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Basin-scale fluid-flow models of the McArthur River mineral system: constraints from geochemistry, geophysics and sequence stratigraphy

Peter Schaubs*
CSIRO Mineral Resources
Kensington, WA
Peter.Schaubs@csiro.au

Heather Sheldon
CSIRO Mineral Resources
Acton, ACT
Heather.Sheldon@csiro.au

Teagan Blaikie
CSIRO Mineral Resources
Kensington, WA
Teagan.Blaikie@csiro.au

Marcus Kunzmann
CSIRO Mineral Resources
Darwin, NT
Marcus.Kunzmann@csiro.au

Susanne Schmid
CSIRO Mineral Resources
Kensington, WA
Susanne.Schmid@csiro.au

Sam Spinks
CSIRO Mineral Resources
Kensington, WA
Sam.Spinks@csiro.au

SUMMARY

This abstract reports on the insights gained from numerical simulations which have been used to place constraints on the nature of critical geological processes responsible for sediment-hosted base metal mineralisation in the southern McArthur Basin, Australia. The study was undertaken as part of a multidisciplinary study which also included the interpretation of new and existing geophysical datasets; detailed sedimentological and stratigraphic analysis; petrography; geochemistry; and the basin-scale numerical modelling of fluid flow described here. The integration of information from this multidisciplinary study has been used to refine and constrain these coupled 3D deformation – heat transport – fluid flow simulations to determine 1) the relative effects of deformation and heat transport (convection) in driving fluid flow, 2) how extensional versus contractional deformation effects fluid flow direction within faults and 3) conditions conducive for syngenetic vs diagenetic mineralisation. Numerical models suggest that the convective flow (and potential mineralisation) would have continued during extensional deformation, unless the deformation occurred at an extremely high strain rate, while contractional deformation would have enhanced the upward convective flow. These results indicate that it is not necessary to invoke inversion to explain upward flow of mineralising fluids in this system, although an inversion event may have enhanced mineralisation in areas of convective upwelling. Geochemistry and petrography support a diagenetic origin for the mineralisation, implying low permeability at the top of the Emu Fault which is consistent with stratigraphic and sedimentological analysis of the Barney Creek Formation. Numerical modelling confirms that such a permeability scenario would result in upwelling fluids being diverted out of the Emu Fault into the Barney Creek Formation.

Key words: Fluid-flow, McArthur River, zinc, simulation

INTRODUCTION

Within the southern McArthur Basin significant base metal mineralisation occurs at the 1640 Ma McArthur River and Teena Zn-Pb-Ag deposits, located on the eastern side of the Batten Fault Zone (Figure 1). The basin consists of a Palaeo- to Mesoproterozoic succession of carbonate, siliciclastic and volcanic units, deposited in an intracratonic basin to the north of the southern margin of the North Australian Craton (Ahmad et al 2013). Far-field plate boundary processes resulted in a long history of extension and shortening events, creating a complex depositional architecture and fault network (Betts and Giles 2006; Blaikie and Kunzmann 2019). The deposits occur in the Barney Creek Formation (BCF), a succession dominated by dolomitic siltstones deposited in fault-bounded sub-basins that formed during north-south extension (Kunzmann et al 2019; McGoldrick et al 2010). Mineralisation occurred by reaction of an oxidised basinal brine with anoxic sediments of the BCF, at or below the sea floor (Rye and Williams 1981; Eldridge et al 1993; Hinman 1995; Large et al 1998). The brine likely originated from evaporitic deposits and leached metals from deeply buried volcanic units before travelling through permeable sandstone aquifers and returning to the seafloor via the Emu Fault, a long-lived structure that forms the eastern boundary of the Batten Fault Zone (Figure 1) (Williford et al 2011; Cooke et al 1998; Large et al 1998).

