FUTURE PROSPECTS FOR OPAL MINING IN THE LIGHTNING RIDGE REGION

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ABSTRACT

Opal has been mined at Lightning Ridge since 1903. During this time a moderate production was achieved until the late 1950's when production increased markedly due to the introduction of mechanized mining methods. Estimated production over the last 6 years has averaged $13 million per annum. Processing methods, although still water intensive, have become significantly more efficient. Based on rates of water consumption, the extraction (or processing) rate of potentially opal-bearing claystone is estimated at 206 000 tonnes per year.

Opal is found at shallow depths in the deeply weathered portion of the Early Cretaceous Griman Creek Formation. Tertiary sediments, common throughout the Lightning Ridge region, are generally absent in opal-producing areas. Opaline silica, derived from the weathering of Cretaceous sandstones, has been dissolved and transported in groundwater and trapped above permeability barriers. The permeability barriers, generally soft claystones, have also provided the depositional sites for opal development. The sites of major opal deposition (opal fields) appear to be structurally controlled, i.e., they have developed adjacent to lineaments (lines - probably major joints or faults - visible on aerial photographs or Landsat imagery) or at the intersections of lineaments. Smaller scale structural features (faults, joints) and sedimentary depositional features ('rolls', 'domes') have controlled the localization of siliceous solutions. Opal is considered to have been formed during the early Tertiary and is associated with a Late Cretaceous to early Tertiary weathering event. Opal formation is therefore not connected with silcrete formation which is considered to have occurred during a second period of silicification during the late Tertiary.

The estimated life of the existing opal fields at Lightning Ridge is about 50 years. The potential for significant new discoveries of opal which may extend this life is moderate. There is good potential for new discoveries in outlying areas particularly in the 'seam country' near Grawin.

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INTRODUCTION

Lightning Ridge is the most productive opal field in New South Wales and the world's major source of high-quality black opal*. The term "Lightning Ridge opal field" refers to the large number of fields (approximately 60) located within 10 km of the township. In addition to this main field, opal is mined in the smaller outlying fields of Glengarry, Grawin, Carters Rush, Coocoran, New Coocoran, and New Angledool (Mehi).

Lightning Ridge is situated in central northern New South Wales, approximately 770 km by road from Sydney, 74 km north by road from Walgett, and 50 km due south from the Queensland border (see figure 1). The occurrence of opal in the Lightning Ridge area has been known since the early 1880's. The Department of Mineral Resources' production records go back to 1904, but are based on estimates only. Hence, no valid total of past production can be made. The estimated value of production for 1983/84 was $14.9 million.

Between late 1982 and early 1984, the Department of Mineral Resources investigated the nature and distribution of the opal deposits in the Lightning Ridge region and their relationship to the geology. This study was undertaken following a request from the Department of Environment and Planning for a mining study of Walgett Shire, specifically concentrating on Lightning Ridge. It was indicated that the mining study should focus on the opal mining industry and define its character, potential, and likely life span. This information is required to assist with future planning decisions for the area, particularly regarding additional infrastructure for Lightning Ridge (e.g., augmentation of the water supply, graded mining roads, the need for ambulance and hospital services, and an upgrading of the landing ground). Whilst the Lightning Ridge opal field was emphasised during this investigation, it was also important to understand the future potential of this area within a regional context. Hence, the outlying fields together with unworked, prospective areas (from the Barwon River near Walgett to the Queensland border) were also examined, but at a reconnaissance level only.

Previous investigations (Whiting and Relph 1961, MacNevin and Holmes 1979) into the nature and occurrence of opal in northwestern New South Wales identified the stratigraphic sequence with the greatest potential for opal. However, because of the extensive distribution of potentially opal-bearing areas, the highly sporadic nature of opal occurrence, and the lack of prospecting information, no estimate of opal reserves or the likely life span of the opal fields (particularly the main Lightning Ridge opal field) could previously be made. The main objectives of the present study were to refine and increase the understanding of the distribution of opal within the opal-bearing sequence, to delineate controls over opal occurrence, and thereby to estimate the future prospects for opal mining in the Lightning Ridge region. The study included:

1. Interpretation of aerial photographs and Landsat imagery.
2. Examination and logging of 58 selected shafts and open cuts (mostly within the Lightning Ridge opal field).

* Black opal is a variety of precious opal which has a dark body colour. It commands a much higher price than other types of opal due to its greater depth of colour, large colour pattern, and rarity. However, black opal only represents a small proportion of the opal found at Lightning Ridge.

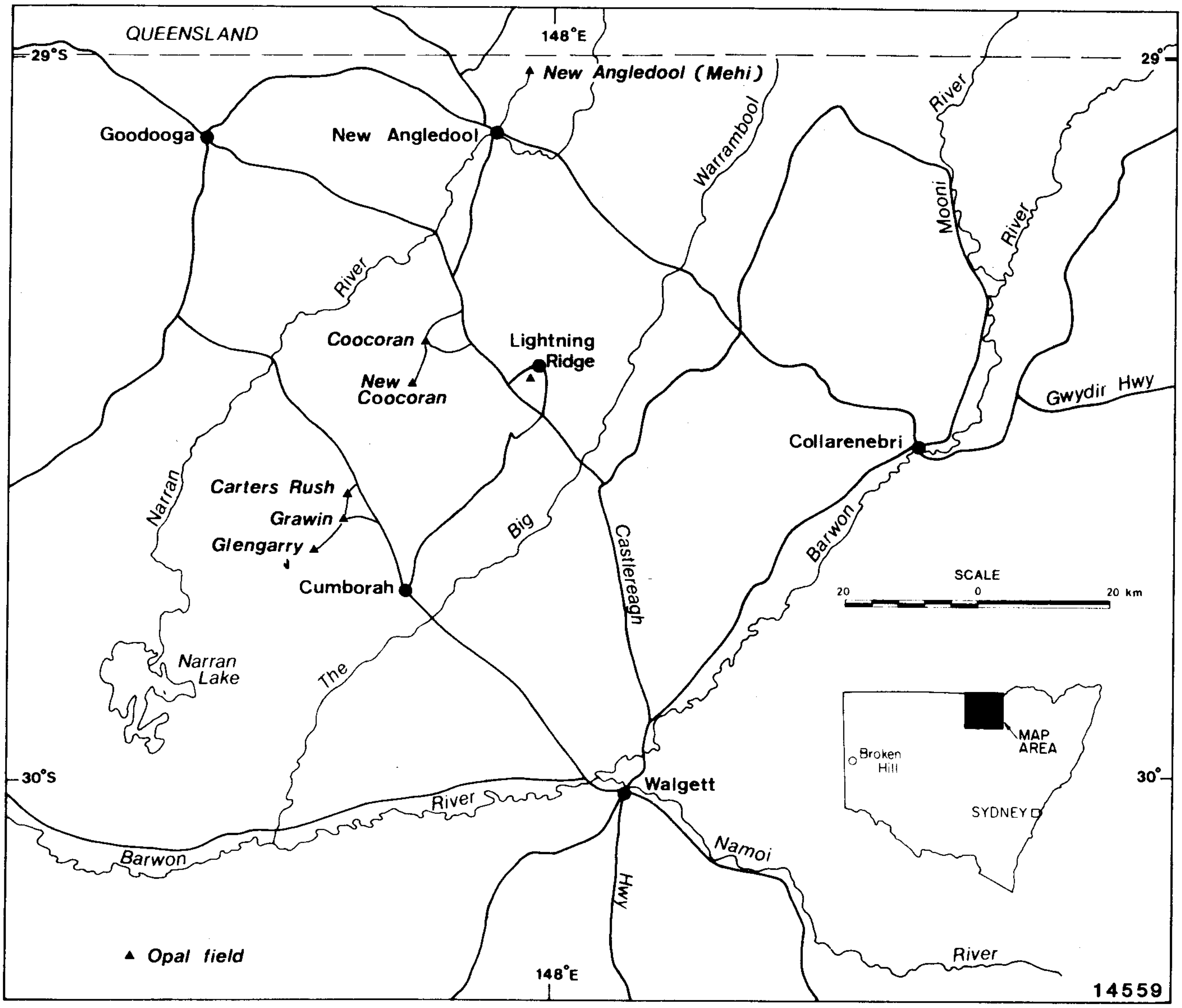

FIGURE 1: Location map, Lightning Ridge region

3. Drilling and logging of 26 large diameter Calweld boreholes; 14 located in the Lightning Ridge opal field, 12 located in outlying areas.

4. Re-interpretation of drilling logs for water bores within the Angledool 1:250,000 sheet area.

5. Petrography, clay mineralogy, and microfossil studies.

It is hoped that the results and recommendations of this study will encourage and assist opal prospecting and mining in the Lightning Ridge region.

The information presented herein has been extracted from a more comprehensive report: "Opal Resources of the Lightning Ridge Region" by J.J. Watkins, New South Wales Geological Survey - Bulletin (in prep.).

HISTORICAL REVIEW

Opal was first discovered at Lightning Ridge (previously known as Wallangulla) in the late 1880's, possibly around 1887, but its commercial value was not recognized. In February 1903, Charlie Nettleton sunk the first shaft in the area now known as the "McDonalds Six Mile" (see figure 2). Very little opal was recovered from this mine. Nettleton continued his prospecting and whilst following floaters and trenching in about 1 metre of ground where the "Nobbies" field is today, he unearthed about 480 grammes of gem-quality black opal. Nettleton sold the first parcel of gems from the field at White Cliffs in 1903. By 1904 the field had been established by the influx of a number of miners from White Cliffs. In 1907, the major outlying field of Grawin was discovered. By 1909, workings had extended along the ridge from the township as far as the "Nine Mile" (8 km west of the township), and the population on the field rose to 1,000. In 1910, operations were extended over a wide area and recorded production reached an early peak at $92,400 (MacNevin and Holmes 1979). This estimated production figure* was not exceeded until 1961 (see MacNevin and Holmes 1980, pp. 10-11 for further details). A moderate production was achieved from 1911 to 1920, after which activity on the field lapsed and little production was recorded until 1958 when a marked increase resulted from both the introduction of mechanization and increased demand for black opal. Increasing prices and demand for opal also stimulated a good deal of underground mining and eventually led to the development, by 1969, of large open-cut mining operations. In 1983, the fields comprising the Lightning Ridge opal field covered an area of approximately 650 ha. The distribution of the fields is shown on figure 2. Since 1958, estimated opal production has steadily increased, and in 1983/84 it reached an estimated $14.9 million (compared to $10.7 million in 1982/1983 and $14.3 million in 1981/1982).

MINING AND PROCESSING

Opal mining at Lightning Ridge has traditionally been the domain of the smaller miner. The main reasons for this seem to be:

1. The sporadic occurrence of precious opal.

* Department of Mineral Resources' opal production records are essentially only estimates and probably do not reflect the actual value of production. These records can be used to infer trends only.

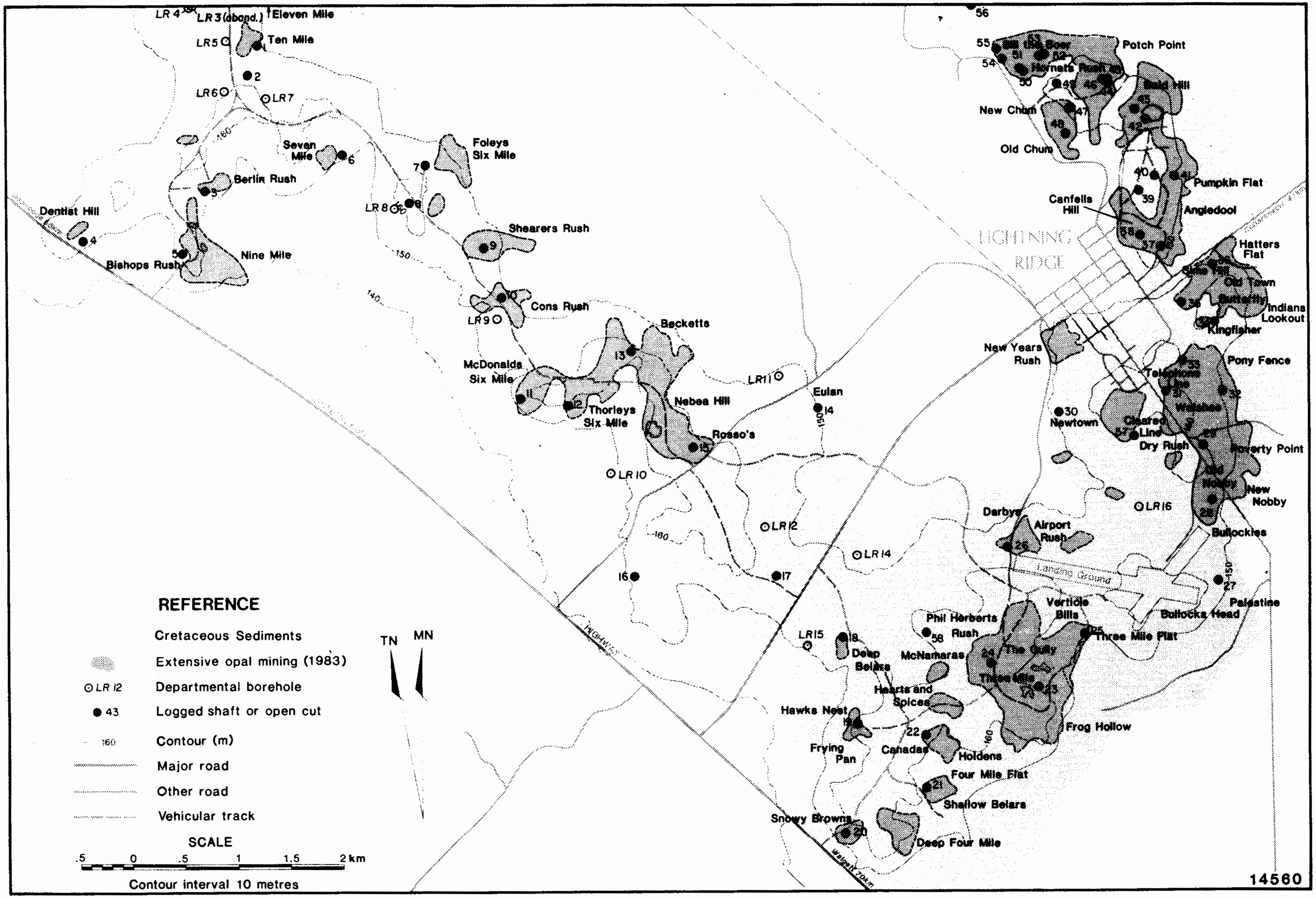

FIGURE 2: Lightning Ridge opal field

2. The small size of the mining tenement, or claim (50 m x 50 m).

3. The restriction on the number of claims per person (2).

The preference given to the small opal miner in New South Wales was established in 1901 by a Royal Commission appointed to inquire into the opal mining industry at White Cliffs. The Commission recommended that the Government redeem titles from the operating company and only allow small areas to be taken up by miners.

Opal is won at Lightning Ridge from horizontal drives and stopes in opal-bearing claystone lenses ("opal dirt levels"), by working through old dumps or, more recently (since 1969), by open-cut mining methods. Although individual hand mining operations still exist, increased mining costs (particularly fuel and machinery maintenance) and more mechanized mining methods favour larger operators and small syndicates with sufficient capital to purchase and maintain "new technology" machinery. In recent years, miners have been severely affected by rising fuel costs and inflation. Many miners believe the only way to find enough opal to cope with these rising costs is to mine and process large quantities of "opal dirt" as quickly as possible.

Mining Methods and Machinery

Hand Mining

This simplest form of mining, using pick and shovel and hand windlass, has largely been superseded. Extraction rates for this method of mining are estimated at 10 to 20 buckets a day (approximately 200 kg to 400 kg per day).

Self-tipping Hoist

This method of raising mullock or "opal dirt" can be controlled by one miner from underground. Extraction rates are in the order of 50 to 70 buckets of potentially opal-bearing claystone per day (approximately 1000 to 1400 kg per day).

Blower

A blower is a truck-mounted machine which is similar to a vacuum cleaner. A large fan or blower driven by a diesel engine draws potentially opal-bearing claystone out of the shaft through a series of pipes to collect in a bin at the surface. Extraction rates for a blower can be up to 200 buckets (or 4 tonne) per day or more. The blower, however, is expensive to run; for example, a blower driven by a 100 to 200 kw diesel engine operating 4 to 5 hours per day can consume 100 to 200 litres of fuel, costing approximately $50 to $100.

