Australian Opal - How did it form?

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Introduction

Precious opal is an iconic jewel for many Australians, and is Australia's National Gemstone: we produce over 95% of the world's supply. Opal is found in many geographic locations within the Cretaceous sediments (100-113 million years old) of the Great Artesian Basin (GAB) (Figure 1). How these precious stones formed is still the subject of much debate amongst geologists and miners'. A better understanding of the genesis of these deposits will help explorers find new deposits to maintain the Australian Opal Industry in the future. This case study of the Lightning Ridge Opal Fields examines the geological setting of the deposits and explores three scientific models that endeavor to explain how opals may have been formed in the GAB.

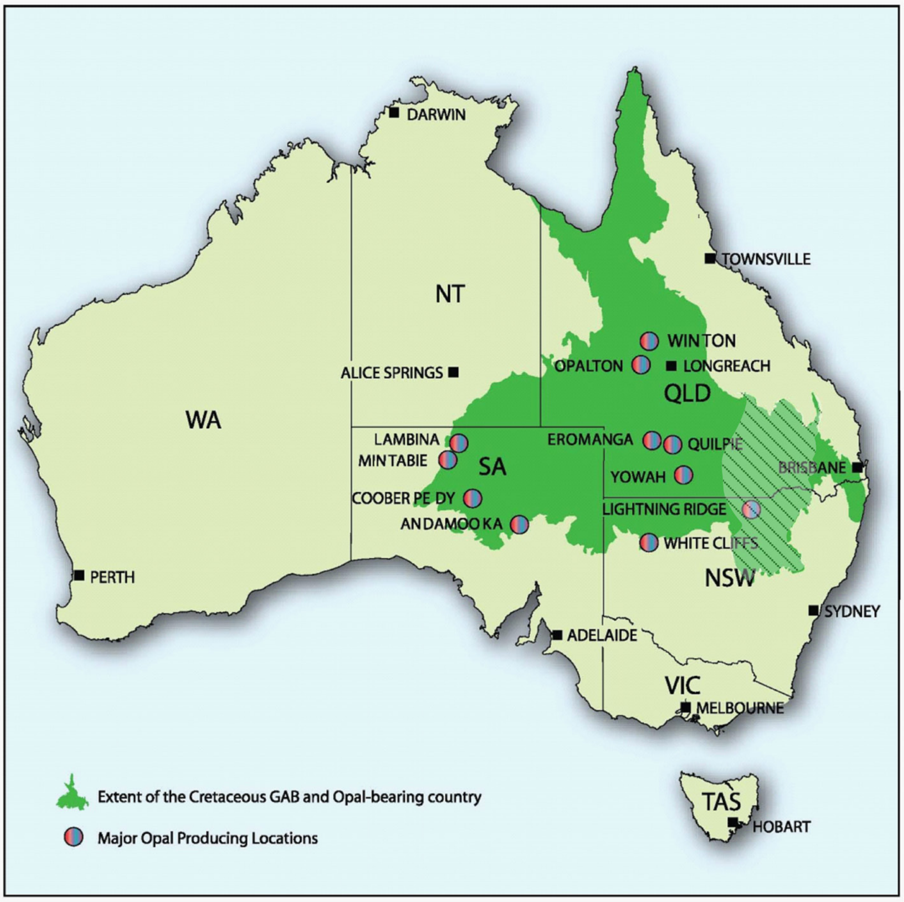

Figure 1. Distribution of major opal producing areas in the Great Artesian Basin. Miocene Epoch age opal deposits are mainly hosted by highly fractured sedimentary rocks of Cretaceous age. The Lightning Ridge opal deposits occur within a smaller sub-basin, known as the Surat Basin. Graphic by Dr. S. Pecover.

Opal is composed of a hydrated form of silica ($SiO_2.nH_2O$) and precipitated from solutions rich in silicon to form a viscous silica gel containing molecular water. Australian opal is known as Opal-AG (Amorphous Gel). Solidified amorphous silica is similar to glass in that it has no atomic crystalline structure.

There are two types of opal in GAB rocks: the common potch and the much rarer precious opal. Precious opal is a gem made of silica spheres which are arranged in an orderly packing array which diffracts white light into different spectral colours (Figure 2A & 2C). In contrast, potch opal is made of a jumbled mass of silica spheres which does not diffract white light (Figure 2B).

The orderly arrangement of silica spheres in precious opal forms photonic colloidal crystals (Figure 6B), which are similar to atomic crystalline structures, but are composed of much larger (than atoms) silica sphere nanoparticles (Figures 2A & 2C). These colloidal crystals diffract white light (Figure 2C), so that the light returning to the eye is seen as a spectrum of flashing colours when the gem is rotated.