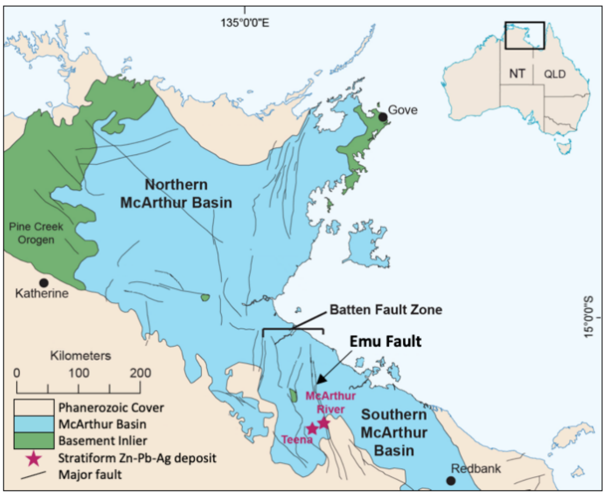

Figure 1. Location map of the McArthur River and Teena deposits.

This study presents coupled deformation – fluid flow – heat transport numerical models which have been used to constrain 1) the relative effects of deformation and convection on driving fluid flow to areas of known mineralisation 2) the effect of extensional versus contractional deformation on directing fluid up and down the Emu Fault and 3) the effect of permeability variations in the upper portions of the Emu Fault in enhancing fluid infiltration into the BCF. The project has taken an integrated approach, including acquisition and interpretation of new gravity data; re-interpretation of existing geophysical datasets; detailed sedimentological and stratigraphic analysis; petrography; geochemistry; and basin-scale numerical modelling of fluid flow.

NUMERICAL MODELLING APPROACH

We use the open-source finite element code MOOSE (Multiphysics Object Oriented Simulation Environment; https://mooseframework.inl.gov) to solve the equations describing elasto-plastic deformation, fluid flow and conductive-advective heat transport in a fluid-saturated porous rock (Idaho National Laboratory 2019). Fluid flow is driven by changes in fluid pressure caused by deformation, and by density variations associated with the temperature gradient (i.e. thermal convection). Variations in permeability between the geological units in the model further control the direction and magnitude of fluid flow. Heat is transported by conduction and advection with the moving pore fluid.

The geometry of the model is a simplified representation of the key hydrostratigraphic units on the eastern side of the Batten Fault Zone (Figure 2) and we explore a scenario where an east-dipping aquifer intersects the seafloor to the west of the Emu Fault. The geometry is similar to that used in some previous 2D modelling studies, which predicted convective fluid flow through the aquifer and up the Emu Fault (Garven et al 2001; Yang et al 2004a, b). We have included a cross fault terminating at the Emu Fault, representing one of the approximately east-west oriented normal faults that are associated with known mineralisation. This simplified geometry represents the key features relevant to this study of fluid flow in the Batten Fault Zone and is not intended to reflect the complex fault and depositional architecture of the area (c.f. Blaikie and Kunzmann 2019). The geological units were assigned appropriate mechanical, thermal and fluid flow properties consistent with their lithologies, with the fault and aquifer having relatively high permeabilities and the fault being mechanically weaker than the other units. The pore fluid was treated as pure water with properties determined by the IAPWS-95 equation of state (Wagner and Pruß 2002).

The top boundary represents the seafloor at 200 m water depth, consistent with the inferred depositional environment of most parts of the BCF below storm wave base (Bull 1998; Schmid 2015; Kunzmann et al 2019). The initial fluid pressure gradient is hydrostatic. The base of the model is subject to a fixed heat flux of 100 mW/m2. The model is initialised in a conductive steady state to establish the initial conductive geothermal gradient, prior to simulation of convection and deformation.

NEW INSIGHTS INTO THE MCARTHUR RIVER MINERAL SYSTEM

The current multi-disciplinary project has resulted in some important new insights into the McArthur River mineral system, which we have explored through numerical modelling. The timing of mineralisation at McArthur River has been the subject of much debate, with some authors arguing for syn-depositional mineralisation (e.g. Large et al 1998; Ireland et al 2004), while others argue for a diagenetic or epigenetic origin (Eldridge et al 1993; Rye and Williams 1981; Logan et al 2001; Symons 2007). Previous numerical modelling studies treated the Emu Fault as a high-permeability pathway from the basement to the seafloor, resulting in discharge of hot fluids onto the seafloor, consistent with the syn-depositional mineralisation model. However, geochemical and petrographic studies conducted in this project support a diagenetic origin (Spinks et al 2019), with mineralisation potentially occurring tens to hundreds of metres below the seafloor. This implies that the mineralising fluid moved laterally out of the Emu Fault into the adjacent BCF, instead of continuing its ascent up the Emu Fault to the seafloor. Consequently, we infer that the Emu Fault did not act as a high-permeability fluid pathway all the way to the seafloor. This assumption is reasonable, because faults in porous sediments often act as low permeability barriers rather than pathways for fluid flow (e.g. Barnicoat et al 2009).

