limited number of joint and fault observations is too small to draw any meaningful conclusions.

At Purnanga, interpreted photolineaments trend north-west to west-northwest, north-northwest to northerly and north-easterly (figure 3). Some of the workings are situated close to lineament intersections.

Regional scale structures

Interpretations of aeromagnetic, gravity and Landsat images of the White Cliffs 1:250 000 map sheet area were carried out in order to detect any regional structures which may have been important structural controls for the formation of opal.

Interpretation of aeromagnetic features of the White Cliffs 1:250 000 map sheet area

Figure 4 gives the aeromagnetic interpretation of the White Cliffs 1:250 000 map sheet area, with figure 1 showing the outcrop geology of the same area with the outlines of the aeromagnetic domains. The data used are from the Department of Mineral Resources' state-wide aeromagnetic database with some CRA Exploration data and recently collected Discovery 2000 data along the western side of the map area. The sources of the magnetic anomalies are considered to be within the basement rocks rather than the mostly (in places ?totally) non-magnetic Cretaceous and Tertiary rocks.

The northwest-trending Koonenberry Belt is responsible for the magnetically high zone (A) and magnetically low zone with sporadic highs (B) in the southwestern corner of the area (figures 1 and 4). Zone C corresponds to a probable uplifted, but still buried, basement block (?Devonian). Magnetic zone E (a weak high) may be part of the same block but at greater depth. A narrow magnetically high zone (D) trending north-northwest represents a strongly magnetic unit within the basement. Zone H, to the north, may have a similar source (figure 4).

A low magnetic zone (G_1) (figure 4) coincides with an area of sparse outcrop of Early to Middle Cambrian Teltawongee beds (quartzo-feldspathic lithic sandstone and slate: Mills 1992), with some Cretaceous and Tertiary rocks. The entire area of zone G_1 may be underlain by Teltawongee beds.

Devonian rocks in the Mount Jack area (figure 1) do not show any systematic magnetic response. In the extreme southeast of the White Cliffs 1:250 000 map sheet area, they are mainly associated with a magnetically low zone (F) and overlap magnetic zone E. The Devonian rocks terminate against a narrow, west to northwest-trending magnetically low zone (G_2) which extends into zone G_1 (figure 4).

A moderately high magnetic zone (I) coincides with outcrop of Cretaceous and Tertiary rocks, particularly in the north-west of the area, where the

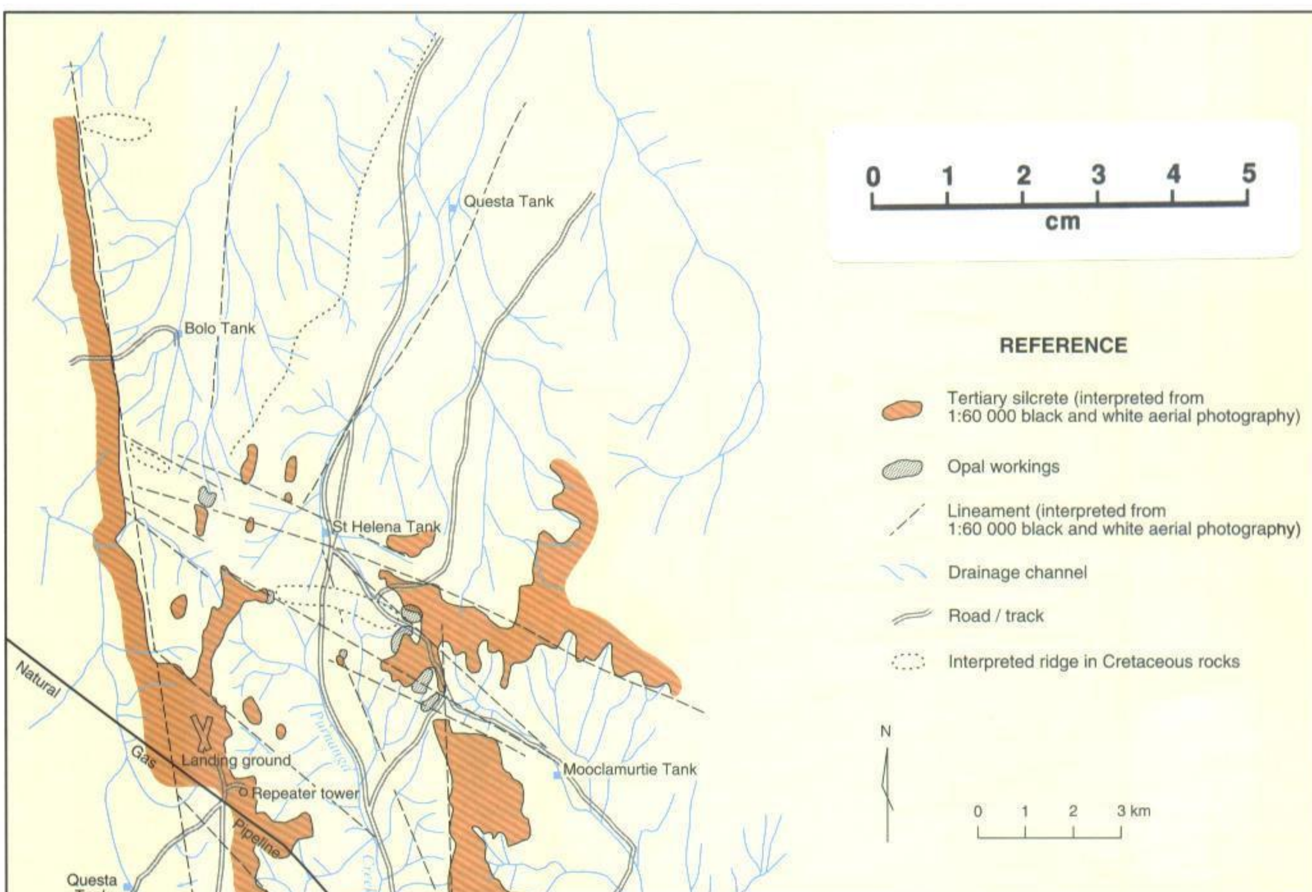


Figure 3. The Purnanga opal field, showing lineaments interpreted from aerial photographs, and Tertiary cover

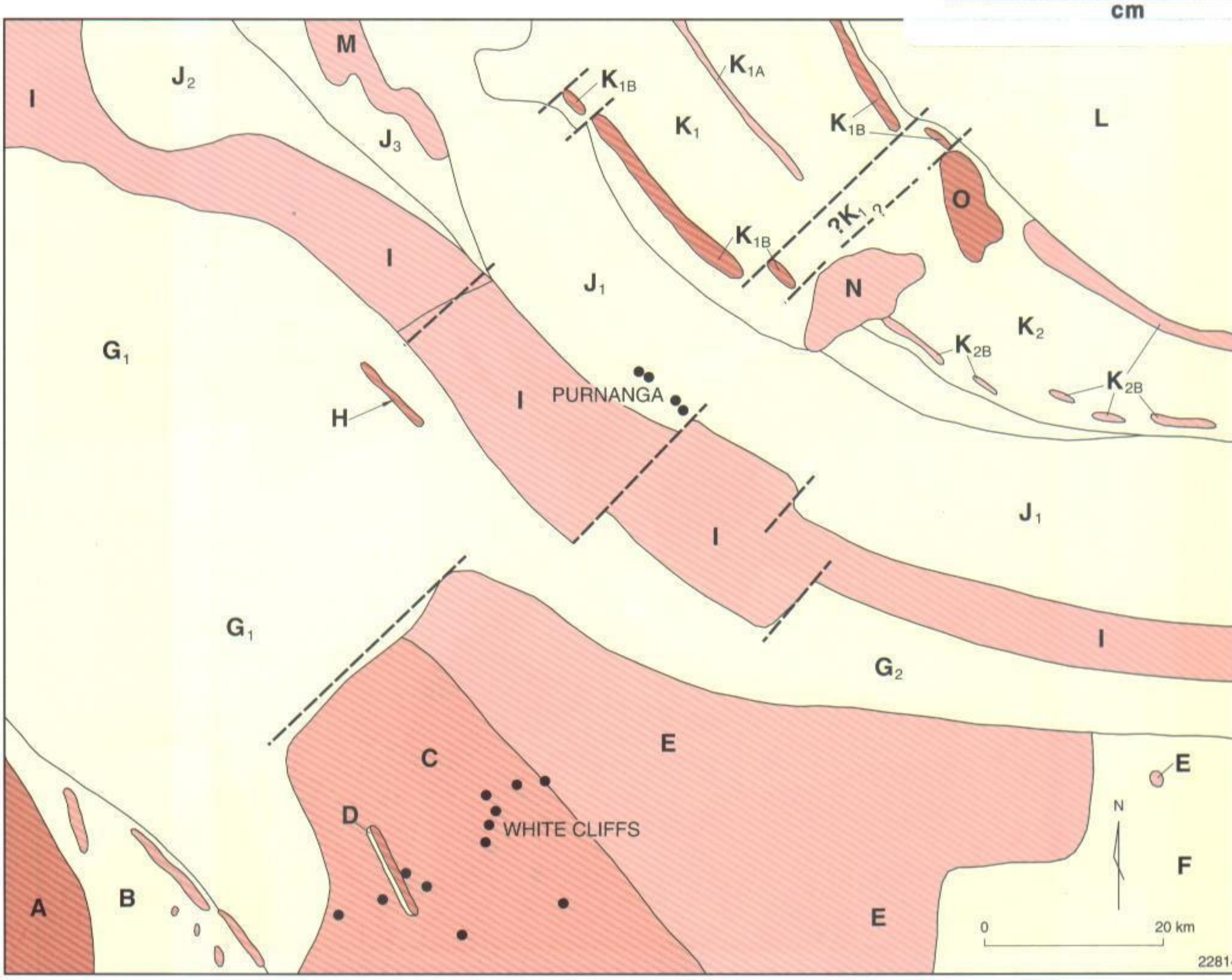


Figure 4. Interpreted aeromagnetic domains, opal mining areas (dots) and inferred faults (dashed lines) in the White Cliffs 1:250 000 map sheet area (see text for details)