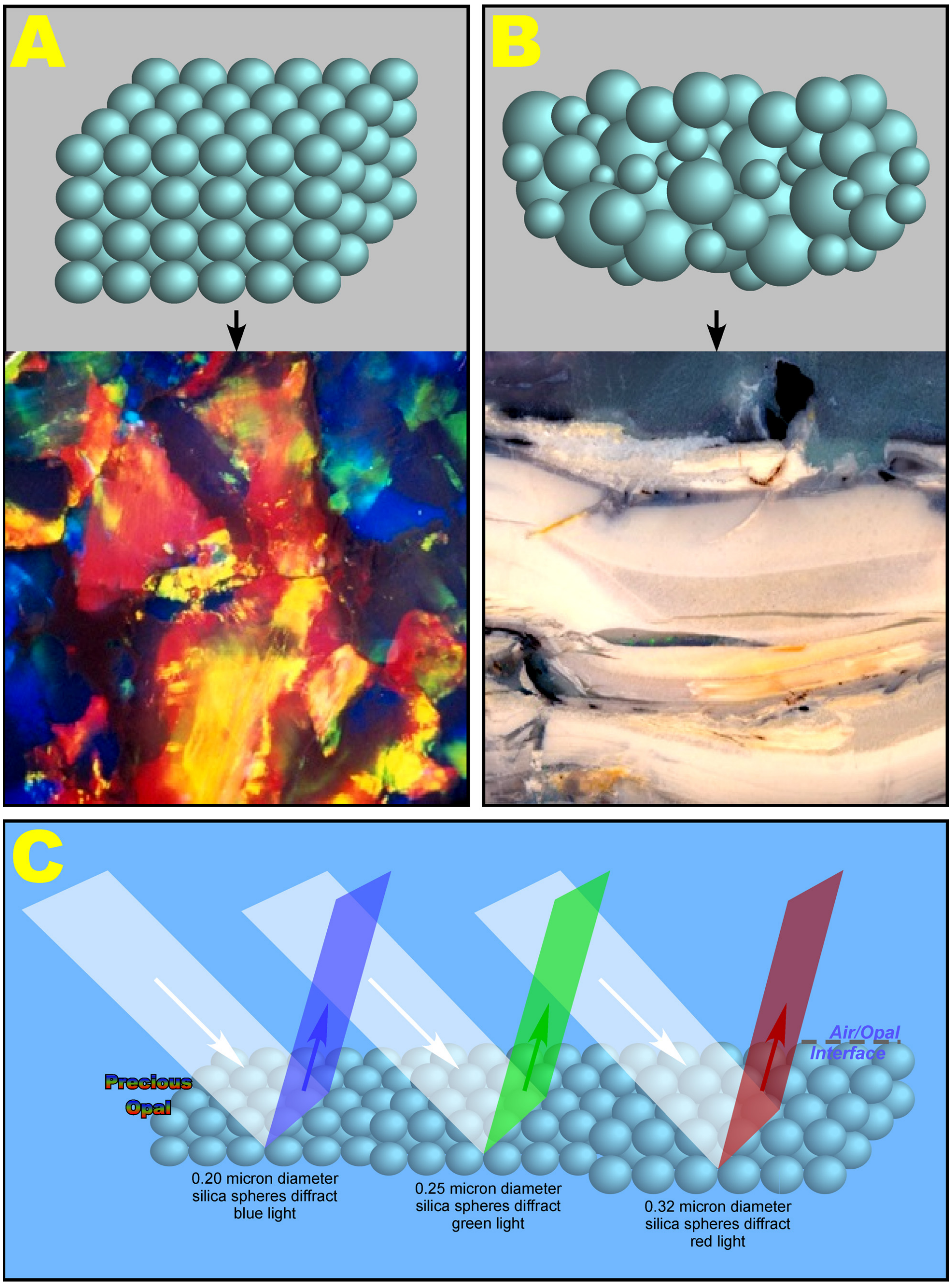

Figure 2. Differences between precious opal and potch opal. A shows orderly packing of silica spheres at the top, making-up the precious opal at the bottom. B shows disordered packing of silica spheres at the top, making-up the potch opal at the bottom. C shows how the colour of precious opal is produced by light diffraction through an orderly packing of silica spheres, with smaller spheres producing blue light through to larger spheres producing red light. Graphics and photos by Dr. S. Pecover (A,B & C).

Both potch and precious opal in GAB rocks typically occur in sub-horizontal and sub-vertical veins, as well as infillings in ironstone concretions, or as replacements of shell, bone and plant fossils. These accumulations of Opal-AG are mainly confined to clay-rich rocks within layered sedimentary sequences comprising sandstones and claystones.

Opal deposits in GAB rocks are typically associated with areas of gently warped sedimentary strata which have been highly faulted and fractured. Normal and reverse faults are common in opal-producing areas.

Lightning Ridge—home of the famous 'black opal'—in north-western New South Wales has opal deposits that provide an excellent example of the geology and formation of opal deposits in the GAB.

Lightning Ridge Opal Fields

Regional Geological Setting

The Cretaceous opal-hosting sedimentary rocks at Lightning Ridge occur within the Surat Basin, which is one of several smaller sedimentary basins making up the GAB (Figure 1). These sedimentary rocks have been gently warped into a series of north-east trending discontinuous ridges.

Stratigraphy and Lithology

The opal fields occur within GAB Rolling Downes Group rocks, and are locally referred to as 'Lightning Ridge Group' sediments, where they form the upper ~50 m of the Griman Creek Formation. The Lightning Ridge Group sedimentary rocks mainly comprise the Coocoran Claystone Member which overlies the Wallangulla Sandstone Member. The vein opal deposits themselves are generally confined to discontinuous claystone lenses within the Wallangulla Sandstone Member and are referred to locally as the 'Finch Clay Facies' (Figure 3).