Electric and Pneumatic Jackhammers

These have generally replaced the pick for more rapid removal of potentially opal-bearing claystone from the drive or stope. These are powered by motors driving either an electric generator or a compressor at the surface.

Underground Diggers

A small air operated backhoe is becoming popular as a replacement for the jackhammer and is used in conjunction with a blower. The backhoe is apparently easier to use and can extract "opal dirt" at an increased rate.

Calweld Drilling

Calweld drilling rigs bore large diameter holes (about 1 m in diameter) to depths of approximately 25 m in a matter of hours. A telescopic shank holding a steel bucket with cutting teeth is mounted on the rear of a truck. The bucket cuts a circular hole and is filled by rotary action. When full, the bucket is brought to the surface; the hinged base of the bucket is opened to dump the mullock about 5 m from the drillhole collar.

Bulldozing

Open cut mining using bulldozers is presently confined to areas where extensive underground mining had previously taken place, leaving them in a condition unsuitable for further work of that type; or in sections of the fields where potentially opal-bearing claystone lenses ("levels") occur at very shallow depths. This method extracts potentially opal-bearing claystone at a far greater rate than any underground techniques. However, due to the range of machinery used and the variation in overburden ratios, the rate of extraction from open cut operations cannot be reliably estimated.

Processing Methods

In the Lightning Ridge field opal is generally found as nodules (in groups or singly) distributed throughout claystone lenses near their junction with the overlying sandstone. Any extraction process which removes the claystone in bulk must therefore have a secondary process to separate the nodules from the claystone. This separation may be achieved by dry methods or wet methods.

In contrast to the nodular occurrence of opal at Lightning Ridge, opal is present as seams in the outlying fields of Grawin, Glengarry, and Carters Rush and is removed from the claystone in situ; secondary separation methods are thus not required.

Dry processing is generally termed *"dry puddling"*. The "dry puddling" machine consists of a wire mesh basket inside which is a rotating shaft with rubber paddles. "Opal dirt" is placed inside the basket and broken by the paddles. The soft material is removed through the mesh leaving the hard nodules ("nobbies") which are then picked over for opal. The rotating shaft is driven by a small motor.

The "dry puddling" method has a low efficiency (i.e., ability to separate claystone and "nobbies") and a low throughput of material. Its usage is now generally restricted to weekend or itinerant miners who process the old dumps.

Wet processing methods include the "wet puddler" machine and the "agitator". These methods are substantially more efficient than the dry processing methods and have come into widespread usage following the improvement to the town water supply in 1972. The *wet puddler* is similar in construction to the "dry puddler". The units are permanently sited adjacent to a dam from which water is pumped and jetted into the basket as the paddles within the basket rotate. This action reduces the claystone to a sludge which flows through the mesh to leave the "nobbies" and any harder sandstone fragments behind in the basket for removal and sorting.

The "wet puddler" commonly uses 4 to 5 kilolitres of water to process 1 tonne of potentially opal-bearing claystone in 10 to 15 minutes. There are approximately 90 wet puddlers presently located on the Lightning Ridge opal field.

With the expansion of open cut mining and the advent of "new technology" machinery (e.g., the "blower", underground diggers) came the necessity for a processing technique which could handle larger volumes of potentially opal-bearing claystone and make reasonably efficient use of a regulated water supply. The *agitator* is constructed by converting the barrel of a ready-mix concrete mixer and is permanently sited adjacent to a dam. During operation, water is pumped into the revolving barrel; the water breaks down the claystone which then flows out as a sludge through the wire mesh ports.

The agitator uses approximately half the quantity of water per tonne of claystone processed when compared to the "wet puddler" (i.e., 2 to 2.5 kilolitres for each tonne of potentially opal-bearing claystone processed). There are approximately 60 agitators on the Lightning Ridge field at present.

Both, the wet puddler and agitator are highly water intensive. Because miners cannot economically transport "opal dirt" large distances, the availability of water for processing is a major limiting factor to mining operations. It is also an added disincentive for prospecting in outlying areas.

RATE OF EXTRACTION OF OPAL-BEARING CLAYSTONE

The rate of extraction of potentially opal-bearing claystone ("opal dirt") at Lightning Ridge could be determined by two methods, based on:

1. The volume of "opal dirt" extracted.
2. The volume of "opal dirt" processed.

The parameters necessary to estimate the volume of "opal dirt" extracted by the various machines throughout the fields are many; and detailed discussion is beyond the scope of this study. However, a reasonable estimation of the volume of "opal dirt" processed can be made using water consumption figures.

Water for the processing of "opal dirt" is available from a number of dams located on, and peripheral to, the opal fields. At present these various dams can be grouped as follows:

(a) Lightning Ridge Miners Association dams;

(b) dams sourced from private bore trusts; and

(c) dams on mining purposes leases or claims.

Table 1 summarises the estimated distribution of agitators and puddlers and, where known, the average daily water consumption by these machines at the various dams.

The following assumptions are made for estimating the rate of processing of "opal dirt" at Lightning Ridge:

1. Rates of processing at dam groups (b) and (c) are both equal to rate of processing at dam group (a) (where water consumption is known).

TABLE 1

ESTIMATED DISTRIBUTION OF AGITATORS AND PUDDLERS

Dam Group *	Agitators	Puddlers	Average Water Consumption (kl/day)
(a)	15	40	403
(b)	15	40	Unknown
(c)	25	10	Unknown

* See text above for explanation

2. Ninety per cent of all processing (by volume) is undertaken using agitators.
3. The agitator uses 2.25 kl of water per tonne of "opal dirt" processed. The puddler uses 4.5 kl. of water per tonne.
4. All equipment is operating at an equal efficiency, and water pumps are not left operating after processing is completed.

Based on these assumptions, and on the average daily water consumption (403 kl/day) at dam group (a), it is calculated that an average total of 160 tonnes of "opal dirt" is processed each day at the Miners Association dams. Of this figure 144 tonnes is processed in agitators and 16 tonnes is processed in puddlers. Extrapolation of these figures to dam groups (b) and (c) suggests that 404 tonnes of "opal dirt" is processed daily at these sites. Thus, the total estimated daily rate of processing for the Lightning Ridge area is 564 tonnes of "opal dirt" or approximately 206 000 tonnes per year. This figure, which should be regarded as an estimate only, is used in a later section to estimate the likely life of the existing opal fields at Lightning Ridge.

PROSPECTING

The lack of recognized prospecting guides for opal has led to a rather haphazard approach to prospecting in the Lightning Ridge region. Opal miners rarely sink "wildcat" prospecting shafts and site selection is commonly guided by proximity to known productive areas. Experienced miners have long recognized that joints and minor faults (referred to as "verticals" and "slides" on the field) have had a controlling influence on opal occurrence. Many miners use "wires" to divine for "slides"; others use the presence of wild orange trees (the roots often extend down joints and faults in search of water) or large Box or Belah trees as indicators of prospective ground. "Disturbed" or "broken" ground is considered to indicate the presence of "blows" (collapse breccia pipes) - recognized to be a good prospecting guide.

The Calweld drill has replaced the pick and shovel as the most commonly used method of prospecting. (In the outlying fields to the southwest of Lightning Ridge i.e., at Carters Rush, Grawin, and Glengarry, opal generally occurs in seams and here auger-type drilling rigs are also used). As the holes are drilled, the spoil heap is examined for the presence of a "good sandstone" followed by an "opal level" claystone. If this sequence is intersected then the first 4 to 6 bucket loads of claystone from the drill are placed in a truck for transport to a puddling site for treatment and then examination for the presence of opal. Following completion of drilling, the shaft may be examined by using portable ladders or a bosuns chair attached by cable to the drilling rig. Driving and additional sampling may be carried out at this time.

Prospecting Titles

Two forms of title are available under the Mining Act, 1973 for opal prospecting; namely, the opal prospecting licence and the claim. The holder of an *opal prospecting licence* (OPL) may prospect for opal in any area of Crown Land specifically set aside for this purpose. Currently there are two opal prospecting areas which together comprise most of the Cretaceous outcrop from the Lightning Ridge opal field to the Queensland border (see figure 3). Each opal prospecting area is divided up into a number of smaller blocks. These blocks vary in size but are, in general, several hectares. There are no opal prospecting blocks located over the main Lightning Ridge opal field. For each opal prospecting block a licence can be issued for a period of 28 days. The licence gives the holder the exclusive rights to prospect and to apply, during the currency of the licence, for an opal mining claim. Prospecting methods permitted under this title are limited to drilling or shaft sinking. Driving of a prospective opal "level" is not permitted, restricting the sample size to the volume of claystone penetrated during drilling. This is generally inadequate to properly assess the prospectivity of an area. All drill holes or shafts must be backfilled or otherwise secured and a bond, ranging from $200 to $500 (depending on the size of the block), is required to ensure compliance with environmental conditions. Currently there are no reporting conditions on this form of title and this at times results in a duplication of prospecting efforts and a considerable waste of money.

A *claim* is an area of Crown Land (50 m x 50 m) lawfully occupied for the purposes of prospecting and mining. Within the designated opal fields this form of title is commonly used for prospecting.

Claims are rarely used for prospecting in outlying areas because of their small size and the general lack of survey datum points for easy marking out. When a claim is used for prospecting purposes, it is not uncommon for the claim to be registered, prospected, and cancelled in the same day.

A comparison of these two forms of title is set out below in table 2.

Many miners and prospectors consider that neither form of title is entirely satisfactory. The term of opal prospecting licences is generally regarded as too short. Most miners agree that some form of reporting on both opal prospecting licences and claims would be desirable to prevent duplication of prospecting efforts.

Irrespective of the form of title used the costs associated with opal prospecting can be relatively high. The current (1984) rate for drilling, using a Calweld rig, is about $16 - $17 per metre. Thus, in excess of $10,000 (representing 25 holes to 20 m) could easily be spent assessing the potential of an opal prospecting block in 1 month. Most "small miners" do not prospect on this scale and commonly restrict themselves to 1 or 2 holes located in extensions of known and proven areas. The opal prospecting blocks that have been prospected to date are mainly those blocks close to or adjacent to the known fields. Here, prospecting has generally been undertaken by the "larger miner" or mining syndicate that owns and operates its own drilling rig.

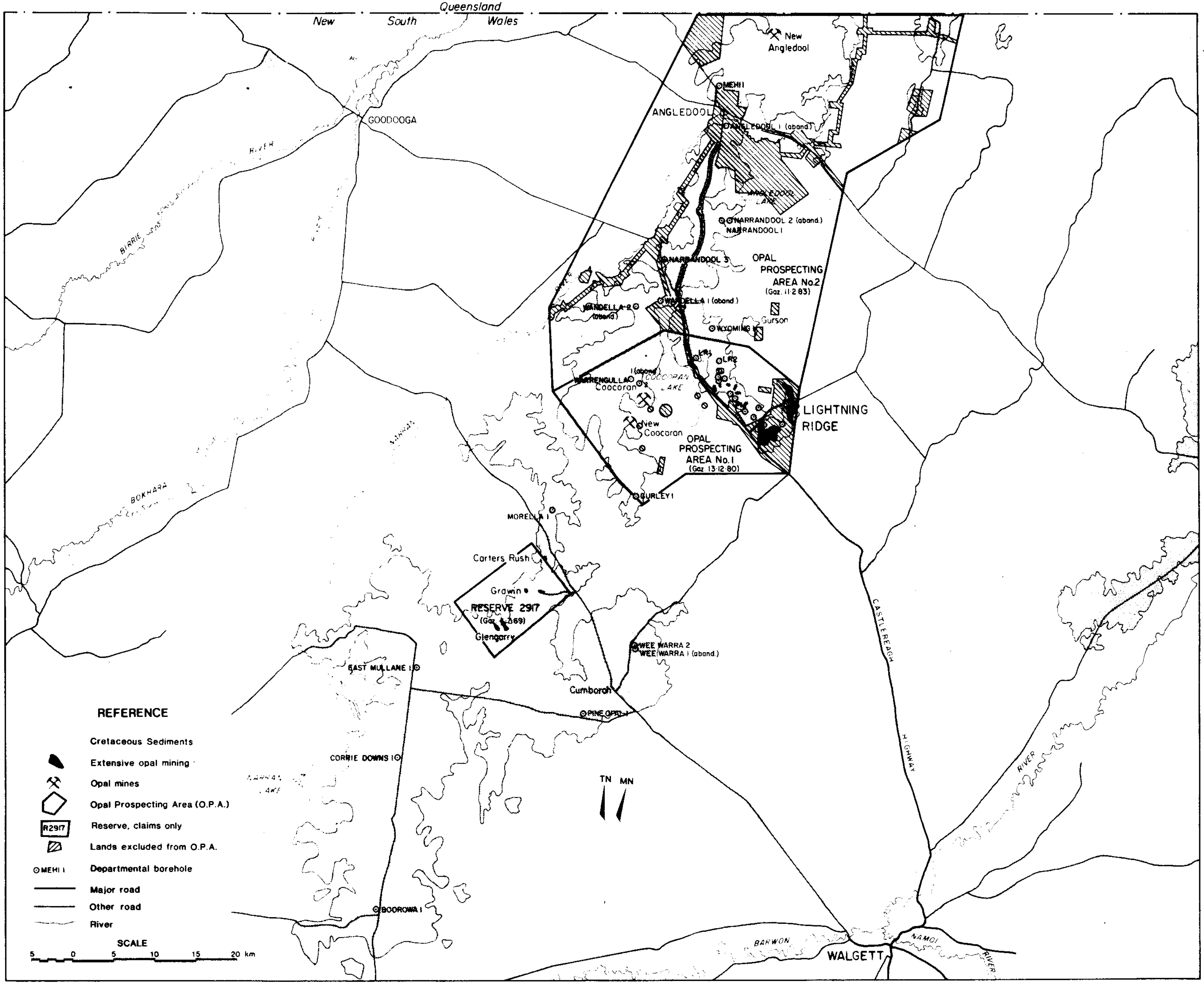

FIGURE 3: Opal Prospecting Areas

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TABLE 2

COMPARISON OF THE TWO FORMS OF OPAL PROSPECTING TITLE

	Opal Prospecting Licence	Claim
Registration Fee	$ 12 to $ 50	$25
Bond	$200 to $500	$50
Term	28 days	1 year
Marking out required	No	Yes
Methods permissible	Drilling only	Drilling and mining
Reporting conditions	N/A	N/A

GEOLOGY

General

Virtually all of the precious opal produced in Australia is won from rocks that were affected by deep weathering during the Late Cretaceous and Tertiary Periods. At Lightning Ridge and White Cliffs in New South Wales, at Coober Pedy and Andamooka in South Australia, and in southern central Queensland, the host rocks for opal are bleached claystones and sandstones which were deposited in the Great Australian Basin during the Cretaceous period. At Mintabie in South Australia precious opal also occurs in bleached Palaeozoic sandstone.

At Lightning Ridge, opal is found at shallow depths, usually less than 30 m, in the deeply weathered portion of the Early Cretaceous Rolling Downs Group. These sediments crop out as low ridges and mesas rising, on average, to between 15 and 20 m above the general level of the surrounding flat black soil plains. The weathered Cretaceous sediments are essentially horizontal and the ridges and mesas form obvious erosional highs. A reinterpretation of water bore logs for the Angledool 1:250,000 sheet area indicates that they may also be structural highs.

Stratigraphy

A summary of the regional stratigraphic sequence, based on data from the Lightning Ridge Town Water Supply Bore (Bourke 1973) and modified by Holmes and Senior (1976), is shown in table 3.

Rolling Downs Group

The Rolling Downs Group consists of the Doncaster and Coreena Members of the Wallumbilla Formation, the Surat Siltstone, and the Griman Creek Formation, all of Early Cretaceous age. These units are all characterized by claystone, siltstone, or clayey sandstone.

In the Lightning Ridge area the outcropping Cretaceous sediments belong to the Griman Creek Formation. This unit consists dominantly of finely

TABLE 3

STRATIGRAPHY OF THE LIGHTNING RIDGE AREA
(after Bourke 1973 and Holmes and Senior 1976)

ERA	PERIOD	UNIT			ESTIMATED THICKNESS** (metres)	
CAINOZOIC	Quaternary		black soil		17	
	Tertiary		silicified conglomerates		4 (max)	
MESOZOIC	Early Cretaceous	*ROLLING DOWNS GROUP	Griman Creek Formation		197	
			Surat Siltstone		120	
			Wallumbilla Formation	Coreena Member	82	489
				Doncaster Member	90	
			Bungil Formation		241	
			Mooga Sandstone		56	
	Late Jurassic		Orallo Formation		188	
			Pilliga Sandstone		57	
PALAEOZOIC			basement (andesite)			

* The near-surface weathered Rolling Downs Group at Lightning Ridge was previously termed the "Lightning Ridge Group" (Whiting and Relph 1961).

