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Relationships between palaeogeography and opal occurrence in Australia: A data-mining approach

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ABSTRACT

Age-coded multi-layered geological datasets are becoming increasingly prevalent with the surge in open-access geodata, yet there are few methodologies for extracting geological information and knowledge from these data. We present a novel methodology, based on the open-source GPlates software in which age-coded digital palaeogeographic maps are used to "data-mine" spatio-temporal patterns related to the occurrence of Australian opal. Our aim is to test the concept that only a particular sequence of depositional/erosional environments may lead to conditions suitable for the formation of gem quality sedimentary opal. Time-varying geographic environment properties are extracted from a digital palaeogeographic dataset of the eastern Australian Great Artesian Basin (GAB) at 1036 opal localities. We obtain a total of 52 independent ordinal sequences sampling 19 time slices from the Early Cretaceous to the present-day. We find that 95% of the known opal deposits are tied to only 27 sequences all comprising fluvial and shallow marine depositional sequences followed by a prolonged phase of erosion. We then map the total area of the GAB that matches these 27 opal-specific sequences, resulting in an opal-prospective region of only about 10% of the total area of the basin. The key patterns underlying this association involve only a small number of key environmental transitions. We demonstrate that these key associations are generally absent at arbitrary locations in the basin. This new methodology allows for the simplification of a complex time-varying geological dataset into a single map view, enabling straightforward application for opal exploration and for future co-assessment with other datasets/geological criteria. This approach may help unravel the poorly understood opal formation process using an empirical spatio-temporal data-mining methodology and readily available datasets to aid hypothesis testing.

1. Introduction

Exploration practices and data analysis and modelling related to mineral and hydrocarbon systems are making increasing use of integrated geological datasets for understanding resource formation processes and thus improving exploration decision making. This is made possible by the rapid increase in the interconnected digital storage of data and the rapidly increasing power of computing systems. An important factor for many studies is the consideration of the palaeogeographic/depositional environment through time as inferred from the geological record, since the configuration of a particular region as observed today is nearly always substantially different from the geological past. This, together with an understanding of the physical processes involved, is particularly important for identifying niche geological conditions that result in a phenomena such as ore deposits, since only a consideration of the relevant geological history leads to an appropriate contextualisation of present-day observations. Thus investigating the nature and relationships involved in time-varying spatial data is a promising area for developing and applying machine learning to geological data. In this paper we develop a quantitative approach for utilising the palaeo-environmental history over a large portion of Australia to investigate some key factors associated with opal formation, as a step towards establishing more quantitative exploration criteria. A data-mining approach is taken here to cope with the large datasets involved, and to handle some degree of noise present in the datasets utilised, especially considering that the digital palaeogeographic maps this approach is based on involves interpretations and interpolations of sparse data points. The study is made possible through use of the GPlates plate tectonic geographic information system (Qin et al., 2012) and Gplates data-mining functionality (Landgrebe and Mueller, 2008), in which time-varying data are explicitly modelled, allowing for direct extraction of spatio-temporal associations.

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Opal is a form of hydrated silica ($SiO_2 \cdot n\ H_2O$) found predominantly throughout the Great Artesian Basin in Australia. Although the Australian opal fields are responsible for over 90% of the world's opal supply, there has been a decline over the past 20 years in the number of high quality gemstones produced by the fields (Smallwood, 1997). This is accounted for, to some extent, by the absence of formal exploration models for Australian opal, which has led to an over-reliance on mining old opal fields discovered in the early 20th century (Barnes and Townsend, 1990). Making use of known locations of opal, we construct a method allowing us to search for other locations that possess similar palaeogeographic sequences throughout the entire Great Artesian Basin, and help establish important time-varying palaeogeographic/depositional/facies conditions favourable for opal formation.