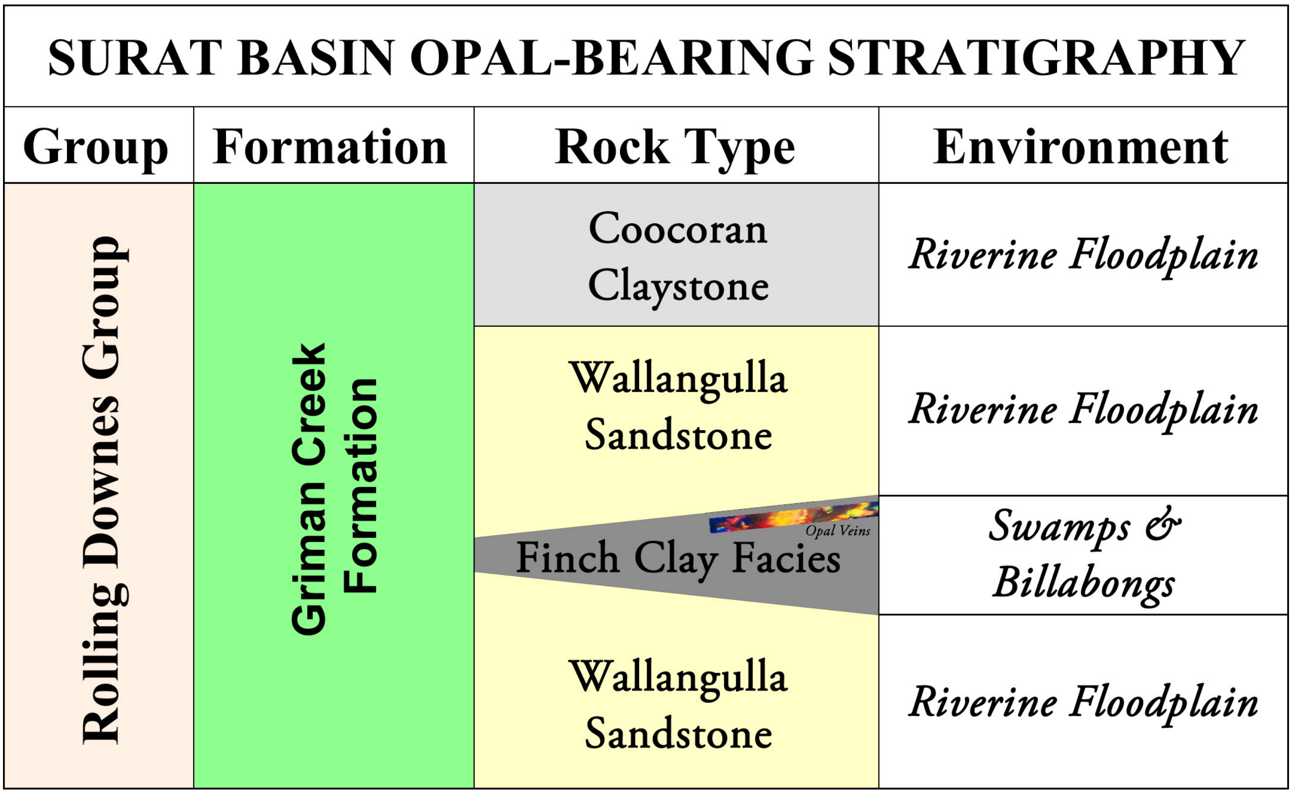

Figure 3. Stratigraphic and lithologic relationships of opal-bearing host rocks at Lightning Ridge. The opal occurs in sub-horizontal veins associated with locally faulted and fractured lenses of Finch Clay Facies rocks, which are enclosed within the Wallangulla Sandstone Member. Graphic by Dr. S. Pecover.

In the opal workings, the Wallangulla Sandstone Member occurs as a fine to medium-grained, white to salmon-coloured sedimentary rock. It consists of ~60% kaolinised feldspar, ~20% quartz and ~10% lithic fragments, all set within a much finer-grained matrix of clayey material comprising ~10% of the total rock mass. The thickness of this unit is highly variable and ranges from <1 m to >6 m.

Lenses of Finch Clay Facies sediments consist of very fine-grained laminated clays, commonly displaying in thicker units light-grey kaolinite-rich upper sections and darker greyish-brown smectite-rich lower sections. The lenses range from several centimetres to several metres thick. The distribution of these claystone lenses within the Wallangula Sandstone is highly variable. Fresh to brackish-water vertebrate and invertebrate fossil remains are common in the Finch Clay Facies, while some opal producing areas also contain abundant plant fossil remains.

When the Finch Clay Facies hosts opal veins and opalised fossils, it is known locally as the 'opal level'. Opal veins are commonly located within the first half metre at the top of the Finch Clay Facies, within zones that show evidence of tensile fracturing, layer-parallel slippage and crude foliation immediately below overlying sandstones. These opal producing zones are referred to locally as the 'opal horizon'. An important characteristic of the opal horizon is that it consists of claystone which has been highly faulted and fractured, both horizontally and vertically. The opal veins in these claystones generally occur within sub-horizontal Mode-1 tensile fractures crudely parallel to sedimentary bedding.