outcrop also corresponds to a moderately high magnetic zone (M) and magnetically low zones (J_2 and J_3) (figure 4). It is probable that the Cretaceous and Tertiary rocks are there resting on uplifted basement. Zone I corresponds approximately with an interpreted fossil volcanic arc, with its south-western boundary corresponding approximately with the Olepoloko Fault (Stevens & Crawford 1992; B.P.J. Stevens pers comm 1996), which separates the Thompson Fold Belt to the north-east, from the Lachlan Fold Belt to the south-west.

Magnetically low zone J_1 (figure 4) coincides with a basement area interpreted by B.P.J. Stevens (pers comm 1996) to be a fossil rift or interarc basin.

Zones K_1 and K_2 (figure 4) are defined by narrow, sub-parallel magnetic highs separated by a broad magnetically low zone. B.P.J. Stevens (pers comm 1996) interpreted the basement beneath this area to represent a fossil volcanic arc. In zone K_1 the highs (K_{1A}, K_{1B}) are strong, while in K_2 (K_{2B}) they are more subdued. Northeast-trending faults are interpreted to separate the two zones, with uplift having occurred on the north-western side. The inferred faults coincide with the headwaters of drainage flowing to the south-east, as well as with a north-western edge to the Cretaceous and Tertiary outcrop. Zone K_1 is covered with Quaternary alluvium. Zone K_2 contains two irregular magnetically high zones (N and O) which may coincide with intrusions in the basement.

A magnetically low zone (L) (figure 4) corresponds with an interpreted basement zone of metasediments (B.P.J. Stevens pers comm 1996).

Interpretation of gravity features of the White Cliffs 1:250 000 map sheet area

Figure 5 gives the interpretation of the Bouguer gravity anomalies over the White Cliffs 1:250 000 map sheet area, with the outlines of the gravity domains indicated on figure 1. The gravity data used for the interpretation are from the Department of Mineral Resources' state-wide gravity database. The gravity features are interpreted to represent basement structures. There is little correlation between the gravity features and aeromagnetic features (figure 4). The magnetic data are regarded as the better data for interpreting basement structures (cf gravity feature 17) and only a brief account of the gravity is given here.

A gravity high (1) in the south-western corner of the map (figure 5) corresponds with Koonenberry Belt rocks. A gravity high (2) overlaps with magnetic zone C but it has a completely different shape. A broad zone of gravity lows (8) extends from the north-western corner of the map area, south-eastwards through the centre of the area. Gravity feature 6 may have a similar source to feature 8. Gravity features 3, 4, 5 and 7 could represent slightly denser or higher blocks in the basement.

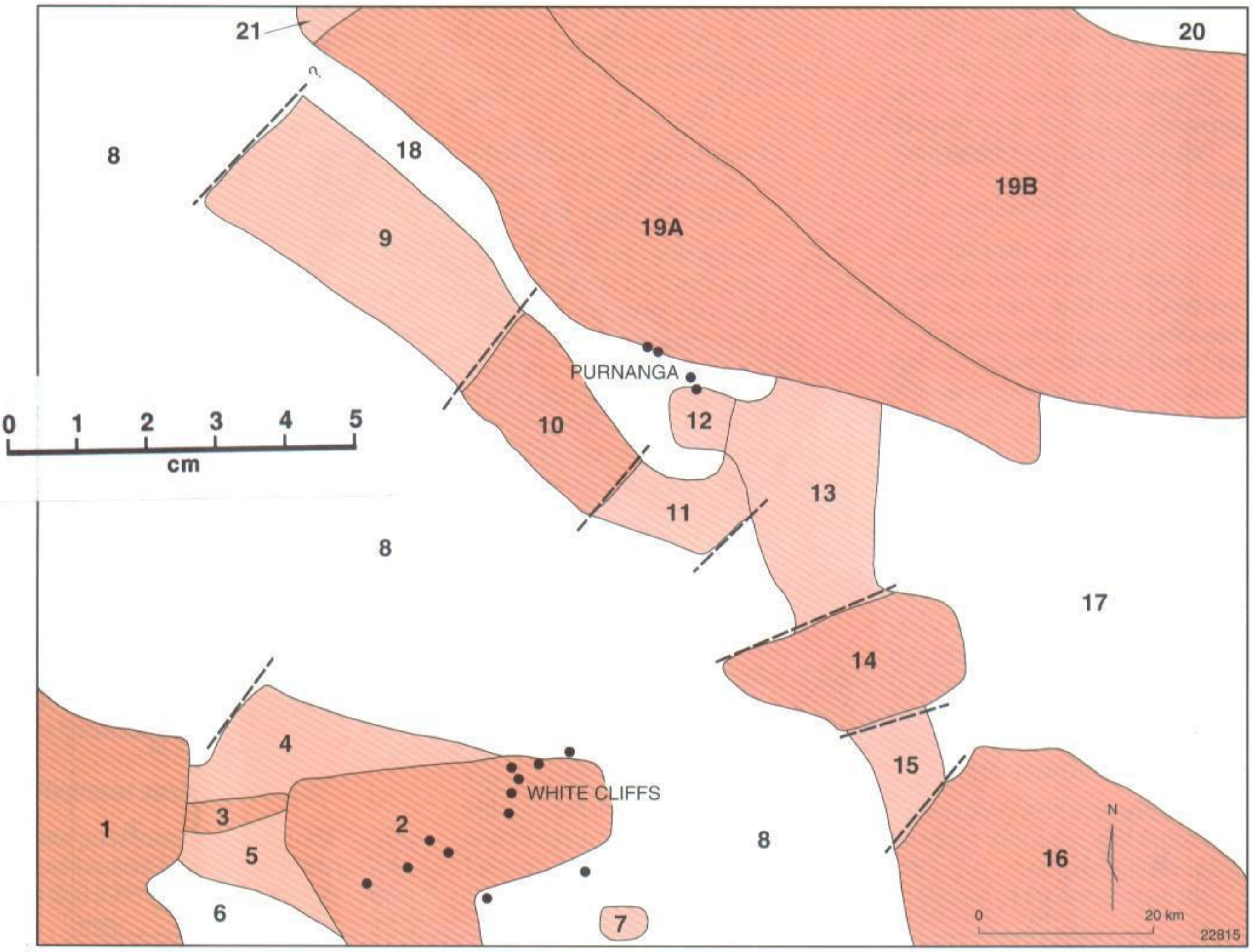


Figure 5. Interpreted Bouguer gravity domains, opal mining areas (dots) and inferred faults (dashed lines) in the White Cliffs 1:250 000 map sheet area (see text for details)

A north-west to south-east group of gravity highs (9, 10, 11, 12, 13, 14, 15 and 16) (figure 5) is terminated by an interpreted northeast-trending fault at its northern end, and extends to the south-eastern corner of the map area where it corresponds with the Mount Jack Block (Scheibner 1985). Gravity zones 9, 10 and 11 correspond with magnetic zone I.

Gravity zone 19 is a broad high in the north-eastern part of the map area, but with a subtle trend to allow subdivision (19A and 19B), while a gravity low (20) in the extreme north-eastern corner (figure 5) may correspond to a granitic intrusion at depth (B.P.J. Stevens pers comm 1996). Gravity features 18 and 21, and 19A, match approximately magnetic zones J and M (figure 4), extending into the arcuate trend of magnetic zone K.

Landsat image analysis

A Landsat image of the White Cliffs area, using bands 1, 2 and 4, was analysed for lineaments. When compared with the White Cliffs 1:250 000 geological map, the interpreted lineaments (figure 6) were found to correspond to drainage and the limits of outcrop of the Cretaceous rocks (figure 1). There are pronounced north-easterly and north-westerly trends in those features. Some lineaments, particularly a fault affecting Tertiary silcrete in the Purnanga area, trend north-northwesterly to northerly and do not reflect any obvious basement structure.

