AUSTRALIAN SEDIMENTARY OPAL – WHY IS AUSTRALIA UNIQUE?

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ABSTRACT

Australia currently produces about 95 per cent of the world's precious opal from widely scattered fields throughout central Australia. No other country on Earth has such an abundance of this rare precious gemstone.

The sedimentary opal deposits of central Australia occur along generally flat-lying horizontal layers within 30 metres of the earth's surface. They are a product of a unique set of geological events which occurred over a 100 million year period. These events can be summarised as follows:

1. Between about 122 million years ago (Ma) and 91 Ma, central Australia was covered by a vast shallow epicontinental sea. The sedimentary rocks which were deposited in this sea were derived from volcanic rocks and were organic-rich. These formed the principal host rocks for opal deposits in central Australia.
2. Following surface exposure through lowering of the sea level, these host rocks were subject to a prolonged sub-tropical weathering regime until about 40 Ma. Central Australia probably looked not unlike today's Amazon Basin. During this time, the water table was close to the surface and was acidic releasing silica and iron from weathering of the host rocks.
3. The climate became more arid from about 40 Ma and, as a result, water table levels gradually lowered and the groundwater became alkaline. Mild tectonism at 24 Ma gave rise to subtle extremely long wavelength surface folds which facilitated both lateral and vertical migration under arid conditions of the earlier-released silica. Opal was preserved in the weathered profiles beneath the crests of the developing surface folds as water tables here lowered more rapidly due to tectonic uplift. Siliceous cap rocks discouraged erosion.
4. Over the last 10 million years, dissection and scarp erosion exposed the weathering profiles containing the opal.

Geologists believe that the volume of gems that have been produced over the past 150 years in Australia is but a minute fraction of the amount yet to be discovered.

INTRODUCTION

The opal is the National Gemstone of Australia. Australia currently produces approximately 95 per cent of the world's precious opal and probably has almost all of the world's opal reserves. The only other significant producers are Mexico and Brazil although the deposits in Slovakia and the Czech Republic once provided the bulk of the world's production for over 2,000 years. Other countries where opal has been recorded include Guatemala, Honduras, Nicaragua, the western USA and Canada, Indonesia, Turkey and Ethiopia (Figure 1). With the exception of deposits in Australia and Brazil where most opal deposits are contained in sedimentary rocks, almost all of the remainder are hosted by volcanic rocks. Volcanic-hosted precious opal is generally considered inferior to the more brilliant sedimentary rock-hosted varieties.

This paper examines the depositional, palaeo-weathering, and tectonic history of central Australia in an attempt to define the factors that made Australia a unique environment for the formation and preservation of precious opal.