Faults and Related Fractures

Faulting observed in open-cut and underground exposures across the Lightning Ridge Opal Fields comprise complex mixtures of fault types, including normal and reverse faults (Figure 4). These faults can severely disrupt the 'opal level'. Numerous sub-vertical and sub-horizontal fractures typically accompany areas of intense faulting.

Breccia Pipes

In all the opal fields, pipe-like 'chimneys' of broken rock (breccia) occur in areas of intensely vertically fractured rock (Figure 5). These breccia pipes are known locally as 'blows' and occur as vertical to sub-vertical cylindrical, cone, wedge or irregular-shaped structures. The pipes range in diameter from several centimetres to several metres and can be several tens of metres in length, occasionally breaking through to the surface.

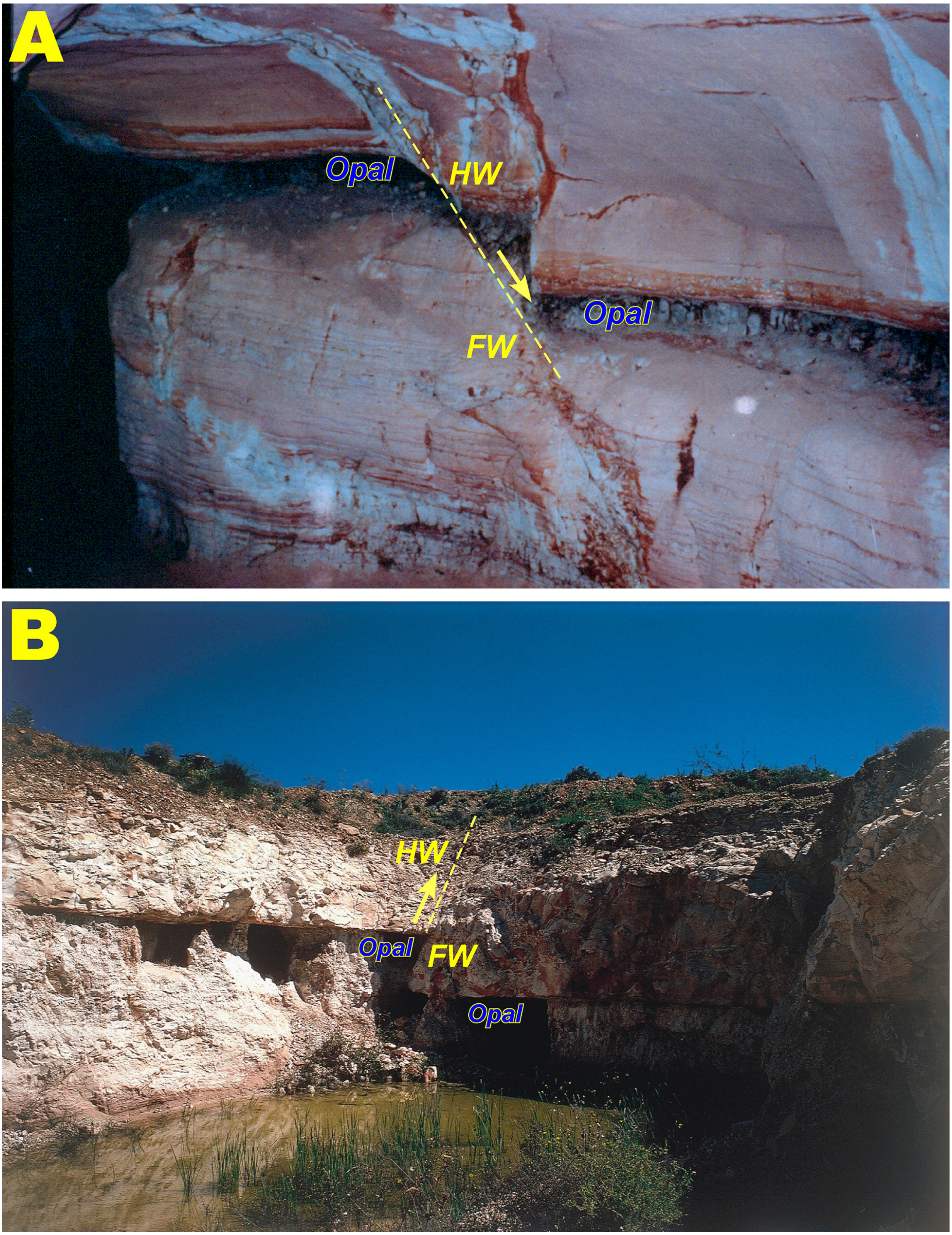

Figure 4. Faults at Lightning Ridge, with opal occurring on both sides of the fault planes (yellow dashed lines). A shows a normal fault, where the hanging wall (HW) has moved downwards relative to the foot wall (FW). B shows a reverse fault where the hanging wall has moved up relative to the foot wall. Normal faults are formed during extension, while reverse faults are formed during compression. Photos by Dr. S. Pecover (A) and Mr S. Aracic (B).