Synthesis of Regional Interpretations

The outcrop pattern of Cretaceous and Tertiary rocks of the White Cliffs 1:250 000 map sheet area seems to reflect tectonism in those rocks parallel to pre-existing basement structures (figure 1). Northwest-trending basement structures appear to be distinct tectonic domains, while northeast-trending basement structures are faults which displace those domains. The north-east trend is parallel to the Darling River Lineament, which is to the south of the White Cliffs area. Scheibner (1973, 1989) considered that there has been a long history of movement along the Darling River Lineament and parallel lineaments. It is possible that these faults were active during the opening of the Tasman Sea in the Late Cretaceous and Early Tertiary (Scheibner 1973; Veevers, Powell & Roots 1991). The earliest Tertiary rocks (conglomerates) in the area suggest that tectonism was occurring at the time of their deposition (Byrnes 1981; Plimer 1994). Faulted silcretes in the Purnanga area indicate that tectonism has occurred since the Late Oligocene. Recent seismic activity in the area (eg, a magnitude 5.1 earthquake at 30.08°S, 143.52°E, 80 km north of White Cliffs on 13 August 1996, D. Denham pers comm 1996) clearly demonstrates that the region is still tectonically active.

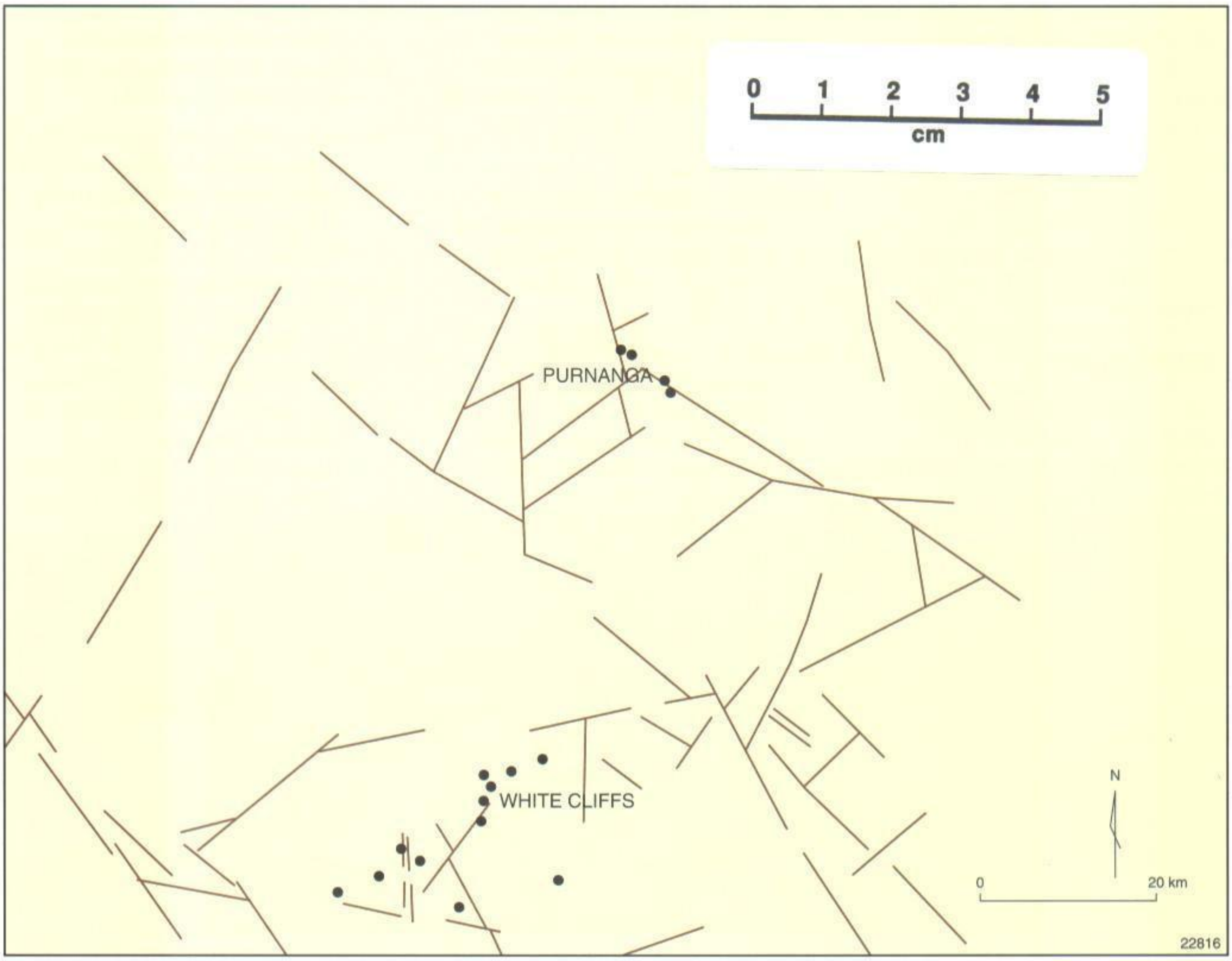


Figure 6. Interpreted lineaments from Landsat imagery (bands 1, 2 and 4) and opal mining areas (dots) in the White Cliffs 1:250 000 map sheet area (see text for details). Lineaments generally correspond to drainage and boundaries of Cretaceous outcrop (cf figure 1)

The opal fields at Purnanga very closely overlie the intersections of interpreted basement faults and tectonic domain boundaries. However, while some of the opal fields in the vicinity of White Cliffs occur near the edge of a gravity domain they do not seem to have any direct relationship to interpreted basement structures. Hence, a direct relationship between opal fields and basement structures is equivocal.

Interpreted north-easterly trending and north-westerly trending photolineaments parallel basement structures. The relationship between northerly trending photolineaments and basement structures is unclear, though some northerly trending basement structures have been interpreted. Regardless of this, it seems likely that basement structures have influenced faults and fractures within the Cretaceous rocks — and in turn these near-surface structures have had some control on the formation of opal, with opal fields tending to occur near lineament intersections.

CONCLUSIONS, EXPLORATION GUIDELINES AND FUTURE WORK

The occurrence of opal is restricted to the near-surface, weathered Cretaceous rocks. As the Maastrichtian to Eocene weathering event was regional in extent, the entire outcropping area of Cretaceous rocks in the White Cliffs area should be considered prospective for opal. Numerous verbal reports of opal being found in float and alluvium throughout the region (this study) certainly support this conclusion.

At Lightning Ridge, the two main factors controlling the formation of opal which can be used in exploration are vertical facies changes within the Cretaceous rocks, and structure. At White Cliffs, facies changes are not a useful exploration criterion. However, there is some evidence that faults and fractures have been important in localising opal and hence recognition of these structures may assist in finding new opal deposits. Faults and fractures will be best identified from aerial photograph and Landsat image analysis and ground inspection.

Although a direct relationship between opal fields and interpreted basement structures, particularly structural intersections, cannot be demonstrated unequivocally, the possibility that such a relationship exists should not be ignored (eg, Purnanga area). Therefore, perhaps areas of Cretaceous rock overlying basement structure intersections should be selected initially for more detailed work. Not all opal in the White Cliffs area is obviously related to faults and therefore some opal deposits may not be detectable by any indirect means.

Further work which could be undertaken to improve knowledge of the controls on opal localisation include:

- detailed examination of the relationship between opal, faults and joints within the Cretaceous rocks;
- detailed lithological logging of shafts in which opal has been found, noting the position in the sequence in which

the opal occurred, together with studies of the distribution of clay minerals and of the porosity and permeability of the rocks within the sequence; and

- a study of possible chemical controls on opal formation, assessing such factors as the pH of water and clays, one possible aim being to understand why potch forms in preference to precious opal.

ACKNOWLEDGMENTS

The authors would like to thank the numerous opal miners of the White Cliffs area for their time and enthusiasm in assisting with this study.
John Watkins (Department of Mineral Resources) is thanked for discussions concerning the formation of opal as well as supplying useful references and reviewing the manuscript. Brenda Franklin's constructive review is also very much appreciated.

REFERENCES

BARNES L.C. & TOWNSEND I.J. 1982. *Opal, South Australia's Gemstone.* Geological Survey of South Australia, Handbook No **5**, 157 pp.

BESLEY R.E. & MARTIN N.H. 1993a. Redfire Resources NL, Australian Opal Joint Venture, Exploration Licence 3577, White Cliffs N.S.W., third annual report to July 1993. Geological Survey of New South Wales, File GS1992/248 (unpublished).

BESLEY R.E. & MARTIN N.H. 1993b. Redfire Resources NL, Australian Opal Joint Venture, Exploration Licence 3578, Purnanga N.S.W., third annual report to July 1993. Geological Survey of New South Wales, File GS1992/249 (unpublished).

BYRNES J.G. 1981. Occurrence of opal clasts in colluvium beneath water-laid Tertiary sediments at White Cliffs. Geological Survey of New South Wales, Report GS1981/402 (unpublished).

DARRAGH P.J., GASKIN A.J. & SANDERS J.V. 1976. Opals. *Scientific American* **234(4)**, 84-95.

DARRAGH P.J., GASKIN S.J., TERRELL B.C. & SANDERS J.V. 1965. Origin of precious opal. *Nature* **209**, 13-16.

DAVID T.W.E. 1950. Great Artesian Basin, pp 482-516. *In* David T.W.E. & Browne W.R. ed. *The Geology of the Commonwealth of Australia* Vol I. Edward Arnold and Co, London.

EXON N.F. & SENIOR B.R. 1976. The Cretaceous of the Eromanga and Surat Basins. *BMR Journal of Australian Geology & Geophysics* **1**, 33-50.