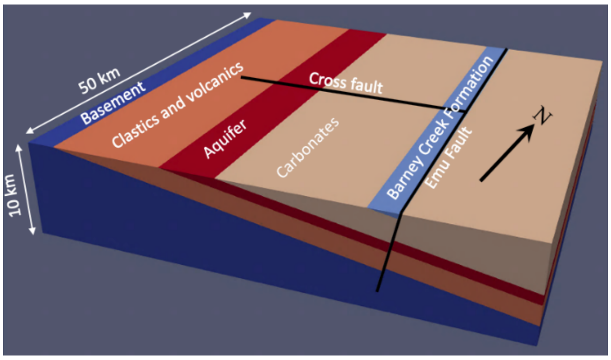

Figure 2. Geometry of the numerical models.

The known mineralisation is hosted by dolomitic and organic-rich siltstones of the HYC Pyritic Shale Member in the lower BCF. A third-order maximum flooding surface in the HYC Pyritic Shale Member is developed as organic-rich black shale and silty shale (Kunzmann et al 2019). Consistent with our model for diagenetic mineralisation, this interval is likely to have acted as an impermeable barrier to ascending brines, because the black shale would have undergone more rapid porosity reduction in the first few hundred metres of burial than the underlying siltstone. Furthermore, shearing of such a clay-rich rock in the Emu Fault zone would have resulted in further permeability reduction. Thus, we postulate that the Emu Fault ceased to act as a fluid pathway where it encountered the black shale, causing ascending fluid to be diverted laterally into the more permeable underlying siltstones where it deposited metals.

To test the effect of different permeability distributions in the Emu Fault, hydrothermal simulations were run with constant high permeability throughout the Emu Fault (Fig. 3), and with lower permeability in the top 300 m of the Emu Fault (Fig. 4). In both cases, thermal convection is established within the faults but the fate of the hot ascending fluid differs depending on the permeability distribution. In the case with constant high permeability throughout the Emu Fault (Fig. 3), most of the hot fluid exits onto the seafloor (consistent with a syngenetic mineralisation scenario), although some of the hot fluid penetrates a short distance into the BCF at the top of each convective upwelling. The convection is three-dimensional, with exchange of fluids between the aquifer and faults facilitating transfer of metals from the source to the site of deposition.