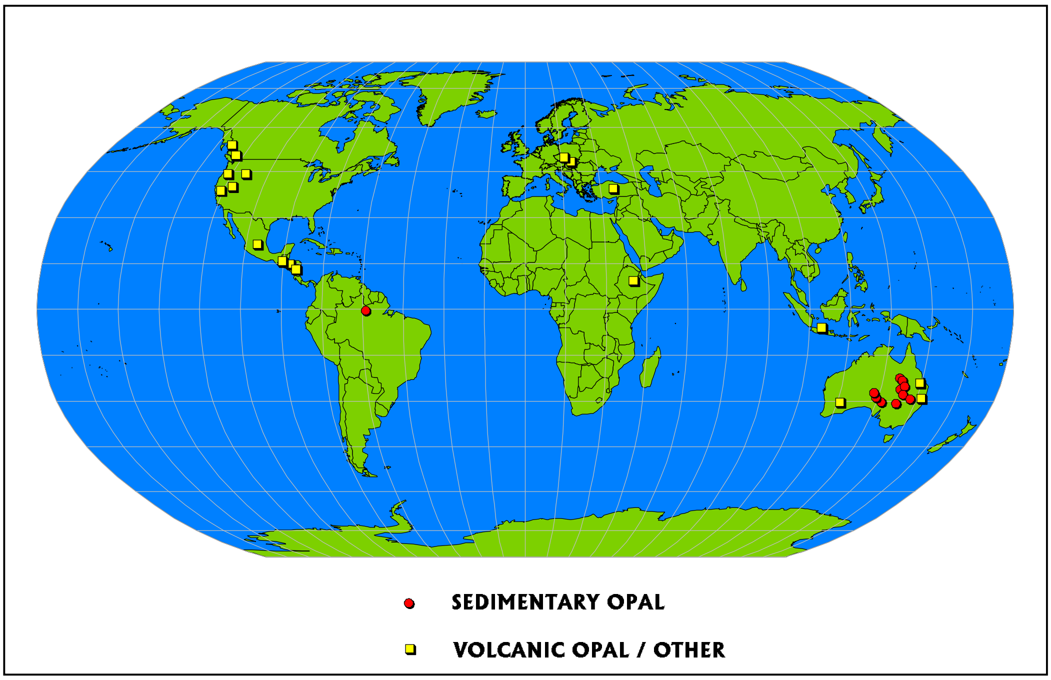

Figure 1: *Precious Opal Deposits of the World*

GEOLOGICAL AND PALAEOWEATHERING RECONSTRUCTION OF THE AUSTRALIAN OPALFIELDS

Early Cretaceous Host Rocks

In central Australia, with the exception of the deposits of the Mintabie opal field in South Australia, opal is almost entirely hosted in chemically-weathered rocks of Cretaceous age (Figure 2) representing the maximum extent of the Eromanga and Surat Basins at this time. More specifically, the host rocks range in age from Barremian to Cenomanian (approximately 122 Ma to 91 Ma). The Mintabie opal field is hosted by kaolinised ?Ordovician sandstones which lie stratigraphically beneath the Cretaceous rocks.

Based on the compilation by McKellar (2002; in press) as well as data from other sources (eg Price, 1997; Burger, 1986), the ages of the various host rocks to the opal fields in Australia are shown in Table 1. Note that the host rocks generally become younger in age towards the north-east of the continent.

Opal Field	Host Unit	Stratigraphic Age*	Absolute Age Equivalent
Queensland fields	Winton Formation	Cenomanian	98 - 91 Ma
Lightning Ridge	Griman Creek Formation	Late Albian	103 - 101 Ma
White Cliffs	Doncaster Member	Late Barremian - Aptian	120 -110 Ma
Andamooka Coober Pedy Stuart Creek Lambina	Bulldog Shale (Marree Subgroup)	Barremian - Early Albian (Barremian - Albian)	122 -103 Ma (122 - 98 Ma)
Mintabie	Mintabie Beds	?Ordovician	

Table 1: *Ages of the Respective Host Rocks to Opal Mineralisation (*with the exception of Mintabie, stratigraphic ages shown are subdivisions of the Cretaceous Period)*

The opal deposits themselves are much younger than their dominantly Cretaceous age host rocks. Consequently, it is important to understand why weathered rocks of this 30 million year period are preferred hosts to opal mineralisation.

The most extensive marine transgression to affect Australia since the early Palaeozoic occurred during the Early Cretaceous (Figure 3; BMR Palaeogeographic Group, 1992) with the peak of transgression occurring in the Late Aptian (Exon & Senior, 1976; Burger, 1986). The provenance of the Early Cretaceous sedimentary rocks also changed at this time from being derived from siliceous basement rocks and sediments (Aptian) to andesitic volcanics (Albian) (Exon & Senior, 1976; Slansky, 1984). This change is also reflected in the composition of their contained groundwaters (Muller, 1989) with sodium bicarbonate waters predominating in the older rocks and sodium chloride waters (with higher salinities) in the younger rocks.

The Cretaceous host rocks, shown in Table 1 and the central part of Australia in Figure 2, comprise a mixture of sediments deposited in a large shallow epicontinental sea partially surrounded by a wide belt of deltas, brackish lagoons, estuaries and wide coastal plains. During this period, the sea level was higher than it is today and successive episodes of high and low global sea level were manifested as regional marine transgressions and regressions (Burger, 1986; Frakes & others, 1987). Glauconie, a rock containing rounded green grains with a variable mixture of illite, montmorillonite and chlorite, has long been recognised as characteristic of the marine Cretaceous sequence in this region (Exon & Senior, 1976). Of the host lithologies listed in Table 1, the Winton Formation and portions of the Griman Creek Formation are freshwater, while the remainder are marine.