IDNURM M. & SENIOR B.R. 1978. Palaeomagnetic ages of Late Cretaceous and Tertiary weathered profiles in the Eromanga Basin, Queensland. *Palaeogeography, Palaeoclimatology and Palaeoecology* **24**, 263-277.

JAQUET J.B. 1893. Appendix 4B. *In* Progress report for 1892 by the Government Geologist. *Department of Mines New South Wales, Annual Report* for 1892, 140-142.

JONES J.G. & VEEVERS J.J. 1984. Eastern Highlands, pp 115-143. *In* Veevers J.J. ed. *Phanerozoic Earth History of Australia.* Oxford Geological Sciences Series No 2. Clarendon Press, Oxford.

KENNY E.J. 1930. Report on the White Cliffs opal field. *Department of Mines New South Wales, Annual Report* for 1929, 98-100.

KENNY E.J. 1934. West Darling District. A geological reconnaissance with special reference to the resources of subsurface water. *Geological Survey of New South Wales, Mineral Resources* **36**, 180 pp.

MACNEVIN A.A. & HOLMES G.G. 1979. Notes on precious opal and its occurrence in New South Wales. Geological Survey of New South Wales, Report GS1979/268 (unpublished).

MCMINN A. 1981. The age of the opal-bearing deposits at White Cliffs, western New South Wales. Geological Survey of New South Wales, Report GS1981/297 (unpublished).

MILLS K.J. 1992. Geological evolution of the Wonominta Block. *Tectonophysics* **214**, 57-68.

PECOVER S.R. 1996. A new genetic model for the origin of opal in the Great Australian Basin. Mesozoic Geology of the Eastern Australia Plate Conference. *Geological Society of Australia, Extended Abstracts* **43**, 450-454.

PITTMAN E.F. 1901. Opal, pp 398-405. *In* The Mineral Resources of New South Wales. Geological Survey of New South Wales, Sydney, 487 pp.

PLIMER I.R. 1994. *Minerals and Rocks of the Broken Hill, White Cliffs and Tibooburra Districts.* Peacock Publications, Adelaide, 144 pp.

RELPH R.E. 1961. The White Cliffs opal field, New South Wales. *Department of Mines New South Wales, Technical Report* **7**, 7-17.

ROBERTSON R.S. & SCOTT D.C. 1990. Geology of the Coober Pedy precious stones field, results of investigations, 1981-86. *Geological Survey of South Australia, Report of Investigations* **56**, 55 pp.

RODGERSON W.C. 1891. Albert District — Wilcannia Division. *In* Wardens' and Mining Registrars' reports. *Department of Mines New South Wales, Annual Report* for 1890, 126-127.

ROSE A.W., HAWKES H.E. & WEBB J.S. 1979. *Geochemistry in Mineral Exploration*, 2nd edit. Academic Press, London, Toronto, 657 pp.

ROSE G., LOUDEN A.G. & O'CONNELL P. 1964. *White Cliffs 1:250 000 Geological Series Sheet SH/54-12.* Geological Survey of New South Wales, Sydney.

SCHEIBNER E. 1973. ERTS-1 geological investigations of New South Wales. Geological Survey of New South Wales, Report GS1973/382 (unpublished).

SCHEIBNER E. 1985. *Schematic Structural Map of New South Wales (western sheet) 1:1 000 000.* Geological Survey of New South Wales, Sydney.

SCHEIBNER E. 1989. Clarke Memorial Lecture: The tectonics of New South Wales in the second decade of application of the plate tectonics paradigm. *Royal Society of New South Wales, Journal and Proceedings* **122**, 35-74.

SENIOR B.R., MCCOLL D.H., LONG B.E. & WHITELEY R.J. 1977. The geology and magnetic characteristics of precious opal deposits, southwest Queensland. *BMR Journal of Australian Geology & Geophysics* **2**, 241-251.

SLANSKY E. 1984. Clay mineralogy, pp 179-214. *In* Hawke J.M. & Cramsie J.N. eds. Contributions to the geology of the Great Australian Basin in New South Wales. *Geological Survey of New South Wales, Bulletin* **31**, 295 pp.

STEVENS, B.P.J. & Crawford A.J. 1992. Early to Middle Cambrian geochemistry and tectonics of northwestern N.S.W. *Geological Society of Australia, Abstracts* **32**, 25-26.

THIRY M. & MILNES A.R. 1991. Pedogenic and groundwater silcretes at Stuart Creek opal field, South Australia. *Journal of Sedimentary Petrology* **61**, 111-127.

VEEVERS J.J., POWELL C.McA. & ROOTS S.R. 1991. Review of seafloor spreading around Australia. I. Synthesis of the patterns of spreading. *Australian Journal of Earth Sciences* **38**, 373-389.

WATKINS J.J. 1985. Future prospects for opal mining in the Lightning Ridge region. Geological Survey of New South Wales, Report GS1985/119 (unpublished).

WOPFNER H., CALLEN R. & HARRIS W.K. 1974. The lower Tertiary Eyre Formation of the southwestern Great Artesian Basin. *Geological Society of Australia, Journal* **21**, 17-51.

THE AGE OF THE NANDILLYAN AND NARRAGAL LIMESTONES, MOLONG HIGH, CENTRAL WESTERN NEW SOUTH WALES

Ian G. Percival

ABSTRACT

A diverse conodont fauna from the base of the Nandillyan Limestone, in the vicinity of Molong in central New South Wales, permits a relatively precise maximum age determination for that unit. However, the fauna is mixed, with late Llandovery taxa such as *Pterospathodus celloni* occurring in combination with species which indicate an earliest Wenlock age (*Pterospathodus procerus* Superzone, or lower part of *Kockelella ranuliformis* Zone). The latter is interpreted as the time of commencement of deposition of the Nandillyan Limestone, with older, reworked, elements being recovered from clasts in the basal breccia of the unit. The depositional span of the Nandillyan Limestone is largely coincident with, though concluding slightly before, that of the Dripstone Formation further to the north. There is no contemporaneity between the Nandillyan Limestone, almost certainly restricted to the Wenlock, and the Narragal Limestone (overlying the Dripstone Formation), which is demonstrated to be of early to middle Ludlow age (*Ancoradella ploeckensis* and *Polygnathoides siluricus* Zones). Limestones of this latter age, incorporated in the overlying (and partially laterally equivalent) Barnby Hills Shale, are deduced to be of allochthonous origin.

Keywords: Molong High, Llandovery, Wenlock, Ludlow, conodonts, Mumbil Group

INTRODUCTION

Limestones of broadly middle Silurian age are widespread on the Molong High, within the Lachlan Fold Belt in central New South Wales (figure 1). In a synthesis of Silurian stratigraphy in the Molong area, Byrnes (in Pickett 1982, p 149) regarded the Nandillyan Limestone Member as a synonym of the Narragal Limestone. Faunal differences obvious in the macrofauna — such as dominance of stromatoporoids combined with exclusion of halysitids in the Narragal Limestone, compared to the abundance of halysitids in the Nandillyan Limestone — have previously been interpreted as biofacies variants of the one apparently contemporaneous carbonate body. Conodonts are generally sparse to absent in both units, so that little precise biostratigraphic control was possible. During fieldwork by geologists preparing the second editions of the Bathurst and Dubbo 1:250 000 geological maps, the distinction between the Narragal and Nandillyan Limestones became increasingly apparent, and sufficient age-diagnostic conodonts were obtained to provide conclusive evidence for non-contemporaneity of the two formations. Regional stratigraphic correlations (Pogson & Watkins 1998; Meakin & Morgan in press) now distinguish between these limestones.

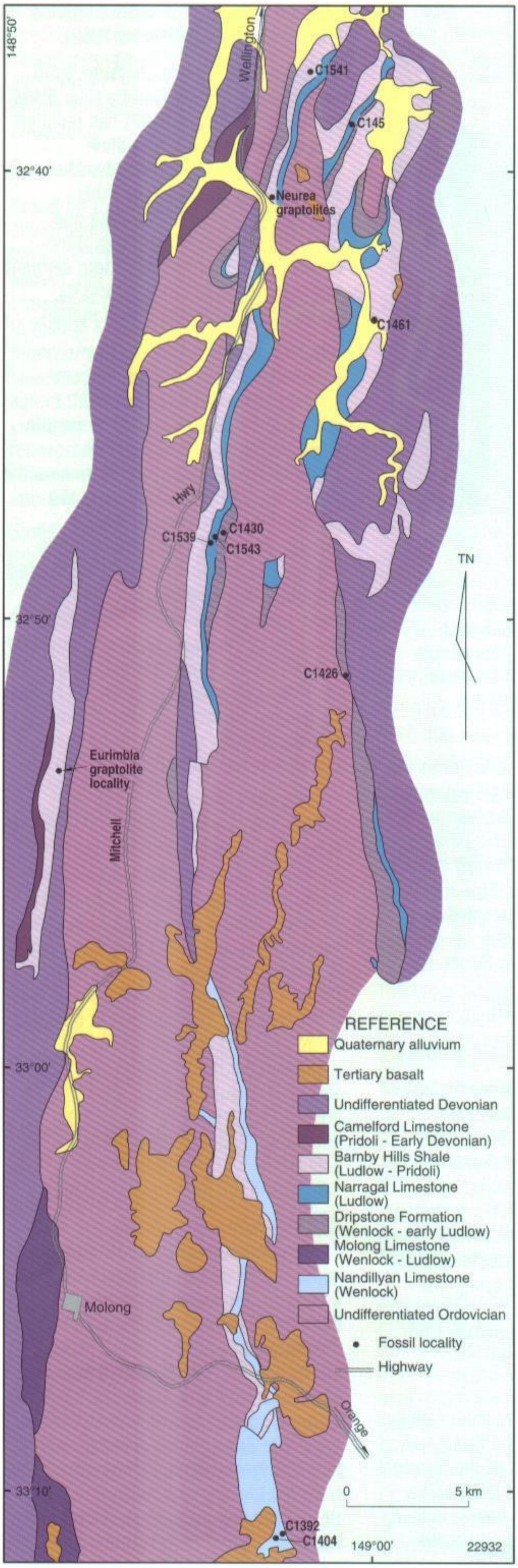
This paper presents the detailed biostratigraphy on which these revisions rely (figure 2), and compares the age data with those of stratigraphically adjacent formations. Lithological descriptions, field relationships, and history of nomenclature of the Nandillyan Limestone was presented in Pogson and Watkins (1998); and for the Narragal Limestone are to be presented in Meakin and Morgan (in press). The two limestones, together with the Dripstone Formation and the Barnby Hills Shale, are constituents of the Mumbil Group.