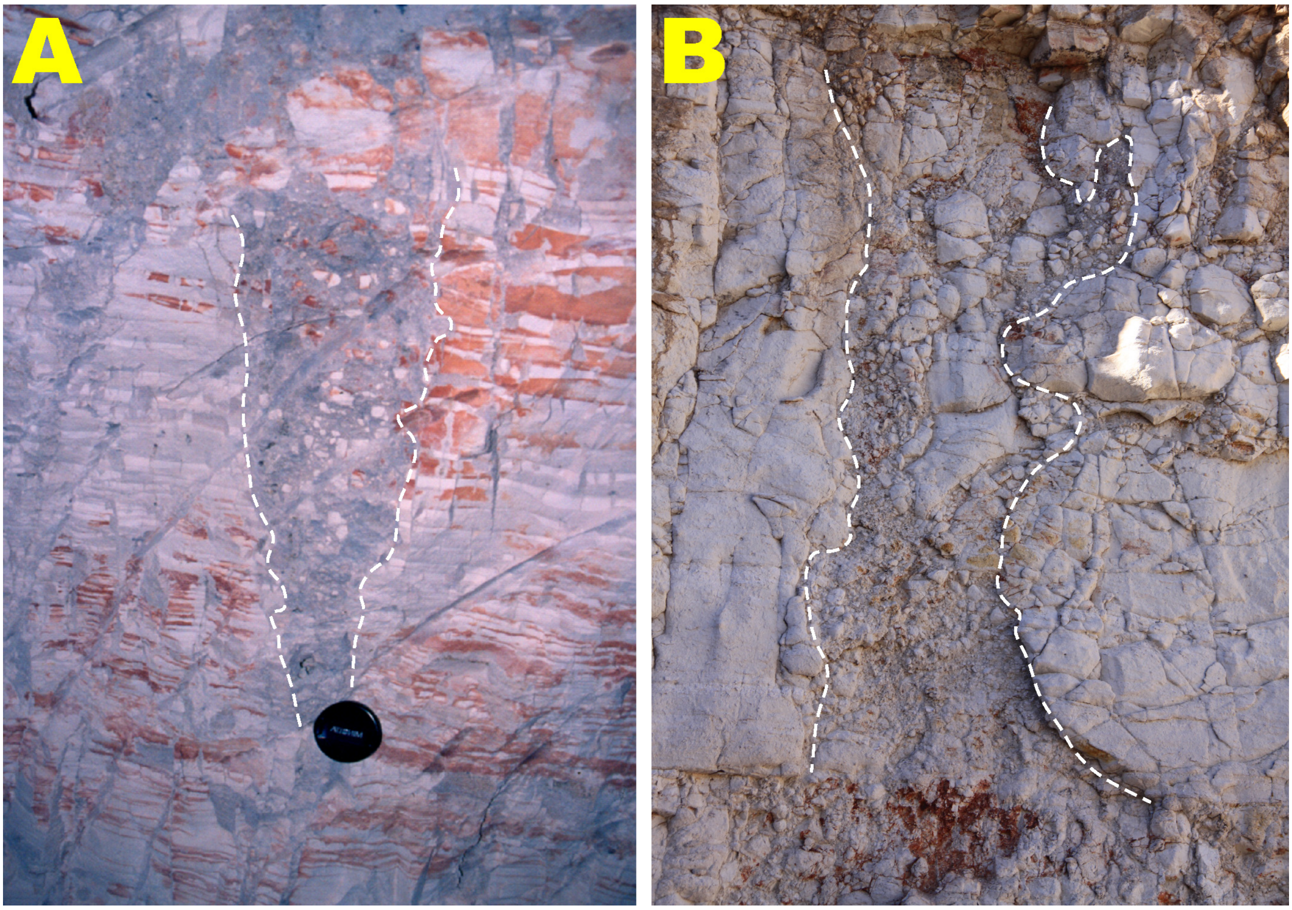

Figure 5. Breccia pipes at Lightning Ridge. A shows a breccia pipe in a underground opal mine containing broken fragments of the same rock that encloses the pipe. B shows a breccia pipe in the wall of an open cut mine. These pipes are formed during vertical fluid flow, with the fragments becoming rounded as water flows upwards under pressure. Some breccia pipes may also contain fragments of opal brought up from deeper down. Most pipes never reached the surface, but those that did may have erupted violently, building aprons of opal-bearing ejecta around their surface vents. Photos by Dr. S. Pecover (A & B).

Some intrusive breccia pipes contain fragments of opal which have been swept up into the pipes when they passed through horizons containing opal veins. Rock fragments broken off the walls of some of these pipes have been sorted by size and are rounded, which strongly indicates that moving fluids have travelled vertically upwards in the pipes during vigorously fluidising hydraulically pressurised fluid flow conditions which affected the sedimentary sequence long after it was laid down.

This cross-cutting relationship shows that the pipes are younger than the enclosing sedimentary rocks (and commonly slightly younger than the opal veins in some areas), and that significant volumes of pressurized fluids have passed through the sedimentary sequence since it was formed. The extent of brittle fracture deformation coincident with these pipes strongly suggests that these structures were formed by tectonically-driven overpressure-induced fluid flow during post-depositional compression of the overall sedimentary sequence.

Opal Veins

The opal veins at Lightning Ridge are dominated by potch, which typically exhibits textures indicating there were multiple episodes when viscous opaline fluid was injected into fractures during brittle fracture deformation. The veins are usually completely filled with opal and contain broken fragments of the enclosing wall rocks as well as broken fragments of previously formed opal veins (Figure 6A).