** Estimated thickness of stratigraphic units based on Lightning Ridge Town Water Supply Bore (Bourke 1973).

interbedded sandstone and siltstone with subordinate sandstone, clayey siltstone, and intraformational conglomerate, and is characterized by its relatively thick sandstone beds. The near-surface highly weathered portion of the Griman Creek Formation at Lightning Ridge comprises sediments which are strongly argillized with feldspar completely altered to kaolinite. This sequence was informally termed the "Lightning Ridge Group" by Whiting and Relph (1961) and divided into the "Finch Claystone" (2-6 m thick), the "Wallangulla Sandstone" (4-19 m thick), and the "Coocoran Claystone" (0 - 3.6 m thick). The subdivision is not a valid one on a regional scale (Holmes and Senior 1976). Byrnes (1977) suggested that the "Coocoran Claystone" and "Wallangulla Sandstone" be recognized as members of the Griman Creek Formation and that the "Finch clay facies" be included in the Wallangulla Sandstone Member.

The results of the present study indicate that the nomenclature proposed by Byrnes (1977) is more correct and hence is used herein. However, this nomenclature is restricted to the main Lightning Ridge opal field. In the outlying areas the near-surface Cretaceous sediments commonly comprise interbedded sequences of sandstones and sandy claystones.

Descriptions of Lightning Ridge Opal Field Sediments

Coocoran Claystone Member

This uppermost unit comprises a fine-grained, white to cream kaolinitic claystone which is commonly silicified to porcelanite, locally termed "shincracker". It varies in composition from massive claystone to a laminite (alternating sandy and clayey laminae of 1 cm or less thickness). Where silicified the rock is tough and commonly displays a subconchoidal fracture. The Coocoran Claystone Member is generally jointed and the uppermost portion commonly has a blocky habit; ironstaining is common on the joint surfaces. The unit is generally 2 to 4 m thick; however a thickness of 11.3 m was recorded in the "McNamaras" field.

The thick distributary sands of the underlying Wallangulla Sandstone Member commonly grade up into this unit, suggesting that it was deposited during channel avulsion (change of course). Some crossbedded lenticular sandy laminae are present in the laminite. These and sporadic open and infilled vertical tubes (biogenic disruption) indicate a fairly shallow water environment of deposition.

Wallangulla Sandstone Member

The Wallangulla Sandstone Member is a fine to medium-grained, pale-coloured clayey sandstone (ironstained in part) which in places is crossbedded. The rock consists mainly of detrital quartz grains (about 50% by volume) distributed through a kaolinite matrix. The unit is commonly 4 to 6 m in thickness; however, thicknesses of up to 20 m have been recorded.

A thin (0 - 0.3 m), discontinuous, silicified layer ("steel band") is present in places within the Wallangulla Sandstone Member. This layer is usually less than 0.1 m in thickness and overlies the uppermost Finch clay facies lens. The siliceous cement of this layer is mostly opaline (Burns 1973).

Figure 4 shows isopachs for the Wallangulla Sandstone Member above the uppermost Finch clay facies lens. This indicates a northeast-southwest trending linear feature south of the landing ground. this feature reflects a lateral variation in sandstone thickness from 1.1 m to 11.3 m (from edge to axis) over a distance of 700 m, which is interpreted as a distributary channel. The site of this large sand body correlates well with the sites of some of the most productive opal fields in the Lightning Ridge area. Thus, there appears to be an association between relatively thick sandstone and the occurrence of opal.

Finch clay facies

The Finch clay facies comprises a grey to buff, clay-rich rock (claystone) which is generally soft and virtually grit-free. The claystone is composed of the clay minerals kaolinite (dominant), smectite, and illite. Compared to the Wallangulla Sandstone Member and Coocoran Claystone Member (where kaolinite is also the dominant clay mineral), the amount of smectite present is generally higher, at the expense of some kaolinite. The presence of smectite results in the claystone having a slightly greasy feel and being puggy when wet. The upper one-third of the unit is usually well-jointed and of blocky habit. The joint surfaces and blocks are commonly coated with iron oxides.

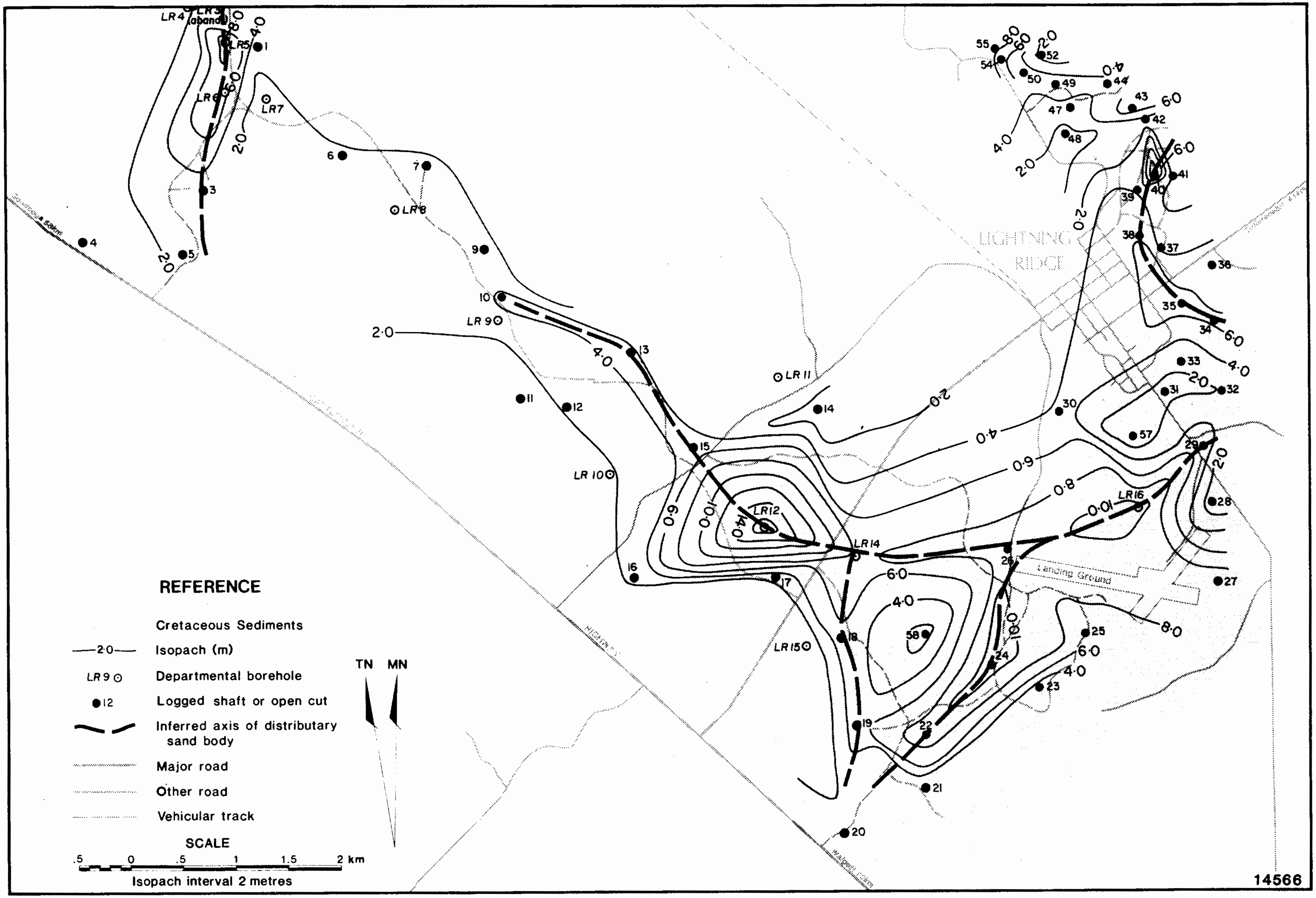

FIGURE 4: Isopachs for Wallangulla Sandstone Member above uppermost Finch clay facies lens

The Finch clay facies is present as discrete layers or lenses within the Wallangulla Sandstone Member. It varies in thickness from a 15 m to 5 m (average 1.5 m to 2.0 m) and generally has a very low sand or silt component (less than 5%).

The overall very fine grainsize of the claystone indicates deposition in a very low energy environment, possibly stagnant water. Byrnes (1977) noted that the claystone lenses frequently carry abundant small vertical tubes and proposed a marshland environment for their deposition. The presence of foraminifera (Scheibnerova 1983) and other fossils suggests that the marshes were marginal marine.

Geological mapping of a number of shafts and open cuts throughout the Lightning Ridge field indicates that most of the lenses are of very limited lateral extent. A structure contour map for the top of the uppermost clay lens (figure 5) shows the variation in relative elevation. The "average" elevation for the top of the uppermost lens is 148 m above sea level (a.s.l.) Figure 5 was compiled to examine the variation in elevation of the uppermost clay lens in various parts of the field. It is not intended to imply the presence of clay lenses throughout the entire field.

Cainozoic Sediments

Unconformably overlying the weathered Cretaceous sediments throughout a large portion of the region surrounding Lightning Ridge is a sequence of predominantly quartzose fluviatile gravels and sands. These sediments are restricted in outcrop to the ridges and reach a maximum thickness of 4 m near Cumborah; generally however, the sediments are less than 1 m thick. They are composed of about 50% gravel and 50% sand and silt matrix. The gravel fraction is mainly quartz with minor chert, jasper, silicified wood, agate, and silicified Cretaceous sediments. In places, the sediments are partially cemented by cherty silica (and iron oxides) to form "greybilly" (silicified sands) and conglomerate (silicified gravels). These deposits are Oligocene or early Miocene (i.e., mid Tertiary) in age and were deposited by westerly flowing streams. Younger Cainozoic sediments are mainly unconsolidated and comprise fluvial sands and clays.

Unconformably overlying the fluviatile gravels and sands are thin (<0.5 m) deposits of reworked and redistributed clasts of Cretaceous sediments, silcrete developed on the Cretaceous sediments ("skincracker"), and fluviatile gravels and sands and their silicified equivalents ("greybilly" and conglomerate). These deposits, of probably Quaternary age, are easily distinguished from the Tertiary deposits as the clasts have a heavy coating of sesquioxides mainly iron oxide (Fe_2O_3). They comprise the deposits colloquially referred to on the opal field as "ironstone gravels".

In areas of low relief, and in the flatter central areas of broad plateaux or "ridge country" a number of internal drainage areas of varying size have been developed. These are infilled with quartz sand or fine clayey material (usually ironstained red) of Quaternary age.

Within the known opal-producing areas deposits of Tertiary sands and gravels are generally thin or absent altogether. Outcrop in these areas commonly comprises bleached sediments of the Coocoran Claystone Member or Wallangulla Sandstone Member (or their equivalents) overlain by deposits of Quaternary "ironstone gravels", intermixed with a sandy soil. A diagrammatic representation of a typical section from the Lightning Ridge opal field is shown in figure 6.