NANDILLYAN LIMESTONE

Previous biostratigraphic studies

Pickett (1993) listed coral and stromatoporoid assemblages sampled from a measured section through the Nandillyan Limestone on Barham Winchester property east of Molong (cf figure 1). He commented that, with the exception of the tryplasmatids, all coral species present also occurred in the 'Catombal Park Formation' (now Bell River Member of the Dripstone Formation). The age of the Bell River Member is now known to be most probably Homerian — ie, late Wenlock (Strusz et al 1998). Limited evidence of age was obtained from the few diagnostic conodonts yielded by the Nandillyan Limestone in the Barham Winchester section. Pickett (1993) identified *Kockelella walliseri* and *K. ranuliformis* from samples in the lower and middle parts of the section, for which he suggested an age of early Wenlock, based on the local zonation established by Bischoff (1986). This has been confirmed by the work of Jeppsson (1997), where the overlap of the two species is confined to the lower *K. walliseri* Zone, of middle Sheinwoodian age (equivalent to the international standard (European) *Monograptus belophorus* graptolite Zone = *M. flexilis* Zone). In the Barham Winchester section the lowermost Nandillyan Limestone rests unconformably on Late Ordovician sedimentary rocks, but it is not apparent how low in the total limestone succession this local contact lies.

The evidence presented below suggests that the maximum age of the Nandillyan Limestone equates with the early Sheinwoodian *Pterospathodus procerus* Superzone, or about four graptolite zones older than observed in the Barham Winchester section. The minimum age of the formation is undetermined at present, but the faunal similarity with the Dripstone Formation recognised by Pickett (1993) suggests that the Nandillyan Limestone probably extends into the late Wenlock, while the presence of an early Ludlow graptolite in the overlying Barnby Hills Shale near Eurimbla to the north (Sherwin 1997) provides a further upper age constraint.



Faunal analysis

Two samples from the Nandillyan Limestone were dissolved in dilute acetic acid to yield the conodonts listed below. Conodont sample (prefix C) numbers refer to picked residues catalogued in the Microfossil Collection of the Geological Survey of New South Wales. Macrofossils examined in thin section add nothing new to determinations made previously by Pickett (1993). Sample localities are shown in figure 1. Significant conodonts are illustrated in figure 3 (on page 16).

Conodont sample C1392

GR 682955E 6326666N, Molong 1:50 000 map; limestone breccia 1 m above base of Nandillyan Limestone, Billeroy property, Goanna Hill, south of the Mitchell Highway.

Aspelundia fluegeli

Dapsilodus sp

Distomodus staurognathoides

Ozarkodina waugoolaensis

Panderodus recurvatus or *P. panderi* (late form)

Panderodus serratus

?*Pterospathodus cadiaensis*

Pterospathodus celloni

Pterospathodus procerus

This assemblage is atypically rich in conodont elements (98 in total) compared with most other samples obtained from Silurian limestones in the Lachlan Fold Belt. The unusual abundance, together with the occurrence of a mixture of non-contemporaneous species, and combined with the sedimentological setting of a breccia very near to the base of the limestone, suggests the presence of a lag deposit incorporating reworked fossils.

Using the stratigraphic ranges of species determined by Bischoff (1986), the sample appears to span graptolite zones 21-24 (*Monograptus sedgwickii* to *M. griestoniensis* zones, late Llandovery) to at least 27 (*M. riccartonensis* Zone, early to middle Wenlock). Detailed analysis of significant species indicates co-occurrence of older taxa — such as *Ozarkodina waugoolaensis* (Zones 21-24, ?25), *Aspelundia fluegeli* (previously *Oulodus planus planus* of Bischoff: see McCracken 1991) (Zones 18-19, 21-24), ?*Pterospathodus cadiaensis* (Zones 18-19, 21) and *Pterospathodus celloni* (Zone 24) — with younger species, normally mutually exclusive, such as *Pterospathodus procerus* (Zone ?24, 25-27). Other species present, such as *Distomodus staurognathoides*, occur in all zones from 21 to 27.

Revised conodont ranges discussed by Jeppsson (1997) include those of panderodids such as *Panderodus serratus*, which is present in the basal Nandillyan Limestone. While this species is long-ranging, it is well-represented in the newly recognised *Pterospathodus procerus* Superzone, occurring in association with the nominate species and the long-ranging *Distomodus staurognathoides*. Jeppsson (1997) correlated

Figure 1. Simplified geology of the north-western sector of the Bathurst 1:250 000 map sheet (2nd Edition) and south-western portion of the Dubbo 1:250 000 map sheet (2nd Edition), highlighting the distribution of Silurian sedimentary rocks

A4 col

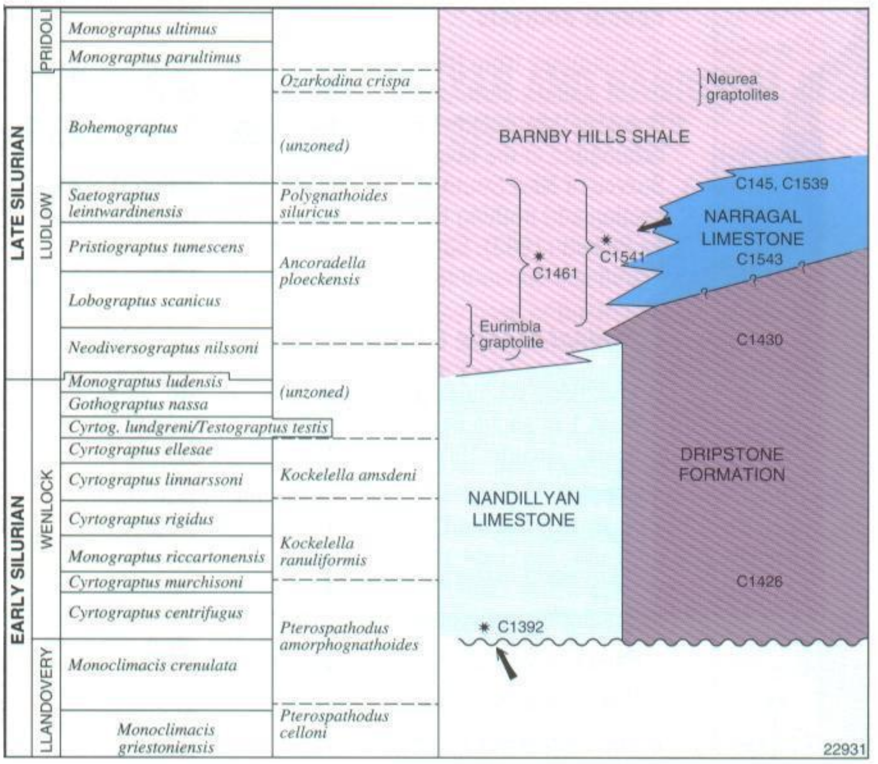


Figure 2. Correlation of Silurian formations discussed in the text, with the standard Australian graptolite and conodont zonation (after Strusz 1996). Approximate stratigraphic levels or ranges of samples are indicated. (Note that for space reasons, the Llandovery and Ludlow–Pridoli sections of the column are truncated.)

the *P. procerus* Superzone with the lower part of Bischoff's (1986) concept of the *Kockelella ranuliformis* Zone, and further placed that Superzone firmly within the early Wenlock (*Cyrtograptus centrifugus* Zone). This has the effect of confirming an earliest Wenlock age for the basal Nandillyan Limestone, and implies that any stratigraphic hiatus beneath this formation (during which older species were reworked) was of limited duration. Hence the depositional age of the basal Nandillyan Limestone is interpreted as equivalent to graptolite Zone 26 (*Cyrtograptus centrifugus* Zone), incorporating late Llandovery clasts ranging in age from *Monograptus sedgwickii* to *M. griestoniensis* Zones.

Conodont sample C1404

GR 682600E 6326650N, Molong 1:50 000 map: Section along a tributary of Borenore Creek; level within Nandillyan Limestone unknown.