2. Eastern Australian opals and palaeogeography

Opal in the Great Artesian Basin is found within fractures and primary and secondary pore spaces in the upper 30 m throughout the highly weathered Cretaceous sedimentary sequence of the Eromanga and Surat basins (Barnes and Townsend, 1990). The location of opal deposits is shown in Fig. 1, and includes primary opal mining regions from which a total of 1036 mining localities were identified for this study. The locations were taken from maps published by the state geological surveys (Carr, 1979; Carter, 2005; Geological Survey of Queensland, 2012; Robertston and Scott, 1989), and were digitised and geo-referenced using the GIS software. The shallow stratigraphy of both basins consists of alternating layers of sandstones, claystones and siltstones deposited during the Early Cretaceous (ca. 135–95 Ma) (Campbell and Haig, 1999; Frakes et al., 1987). The generalised sequence consists of lower facies consistent with deposition in a cyclical marine environment followed by a marine regression leading to a fluvial–deltaic environment (Exon and Senior, 1976). Deposition ceased towards the end of the Cenomanian, and until the Palaeogene the area experienced uplift and erosion resulting in up to 3 km of sedimentary rock being eroded (Raza et al., 2009). Further sediment deposition initiated in the Palaeogene (Alley, 1998), as well as substantial periods of silicification of the outcropping sedimentary rocks due to weathering (Alley, 1998; Thiry et al., 2006). However, the relative tectonic stability of the Australian plate (Veevers, 2000) and the weathering history since the late Cretaceous has allowed for the (partial) preservation of the Cretaceous sedimentary sequences, either allowing for the preservation of opal or for the necessary constituents for the formation of opal (e.g. source of silica). Since Australia produces over 90% of precious sedimentary opal globally, this suggests that the palaeogeographic evolution of Australia is important for understanding how opal may have formed and for determining where it may be found.

The Australian palaeogeographic atlas dataset (Langford et al., 1995; Totterdell, 2002) is a digital version of a compilation of maps based on palaeo-reconstructions of the environment, latitude, and sedimentology of the Australian continent. The dataset distinguishes between 16 differing palaeo-environments (defined in Table 1) and provides a geological reconstruction back to 542 Ma, comprising 70 time slices. As opal is found predominantly in Cretaceous sedimentary rocks, the analysis of the dataset was constrained to the time period from 145 Ma to the present-day. In total this comprises 19 time slices, depicted in the time-slice maps in Fig. 2 (note that the figure involves only 9 of the 16 defined environments that pertain to these time slices).

Fig. 3 illustrates the various palaeogeographic time series profiles for major Australian opal-mining locations. This plot clearly shows that there are broad similarities in the palaeogeographic sequences across the various localities (i.e., there is a subset of profiles to explain the majority of the environmental evolution through time), in

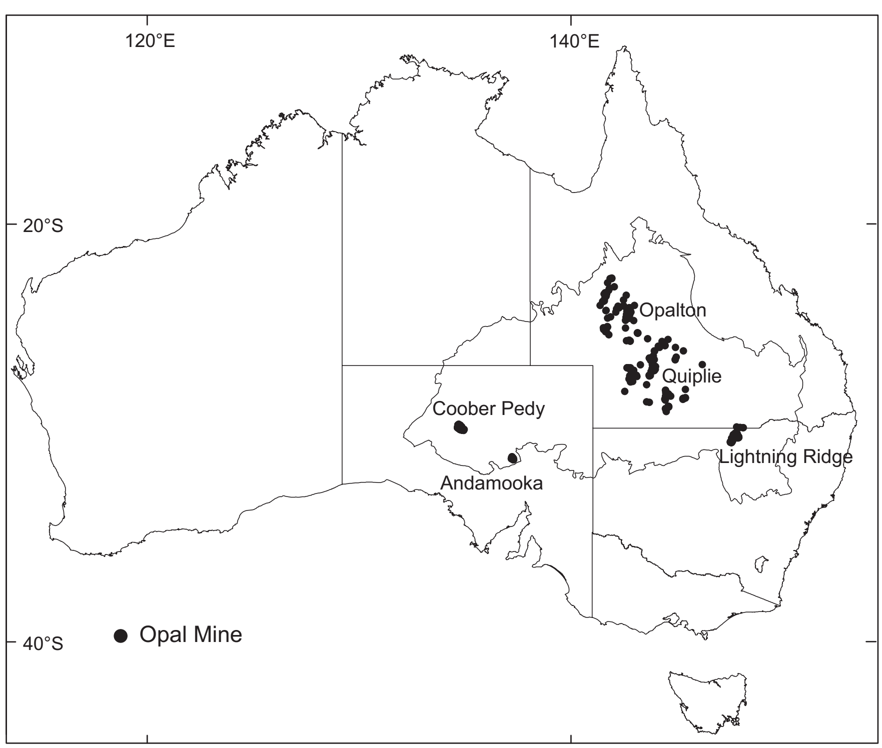

Fig. 1. Location map for this study, with the outlined Great Artesian Basin defining the broad prospective region in which most Australian opals are found. The locations of opal mining localities used in this study are shown.