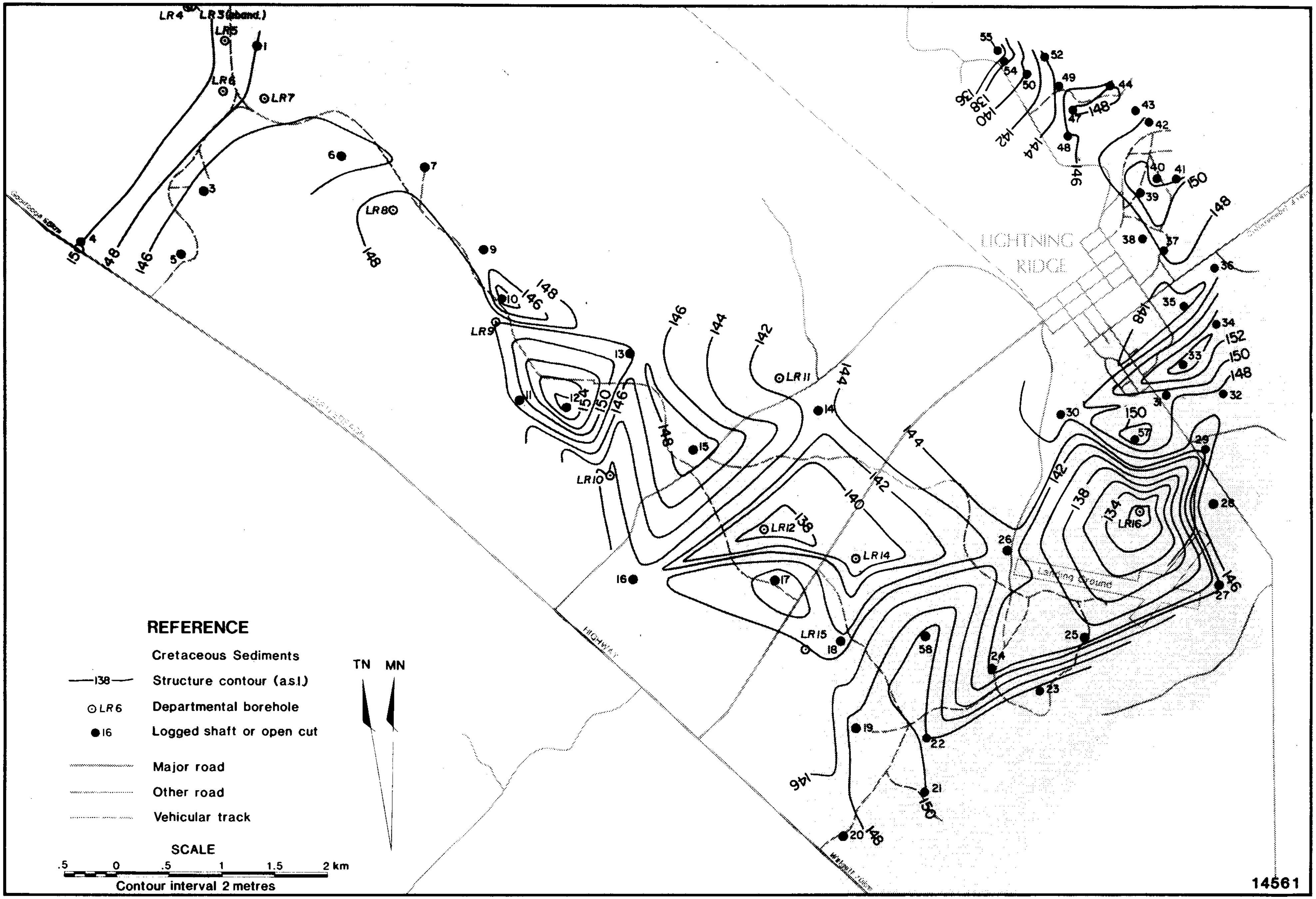

FIGURE 5: Structure contours on top of uppermost Finch clay facies lens

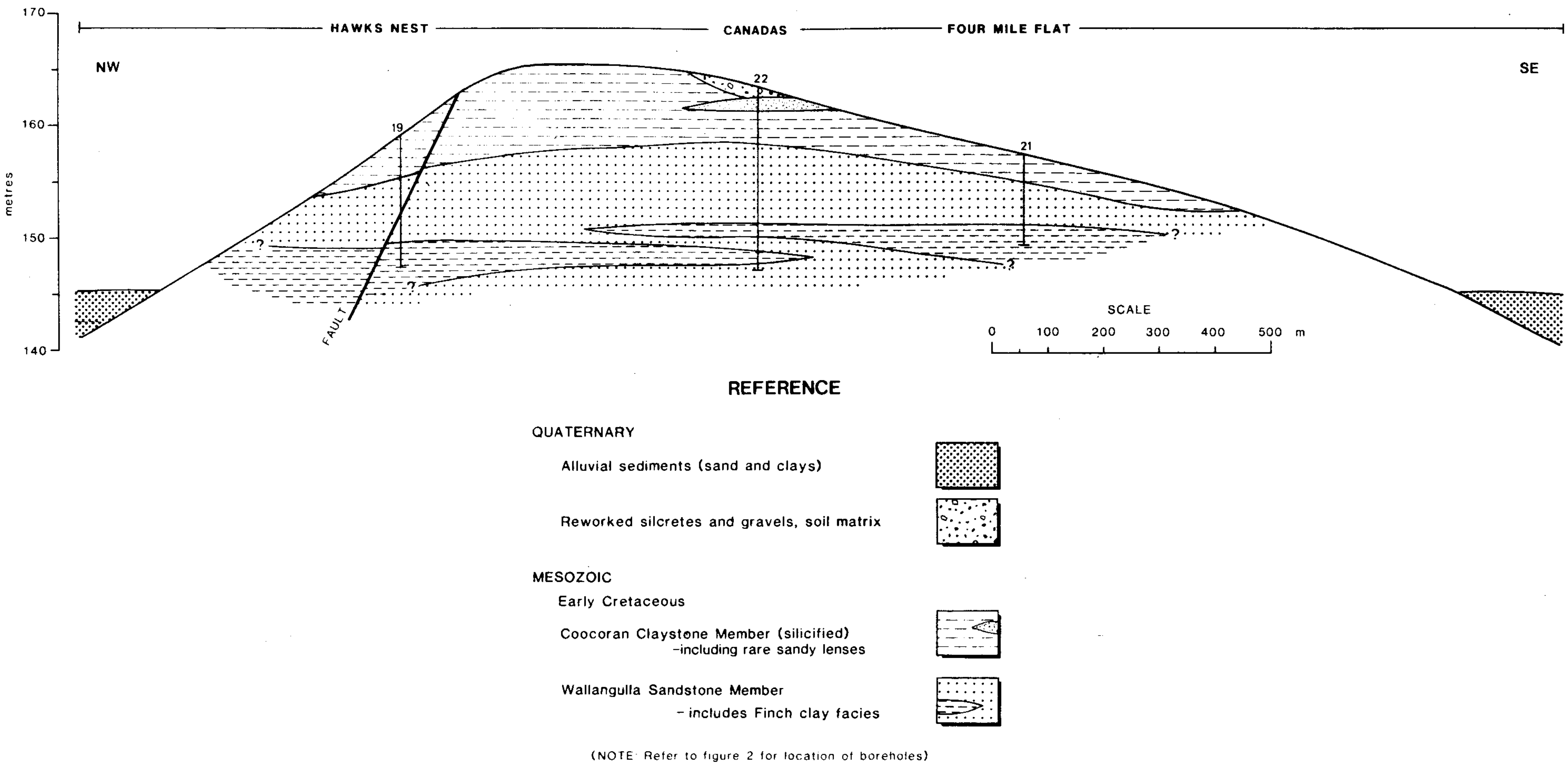

FIGURE 6: Diagrammatic cross section: Hawks Nest - Four Mile Flat

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In the outlying areas a large proportion of the outcrop (possibly up to 50%) comprises Cretaceous sediments which are overlain by deposits of Tertiary and Quaternary sediments. The Tertiary sediments are commonly less than 2 m thick and silicified to form silcrete. The thickest sediments accumulated in shallow erosional valleys which probably developed in areas where Cretaceous sediments were only weakly silicified or not silicified at all. Since the formation of opal is associated with silicification of the Cretaceous sediments, it follows that areas of Tertiary sediments, particularly silicified sediments, should be regarded as areas of low opal prospectivity. A diagrammatic representation which contrasts the generalized stratigraphy in prospective and unprospective outlying areas with the Lightning Ridge opal field is shown in figure 7.

Weathering and Silicification

In the Lightning Ridge area two main periods of silicification are postulated: Late Cretaceous to early Tertiary and late Tertiary. The two periods of silicification are associated with different lithologies. The first period of silicification appears to be related to a major weathering phase.

Late Cretaceous-Early Tertiary

This period of weathering and silicification produced the bleached kaolinitic profile which characterizes the Cretaceous sediments throughout the region. It also produced widespread, but relatively thin and sporadic silicification. The silicification takes three common forms: thin discontinuous bands ("porcelanite", "steel band"), veins and nodules of common and precious opal, and a thin capping of weakly silicified sediments, mostly sandy claystones ("shincracker").

All of the outcropping Cretaceous Rolling Downs Group sediments in the study area are kaolinized, partly silicified, and ferruginized. The sediments comprise a complexly bedded, repetitive sequence of fine-grained clayey sandstones, sandy claystones, and claystones. The clay mineral composition of all rock types is kaolinite (dominant) with lesser amounts of smectite and illite. The non-clay components are invariably quartz, with some calcite and anatase.

An interpretation of bore data recorded by the Water Resources Commission indicates that a deep weathering profile up to 50 m thick is developed on the Early Cretaceous sediments. These bore logs describe light coloured, generally white and yellow, Cretaceous sediments (the weathering profile) grading downward into grey and blue/black "shale" (unaltered Cretaceous sandstone and claystone). Numerous bores also recorded the presence of hard "limestone" (possibly subsurface silcrete — porcelanite or "steel band") beds within the profile.

The weathering profile in the Lightning Ridge area is herein informally termed the "Lightning Ridge profile".

Lightning Ridge Profile

The Lightning Ridge profile is comprised of white or mottled kaolinitic beds (mostly sandstones) which are randomly interbedded with iron-rich beds (mostly claystones); it has a thin capping of weakly silicified sediments (mostly sandy claystones). The sediments within this profile are inferred to

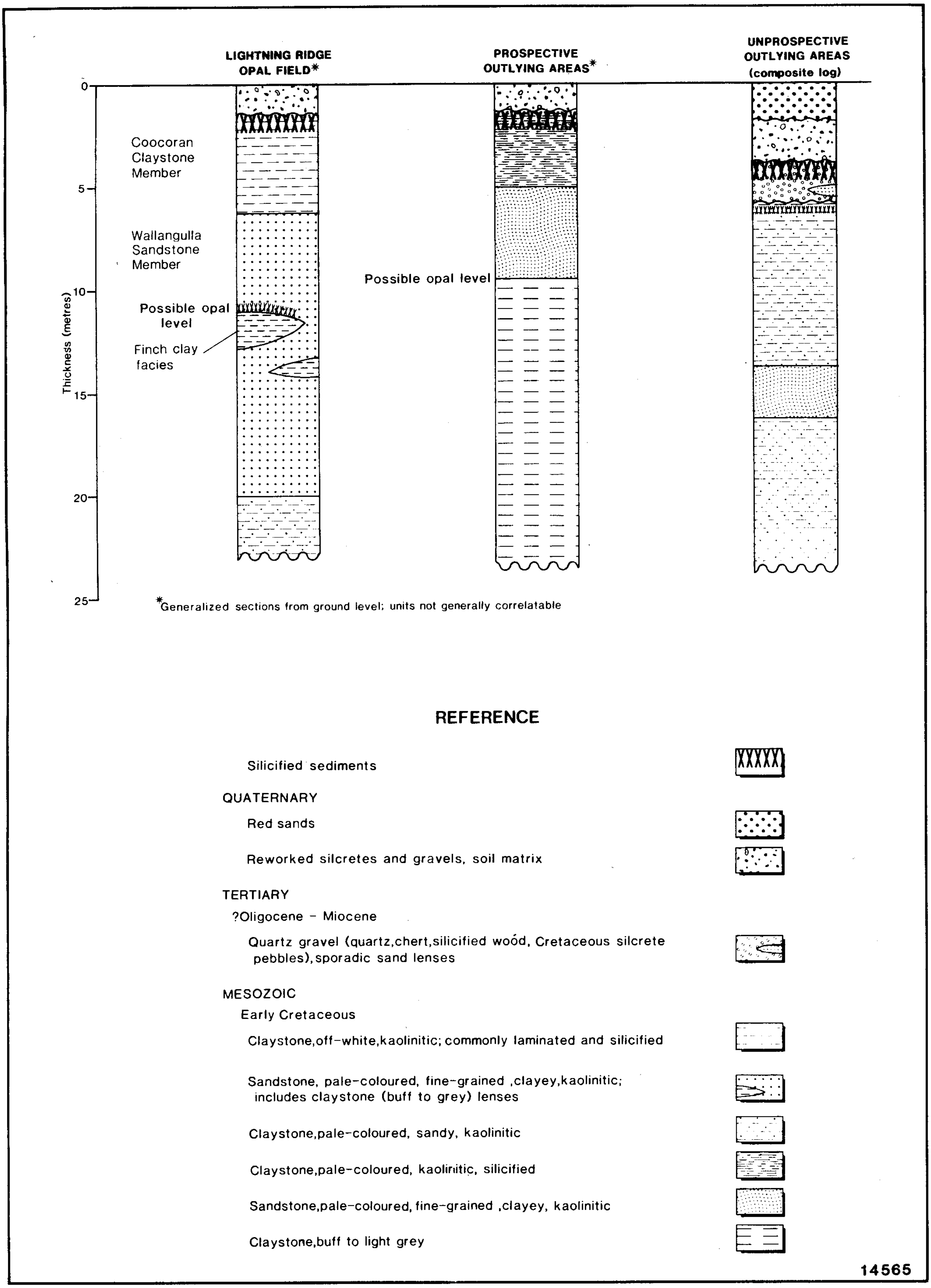

FIGURE 7: Generalized Stratigraphy, Lightning Ridge and outlying areas

be the source of opaline silica. Silicification within this profile may also take the form of thin discontinuous bands termed "porcelanite" (where developed in fine-grained sediments) or "steel band" (where developed in coarser grained sediments).

Underlying the kaolinized weathering zone (generally at depths of between 20 and 50 m) is a gradational weathering interface composed of less kaolinitic, fawn to light brown, fine-grained sediments. Miners refer to this interface as the "mud level" and recognize it as the lower limit of a prospective sequence.

Within the kaolinized zone, iron oxide enrichment has occurred within the upper portions of the claystone beds. The claystone beds are generally soft and well jointed (horizontally and vertically) in their upper portions, grading down into more massive claystone. Iron oxide coatings are common on the blocky claystones. Iron oxides also coat joint surfaces and fault planes (transgressing the entire kaolinitic sequence) and bedding contacts. The presence of iron oxides (probably derived from the weathering of Late Tertiary sediments) beneath the previously formed subsurface silcrete ("steel band") suggests a lateral as well as a vertical mode of transport for the iron oxides from areas of weathered mid Tertiary sediments.

Clay Mineralogy

A total of 75 samples from the weathering profile were submitted for clay mineral analysis. Of these, 46 samples were collected during the mapping component of the study and comprised mostly claystones from the "opal levels" (prospective claystone lenses) of known opal fields. The remaining samples were collected during the drilling component of the study and represent the various lithologies (from surface to total depth) from 6 selected boreholes; 3 in the Lightning Ridge field and 3 from outlying areas.

The clay fraction of claystones from the "opal levels" was shown to be comprised of kaolinite (average about 75%), smectite (20%), and illite (5%). Mineralogical studies of samples from selected boreholes show a general tendency for the percentage of smectite to increase with increasing depth in the weathering profile. The smectite content was found to be generally higher in "opal levels", than in the surrounding clayey sandstones. These data support the view that the claystone beds were probably strongly smectitic in the unweathered form and during weathering the smectite was largely transformed to kaolinite.

As another possible meaningful parameter, Hinckley's index of crystallinity of kaolinite, was measured and plotted against depth in selected boreholes. Values are higher in the near-surface weathered zones and generally decrease with depth. They are also higher in sandstones than in claystones. These results support an authigenic origin (formed in place) for the kaolinite in the sequence and hence a local origin for the opaline silica.

Late Tertiary

Following the Late Cretaceous to early Tertiary weathering and silicification period (to which the formation of opal is assigned) the Lightning Ridge region experienced an erosional and depositional period during the late Tertiary. This is represented by reworked silicified Cretaceous breccias and middle Tertiary quartzose fluviatile sediments. The Tertiary sediments, which occur widely throughout the area, are generally less than 2 m thick and are commonly silicified, forming a silcrete profile. No opal has been reported from these sediments.

It is unclear whether the development of these silcretes is related to in situ weathering and leaching of the sediments. It is more likely that the silica was precipitated from solutions that moved along the ancient drainage system and were trapped by permeability barriers at the base of the Tertiary sediments. The presence of detrital chert and the absence of pitting and embayments in quartz grains within the silicrete (observed in thin section) supports a distal source for the silica.

Structural Features

The Lightning Ridge opal field comprises an "L" shaped southeast trending ridge with an average width of 2 km and an average height of 25 m above the surrounding plains. In contrast, the ridges and mesas comprising the outlying areas tend to be much broader, commonly 10 to 15 km in width, and are generally less than 10 m above the surrounding plains. The Lightning Ridge opal field forms part of a much larger belt of low ridges of outcrop which strike approximately 025 degrees (magnetic) across the central part of the Angledool 1:250,000 sheet.

Regional Features

The Cretaceous sediments cropping out on the Angledool 1:250,000 sheet form ridges and mesas which are obvious erosional highs. Insufficient evidence is available to determine if they are also structural highs.

The basement structural features interpreted from the Surat - Bowen Basin Airborne Magnetometer Survey by Hartmann (1963) are summarised below:

1. Two lineaments striking 020 degrees (magnetic) and trending sub-parallel to the Cretaceous ridges are located to the west of and beneath the central area of Cretaceous outcrop. These separate an area of broad, low magnetic anomalies in the western portion of the Angledool 1:250,000 sheet from the area of higher anomalies trending north-south in the centre of the sheet area. The lineaments are probably basement contacts between different lithologies; however, they may be fault controlled.
2. A number of faults with a dominant strike direction of 140 degrees (magnetic).

The distribution of lineaments interpreted from Landsat imagery is shown on figure 8. An examination of the variation of density of the interpreted lineaments shown on this figure indicates that much of the outcrop in the outlying areas has a similar lineament density to the known opal producing area at Lightning Ridge. Within the central area of Cretaceous outcrop, i.e. between Lightning Ridge and Cumborah, the density of lineaments and lineament intersections is greatest, particularly in the known opal field areas of Grawin, Glengarry, and Carters Rush. To the north of Lightning Ridge and to the south of Cumborah there is a marked decrease in lineament density.

An analysis of the identified lineaments suggests there are two major sets, one striking 120 degrees (magnetic) and a second striking 060 degrees (magnetic). These two sets appear to be developed sub-equally and are bisected by a third set (less well developed) striking 360 degrees (magnetic). The lineaments identified on Landsat imagery subparallel the basement features identified by Hartmann (1963). This suggests a possible genetic relationship; i.e., the lineaments may be associated with movements generated along basement features.

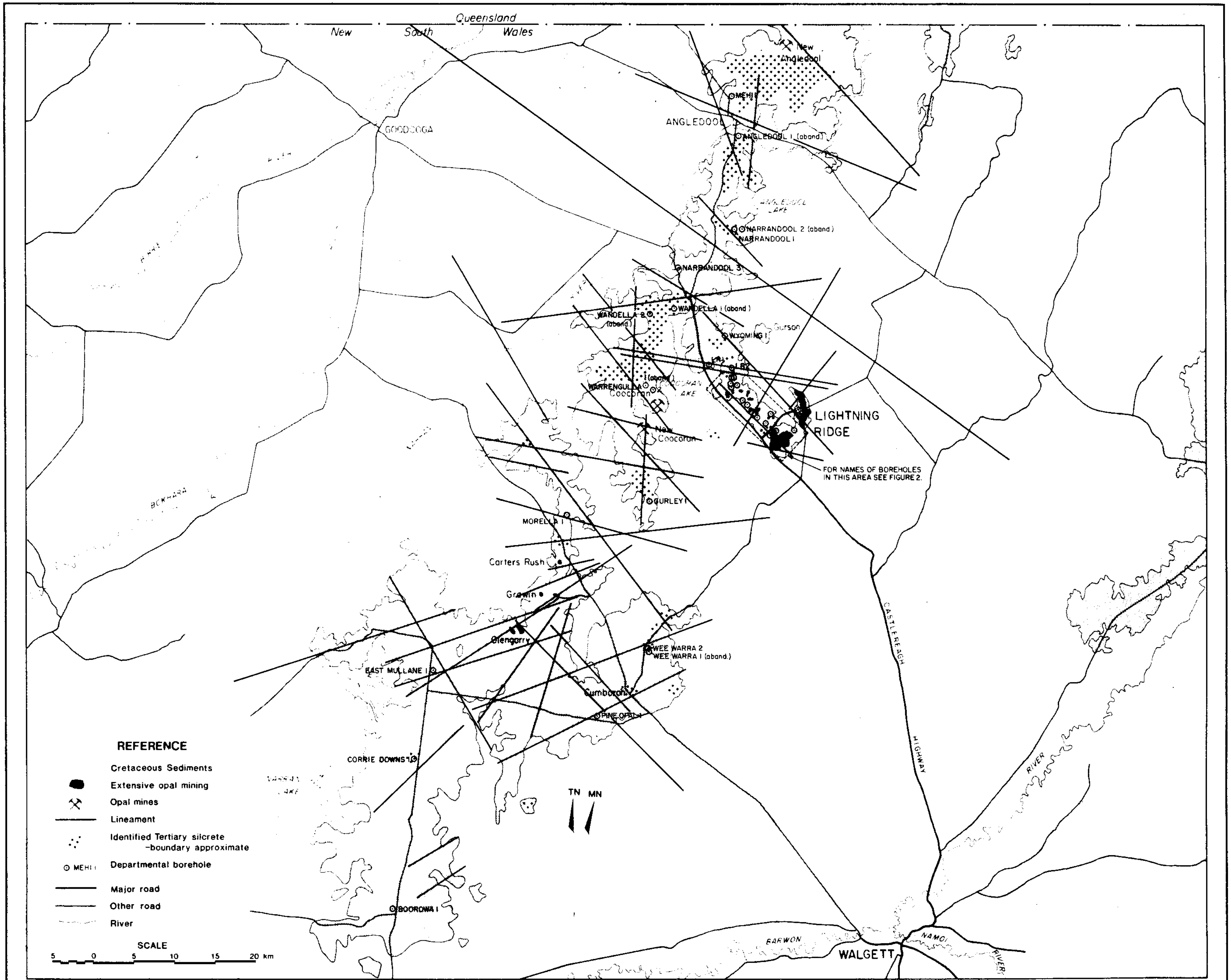

FIGURE 8 : Prospecting criteria for outlying areas, Lightning Ridge region

Local Features

The lineaments identified from aerial photographs of the Lightning Ridge opal field are shown on figure 9. Most of the lineaments have been interpreted from the 1959 series black and white photographs; these are the oldest available series and show minimal ground disturbance. The relationship between the distribution of lineaments and the subsequent development of opal fields is also readily seen from these photos.