Panderodus recurvatus or *P. panderi* (late form)

Panderodus sp

Ozarkodina ?excavata

The low diversity and abundance (9 panderodids, 1 ozarkodinid) of conodont elements in this sample is more typical of Silurian limestones in the Molong High. The single element referred to *Panderodus recurvatus* (figure 3.11) or *Panderodus panderi* — is distinguished by its strongly curved cusp (cf Jeppsson 1997, fig 7.6). An early Wenlock age is suggested, possibly encompassing the *Pterospathodus procerus* Superzone.

NARRAGAL LIMESTONE

Previous biostratigraphic studies

Biostratigraphic evidence for the age of the Narragal Limestone has been reviewed by Simpson (1995), who queried earlier reports of conodont occurrences in this formation by Vandyke and Byrnes (1976). It should be remembered that considerable re-evaluation of conodont identifications has taken place in the ensuing two decades, particularly as the early part of this period spanned the change from form-species to apparatus nomenclature.

Simpson (1995) noted an inconsistency between identification of *Ozarkodina crispa* from near the top of the Narragal Limestone, suggesting a late Ludlow age, and a record of the basal Ludlow zonal graptolite *Neodiversograptus nilssoni* in the conformably overlying Barnby Hills Shale (Pickett 1982).

Revision of the graptolite fauna from the lower part of the Barnby Hills Shale (Rickards & Wright 1997) has resulted in recognition of a late Ludlow (*Bohemograptus inexpectatus* to *B. kozlowskii* Zones) age at this location, therefore eliminating one potential source of biostratigraphic conflict (although the conodont element has never been illustrated, and its identification remains questionable).

Simpson (1995, p 340) further suggested that the conodont form-species "*Ozarkodina gaertneri*", identified by Pickett (1975) in sample C145 (GR 685800E 6385086N, Wellington 1:50 000 map) from near the top of the Narragal Limestone, and reported by Vandyke and Byrnes (1976), probably equated to another example of this form-species illustrated from the early Ludlow (Gorstian to basal Ludfordian) Barrandella Shale Member of the Yass district by Link and Druce (1972). Those authors also recorded "*O. gaertneri*" from the Hume Limestone Member, of slightly younger *Polygnathoides siluricus* Zone (early Ludfordian, about middle Ludlow) age.

"*Ozarkodina gaertneri*" of Link and Druce (1972) was regarded by Simpson (1995) as possibly referable to the Pb element of *Ancoradella ploeckensis*, nominate genus of the early Ludlow *A. ploeckensis* Zone. This supposition cannot be tested until the apparatus of *A. ploeckensis*, currently only known from its distinctive Pa elements, is fully reconstructed. The element in question from C145 has recently been re-appraised by John Pickett (pers comm 1997), who suggests it is closer to an unnamed ozarkodinian Pb element illustrated by Jeppsson (1983, fig 1G), associated with *Polygnathoides siluricus* in the upper Hemse Beds of Gotland.

Other elements from sample C145 appear to be part of the *Ozarkodina confluens* apparatus, although the definitive Pa element is not present in the material available. Strusz (1996) placed the *Polygnathoides siluricus* conodont Zone directly beneath the *Bohemograptus tenuis – B. kozlowskii* graptolite Zone, which correctly reflects the relative stratigraphic positions of the Narragal Limestone and Barnby Hills Shale. The presence, in limestone within the latter formation (sample C1541, discussed further below), of a new species of ?*Ozarkodina* which also closely resembles "*O. gaertneri*" of Link and Druce (1972) suggests derivation of this limestone from the Narragal Limestone.

Faunal analysis

Based on the evidence of the samples discussed below, and reinterpretation of the conodont fauna of C145 (discussed above), the age of the Narragal Limestone can be restricted to the early to middle Ludlow, *Ancoradella ploeckensis* and *Polygnathoides siluricus* Zones. This correlates with the age of the upper part of the Molong Limestone, from which have been recovered conodonts of both Zones (Simpson 1995, pp 338-339; Pickett, unpublished data).

Significant conodonts recovered from the Narragal Limestone are illustrated in figure 3.

Conodont sample C1543

GR 680500E 6368750N, Cumnock 1:50 000 map; lower Narragal Limestone (?near base) at Spring Creek.

Coryssognathus dubius
?*Distomodus* sp
Kockelella variabilis
Oulodus elegans
Ozarkodina confluens
Ozarkodina ?*excavata*
Panderodus sp

Barrick and Klapper (1976, p 65) defined the base of the *Kockelella variabilis* Zone in the Silurian of Oklahoma as coincident with the first occurrence of the nominate species. They equated this level with the base of the "*Ozarkodina*" *crassa* Zone in the European standard succession. In the Australian region this horizon is less well-constrained. Link and Druce (1972, p 42) reported the range of the form species *K. variabilis* (now interpreted as the distinctive Pa element of the complete apparatus) as extending from the early early Ludlovian ("*O*". *crassa* Zone) to early late Ludlovian (*Polygnathoides siluricus* Zone). The equivalent of the "*O*". *crassa* Zone locally is still undefined (Simpson 1995, text-fig 4). However, *K. variabilis* certainly extends through the *Ancoradella ploeckensis* and *P. siluricus* Zones, a range which covers most of the (if not the entire) early Ludlow and the initial late Ludlow.

A species similar to *Oulodus elegans* ranges through the *Polygnathoides siluricus* Zone in North America (Klapper & Murphy 1975) and elsewhere extends into the terminal Silurian *Ozarkodina eosteinhornensis* Zone. Locally, *Oulodus elegans* first occurs in the Hume Limestone Member at Yass (Link & Druce 1972), of *P. siluricus* Zone age, where it is represented by the form species "*Ligonodina*" *elegans* and "*Lonchodina*" *walliseri.*

On the basis of the overlap in range between *Kockelella variabilis* and *Oulodus elegans*, the age of sample C1543 is almost certainly no younger than *Polygnathoides siluricus* Zone, and could be slightly older due to the presence of ?*Distomodus.* Longer ranging species, such as *Ozarkodina confluens*, and *Coryssognathus dubius*, which ranges locally from latest Wenlock into the *O. confluens* Zone of the latest Ludlow (Simpson & Talent 1995), span this interval.

Conodont sample C1539

GR 680300E 6368690N, Cumnock 1:50 000 map; top of the Narragal Limestone, Spring Creek

Kockelella sp
Ozarkodina ?*confluens*
Ozarkodina excavata excavata

Both conodont species present are long-ranging — their overlap extends through the Wenlock, Ludlow, and possibly the Pridoli. Little precision is therefore available for this level. However, an upper age constraint is provided by graptolites in the overlying Barnby Hills Shale from the nearby Neurea area which have recently been determined (Rickards & Wright 1997) to belong to the late Ludlow *Bohemograptus inexpectatus – B. kozlowskii* Zones.

ALLOCHTHONOUS LIMESTONES IN THE BARNBY HILLS SHALE

The relationship between the Narragal Limestone and the Barnby Hills Shale is not everywhere as clear-cut as it appears in the Neurea–Spring Creek area. From the westernmost belt of exposure of the Barnby Hills Shale at GR 673850E 6359110N (Cumnock 1:50 000 map), Sherwin (1997) reported the occurrence of *Monograptus (Saetograptus) colonus*, indicative of an early Ludlow age (*Neodiversograptus nilssoni* to early *Lobograptus scanicus* Zones). Thus at least in this region, the Barnby Hills Shale is a lateral facies equivalent of the Narragal Limestone to the east. This relationship has also been mapped at Mumbil (Des Strusz pers comm, 1998). An increasing body of evidence supports the idea that the Narragal Limestone was probably being eroded contemporaneously with accumulation of the Barnby Hills Shale (Morgan 1997), with the former unit providing the source of carbonate pods found in the Shale.

Biostratigraphically useful conodonts (figure 4) were recovered from two limestones incorporated within the Barnby Hills Shale in the central belt, in the general vicinity of the Oakdale Anticline. Occurrence of an accompanying macrofauna dominated by corals and stromatoporoids in these limestones, suggestive of relatively shallow-water depositional regimes, is at variance with the deeper-water graptolitic facies typical of the Barnby Hills Shale. This observation, combined with the occurrence of conodonts indicating ages for the limestones generally older than those of the enclosing fine-grained clastic rocks, supports their allochthonous origin.

Conodont sample C1461

GR 687180E 6377500N, Wellington 1:50 000 map; Narroogal, in Oaky Creek.