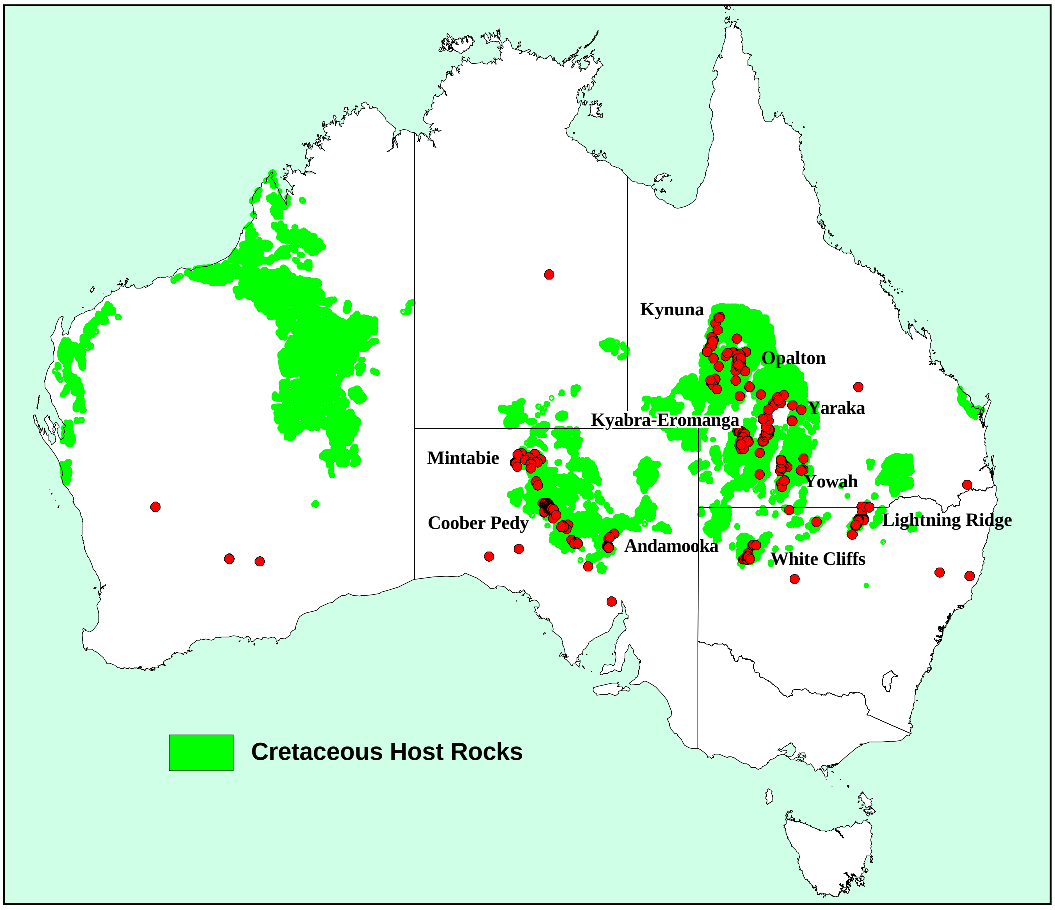

Figure 2: *Australian Opal Occurrences*

The period from Aptian to Albian was the time large quantities of black shales and organic-rich sediments accumulated in many oceans and basinal settings (Frakes & others, 1992). For example, McKirdy & others (1986) note that the Bulldog Shale is one of several organic-rich Early Cretaceous units in the Eromanga Basin sequence that, given appropriate dispersed organic matter and adequate thermal maturity, could be effective source rocks for petroleum hydrocarbons. The lower one-third of the unit, which is time equivalent to the Doncaster Member, is particularly dark and shaley.

In the absence of comparative whole rock geochemical data, there could be several reasons why weathered Cretaceous rocks of this particular 30 Ma period from the Barremian to the Cenomanian are preferred hosts to opal mineralisation. These factors could be:

1. the high organic content of the host rocks. However, this is variable and could have more to do with the type of opal found (eg black opals).
2. their andesitic provenance which is reflected in their clay mineralogies. However the type and content of clay species differ from opal field to opal field.
3. their presumed high sulphide content. Relict sulphate minerals are still present in many weathered profiles (eg Coober Pedy) but are rare in others (eg Lightning Ridge).
4. the presence of occasional carbonate. Coquina layers, for example, are present in the base of the Griman Creek Formation (Exon & Senior, 1976) and calcite nodules are common in the Winton Formation (Senior & others, 1978).
5. the presence of glauconie. However Exon & Senior (1976) note that while it is abundant in some units (eg Doncaster Member), it is rare in others (eg Winton Formation).
6. a combination of all five above.