The identified lineaments suggest a system comprising two major sets (?mostly joints), one striking 010 degrees (magnetic) and a second striking 110 degrees (magnetic). These two major sets (which also subparallel the regional basement features identified by Hartmann (1963)) are bisected by two less well developed sets striking 070 degrees and 150 degrees (magnetic).

Figure 9 shows the interpreted lineaments and the location of the opal fields at Lightning Ridge (as at 1983). The present investigation has indicated that the opal deposits at Lightning Ridge are not randomly located, but are structurally controlled. The following observations support such a conclusion:

1. There is an apparent increase in the density of lineaments and lineament intersections in areas which have historically been very productive. Such areas include the area between "McDonalds Six Mile" and "Rosso's", the area southwest of the landing ground between "Verticle Bills" and the "Deep Four Mile", the "Nine Mile" area, and the area from the "Old Nobby" field to "Canfells Hill".
2. The apparent absence or very low density of lineaments in areas of known low production and low prospectivity. Examples include the area immediately north and west of the landing ground, the area between "Foleys Six Mile" and the "Ten Mile", and the area northwest of "Hawks Nest" to "McDonalds Six Mile".
3. Within areas of high lineament density many opal fields have developed at the site of lineament intersections. These include "Nebia Hill", "Rosso's", "Hawks Nest", "Verticle Bills", "Old Nobby", "Telephone Line", "Pony Fence", "Angledool", "Thorleys Six Mile", "Nine Mile", "Deep Four mile", "Walshes", "Poverty Point", and "Canfells Hill".
4. The "Hawks Nest" field is bisected by a prominent lineament and has developed parallel to and on both sides of the lineament.

The role of these lineaments in controlling the sites of opal formation is discussed further under "Opal Genesis".

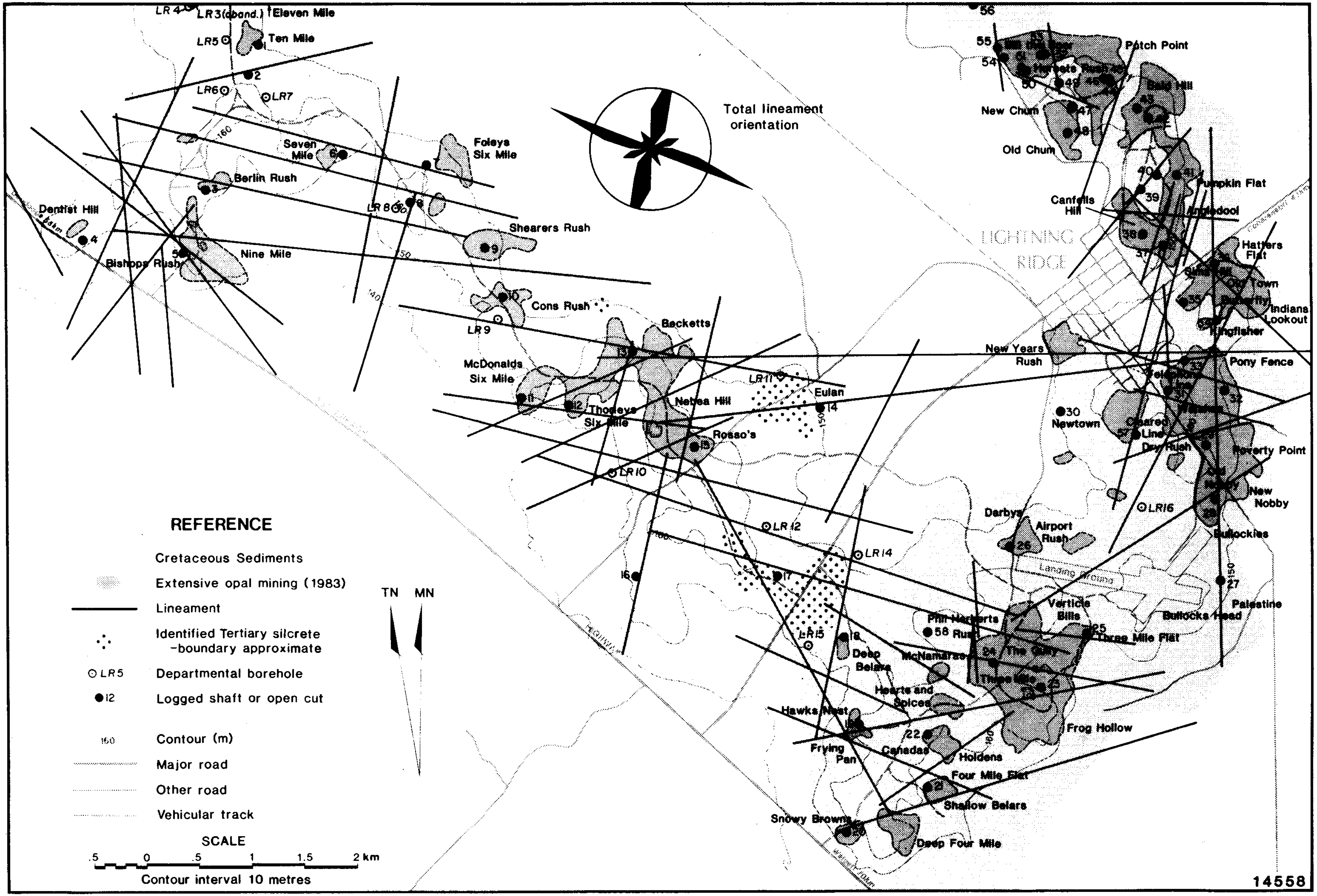

FIGURE 9 : Prospecting criteria for Lightning Ridge opal field

OPAL GENESIS

Structure of Opal

Opal is a hydrated form of silica, $SiO_2.nH_2O$ with a water content usually between 3-10 percent by weight, but which may be as high as 20 percent. It is composed of close-packed aggregates of silica spheres, 50-500 x 10^{-6} mm in diameter, which have grown in a series of concentric rings around a central nucleus.

Precious opal is translucent to transparent and exhibits bright spectral colours or a "play of colour" when rotated. In precious opal, the spheres are generally greater than 150 x 10^{-6} mm in diameter and are packed in an orderly array producing a regular three dimensional network of voids. Light passes through the transparent sphere but is scattered at the void interface. Colours are determined by refractive index, which depends on water content, and sphere diameter. Opal which flashes deep red can exhibit all other colours when viewed at suitable angles (Darragh et al. 1976). If no play of colour is produced the opal is termed "*common opal*" or, when found in association with precious opal, "*potch*". In common opal, the silica spheres are either of assorted sizes and do not produce the regular array required for colour diffraction, or are too small to produce blue colour even when arranged in a regular pattern.

The conditions required for the formation of great numbers of perfectly sized and regularly packed spheres (that comprise precious opal) are so stringent that they are rarely fulfilled. Jones et al. (1964), in describing the structure of precious opal, indicated that the silica particles have developed from an aqueous colloidal (gel-like) state.

Formation of Opal

The proportion of opal present in the Finch clay facies at Lightning Ridge is uncertain and probably varies considerably throughout the fields. It is probably less than one per cent, and of that, only about one per cent would be of the precious variety (MacNevin and Holmes 1979). The geological conditions necessary for the formation of opal at Lightning Ridge have, to date, not been widely understood. The present study has enhanced the understanding of these conditions, particularly in relation to the source of colloidal silica and the structural control on the opal deposits. There appear to be three main geological conditions which are necessary for the formation of opal. They are:

1. A source of colloidal silica, i.e., a relatively thick and weathered sandstone unit.
2. Vertically enhaced permeability, i.e., joints, faults, breccia zones.
3. Suitable depositional sites.

Source of Silica

In the Lightning Ridge opal field, most opal is generally recovered near the top (upper 0.5 m) of the various Finch clay facies lenses, immediately below the overlying Wallangulla Sandstone Member. There appears to be a good correlation between the distribution of relatively thick (4 to 6 m), massive sandstone units and the presence of opal. The high permeability of the sandstone units, enhanced in places by a well-developed joint system, would have facilitated the movement of groundwater, and hence the weathering and alteration of the host rock.

Within the deep weathering profile of the Cretaceous sediments kaolinite is the dominant clay mineral. The crystallinity of the kaolinite is high in the near surface zones and generally decreases with depth. It is also higher in sandstones than in claystones.

In view of the conclusion (from stratigraphic studies) that opal was formed prior to the deposition and subsequent silicification of the Tertiary sediments, it is considered that the opaline silica at Lightning Ridge was formed during a late stage in the kaolinization of Cretaceous sediments (particularly the Wallangulla Sandstone Member). The alteration of feldspar to kaolinite provided a large, ready source of silica.

The occurrence of opal in the uppermost portions of the Finch clay facies is consistant with the concept that siliceous solutions percolated down from their source rock (Wallangulla Sandstone Member) and were trapped by the impervious barrier presented by the clay facies.

Vertically Enhanced Permeability

The relationship between lineaments and the development of opal fields (particularly in areas where the density of lineaments increases or where lineaments intersect) was discussed previously under "Structural Features". The lineaments are interpreted to be a system of joints and their development may be related to movement associated with basement faults. On a more local scale, small faults, joints, and subvertical breccia zones ("blows") have played a role in the formation and localization of individual opal deposits.

The lineaments identified from air photos are shown on figures 8 and 9. They are commonly several kilometres in length and may be expressed at the surface by a number of large Belah or Box trees following the linear trend. Wild orange trees, whose roots follow fault and joint planes down to moisture (commonly the uppermost claystone lens or "opal dirt level"), are often used by miners to locate prospective ground.

Jointing and small-scale faulting ("slides" or "walls") are abundant in most workings examined in the Lightning Ridge area. These small-scale features strike in all directions and may be linear or arcuate. Most joints are vertical or sub-vertical, whilst fault planes are generally inclined between 45 degrees and 60 degrees. The faults offset the claystone lenses in both normal and reverse directions, the latter being more common. Vertical displacement varies from several centimetres to several metres. Opal within the claystone lenses is mostly present on the hanging wall adjacent to the fault plane. Opal may also occur adjacent to vertical joints where they intersect the top of a claystone lens.

Thus major lineaments appear to have controlled the occurrence of opal fields, by facilitating initial groundwater movement; whilst small-scale joints and faults have localized opaline silica deposition and subsequent opal formation. The relationship between these two scales of structural features is unclear. Perhaps the smaller scale features are evidence of volume adjustments caused by the swelling of clays on hydration. The major lineaments, by influencing initial groundwater movement, have controlled the sites of hydration and hence the sites of small-scale fault and joint development. All these structural features pre-date the deposition of Tertiary sediments.

In addition to joints and faults, subvertical breccia zones or "blows" are common throughout the opal fields. They are regarded as a good prospecting guide for opal. Opal is commonly located in the top of a claystone lens adjacent to a breccia zone; however, rare angular clasts of opal within a breccia have also been reported. The breccia zones are commonly circular in plan and 1 m to 2 m in diameter. They generally extend from the surface down to the "opal dirt level" and contain a mass of jumbled, angular fragments of Cretaceous claystone and sandstone. Near the surface they may contain younger (Tertiary and/or Quaternary) reworked sediments. During the late Tertiary period many of these breccia zones were silicified.

The breccia zones are interpreted to have developed at the site of intersecting joints. Continued downward movement of groundwater at these sites could have resulted in the partial dissolution of the rocks, forming a cavity. Collapse into the cavity would then extend upward to the surface to yield a mass of broken rock.

The enhanced vertical permeability produced by joints, faults, and breccia zones throughout the opal fields has probably had a dual role. It has facilitated the movement of siliceous groundwater to sites suitable for the formation of opal and it has increased the rate of transmission of water vapour from the depositional site to the surface. Evaporation of groundwater from the depositional sites is necessary to concentrate the silica particles and enable the growth of uniform close-packed arrays of silica spheres, which comprise precious opal.

Suitable Depositional Sites

As noted previously, most opal at Lightning Ridge is located within the top 0.5 m of the various Finch clay facies lenses. In most opal fields it is common to intersect more than one lens. In general, the first or uppermost lens is the most productive, whilst the lower lenses are generally less persistent.

The structure contour map for the top of the uppermost Finch clay facies lenses (figure 5) emphasises the variation in elevation of the lenses within the Wallangulla Sandstone Member. Figure 5 is not intended to imply the existence of Finch clay facies lenses throughout the contoured area, nor the existence of implied undulations or sinks. The clay lenses are essentially horizontal. The purpose of the structure contour map was to examine the relative elevations and continuity of the lenses throughout the various fields. At Lightning Ridge the productive lenses or "levels" all occur between the elevations of 144 m and 158 m a.s.l. The "average" elevation of the productive "level" is 148 m a.s.l.

Within the near-surface weathered sequence, the Finch clay facies lenses have acted as a permeability barrier, or aquiclude, to the downward moving siliceous groundwater. At the interface between the clay beds and the overlying sandstone various irregularities (mostly primary sedimentary structures) have provided partial lateral closure for the silica-laden water. For example, the interface usually undulates and "rolls" and "domes" are common. Such "rolls" may result from the deposition of a sand layer over a hydroplastic mud layer, leading to unequal loading and vertical adjustments at the sand-mud interface. These structures (termed load structures) are known to occur in shallow water environments.

Within the uppermost portion of the Finch clay facies lenses, suitable cavities have acted as reservoirs in which the silica can precipitate and/or flocculate from the virtually static siliceous groundwater. The infilling of these cavities has resulted in the formation of nodular or "nobby"-type opal;

a type of opal that is mainly peculiar to the Lightning Ridge area. The nobbies may occur singly or in clusters separated by barren ground. Opal may also be present as a filling in both horizontal and vertical joints.

Nobbies from Lightning Ridge can be roughly divided into two groups: firstly the rounded nodules, of varying shapes and sizes, that are generally rather irregular in form; and secondly, the distinctive "chinese hat" nobbies, that exhibit a conical shape with well-defined striations running from the central peak to the edge of the nobby. Approximately 10 to 20 per cent of the nobbies found are of the "chinese hat" variety. Nobbies vary in size, but average 40 to 50 mm in diameter.

Opalized shells are also found at Lightning Ridge. These are mainly bivalves and represent moulds of the original shell, the cavity having been infilled by opal. Other opalized fossils (e.g., reptilian remains) are less common.

Regardless of form, however, the essential control on opal formation at Lightning Ridge is the infilling of cavities; cavities that were located in the uppermost portion of the Finch clay facies lenses. There has been much speculation concerning the origin of these cavities. Clearly, any hypothesis concerning their origin must account for the known distribution of these forms of opal, i.e., the apparent random occurrence of rounded nobbies and "chinese hat" nobbies (commonly adjacent to each other) and their location in the stratigraphic sequence.