Much rarer precious opal appears to be confined to pockets within the veins where fluid flow has ceased sufficiently to allow the growth of photonic colloidal crystals (Figure 6B). However, after crystallising, pieces of precious opal may be swept up with potch opal and mixed together as viscous fluid flow recommences until finally the viscous mixture loses most of its water and hardens into solid opal (Figure 6C & D).

The opal commonly forms vein arrays which generally show complex meshwork patterns of branching veinlets in which opal has completely filled the widening fractures. However, rare examples of partially filled vein spaces have occasionally been found. These partially filled veins can exhibit meniscus-like fluid tops and gel sag features formed by viscous opaline fluids draining along leaky fractures after significant fluid-flow had ceased. This is similar to water draining from a leaky bath after the tap has been turned off.

The viscous fluid-flow and brittle fracture deformation textures in these opal veins strongly indicate that opal vein formation involved fluids that were able to move through the rock under pressure along developing fractures. These fluid-flows were moving with sufficient force to widen the fractures while simultaneously depositing opal from the silica-saturated waters. However, the rocks on either side of the opal veins show no evidence of high temperature alteration (typical of some metamorphic vein-forming geological environments), indicating that the opal-forming fluids were probably flowing at <50°C through the host sedimentary rocks.

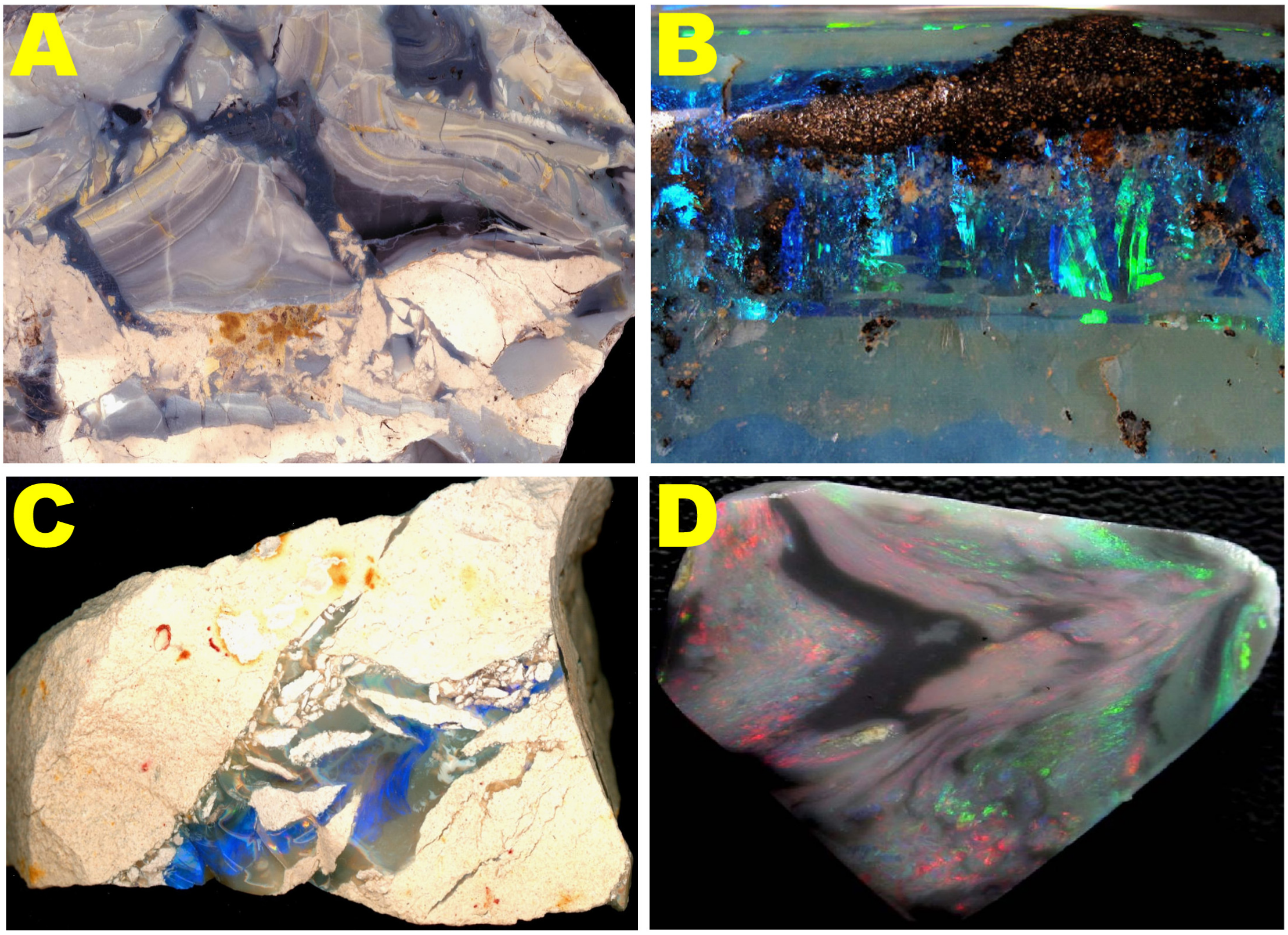

Figure 6. Opal specimens. A shows a complex vein of potch, with broken fragments of previously formed greyish-coloured banded opal, surrounded by later dark bluish-coloured opal, which has been squeezed into curved viscous flow bands between the grey fragments. B shows photonic colloidal crystals of precious opal, which have grown normal to the walls of the vein. C shows a vein with a mixture of potch and precious opal, where the viscous fluids have dragged broken fragments of cream-coloured wall rock along in the flow. D shows potch and precious opal which has mixed together during viscous fluid flow, forming complex patterns before hardening into solid opal. Photos by Dr. S. Pecover (A & C), Mr L. Cram (B) and Opal Auctions.com (D).