Late Cretaceous / Early Tertiary Weathering

The period from the mid-Cretaceous (mid-Albian) to the mid-early Eocene (~105 Ma to 55 Ma) was one of the warmest times in the late Phanerozoic. The average global temperature was probably about 6ºC higher than that of today allowing polar regions to be free of permanent ice. The mid-Cretaceous was also a time of globally high sea levels and extensive areas of shallow shelf seas favouring moderate climates and increased evaporation and precipitation. This is in contrast to the middle Jurassic to early Cretaceous which was cool (Frakes & others, 1992).

Following lowering of the sea level (shown diagrammatically in Figure 3) a prolonged sub-tropical (warm and wet) deep weathering event affected central Australia from the Late Cretaceous to at least the mid-Eocene (Senior & others, 1997; Bird & Chivas, 1989; 1993; Benbow, 1983; Spath, 1987). However sedimentation in the Lake Eyre Basin (Eyre Formation, Glendower Formation, Marion Formation) from the Late Palaeocene to the end of the Middle Eocene impeded the uniform development of deeply weathered profiles over much of central Australia during this time.

Prior to the deposition of the Eyre Formation, the Morney Profile (Senior & others, 1977; Senior & Mabbutt, 1979), a weathering profile of Late Cretaceous and Palaeocene age, affected western Queensland and the Lake Eyre and Eucla Basins (Alley, 1998; Benbow, 1983). This profile, believed to be caused by acid leaching of Cretaceous rocks, is in excess of 90 m thick and is characterised by pedogenic silcrete overlying a kaolinite-rich profile with a lower ferruginous zone often containing concretions or accumulations parallel to bedding. Some of the ironstones may have replaced former calcareous horizons (Senior & Mabbutt, 1979). Often the siliceous duricrust cap of the Morney Profile is thin, sparsely distributed or missing.

Idnurm & Senior (1978) using palaeomagnetic studies of ironstones from the lowest zone of the Morney Profile point to a Late Cretaceous to Early Eocene age for this profile, consistent with stratigraphic relationships. The Eyre Formation unconformably overlies the Morney Profile. Basal strata of the Eyre Formation contain clasts of the Morney Profile (Idnurm & Senior, 1978; Senior, 1979). It is likely that weathering of the Morney Profile was partly contemporaneous with deposition of the Eyre Formation in structural depressions.