Kockelella variabilis
Ozarkodina excavata excavata
Panderodus sp

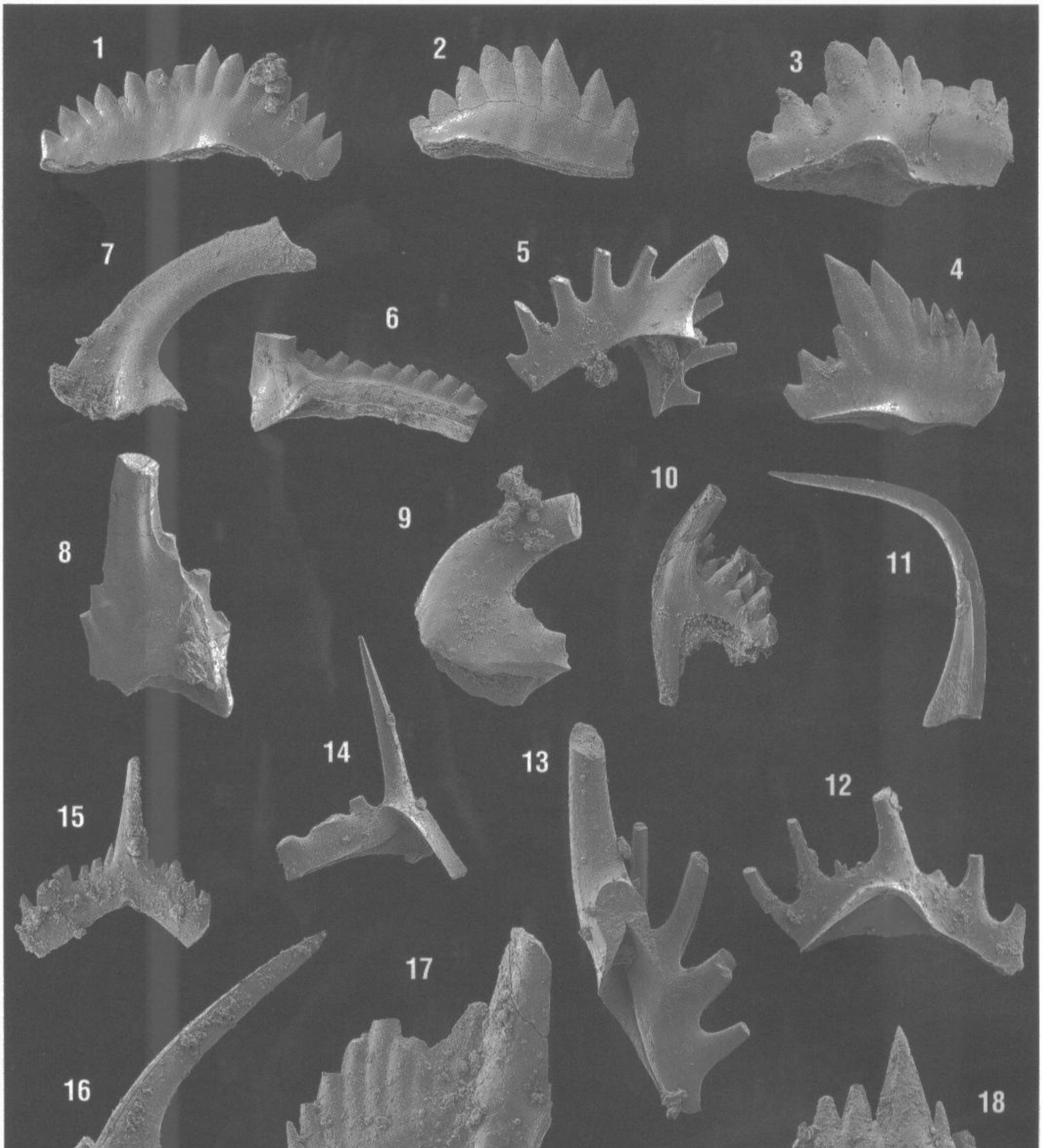
As previously discussed (sample C1543, above), the presence of *Kockelella variabilis* indicates an age no younger than the *Polygnathoides siluricus* Zone (early late Ludlow).

Conodont sample C1541

GR 684580E 6388300N, Wellington 1:50 000 map; Ringaroo.

Panderodus sp
Ozarkodina excavata excavata
?*Ozarkodina* sp nov

The new species of ?*Ozarkodina* found in this sample is a massive form with one element apparently identical with the conodont form-species "*Ozarkodina gaertneri*" illustrated by Link and Druce (1972 plate 6, figs 10 & 13) from the Barrandella Shale Member of the Yass


1
2
3
7
5
4
6
8
9
10
11
14
13
12
15
17
16
18
21
20
19

district. As the known range of this conodont, both in the Yass succession and the Narragal Limestone, is confined to the early to middle Ludlow, its presence in the Barnby Hills Shale (of late Ludlow age near its base in this area) implies derivation from the Narragal Limestone.

AGE OF THE DRIPSTONE FORMATION

Within the Spring Creek section, in sample C1430 (GR 680940E 6367780N, Cumnock 1:50 000 map), stratigraphically underlying the lower (probably basal) Narragal Limestone of *Polygnathoides siluricus* Zone age (conodont sample C1543, discussed above), the conodonts *Coryssognathus dubius* and *Panderodus* spp occur in the Dripstone Formation. In northeastern Victoria, Simpson and Talent (1995) found *C. dubius* in strata ranging from possibly latest Wenlock (but no older) to Ludlow. At Yass, New South Wales (Link & Druce 1972), the range of *C. dubius* may start in the Wenlock and extend into the *P. siluricus* Zone (early Ludfordian) of the late Ludlow, according to Simpson (1995). These occurrences imply that at Spring Creek the upper Dripstone Formation is late Wenlock to possibly as young as middle Ludlow in age, unless there is a significant unrecognised disconformity intervening in the section.

Another sample, C1426 (GR 685890E 6362750N, Cumnock 1:50 000 map), was collected from a fault-bounded outcrop whose stratigraphic level within the Dripstone Formation is unclear. Its conodont fauna includes *Kockelella ranuliformis*, *Oulodus* ?sp nov, *Ozarkodina excavata excavata* and *Panderodus* cf *unicostatus*. Bischoff (1986) noted that in central New South Wales *Kockelella ranuliformis* extended beyond its nominate zone into at least the lower part of the overlying *K. amsdeni* Zone (ie, throughout the early Wenlock) (figure 2). He also suspected that Pa specimens from the Late Silurian Yass Basin sequence, assigned to "*Spathognathodus*" sp cf "*S.*" *ranuliformis* by Link and Druce (1972), also belonged in *K. ranuliformis* (a view concurred with by Simpson 1995), so extending the range of this species into the early Ludlow *Ancoradella ploeckensis* Zone and possibly also the lowermost part of the overlying *Polygnathoides siluricus* Zone. Thus the maximum age range of the sampled horizon is from early Wenlock into the middle Ludlow. However, the recovery of *Distomodus staurognathoides* from a nearby sample by Mawson and Talent (1998) supports an earliest Wenlock age (lower *K. ranuliformis* Zone). Presumably this horizon equates to the Wylinga Member at the base of the Dripstone Formation. It is also close to the age of the basal Nandillyan Limestone sample C1392.

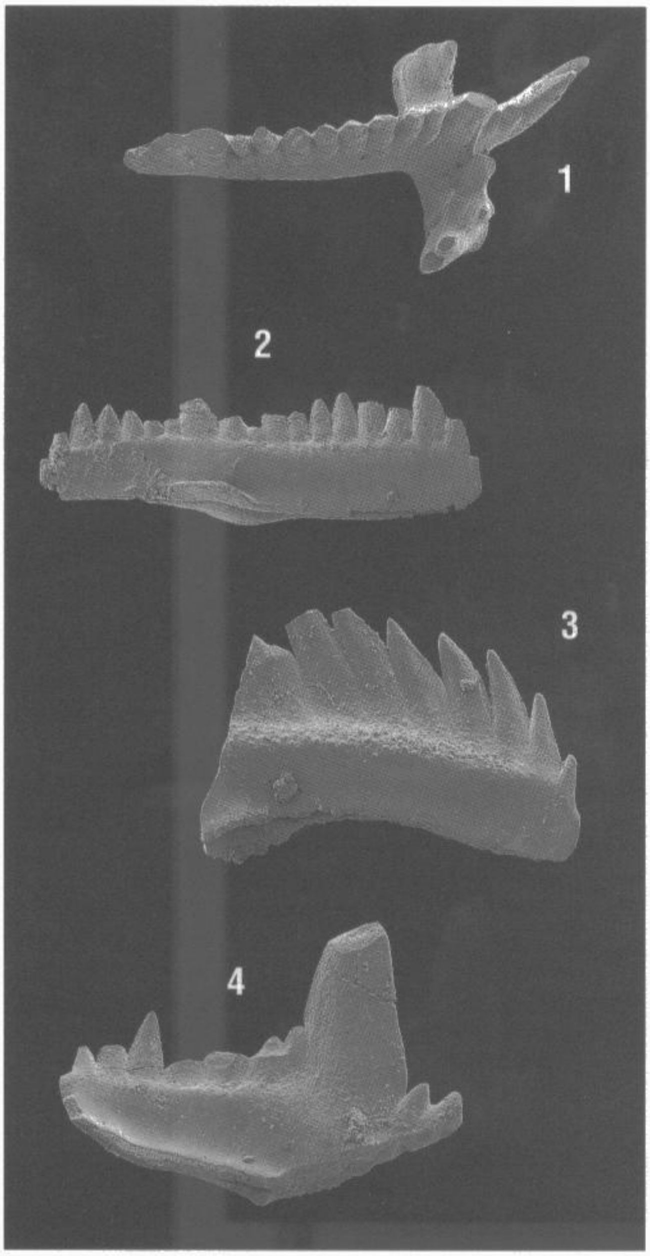


Figure 4 Representative conodonts from allochthonous limestones in the Barnby Hills Shale
4.1 *Kockelella variabilis* Pa element, x70;
4.2 *Ozarkodina excavata excavata* Pa element, x55; both from conodont sample C1461
4.3 ?*Ozarkodina* sp nov Pa element fragment, x70;
4.4 ?*Ozarkodina* sp nov Pa element fragment, x70; both from conodont sample C1541.