Age of the Opal Deposits

Debate about the age of the opal deposits in the GAB continues. Some researchers advocate a Cretaceous age (100-113 million years ago) for the deposits based on biological and/or acid weathering processes that are hypothesized to have been operating in the rocks at the same time as the opal-hosting sediments were laid down.

A Late Eocene-Oligocene age (around 35 million years ago) is favored by some researchers who advocate surface weathering and soil forming processes (i.e. regolith) as a mechanism for opal formation.

However, some structural geologists suggest that the viscous fluid-flow and brittle fracture tectonic features evident in most GAB opal veins indicate they were formed during the Miocene (5 to 20 million years ago) when the Australian Plate was undergoing compressional deformation.

Finally, based on radiocarbon dating of organic matter found in some opals, other researchers consider that the opal deposits were formed as recently as during the last 7 to 12 thousand years.

Geological Models/Theories of Opal Formation

Three very different geological models have been proposed to explain the opal deposits of the GAB: the 'Weathering Model', the 'Microbe Model' and the 'Syntectonic Model'. Each model attempts to explain how the opal deposits may have been formed.

Weathering Model

The “Weathering Model” is the oldest of the scientific theories of opal genesis in the GAB and advocates a regolith-forming process in which rainwater is thought to have moved vertically downwards by gravity from the surface over millions of years. This water is thought to have saturated Cretaceous sandstones and formed acidic solutions which weathered feldspars and clay minerals in the sediments, releasing silica. The resulting silica-rich solutions continued to move slowly downwards through the sedimentary pile until they pooled within the upper parts of claystone beds, passively filling in pre-existing open cracks and replacing fossil remains with opal.

Microbe Model

The "Microbe Model" proposes that aerobic microbes secreted enzymes and acids, which attacked feldspars and clay minerals over millions of years producing silica-rich solutions which passively filled adjacent open cracks in the sediments while they were being laid down.

Syntectonic Model

The newer modern "Syntectonic Model" advocates a much more rapid and dynamic process in which silica-saturated fluids, which possibly derived their silica from the alteration of smectite to kaolinite, and/or the remobilization of pre-existing fossil plant silica (e.g. preserved phytogenic silica derived from the decay of ferns, liverworts and horsetails which once grew along river and lake margins in the Early Cretaceous), were squeezed out of hydrated clayey rocks during low temperature (i.e. <50°C) syntectonic compressional warping and faulting of the sediments in the Miocene Epoch. During compressional dewatering of the Finch Clay Facies, these silica-laden fluids were locally sucked, pumped and pushed into progressively widening Mode-1 tensile tectonically formed fractures within the claystones over very short periods of time (i.e. days to years). This 'fluid-assisted' rock-cracking process is known as 'hydraulic extension fracturing'. When the concentration of silica in solution became supersaturated as the fluids were sucked into the widening fractures, rapid precipitation resulted in the fractures becoming completely filled with opal, thus forming veins. Complex shear-thickening processes caused the viscosity of the opaline fluids within the veins to increase during fluid flow, forming and preserving a wide variety of opal vein textures. As processes of this type commonly occur progressively over a number of tectonic cycles, then these vein systems should and do contain complex intermixed multiple generations of precipitated potch and precious opal.

Concluding Remarks

While each of these models attempts to address questions of opal deposit genesis, much more research is needed to determine the source of the silica-rich fluids and how, when and where they were transported and concentrated into economic vein deposits within their Cretaceous sedimentary host rocks.

The following activity explores some of the ways geoscientists build genetic models by using evidence derived from the rocks themselves.

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*Dr Simon Pecover is a geologist and mineral deposit formation research scientist who has worked in a variety of government, industry and academic positions since the mid 1970's. His gemstone research work has included the study of lahar-type sapphire deposits in Eastern Australian Tertiary basaltic volcanic terrains (for which he was awarded a PhD from the University of Sydney), and the study of syntectonic fault-controlled precious opal vein deposits hosted by Cretaceous sedimentary rocks in the Great Artesian Basin.

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Student Activity

1) Examine the rock specimen photo shown in Figure 7A. Draw what you see in the photo and identify and describe the following features:
a) Evidence for hydraulic extension fracturing.
b) Type of opal in the veins.
c) Evidence of viscous fluid flow in the veins.
d) Evidence of broken fragments of host rock in the veins.
e) Shape of broken host rock fragments in the veins.
f) Do any of the veins appear to connect to each other, and if so where?

2) Examine the rock specimen photo shown in Figure 7B. Draw what you see in the photo and identify and describe the following features:
a) Areas where potch and precious opal have formed separately.
b) Shape and orientation of photonic colloidal crystals.
c) Which came first the potch or the precious opal? Why?