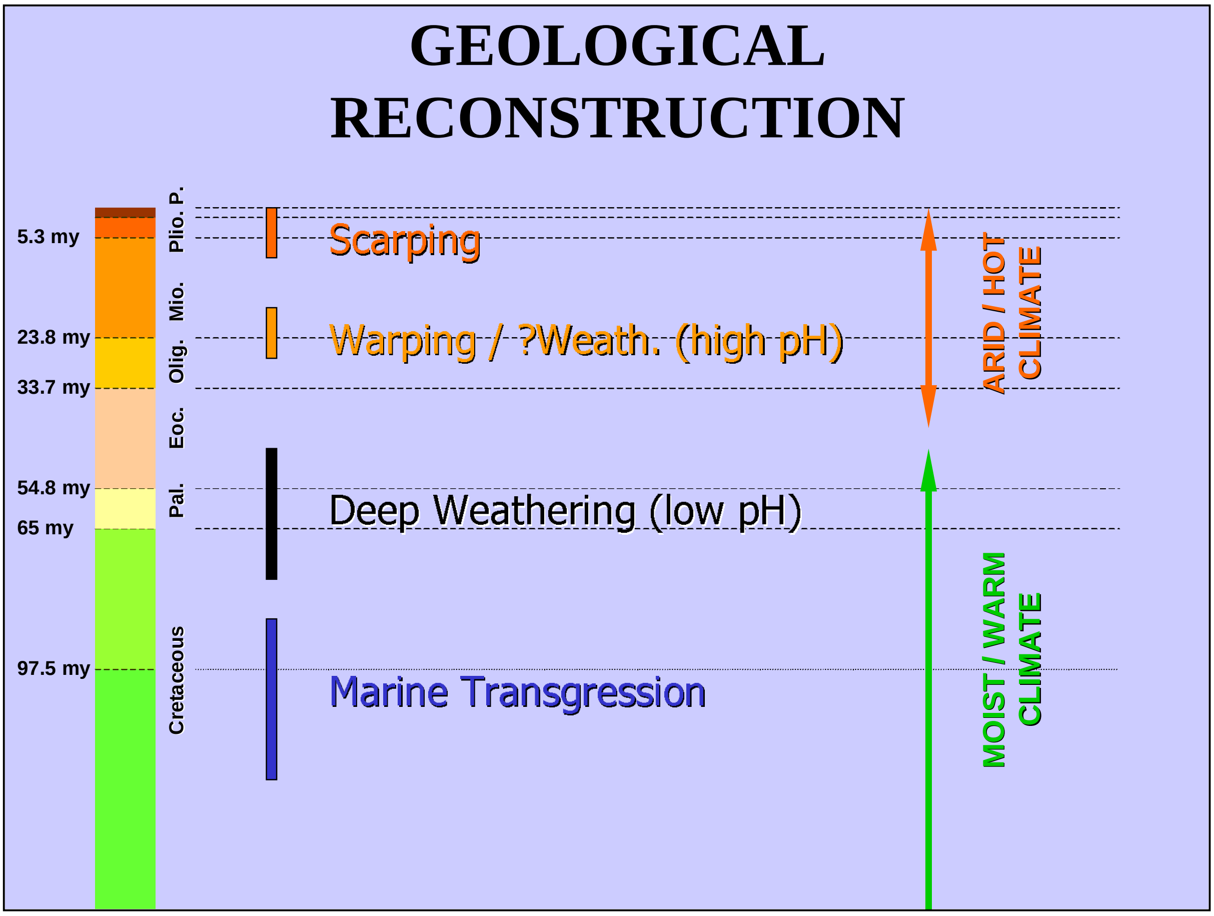

Figure 3: *Timeline for Opal Development in Central Australia*

The association of opal mineralisation with kaolinised Cretaceous host rocks has been noted by all previous researchers (eg Barnes & Townsend, 1990; Watkins, 1999; Krosch, 1983). It is likely that these rocks would have been subject to particularly intense weathering, exacerbated by both biota and acid leach conditions (marsh-like environments) during the development of the Morney Profile and time equivalent profiles. The high organic and sulphur contents of these rocks would have promoted this type of weathering. It would also help explain why rocks immediately adjacent to Cretaceous host rocks (eg the underlying ?Ordovician sediments at Mintabie) might also be affected by this style of weathering and also host opal mineralisation.

Late Tertiary Weathering, Warping and Dissection

From the mid-Eocene, the climate in Australia became progressively drier (Figure 3) until by Miocene times central Australia was dominated by alkaline lakes (Alley, 1998). The sub-tropical style of weathering prevalent in the Early Eocene also slowly changed and resulted in the development of more arid siliceous and ferruginous duricrusts. The materials for these were derived, to a large extent, from the earlier weathering profiles. Drier conditions also allowed the formation of minerals such as alunite and gypsum in the weathered profiles.

Several weathering surfaces (including silcrete horizons) formed during the ?Late Oligocene. These include the Canaway Profile of western Queensland (Senior & others, 1977; Senior & Mabbutt, 1979), silcrete of the Cordillo Surface of northern South Australia (Wopfner, 1974; 1978) and siliceous duricrusts of the Curalle and Haddon Silcrete Profiles (Senior & Mabbutt, 1979). Similar silcrete horizons can be found in the coeval Glendower Formation of western Queensland (Ingram, 1968) and the Eucla Basin in southern Australia (Benbow, 1983). In eastern Australia, silcretes of comparable age can be found beneath basalt cover (Connolly, 1983; Gunn & Galloway, 1978; Webb & Golding, 1998). Many of these surfaces may be time equivalents as exact dating of them is imprecise.

At least one period of mild tectonism is recognised in central Australia during Late Oligocene-Early Miocene times (Jones & Segnit, 1966; Ingram, 1968; Hutton & others, 1978; Grimes, 1983). This is represented by broad-wavelength folding and faulting (warping) Fold wavelengths are of the order of 2 to 50 km or more with amplitudes of the order of 20 to 200 m. Many of these surface anticlines are covered with silcrete and several early authors interpreted this to mean that the silcrete horizons had been folded (Ingram, 1968; Hutton & others, 1978; Summerfield, 1983).

It appears more than coincidental that Late Oligocene-Early Miocene tectonism is more or less contemporaneous with the main period of silcrete development. Several authors (eg Ingram, 1968; Senior, 1978; Wopfner, 1974) have independently noted that silcrete of this age is best developed on the crests and flanks of these surface anticlines and weakly developed or absent in the intervening synclines which are often sediment-filled. Weathering profiles which developed during this period also show a similar distribution with the best-developed profiles on anticlinal crests. The silcrete on the crests of the anticlines is dominantly pedogenic (eg Curalle Silcrete Surface) and that on the flanks is of groundwater origin (eg Haddon Silcrete Profile) (Figure 4). The groundwater silcretes often occur as multiple layers which are interpreted as being caused by lowering of the water table. That is, they are contemporaneous with folding.