Figure 3 (opposite) Representative conodonts from the Nandillyan Limestone (3.1 - 3.11) and Narragal Limestone (3.12 - 3.21)

3.1 *Pterospathodus celloni* Pa element, x55; 3.2 ?*Pterospathodus cadiaensis* Pa element, x70; 3.3 *Ozarkodina* aff. *waugoolaensis* Pa element, x95; 3.4 *Ozarkodina waugoolaensis* Pa element, x95; 3.5 *Aspelundia fluegeli* Sb element, x95; 3.6 *Aspelundia fluegeli* M element, x70 — although this could be an M element of *Ozarkodina excavata excavata* (Andrew Simpson pers comm, 1998); 3.7 *Dapsilodus* sp, x70; 3.8 *Distomodus staurognathoides* Sa element, x70; 3.9 *Distomodus staurognathoides* Sb element, x70; 3.10 *Pterospathodus procerus* M element, x95; all preceding from conodont sample C1392

3.11 *Panderodus recurvatus*, x70; from conodont sample C1404

3.12 *Oulodus elegans* Pb element, x95; 3.13 *Oulodus elegans* Sb element, x95; 3.14 *Kockelella variabilis* Sb element, x70; 3.15 *Ozarkodina confluens* Sa element, x70; 3.16 *Coryssognathus dubius* Pc element, x95; all preceding from conodont sample C1543

3.17 *Ozarkodina* ?*confluens* Pb element, x70; 3.18 *Ozarkodina* ?*confluens* Pa element, x70; 3.19 *Ozarkodina* ?*confluens* Sb element, x70; 3.20 *Ozarkodina excavata excavata* M element, x70; 3.21 *Kockelella* sp Sb element, x70; all preceding from conodont sample C1539.

CONCLUSIONS

Apart from panderodids (which are not age-diagnostic), and possibly the equally long-ranging species *Ozarkodina excavata excavata*, there are no conodont species in common in samples studied from the Nandillyan and Narragal Limestones. These formations can thus be demonstrated to be non-contemporaneous throughout their depositional history. The Nandillyan Limestone is essentially of Wenlock age, and is the temporal equivalent of most of the Dripstone Formation to the north. The Narragal Limestone is early to middle Ludlow in age, and correlates with the upper part of the Molong Limestone to the south. Allochthonous limestones in the Barnby Hills Shale have comparable conodont faunas to those of the underlying to partly laterally equivalent Narragal Limestone, and were presumably derived from this formation.

ACKNOWLEDGMENTS

This report owes much to Lis Morgan and Martin Scott who collected samples and commented on early drafts of the manuscript. Lis in particular shared her insights into the tectonic development of the Molong High during the Silurian. Conodont identifications were checked by John Pickett, Lennart Jeppsson, and Daniel Drygant in the first instance; Andrew Simpson in his capacity as an external reviewer carefully scrutinised final identifications and biostratigraphic conclusions. The paper was also reviewed by Des Strusz, and has benefited from his many years of experience in the Silurian of the Lachlan Fold Belt. For preparation of the conodont residues I thank Gary Dargan, and Peter Cockle, who expertly undertook SEM photography of the specimens. Figures 1 and 2 were drafted by Margaret McLaren and Cheryl Hormann in the Department of Mineral Resources; digital preparation of figures 3 and 4 was facilitated by Departmental photographer David Barnes. I also thank Richard Facer for his editing and judicious attention to detail. This research is a contribution to IGCP Project No. 421 — North Gondwanan Mid-Palaeozoic Bioevent/ Biogeography Patterns in Relation to Crustal Dynamics.

REFERENCES

Barrick J.E. & Klapper G. 1976. Multielement Silurian (late Llandoverian–Wenlockian) conodonts of the Clarita Formation, Arbuckle Mountains, Oklahoma, and phylogeny of *Kockelella*. *Geologica et Palaeontologica* **10**, 59-100.

Bischoff G.C.O. 1986. Early and Middle Silurian conodonts from midwestern New South Wales. *Courier Forschungsinstitut Senckenberg* **89**, 337 pp.

Jeppsson L. 1983. Silurian conodont faunas from Gotland. *Fossils and Strata* **15**, 121-144.

Jeppsson L. 1997. A new latest Telychian, Sheinwoodian and early Homerian (Early Silurian) standard conodont zonation. *Royal Society of Edinburgh, Transactions* **88**, 91-114.

Klapper G. & Murphy M.A. 1975. Silurian–lower Devonian conodont sequence in the Roberts Mountains Formation of central Nevada. *University of California Publications in Geological Sciences* **111**, 62 pp.

Link A.G. & Druce E.C. 1972. Ludlovian and Gedinnian conodont stratigraphy of the Yass Basin, New South Wales. *Bureau of Mineral Resources, Geology and Geophysics, Bulletin* **134**, 136 pp.

Mawson R. & Talent J.A. 1998. North-eastern Molong Arch and adjacent Hill End Trough, eastern Australia: mid-Palaeozoic conodont data and implications. *Geologische Bundesanstalt (Wien), Abhandlungen*, in press.

McCracken A.D. 1991. Taxonomy and biostratigraphy of Llandovery (Silurian) conodonts in the Canadian Cordillera, northern Yukon Territory, pp 65-95. *In* Orchard M.J. & McCracken A.D. eds. Ordovician to Triassic conodont paleontology of the Canadian Cordillera. *Geological Survey of Canada, Bulletin* **417**, 335 pp.

Meakin N.S. & Morgan E.J. in press. Dubbo 1:250 000 Geological Sheet SI/55-4: Explanatory Notes. Geological Survey of New South Wales, Sydney.

Morgan E.J. 1997. Transported carbonate debris in the Late Silurian Barnby Hills Shale, NE Lachlan Fold Belt. Geological Society of Australia Abstracts No. 47. Advances in Sedimentology. ASG Conference '97, December 3-4 1997, Melbourne, 24.

Pickett J.W. 1975. Conodont samples from the Central West. Geological Survey of New South Wales, Palaeontological Report 75/07, Report GS1975/105 (unpublished).

Pickett J.W. ed. 1982. The Silurian System in New South Wales. *Geological Survey of New South Wales, Bulletin* **29**, 264 pp.

Pickett J.W. 1993. Coral and stromatoporoid assemblages from the Nandillyan Limestone (Silurian), Molong district. Geological Survey of New South Wales, Palaeontological Report 92/07, Report GS1992/180 (unpublished).

Pogson D.J. & Watkins J.J. 1998. Bathurst 1:250 000 Geological Sheet SI/55-8: Explanatory Notes. Geological Survey of New South Wales, Sydney, xiv + 430 pp.

Rickards R.B. & Wright A.J. 1997. Graptolites of the Barnby Hills Shale (Silurian, Ludlow), New South Wales, Australia. *Yorkshire Geological Society, Proceedings* **51**, 209-227.

Sherwin L. 1997. Fossils from the Cumnock 1:50 000 sheet. Geological Survey of New South Wales, Palaeontological Report 97/03, Report GS1997/406 (unpublished).

Simpson A. 1995. Silurian conodont biostratigraphy in Australia: a review and critique. *Courier Forschungsinstitut Senckenberg* **182**, 325-345.

Simpson A. & Talent J.A. 1995. Silurian conodonts from the headwaters of the Indi (upper Murray) and Buchan rivers, southeastern Australia, and their implications.

Courier Forschungsinstitut Senckenberg **182**, 79-215.

Strusz D.L. 1996. Timescales 3. Silurian. Australian Phanerozoic Timescales, biostratigraphic charts and explanatory notes, second series. *Australian Geological Survey Organisation, Record* 1995/32.

Strusz D.L., Percival I.G., Wright A.J., Pickett J.W. & Byrnes A. 1998. A giant new trimerellide brachiopod from the Wenlock (Early Silurian) of New South Wales. *Australian Museum, Records* **50(2)** (in press).

Vandyke A. & Byrnes J.G. 1976. Palaeozoic succession beneath the Narragal Limestone, Oakdale Anticline near Mumbil. *Geological Survey of New South Wales, Records* **17**, 123-134.

QUARTERLY NOTES

Quarterly Notes of the
Geological Survey
of New South Wales
No 107

GUEST EDITOR:
Richard A. Facer

GEOLOGICAL EDITOR:
Ross Stewart

MANAGER PUBLISHING & MARKETING:
Peter Walker

CARTOGRAPHY:
Margaret McLaren
Cheryl Hormann

GRAPHIC DESIGN:
Val Grant

PUBLISHING ASSISTANT:
Dora Lum

CONTENTS

NEXT ISSUE

Ordovician evolution of the northern Molong Volcanic Belt: new facts and figures
Ian G. Percival, Elisabeth J. Morgan and Martin M. Scott

Late Ordovician biostratigraphy of the Gulgong Volcanic Belt
Ian G. Percival

Issued September 1998
ISSN 0155-3410

Published under the authority of the
Minister for Mineral Resources
1998

MINERAL RESOURCES
NEW SOUTH WALES