3) Examine the rock specimen photo shown in Figure 7C. Draw what you see in the photo and identify and describe the following features:
a) Zones of potch and precious opal.
b) How many generations of potch and precious opal do you think there are?
c) Map the order of formation of the potch and precious opal zones.
d) Which came first the potch or the precious opal? Why?
e) How do you think that this mixture of potch and precious opal has been formed?

4. Watch the three YouTube videos listed below to understand more about how faults are formed and how fluids carrying valuable minerals can form veins from pressurised fluid flows in rocks.

http://www.youtube.com/watch?v=d5CqYqpmfxM%20
This instructional video shows how faults and joints are formed in the earth's crust.

http://www.youtube.com/watch?v=gPQJ2djYVyo
This video shows a simple animation of how mineral-bearing fluids within the pore spaces of a rock can be mobilized to flow from areas of high pore pressure into an opening fracture of lower pore pressure, where an increase in chemical concentration can lead to rapid mineral precipitation forming a vein.

http://www.youtube.com/watch?v=KDexpMBAs6M
This excellent video shows how gold-bearing quartz veins can form in the earth's crust as a result of faulting, fracturing and high fluid flow pressures.

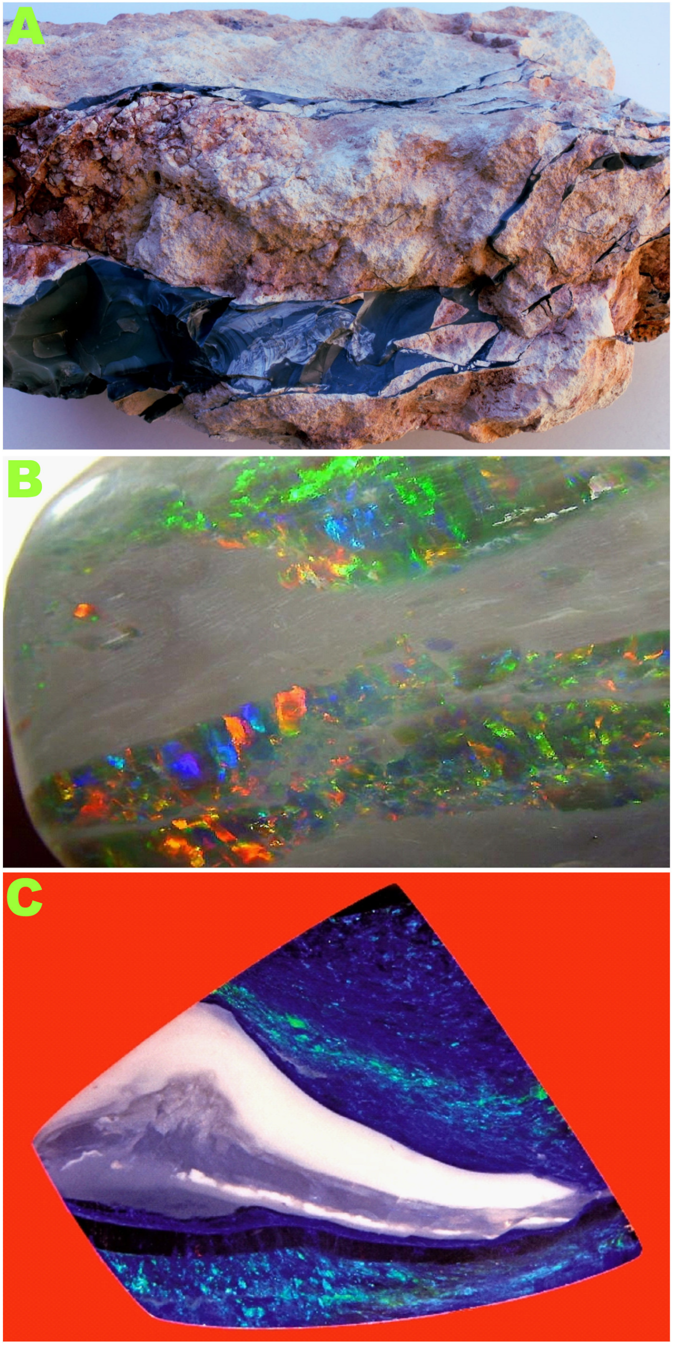

Figure 7A-C. Opal specimens showing typical features of opal veins from the Great Australian Basin. Identify the features of each of these specimens as per the requirements listed in the student activity. Photos by Dr. S. Pecover (A), Opal Auctions.com (B) and Mr L. Cram (C).

After watching these videos, decide which of the geological models described above, you think best explains the features seen in the opal veins in Figure 7 that you have been studying? Why?

If you would like to see an amazing opal vein specimen, showing photonic colloidal crystals of precious opal which have grown in parallel rod-like clusters orientated at right angles to the walls of the vein, then go to https://www.youtube.com/watch?v=JQ0S4U-BD20, and watch the YouTube video entitled "Largest gem rough opal gemstone from Lightning Ridge". When cut and polished, this piece of rough opal may be worth many hundreds of thousands of dollars.

If you would like to see more amazing viscous fluid flow textures in opal veins from Lightning Ridge, go to http://www.opalsinformation.com/index.php/media1/archives/cat_view/62-geology-science-of-opal?start=10, and download the pdf entitled "Key Features of Opal Vein Deposits at Lightning Ridge".

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