A variety of ages have been ascribed to opal development in central Australia, from the Late Cretaceous to Pliocene with a mid-Tertiary age (Late Oligocene or Early to mid-Miocene) considered most likely (Senior & others, 1977; Jones & Segnit, 1966; Bird & others, 1990; Simon-Coincon, 1996). This age is more or less contemporaneous with warping and silcrete development. However it is important to realise that, in general, the ages of opal mineralisation at individual fields are poorly constrained.

While it is possible that there may be several ages of opal formation in central Australia, it appears most likely that the bulk of central Australia's opal formed either contemporaneously with, or immediately following, the folding event at approximately 24 Ma. This period meets all the requirements for opal formation and affords an environment for its preservation:

- There is strong evidence of silica mobilisation in and around anticlinal crests (as demonstrated by the deposition of groundwater silcrete adjacent to the anticlines) (Figure 4). Note that the gradients on these topographic highs are extremely slight. The steepest grades are of the order of 1 in 20 but commonly they may be 1 in 1,000 thus allowing for slow groundwater movement under arid conditions; an ideal situation for silica deposition.

- Weathering profiles, with which opal has a close association, are most strongly developed on the crests of the anticlines.
- The water tables in these anticlinal regions lowered at this time (as demonstrated by stacked multiple groundwater silcretes on their flanks and corresponding multiple opal horizons in the higher parts). Opal formation seems to be an immature phase in the development of a silicification profile with opal precipitated in voids at the bottom of the profile and quartz towards the top (Twidale & Hutton, 1986; Thiry & Millot, 1987; Milnes & Thiry, 1992). Preservation of opal can either be through silica (silcrete) plugging the upper part of the profile or through a permanent lowering of the water table.
- Pedogenic silcrete on the crest of the anticlines considerably slowed their erosion.