With regard to the origin of the cavities that were infilled to form rounded nobbies the hypothesis proposed by Hiern (1964) i.e., sand pockets, is worthy of support. It is probable that these sand pockets were ball and pillow structures (penecontemporaneous deformation structures, see figure 10). Ball and pillow structures are known in shallow water environments and point to rapid sedimentation of the sand unit. Subsequent weathering of the feldspar component of the sand would have aided cavity formation. This mode of formation may also explain why many nobbies have an outer sandy coating or may be "shot with sand", i.e., have quartz sand grains distributed through the opal.

In addition to the geological conditions necessary for the formation of opal, there are chemical factors which influence the precipitation of silica from solution. Smale (1973) concluded the major factors governing the deposition of amorphous silica were:

1. Reduction in pH from greater than 9 to less than 9 (i.e., a change from an alkaline to an acidic environment).
2. Presence of Al_2O_3, Fe_2O_3 or MgO.
3. Presence of NaCl or Na_2SO_4.

Throughout the opal field kaolinite ($Al_2O_3.2SiO_2.2H_2O$) is universally present. Its presence, together with the moderate salinity of the Finch clay facies beds may have been important for the precipitation of silica.

Age of Formation of Opal

The relationship between the kaolinitic sandstone units (e.g., Wallangulla Sandstone Member at Lightning Ridge) and the occurrence of opal suggests that opal was formed during a late stage in the development of the kaolinitic weathering profile. This profile is ubiquitous throughout the

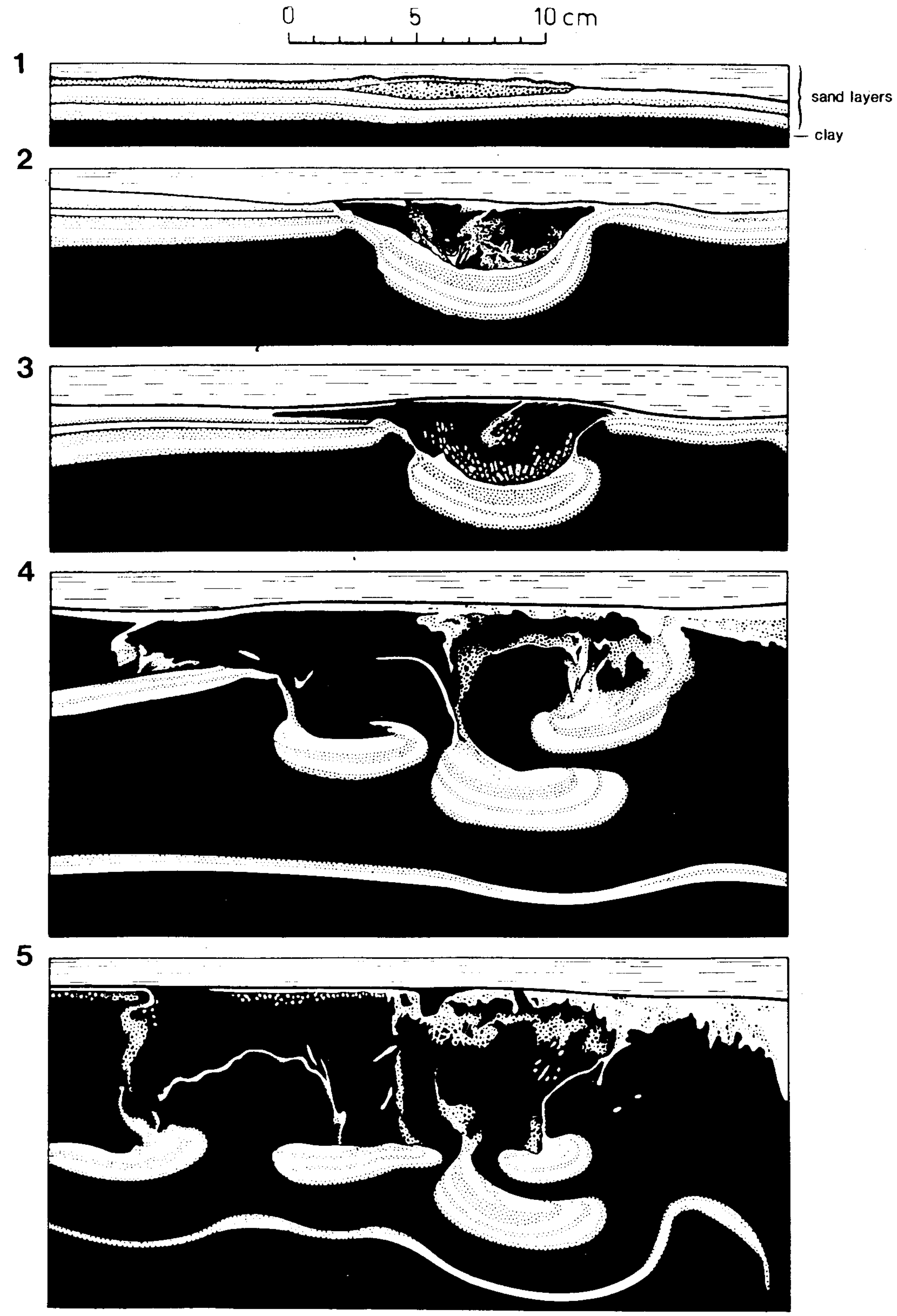

FIGURE 10 : Schematic development of the ball-and-pillow structures
(after Kuenen 1965)

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Lightning Ridge region and southwest Queensland. It is considered to have developed during the Late Cretaceous (Senior 1977).

Whiting and Relph (1961) reported the presence of opal float in gravels on the "Old Chum" field. The gravels are up to 3 m thick; this thickness suggests they are equivalent to the fluviatile quartz gravels (commonly silicified) of the outlying areas. These gravels were described in the Cumborah area by Taylor (1972) who concluded that their age is Oligocene to Miocene (i.e. mid Tertiary). Opal has formed prior to the deposition of these sediments and consequently also pre-dates the silicification associated with these gravels (late Tertiary). No authigenic opal has been recorded in the Tertiary sediments.

Broken clasts of opal (both "seam" opal and "nobby" opal) have been reported to occur in sub-vertical breccia zones ("blows"). The matrix of these breccia zones is commonly silicified and the silicification can be associated with the late Tertiary silicification period.

In summary, evidence from the distribution of opal within the weathering profile, its association with Tertiary sediments, and geomorphological features of mid to late Tertiary age suggest that the age of opal formation at Lightning Ridge is early Tertiary. it is not genetically related to the formation of silicite in the region, as was commonly assumed. This occurred at a later period (late Tertiary).

RESERVES AND PROSPECTIVITY OF LIGHTNING RIDGE OPAL FIELD

General

The Lightning Ridge opal field comprises approximately 60 opal fields together with intervening unworked and variably prospected areas within 10 km of the township. An assessment of the future potential of the Lightning Ridge field is based on an estimation of the potential of the existing fields together with an assessment of the prospectivity of the unworked areas.

Although the controls on opal formation are now thought to be reasonably well understood, the sporadic nature of the occurrence and distribution of precious opal within a prospective sequence precludes any estimation of in situ reserves of opal (and hence grade). However, most opal (up to 95 percent) occurs within the top of the uppermost "opal dirt level" or Finch clay facies lens. Thus an estimate of the *recoverable volume of potentially opal-bearing claystone* remaining in the existing opal fields can be used in conjunction with the previously calculated rate of processing (or rate of extraction) of this material to estimate the likely "life" of the Lightning Ridge opal field. Economic considerations such as production costs (largely fuel costs), future market prices, and future market demands are not known and hence their influence on estimated reserves cannot be established. Thus the term "reserves", as used here, refers to recoverable reserves of potentially opal-bearing claystone in the existing opal fields.

An assessment of the likely life of opal fields in the outlying areas has not been attempted due to a paucity of data. However, the prospectivity of these areas is discussed in a later section.

Criteria for Estimation of Recoverable Reserves

The history of the development of the Lightning Ridge opal field is essentially a history of expansion of known opal-producing areas. Figure 11 shows the approximate boundaries of the various opal fields in the Lightning Ridge area in 1971 and 1983. The 1983 bondaries were interpreted from aerial photographs and modified following field investigations. They essentially define areas where there is a high density of workings and include open cut mining operations, underground mining operations, and prospecting shafts.

In 1971, the total surface area occupied by the opal fields was approximately 180 ha. By 1983, the area had increased to 650 ha. This marked increase in the extent of the opal fields in only 12 years reflects the increased mechanization of mining and the use of "new technology" machinery. It is not known if this rate of growth will continue in the future. Hence, the estimation herein of the likely life of the opal fields is based on current extraction rates (see earlier section).

To facilitate an estimation of the remaining reserves of potentially opal-bearing claystone at Lightning Ridge the fields have been divided into two groups, based on the amount of extraction and development which has taken place:

> *Group 1.* Opal fields in this group comprise a *core area* (equivalent to the 1971 boundaries of the opal field as shown on figure 11) and a *growth area* (equivalent to the 1983 boundaries as shown on figure 11 less the core areas). It is estimated that *50%* of the available potentially opal-bearing claystone has been extracted from core areas. In the growth areas it is estimated that *20%* has been extracted.

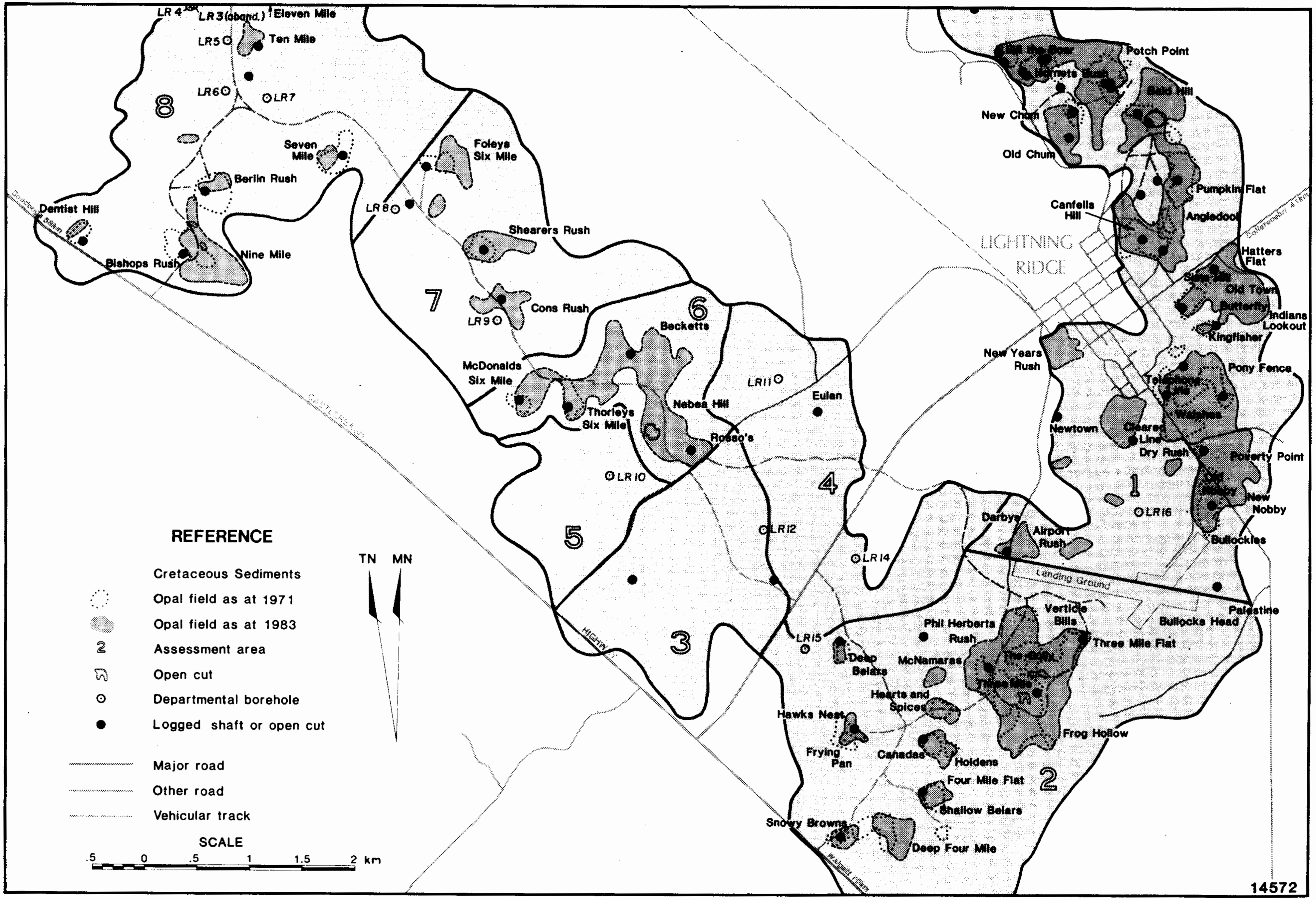

FIGURE 11 : Growth and development of Lightning Ridge opal field, 1971 - 1983

Group 2. Opal fields in this group have historically been very popular and many have been "worked out" by underground methods. Several of these fields are currently mined by open cut methods or have been designated for mining by open cut methods. Core areas and growth areas are defined for this group as for group 1. However it is estimated that *70%* of the potentially opal-bearing claystone has been extracted from the core areas and *50%* of the potentially opal-bearing claystone has been extracted from the growth areas.

During mining the upper portion of the first or most productive Finch clay facies lens is generally removed. The thickness of the potentially opal-bearing claystone removed is, on average, about 1.5 m; this average thickness has been used in conjunction with areal figures, to determine the volume of potentially opal-bearing claystone. Whilst in some areas a second level, and perhaps subsequent levels are developed, their contribution to overall production is generally small and has been disregarded.

Criteria for Determination of Prospectivity

An assessment of the prospectivity of the unworked areas of the Lightning Ridge opal field is based on the following criteria:

1. The presence and density of photolineaments and the occurrence and density of intersections of photolineaments.
2. The presence and thickness of the Wallangulla Sandstone Member above a Finch clay facies lens.
3. The occurrence of a Finch clay facies lens within the productive elevation range of 144 m to 158 m a.s.l.
4. The presence (or absence) of silicified Tertiary sediments.

Reserves and Prospectivity by Areas

For convenience the Lightning Ridge opal field has been subdivided into 8 smaller areas. The boundaries of these areas are shown on figure 11. They are somewhat arbitrary, but an attempt has been made to incorporate areas of similar prospectivity. The estimated reserves and prospectivity of each of these 8 areas are discussed below.

Area 1

This area comprises the north-trending section of outcrop from the landing ground north to "Bill the Boer" field. There are 28 existing fields within this area. Table 4 shows the relevant grouping (as previously discussed) for each of these fields and the estimated reserves of potentially opal-bearing claystone for each group.

In addition to the existing fields, Area 1 comprises a number of unworked areas. With the exception of approximately 50 ha immediately north of the landing ground, these unworked areas have a moderate density of prospecting shafts.

There are a number of photolineaments within Area 1 (see figure 9). Four of the lineaments enter and intersect in the 50 ha unworked site described above. Borehole LR16 was sited adjacent to a lineament in this area, but did not intersect a suitable claystone unit. However, prospectivity may increase away from this site to the northeast. This view is supported by the following observations:

1. Suitable sequences occur in the established fields to the northeast.
2. Two photolineaments within this area (with a north-north easterly trend) are intersected by a third lineament trending east-northeast. The intersections occur in the northeastern portion of this area.
3. The sandstone isopach map (figure 4) suggests a suitable thickness of sandstone (between 6 m and 9 m) may be present in a narrow zone trending in this direction.

TABLE 4

AREA 1 —ESTIMATED RESERVES OF POTENTIALLY OPAL-BEARING CLAYSTONE IN EXISTING FIELDS

Group 1 Fields*		*Group 2* Fields*
Bill the Boer	Indians Lookout	Old Chum
Hornets Rush	New Years Rush	Bald Hill
Potch Point	Dry Rush	Canfells Hill
New Chum	Poverty Point	Kingfisher
Pumpkin Flat	Newtown	Pony Fence
Angledool	New Nobby	Telephone Line
Sims Hill	Bullockies	Walshes
Hatters Flat	Airport Rush	Cleared Line
Old Town	Darbys	Old Nobby
Butterfly		

Sub Totals - Core Areas: Group 1 - 1 million tonnes
Group 2 - 0.64 million tonnes

Growth Areas: Group 1,2 - 5.2 million tonnes

Total - 6.84 million tonnes

* Description of Groups 1 and 2 given under "Criteria for Estimation of Recoverable Reserves".

Summary

The existing fields in Area 1 have estimated reserves of 6.84 million tonnes of potentially opal-bearing claystone. Most unworked areas have been well prospected and the potential for a significant expansion of existing fields into these areas is low. However, the unworked area to the north-northeast of borehole LR16 (i.e., south-southwest of the "Newtown" and "Cleared Line" fields) may be prospective.

Area 2

This area comprises 16 fields to the southwest of the landing ground (see table 5). The most extensively worked and by far the most productive area on the Lightning Ridge field (the "Three Mile") is located in this area. In recent years relatively large scale open cut mining has been established on the "Three Mile" field. The "Three Mile Flat" field has also been designated for open cut mining and the "Hawks Nest" field will soon to be gazetted for this purpose. Area 2 also contains the highest density of identified photolineaments (see figure 9) and a well-developed channel sandstone unit (see figure 4). The sandstone unit trends northeasterly and parallels the main line of workings. The unworked areas located along this trend between the existing fields are inferred to have good prospectivity.

The sandstone isopach map (figure 4) indicates the development of an additional channel sandstone unit trending northwesterly from the "Snowy Browns" field, through "Hawks Nest" to the "Deep Belars" field. Borehole LR15, was sited approximately 300 m to the west of the "Deep Belars" field, but did not intersect a prospective sequence. Claystone was intersected, but at a depth below 144 m a.s.l. The sandstone isopach map together with drilling results in this portion of Area 2 suggests that the more prospective, unworked areas are located in a narrow zone between the existing workings (particularly in the area immediately northwest of the "Hawks Nest" field adjacent to the photolineament - see figure 9).

TABLE 5

AREA 2 —ESTIMATED RESERVES OF POTENTIALLY OPAL-BEARING CLAYSTONE IN EXISTING FIELDS

Group 1 Fields		*Group 2 Fields*
Verticle Bills	Holdens	Three Mile
Phil Herberts Rush	Frying Pan	Three Mile Flat
McNamaras	Four Mile Flat	Hawks Nest
Frog Hollow	Deep Four Mile	
Hearts and Spices	Small Belars	
Deep Belars	Snowy Browns	
Canadas		

Sub Totals - Core Areas:	Group 1	- 0.56 million tonnes
	Group 2	- 0.63 million tonnes
Growth Areas:	Groups 1,2	- 2.0 million tonnes
	Total	- 3.19 million tonnes

Summary

Area 2 has estimated reserves of 3.19 million tonnes of potentially opal-bearing claystone in the existing fields. The intervening unworked areas have good potential for future development.

Area 3

Area 3 comprises a portion of the crest of the main northwest trending ridge and a south-trending spur. There are no established fields in this area; however, there are numerous prospecting shafts located on the western edge of the spur.

Five photolineaments pass through this area. One lineament is located on the western edge of the south-trending spur. Ground reconnaissance indicates that this lineament represents a fault scarp. One shaft located on the spur was inspected; a suitable claystone was present, but there was only a moderate (2.9 m) development of sandstone. The sandstone isopach map (figure 4) indicates a thickening towards the axis of the main ridge and hence prospectivity may also increase in this direction.

The northeastern portion of this area intersects the crest of the main ridge. Here, the Cretaceous sediments are overlain by Tertiary gravels which are up to 2 m thick and commonly silicified. The presence of silcrete is a major deterrent to prospecting and is undoubtably the reason why this area has been neglected in the past. Borehole LR12 was sited just to the northeast of the crest, adjacent to a lineament. In this borehole a thick (17.5 m) channel sandstone unit was intersected; however the only claystone unit present was intersected at an elevation of 139 m a.s.l. (5 m below the general lower level of productive claystone units).

Summary

The presence of faulting, a prospective claystone unit, and an inferred increase in sandstone thickness toward the crest of the ridge suggests that the south-trending spur has good potential for future development. Due to the presence of silcrete the prospectivity of the crest of the ridge in this area remains largely unresolved. However, borehole LR12, sited just off the crest did not intersect claystone beds within the productive elevation range (144 m to 158 m a.s.l.)

Area 4

This area comprises approximately 350 ha; it is largely unworked and only very sporadically prospected. At "Eulan", in the north of this area, opal was recovered from shallow working, but the quantity and quality was apparently insufficient to encourage further development. The "Eulan" workings are located on a photolineament and adjacent to a small area of silcrete.

Additional silcrete is located in the southern portion of Area 4 where it forms a capping to the crest of the ridge; it is contiguous with the area of silcrete in Area 3.

In the eastern portion of this area much of the outcrop is covered with colluvium (comprising large boulders and cobbles of silcrete) and red soil up to 1.5 m thick.

Two boreholes, LR11 and LR14 were sited in the northern and eastern portions respectively. Borehole LR11 intersected an unprospective sequence of interbedded sandstones and claystones with laminites. Borehole LR14, located adjacent to a photolineament, intersected a thick (13.25 m) and partly indurated sandstone unit overlying claystone. The claystone unit in this borehole was well below the prospective elevation, but a quantity of grey chalcedonic silica was observed in the matrix and as small pods (5 mm to 10 mm long) in the sandstone at an elevation of 146 m. a.s.l. The presence of this secondary silica is encouraging as it indicates the downward movement of siliceous solutions through the permeable overlying sandstone.

Summary

The "Eulan" area may have further potential, particularly on the southern side of the lineament (away from the silcrete). The presence of a thick sandstone unit and secondary silica in borehole LR14 (located adjacent to a lineament) is encouraging.

Area 5

This area extends from south of the "McDonalds Six Mile" field to "Rosso's" field. The area is downslope from the ridge crest and its surface is characterized by a relatively thick (1 m to 2 m) blanket of intermixed soil and gravel, with very little outcrop. Air photo interpretation and ground reconnaissance indicate only a very low level of prospecting throughout this area. There is a relatively high density of lineaments which pass through the productive fields to the north and enter and intersect in this area. Borehole LR10 was sited central to this area near the intersection of 3 lineaments.

Borehole LR10 was collared at an elevation of 149 m a.s.l. and penetrated an unprospective sequence comprising thin interbeds of soft, weathered sandstone and claystone with laminated siltstone.

Summary

The paucity of outcrop in this area probably accounts for the lack of prospecting. The area has a high density of lineaments, but the sequence intersected in borehole LR10 was unprospective. The prospectivity and hence the future potential of this area is regarded as low to moderate.

Area 6

Area 6 comprises the continuous line of workings located on the crest of the ridge from "McDonalds Six Mile" field to "Rosso's" field. This area includes the highly productive "Nebia Hill" field which was very intensively worked by underground, and later open cut methods. This area has a relatively high density of lineaments; "Nebia Hill" is located on a set of intersecting lineaments.

The future potential of this area is directly related to the potential of the existing fields. Estimated reserves of potentially opal-bearing claystone remaining in the existing fields are given in table 6.

TABLE 6

AREA 6 —ESTIMATED RESERVES OF POTENTIALLY OPAL-BEARING CLAYSTONE IN EXISTING FIELDS

Group 1 Fields		*Group 2 Fields*
McDonalds Six Mile	Becketts	Nebia Hill
Thorleys Six Mile	Rosso's	

Sub Totals - Core Areas:	Group 1	- 0.15 million tonnes
	Group 2	< 0.01 million tonnes
Growth Areas:	Group 1,2	- 1.65 million tonnes
	Total	- 1.80 million tonnes

Summary

The future potential of this area is directly related to the potential of the existing fields. Based on previously defined criteria, reserves of potentially opal-bearing claystone in existing fields are estimated at 1.80 million tonnes.

Area 7

This area comprises a portion of the main northwest-southeast trending ridge and includes the "Foleys Six Mile", "Shearers Rush", and "Cons Rush" fields. There is a moderate density of lineaments in this area; the "Shearers Rush" field is located on a parallel set of easterly trending lineaments. The "Foleys Six Mile", "Shearers Rush", and "Cons Rush" fields are developed on the northeastern side of the main ridge. The "Cons Rush" field has been designated for mining by open cut methods. Recorded thicknesses of sandstone in these fields range from 2.6 m to 4.8 m. Only very sporadic prospecting has been carried out in the unworked areas between these fields. Two boreholes, LR8 and LR9, were sited in the unworked sections of this area.

Borehole LR8 was sited on the southwestern side of the main ridge and intersected a generally thinly interbedded sequence of sandstone, siltstone, and claystone. The sequence is regarded as unprospective. Borehole LR9 was sited on a small rise to the south of the "Cons Rush" field. Claystone was intersected in this borehole at a similar elevation to the main claystone level worked in the "Cons Rush" field. The overlying sandstone unit however thinned from the 4.8 m recorded in the "Cons Rush" field to 1.7 m in borehole LR9.

The sandstone isopach map (figure 4) cannot be reliably interpreted throughout this area due to the low density of sampling points. However the available data suggests that the thicker sandstone units are confined to the northeastern side of the main ridge; they appear to thin or be interbedded to the southwest.

The future potential of this area is related to the remaining potential within existing fields and the possible development of unworked areas. The indicated potential of the unworked areas appears to be higher on the northeastern side of the main ridge. Estimated reserves of potentially opal-bearing claystone in the existing fields are given in table 7.

TABLE 7

AREA 7 —ESTIMATED RESERVES OF POTENTIALLY OPAL-BEARING CLAYSTONE IN EXISTING FIELDS

Group 1 Fields		*Group 2 Fields*
Shearers Rush		Cons Rush
Foleys Six Mile		
Sub Totals - Core Areas:	Group 1	- 0.20 million tonnes
	Group 2	< 0.01 million tonnes
Growth Areas:	Group 1,2	- 0.68 million tonnes
	Total	- 0.86 million tonnes

Summary

Estimated reserves of potentially opal-bearing claystones for area 7 are 0.86 million tonnes. The prospectivity of unworked areas is higher on the northeastern side of the main ridge.

Area 8

This area comprises the far northwestern portion of the Lightning Ridge opal field and includes 7 existing fields: "Seven Mile", "Berlin Rush", "Bishops Rush", "Dentists Hill", "Nine Mile", "Ten Mile", and "Eleven Mile". The "Eleven Mile" field is the most remote of these fields and is located just off the crest of the main ridge. The ridges and plateau areas which comprise the higher ground in the "Eleven Mile" and the areas beyond this field are generally covered with Tertiary sediments (sands and gravels) and are commonly silicified. All fields within Area 8, with the exception of the "Ten Mile" field, are located on photolineaments. The very productive "Nine Mile" field is near the intersection of 3 lineaments. The density of lineaments decreases to the northwest of Area 8 and beyond; however, the presence of Tertiary sediments may exert a masking effect in some places. Three opal prospecting blocks (numbers 22, 23, 24) comprise most of the unworked portions of this area. However, the backfilling requirement of this form of title and the lack of reporting requirements have resulted in a loss of data from prospecting sites, which could have aided interpretations and assessment. Seven boreholes, LR1, LR2, LR3, LR4, LR5, LR6 and LR7 were therefore sited in the northern part of this area (see figures 8 and 11 for borehole locations). Borehole LR3 was abandoned because a surface silcrete could not be penetrated with the Calweld drill. The relevant intersections in each borehole are summarized below:

LR1 - Prospective claystone level at 148 m a.s.l.; 2.7 m of sandstone overlying claystone. Top 1.5 m of claystone was "puddled", but no opal was recovered.

LR2 - 12 m of interbedded sandstone and claystone with minor laminites overlying 8 m of sandy claystone. Sequence regarded as unprospective.

LR4 - thinly interbedded sequence of clayey sandstones, laminites, and claystones. Sequence regarded as unprospective.

LR5 - 9 m thick sandstone unit (138 m - 147 m a.s.l.) overlain by thin interbeds of sandstone and claystone, with common laminites; no prospective claystone level. Sequence regarded as unprospective.

LR6 - 2 m thick sandstone unit (149.5 m - 151.5 m a.s.l.) overlying possible prospective claystone unit (claystone is high in kaolinite content - termed a "dry level" by miners).

LR7 - prospective claystone level at 147.3 m a.s.l. overlain by 0.5 m of sandstone. Thin (2 mm - 3 mm) band of seam opal was recovered from puddling of this claystone unit. Higher claystone unit (above sandstone) is brecciated in part.

The prospective sequence intersected in boreholes LR1 and LR7 are encouraging. However, these borehole sites are not adjacent to any lineaments and their potential for significant development may therefore be limited. Nevertheless, there is still considerable potential for prospecting the unworked sections of Area 8, particularly along strike of the identified photolineaments.

The estimated reserves of potentially opal-bearing claystone in the existing fields within this area are shown in table 8 below:

TABLE 8

AREA 8 — ESTIMATED RESERVES OF POTENTIALLY OPAL-BEARING CLAYSTONE IN EXISTING FIELDS

Group 1 Fields			*Group 2 Fields*
Seven Mile	Berlin Rush		Nine Mile
Ten Mile	Bishops Rush		
Eleven Mile	Dentists Hill		
Sub Totals - Core Areas:		Group 1	- 0.48 million tonnes
		Group 2	- 0.15 million tonnes
- Growth Areas:		Group 1, 2	- 0.8 million tonnes
		Total	- 1.43 million tonnes

Gurson Area

This area comprises a small inlier of Cretaceous outcrop (approximately 400 ha) adjacent to the "Gurson" property, approximately 10 km northwest of the township. The area is morphologically similar to the Lightning Ridge area and is transgressed by two photolineaments (see figure 8). Air photo interpretation also indicates a lack of silicified Tertiary sediments.

A moderate level of prospecting has been undertaken in the area and several claims have been registered. However the area was not inspected during the study and no attempt has been made to estimate reserves.

Summary of Reserves in Existing Fields

Table 9 shows the estimated reserves of potentially opal-bearing claystone in the core and growth areas of existing fields at Lightning Ridge.

TABLE 9

SUMMARY OF ESTIMATED AVAILABLE RESERVES OF POTENTIALLY OPAL-BEARING CLAYSTONE IN EXISTING FIELDS
(million tonnes)

	CORE AREAS		GROWTH AREAS
	Group 1	Group 2	Group 1, 2
Area 1	1.0	1.64	5.2
Area 2	0.56	0.63	2.0
Area 6	0.15	0.01	1.65
Area 7	0.2	0.01	0.68
Area 8	0.48	0.15	0.8
Sub Totals	2.39	1.44	10.33
Total		14.16 million tonnes	

Likely Life

The total estimated available reserves of potentially opal-bearing claystone in existing fields at Lightning Ridge are 14.16 million tonnes. Of this, 12.72 million tonnes (i.e., Group 1 core areas and Group 1, 2 growth areas) are available for mining by underground methods. An area may become unsafe to work by underground methods following the removal of approximately 60 per cent of the available "opal dirt". Thus, of the estimated 12.72 million tonnes available, only 7.63 million tonnes (i.e., 60 per cent) is recoverable by the current "room and pillar" underground methods. The balance (5.09 million tonnes) may become available for future extraction using open cut methods.

Group 2 core areas contain an estimated 1.44 million tonnes of potentially opal-bearing claystone. These reserves are located in extensively worked fields where open cut methods are the only suitable means of further extraction. Many of the fields in this group are currently designated for mining by open cut methods.

Current Department of Mineral Resources policy only permits open cut mining methods in areas considered unsafe for mining by underground methods. Two possible scenarios will therefore be considered in determining the "likely life" of the Lightning Ridge opal field:

1. ***All fields will become available for open cut mining following exhaustion by underground methods.***

   Assumptions: (i) All fields will be suitable for open cut mining in an engineering and economic sense.

   (ii) All available potentially opal-bearing claystone will be extracted.

   (iii) The extraction rate (or processing rate) will be approximately 0.206 million tonnes per year (as determined earlier herein).

   Total Available Reserves: 14.16 million tonnes

   Likely Life: Approximately 70 years.

   Comment: The probability that all existing fields will become available, or will be suitable, for open cut mining is low. If current general trends in mining and processing continue it is likely that the extraction rate of 0.206 million tonnes per year will be exceeded in the future. The estimate of approximately 70 years for the likely life of the existing opal fields at Lightning Ridge should therefore be considered to be a *maximum*.