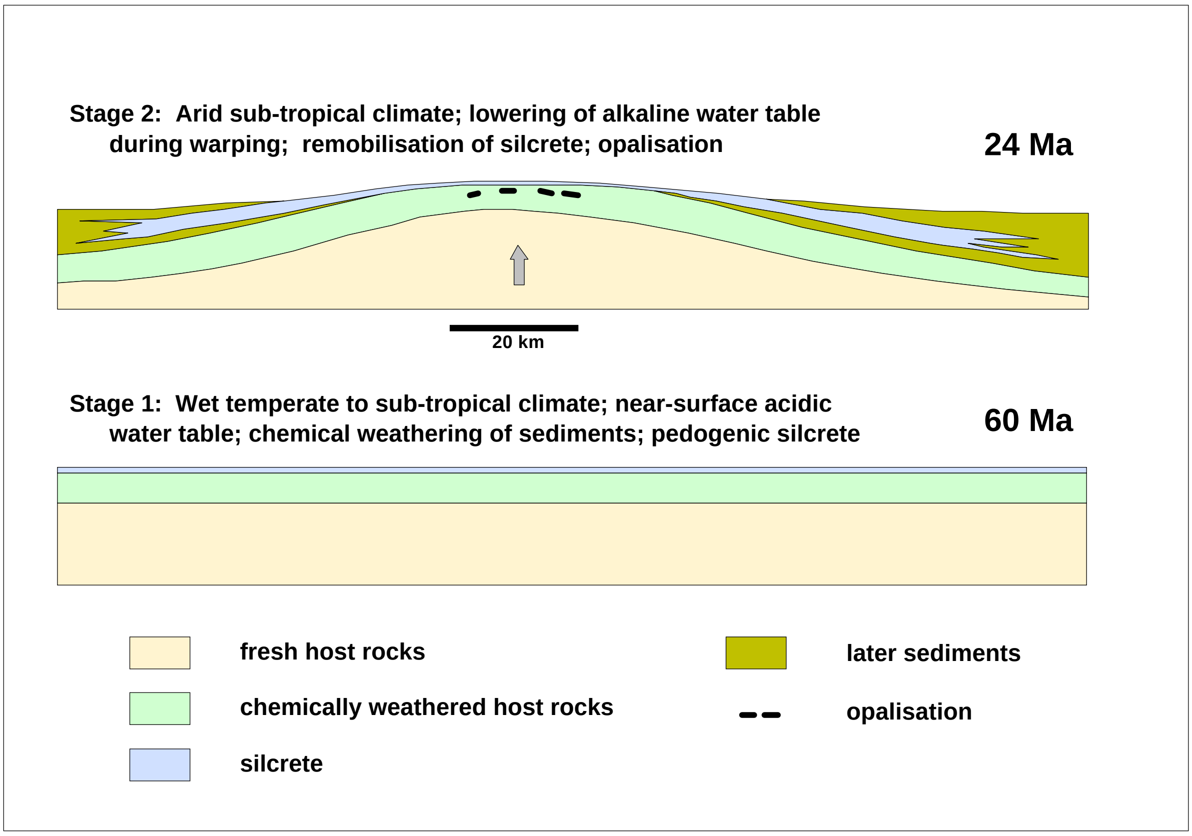

Figure 4: Model of Silcrete Formation and Opal Deposition / Preservation in Central Australia (based on Senior & Mabbutt, 1979)

There is a clear relationship between the distribution of opal mineralisation and subtle topographic highs in most parts of central Australia. However, because of their subtlety, anticlines are not always recognised. For example on the Coober Pedy 1:250,000 Geological Sheet, silcrete forms a capping to a north-west trending anticline with a wavelength in excess of 50 km and an amplitude of 50 m. Opal mineralisation at Coober Pedy is restricted to the upper-most portion of the anticline. The north-eastern portion of this anticline has been eroded. Similar anticlines contain opal mineralisation at Andamooka, Mintabie and elsewhere in their crestal parts. At Lightning Ridge, a possibly more complex anticlinal feature is evident as a low ridge 25 m high (Watkins, 1985) extending in a northeasterly direction into Queensland (the "Lightning Ridge trend"). Similar extremely broad anticlines with opal mineralisation in the fold crests can be found in Queensland.

A lengthy Plio-Quaternary erosion scarp, approximately 20 m high, situated immediately north-east of the opal fields of South Australia forms the south-eastern watershed of the Lake Eyre catchment (Simon-Coincon & others, 1996). This limits the distribution of opals here to the north-east. It is the formation of scarps such as this that has allowed precious opals to be found in the dissected profiles.

Preservation

Darragh & others (1976) note that opal cannot survive exposure to the effects of surface weathering for any appreciable period. Under those conditions, hydrated amorphous opaline silica tends to lose water and to become cracked and opaque. Likely there are also other environmental conditions in nature which will result in the destruction of opal. For example, altered groundwater conditions, either though a change in pH or through the water being silica charged may be sufficient to destroy opal or convert it into other forms of silica. Little is understood about these processes. An understanding of the environmental conditions that can destroy opal is as important as understanding the factors that influence its formation.

Extremely low rates of denudation (0.2 metres per million years) in central Australia in the Tertiary and Quaternary has allowed Tertiary and older weathering profiles to be preserved to the present day (Gale, 1992).

DISCUSSION

A unique combination of geological events appear to have taken place in central Australia over the last 100 million years to form precious opal. These are:

1. deposition of volcanic-derived organic-rich sediments over a 30 million year period during the Cretaceous,
2. weathering under warm wet acidic conditions from the Late Cretaceous to the mid-Eocene which released silica and iron,
3. remobilisation of the silica under warm arid alkaline conditions during a period of tectonic instability during the Late Oligocene-Early Miocene, and
4. preservation of the opal forming in the weathering profile through lowering of the watertable.

There is still much that is not understood about the specifics of the genesis of precious opal particularly at the micro scale. How does it form in the weathering profile? For example, is bacteria involved? Irrespective of the method, there is now general consensus for two styles of opal formation – void fill and replacement. Deposition of precious opal occurs mostly by replacement of layer-silicate clays, gypsum, calcite, goethite, fossils and organic material as well as by infilling of voids particularly in ironstone.

One point of interest to come out of this study is that not only does there appear to be one age of opal formation for sedimentary rock-hosted opal in Australia but there are indications that the isolated occurrences of volcanic-hosted opal in the eastern part of the continent is also of the same age. While further age dating will be required to confirm this point, it is nevertheless interesting to speculate on what environmental or biological conditions were present in Australia 24 Ma to promote the formation of precious opal in such a wide variety of environments.

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