2. ***Only group 2 core areas will be available for open cut mining.***

   Assumptions: (i) 60% of all potentially opal-bearing claystone available for extraction by underground methods will be extracted.

   (ii) All remaining potentially opal-bearing claystone in group 2 core areas will be extracted by open cut methods.

   (iii) The extraction rate (or processing rate) will be approximately 0.206 million tonnes per year.

Total Reserves: 9.07 million tonnes (i.e. 7.63 + 1.44 million tonnes).

Likely Life: approximately 44 years.

Comment: The assumption that 60% of all reserves available for mining by underground methods will be extracted is questionable. Miners have, in the past, tended to selectively follow structural features or other indicators of possible opal occurrence. However, with increasing mechanization and the use of "new technology" machinery there is a trend towards extraction of all available "opal dirt". It is also likely that not all group 2 core areas will be suitable for open cut mining, and the extraction rate (or processing rate) of 0.206 million tonnes will be exceeded in the future. The estimate of 44 years should therefore be considered a maximum for this scenario.

General Comments

The opal mining community at Lightning Ridge is divided over the issue of open cut mining. Thus significant changes in community attitude would be necessary (in addition to changes in Department of Mineral Resources' policy) for scenario 1 to be realized. This is considered unlikely. Scenario 2 indicates a maximum likely life of about 44 years. However this figure applies to existing fields at Lightning Ridge only and takes no account of new discoveries. Whilst the potential for new discoveries is considered to be good, the probability that new discoveries will be sufficiently large to significantly extend the life of the Lightning Ridge opal field is considered to be low. Thus, based on current knowledge and reasonable assumption, the Lightning Ridge opal field is considered to have a likely life of approximately *50 years*. It should be noted that this estimate excludes outlying fields (e.g., Grawin, Glengarry, etc.) and possible new discoveries away from the Lightning Ridge opal field. These aspects are considered in the following section.

GEOLOGY AND PROSPECTIVITY OF OUTLYING AREAS

The present study was undertaken partly to provide geological information to assist with future planning decisions for the Lightning Ridge township and environs. Whilst the study therefore concentrated on the Lightning Ridge opal field, the outlying fields together with unworked, but prospective outlying areas were also examined — but at a reconnaissance level only.

The areas of Cretaceous outcrop shown on figure 8, excluding the Lightning Ridge opal field, are herein termed "outlying areas". The opal fields located in outlying areas are Grawin, Glengarry, Carters Rush, Coocoran, New Coocoran, and New Angledool (Mehi). Many of these fields are separated from each other by considerable distances (e.g., Glengarry is 75 km from New Angledool). The whole of the Cretaceous outcrop has previously been considered to be potentially opal-bearing. Separate estimates of opal production from fields in the outlying areas are not available, and the quality of the opal from these fields is generally poorer than opal won from the Lightning Ridge field. Nevertheless, production is considered to be significant (particularly from Grawin and Glengarry) and should be considered in any future planning decisions. Comments on the geology and prospectivity of the outlying areas are based on the following:

1. The results of logging selected shafts and open-cuts in the Grawin, Carters Rush, Coocoran, and New Angledool fields.
2. The results of 12 widely spaced Calweld boreholes sited in unworked portions of the outlying areas.
3. The interpretation of lineaments from Landsat imagery.
4. Observations on the presence of Cainozoic sediments and the morphology of the outcrop.

These aspects are discussed below:

Results of Logging and Drilling

The weathered and altered near-surface Early Cretaceous sediments which host the opal fields in outlying areas are similar to, but are not correlatable with, the sediments which host the opal deposits at Lightning Ridge; they comprise an undifferentiated group within the Griman Creek Formation. The 12 Calweld boreholes, drilled over a distance of approximately 125 km, all intersected weathered, kaolinitic Cretaceous sediments.

In many respects the nature of opal occurrence in the outlying fields is similar to that at Lightning Ridge, i.e., most opal is found within the uppermost portion of the first impermeable bed (generally a clay bed similar to the Finch clay facies at Lightning Ridge) beneath a relatively thick (4 to 6 m) fine-grained sandstone bed. At Coocoran, New Coocoran, and New Angledool fields, the majority of opal is also found as nodules or "nobbies". At Glengarry, Grawin, and Carters Rush (opal fields southwest of Lightning Ridge) the opal is mainly found in thin (10 to 20 mm) near-horizontal seams. Most of the opal within these seams is light to dark grey potch. In general, the depth to the opal "levels" in the outlying fields varies in a manner similar to the Lightning Ridge area.

Within the known opal fields in outlying areas, Tertiary sediments (and hence Tertiary silcrete) are absent. However, much of the Cretaceous outcrop and near-surface sediments are silicified and texturally resemble the "shincracker" at Lightning Ridge. The sandstone units which overlie the various opal-bearing clay units generally show crossbedding and texturally resemble the Wallangulla Sandstone Member at Lightning Ridge. However, the laminite sequences which are common at Lightning Ridge and the outlying fields of Coocoran, New Coocoran, and New Angledool have not been observed at Grawin or Carters Rush. The apparent absence of laminites in these fields (which are all located to the southwest of Lightning Ridge) together with the nature of opal occurrence in these areas (in seams) suggests that the environment of deposition of the near-surface Cretaceous sediments may also be marginally different, perhaps slightly more terrestrial.

A total of 11 Calweld boreholes were drilled to depth (20 m to 25 m) in the unworked sections of the outlying areas. One borehole was abandoned at a depth of 8 m after intersecting red, unconsolidated ?Quaternary sands, then silcrete. An additional 6 boreholes were commenced, but were terminated at depths of less than 1.5 m because of impenetrable beds of silcrete. The location of the boreholes is shown on figure 8. Most boreholes intersected sequences of sandy claystones and clayey sandstones. All the sediments intersected were weathered and altered (kaolinitic). The more smectite-rich "mud-level" (the interface between the weathered and the less weathered and altered sediments) was generally intersected at depths of about 20 m. With regard to the potential of the outlying areas, 3 of the 11 completed boreholes (Pine Opal 1, Morella 1, and Mehi 1) intersected sequences which are regarded as prospective. The boreholes Pine Opal 1 and Morella 1 are sited adjacent to identified Landsat lineaments—which enhances the prospectivity of the areas adjacent to these boreholes.

Lineaments

The distribution of lineaments interpreted from Landsat imagery is shown on figure 8 and was described in an earlier section ("Geology - Structural Features").

The density of lineaments (identified from aerial photographs) throughout the Lightning Ridge opal field is variable. Areas of high lineament density (particularly a high density of intersections of lineaments) are correlatable with areas of high-opal productivity. Similarly, the density of lineaments identified from Landsat images throughout the outlying areas also varies. An increase in density is apparent in the Lightning Ridge-Coocoran area and south to Cumborah. To the north and south of these areas the density decreases markedly. With the exception of the New Angledool (or Mehi) field, all the opal fields in outlying areas occur within an area of increased lineament density. The outlying fields of Glengarry, Grawin, Carters Rush, and New Coocoran all occur on or adjacent to identified lineaments. In the Grawin and Glengarry areas there is also an increase in the density of lineament intersections.

Cainozoic Sediments and Outcrop Morphology

In all the opal fields in outlying areas, Tertiary sediments (and hence Tertiary silcrete) are absent. The Cretaceous sediments in these areas are generally overlain by a thin covering of Quaternary "ironstone" gravel intermixed with sandy soil.

A large proportion of the outcrop in outlying areas (possibly up to 50 percent) comprises Cretaceous sediments which are overlain by deposits of Tertiary and Quaternary sediments. The Tertiary sediments are commonly less than 2 m thick and strongly silicified (forming silcrete). The presence of silcrete is a major deterrent to prospecting in outlying areas because it cannot generally be penetrated by the Calweld drill without using explosives and jackhammers to fracture it first. This is a slow and costly process and one that is generally avoided. The presence of Tertiary silcrete therefore reduces the area of ground that can be effectively prospected. Areas where Tertiary silcrete is present are generally broad flat plateau areas, in contrast with the more undulating topography which is developed where these sediments are absent. Areas where Tertiary silcrete is present also generally support stands of Cyprus Pine and/or Ironbark trees. Stands of Box, Belah, and Sandlewood are common in areas where Tertiary silcrete is absent. The proportion of Tertiary sediments (particularly silcrete) which comprises the outcrop or subcrop (beneath a thin cover of Quaternary soil and sand) of outlying areas tends to decrease from north to south (see figure 8). The greatest recorded thickness of Tertiary sediments (approximately 4 m) is developed at Cumborah.

Summary

The increase in the density of lineaments in the vicinity of the known opal fields of Grawin, Glengarry, and Carters Rush, together with the similar nature of opal occurrence in these fields and the absence of Tertiary silcrete beds, suggest the area surrounding these fields has a high potential for future development. Boreholes Morella 1, located to the north of this area, and Pine Opal 1, located to the south of this area, intersected sequences which are regarded as prospective.

Between Carters Rush and borehole Morella 1, Tertiary silcrete is common and may discourage prospecting in this area. Between Glengarry and borehole Pine Opal 1, there are numerous lineaments and lineament intersections and an absence of Tertiary silcrete. This area is therefore worthy of future prospecting. Much of the remaining "ridge country" within areas of increased lineament density (particularly the areas west of Lightning Ridge and north to New Angledool) are covered by Tertiary silcrete (see figure 8). This probably accounts for the lack of prospecting activity in these areas in the past. There are, however, numerous outcrops of Cretaceous sediments in outlying areas which are free from Tertiary silcrete and which are possibly prospective for opal. Drilling is required in these areas to establish whether they contain a prospective geological sequence.

CONCLUSIONS

General

1. Opal mining and processing methods at Lightning Ridge are becoming increasingly more mechanized. This trend favours larger operators and small syndicates with sufficient capital to purchase and maintain "new technology" machinery.

2. Most processing of the opal-bearing claystone at Lightning Ridge is undertaken using an "agitator". Although water intensive, the agitator makes more efficient use of the available water when compared to the "wet puddler".

3. The availability of water is a major constraint on the expansion of opal production at Lightning Ridge. Water availability often directly affects the level of production.

4. The winning of "seam" opal requires no processing (i.e., water). This also results in fuel savings and could result in a shift in emphasis from the mining of nodular ("nobby") opal.

5. Open cut mining is a cost-effective method for mining nodular opal. This method has a higher recovery rate than conventional underground techniques.

6. Unauthorized use of mining purposes leases and claims (particularly for housing) has sterilized significant areas of prospective ground.

7. Opal prospecting is mainly undertaken in areas peripheral to known fields. Two forms of title are available for prospecting operations: the opal prospecting licence (OPL) and the claim. Of the two, the claim is more commonly used. Neither form of title is regarded as completely satisfactory by the opal mining industry. The lack of reporting conditions in OPL's and claims often leads to duplication of prospecting efforts. The Department of Mineral Resources is currently examining various issues relating to these forms of title.

8. At present, Calweld drilling and shaft sinking are the only permitted forms of prospecting under an OPL. Drillhole site selection in unworked areas is often random and the sample size obtained (of prospective claystone) is generally inadequate to properly assess the prospectivity of an area.

9. Prospecting in outlying areas is mainly only undertaken by small companies or syndicates. Most small miners do not have sufficient capital to conduct prospecting programmes.

10. Based on the average known water consumption figures and the known rate of water usage of the various processing methods, the rate of processing of potentially opal-bearing claystone at Lightning Ridge is estimated at 206 000 tonnes per year.

11. The establishment of two additional processing dams at Lightning Ridge (of similar size to the present complex operated by the Lightning Ridge Miners Association) is required to accommodate the current demand for sites. With these additional processing facilities it would not be necessary for private dams to be constructed on mining purposes leases which can sterilize prospective ground. The dams would need to be supplied with water from the Town Water Supply Bore to guarantee their continued usefulness.

12. A more desirable, longer term solution to the problem regarding water for processing is the development of more efficient methods for the processing of potentially opal-bearing claystone.

Geology

13. Two main periods of silicification are postulated for the Lightning Ridge region: Late Cretaceous to early Tertiary and late Tertiary. The first period of silicification appears to be related to a major weathering phase and was responsible for the formation of opal (during the early Tertiary). Silcrete was formed on mid Tertiary sediments during the second period of silicification (during the late Tertiary). Thus the frequently assumed genetic connection between the formation of opal and silcrete is considered to be incorrect for the Lightning Ridge region.

14. Analysis of the clay mineral composition of selected samples indicates that kaolinite is the dominant clay mineral in the weathered sequence. Smectite content generally increases with depth and in prospective clay lenses. The kaolinite is authigenic (i.e., has formed in place).

15. Most opal is found within the uppermost portion of the first impermeable bed (Finch clay facies at Lightning Ridge) beneath a generally thick sandstone unit (Wallangulla Sandstone Member at Lightning Ridge). There are three main geological conditions which are considered necessary for the formation of opal. These are: a source of colloidal silica (i.e., a relatively thick sandstone unit); vertically enhanced permeability (i.e., joints, faults, breccia zones); and suitable depositional sites.

16. An interpretation of lineaments from air photos and Landsat imagery indicates that the various opal fields have developed in areas where there is a high density of lineaments, adjacent to lineaments, or at the intersections of lineaments.

17. Basement features interpreted from aeromagnetic data together with data from reinterpreted drilling logs for water bores indicate that the Cretaceous outcrop in the Lightning Ridge region may, in addition to being an obvious erosional high, be a structurally high area (at least in part).

Future Prospects

18. The estimated likely life of the existing opal fields at Lightning Ridge is approximately 50 years. This figure is based on an estimation of recoverable reserves of potentially opal-bearing claystone, rates of processing, and prospects for new discoveries. The potential for significant expansion of the existing fields at Lightning Ridge based on new discoveries is considered to be low.

19. The geological occurrence of opal in the fields in outlying areas is similar to that at Lightning Ridge. However at Grawin, Glengarry, and Carters Rush, opal occurs mostly in seams and not as nodules ("nobbies"). Three Departmental boreholes (Pine Opal 1, Morella 1, and Mehi 1) in outlying areas intersected sequences which are regarded as prospective. Borehole Pine Opal 1 is located adjacent to a set of intersecting lineaments. The area surrounding this borehole is thus considered to have good prospectivity. This area is not currently located within an opal prospecting block.

20. A significant proportion of the outcrop in outlying areas (possibly up to 50 percent) comprises Cretaceous sediments overlain by Tertiary sediments

and silcrete. The presence of silcrete is a major deterrent to prospecting. The Tertiary sediments are essentially quartzose fluviatile sediments deposited in previous topographic lows. These topographic lows probably developed in areas where the Cretaceous sediments were only weakly silicified or not silicified at all during the first period of silicification (to which opal formation is assigned). Hence areas of Tertiary sediments (and silcrete) probably represent areas with low opal prospectivity.

21. The absence of Tertiary silcrete, a high density of lineaments and lineament intersections, and the occurrence of known prospective sequences in the outlying fields of Carters Rush, Grawin, and Glengarry indicate that the unworked areas between these fields have a high potential for future development.

PROSPECTING GUIDES

On the basis of the results obtained during this investigation the following guides for prospecting are suggested:

1. The potential for the occurrence of opal is greatest in areas of Cretaceous sediments with high lineament density; in particular, in areas which have a high density of lineament intersections. Figures 8 and 9 show the location of identified lineaments in the Lightning Ridge region and should be used as a guide for area selection.
2. The potential is probably higher in areas where Tertiary sediments (particularly silicified Tertiary sediments or silcrete) are thin or absent. Areas of silcrete are commonly characterized by stands of Ironbark or Cyprus Pine trees. Areas of identified silcrete occurrence are shown on figures 8 and 9.
3. The most prospective Cretaceous sequence comprises a relatively thick sandstone unit overlying an impermeable clay or claystone unit in the upper portion of the weathering profile (generally at a depth of less than 25 m).
4. Small-scale faults, subvertical joints, and subvertical breccia zones are important features which may have localized opal deposition. The hanging wall side of a fault plane appears to be generally more prospective than the footwall side.
5. Small-scale rolls and domes, commonly present at the sandstone-claystone interface, may also act as a control on opal deposition.
6. Certain geophysical techniques (SIROTEM, resistivity, and seismic refraction) may be useful at Lightning Ridge in locating the uppermost opal-bearing claystone lens (Finch clay facies) or the "steel band", which is present in some places immediately above this lens. If any of these techniques were found to be successful, regional surveys could be undertaken in parts of the outlying areas with high prospectivity. A suitable geophysical technique could have the potential to not only significantly reduce the costs of prospecting, but also make prospecting efforts more effective.

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