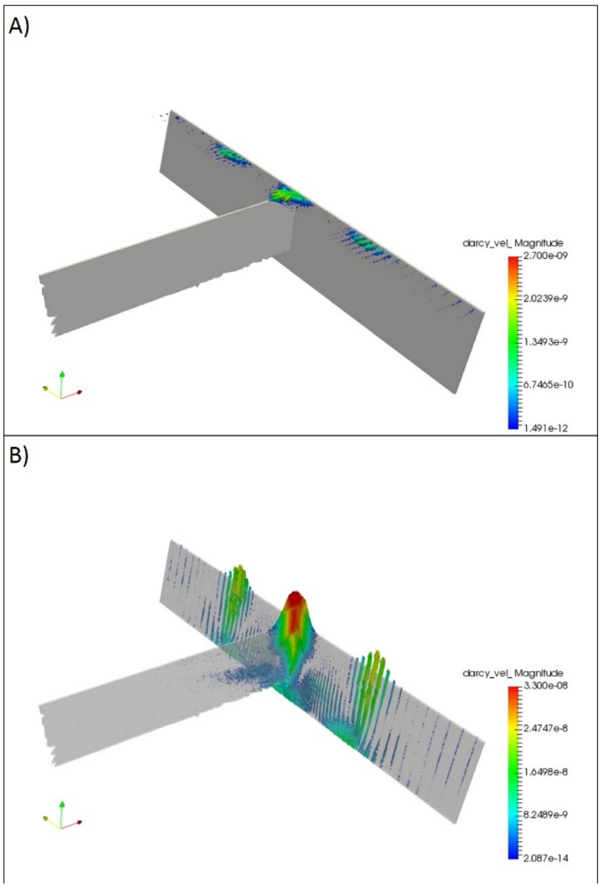

Figure 3. Results of numerical simulations where Emu Fault has constant high permeability. a) Fluid flow within the BCF showing minor infiltration (contrast with Fig. 4a). b) Fluid flow within faults only.

Figure 4 shows the case where the Emu Fault has lower permeability than the BCF in the top 300 m of the model. The black shale is not represented explicitly in this model, but the BCF is assigned a highly anisotropic permeability, implicitly representing the effect of horizontal layers of very low permeability. Convection still occurs in the faults and aquifer, but the upwelling fluid is diverted laterally out of the Emu Fault into the BCF, consistent with the diagenetic mineralisation hypothesis.

On a larger scale, geophysical modelling and stratigraphic analysis have provided insights into the tectonic regime at the time of mineralisation. The HYC Pyritic Shale Member was deposited in rapidly subsiding sub-basins adjacent to the Emu Fault and bounded by east-west normal faults, in a predominantly extensional tectonic setting (Blaikie and Kunzmann 2019). However, our analysis has identified a short-lived inversion event during deposition of the upper BCF, consistent with previous structural analysis of the McArthur River deposit (Hinman 1995). This event would have occurred when the mineralised part of the HYC Pyritic Shale Member was undergoing late-stage diagenesis, tens to a few hundred metres below the seafloor. Thus, the inversion event could correspond to the time of mineralisation.

Extensional deformation tends to result in downward fluid flow (Oliver et al 2006; McLellan et al 2004), which could override convective upwelling. Conversely, inversion would be expected to drive upward flow, enhancing the convective upwelling.

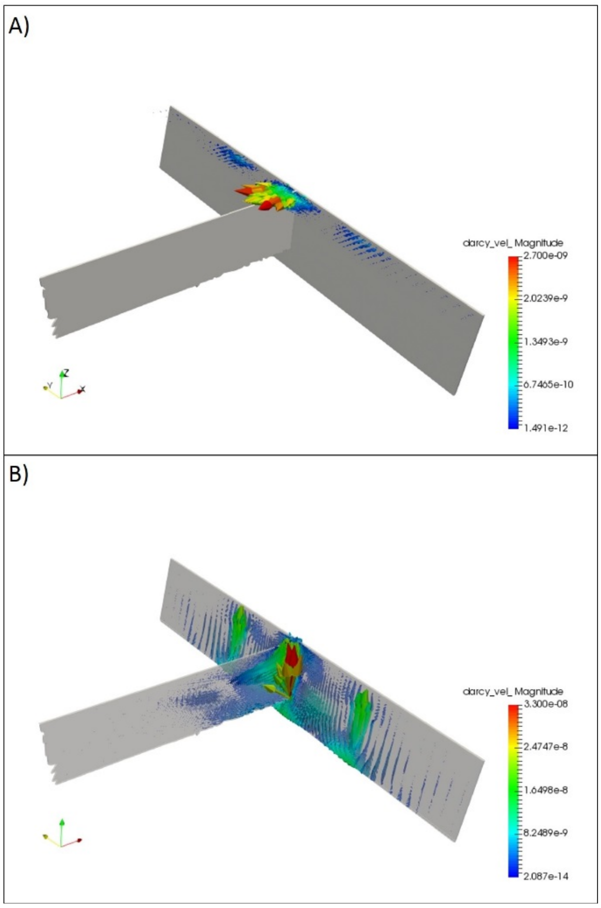

Figure 4. Results of numerical simulations where Emu Fault has low permeability in the top 300m. a) Fluid flow within the BCF showing significant infiltration. b) Fluid flow within faults only.

To investigate the effect of extensional deformation and inversion on convective fluid flow, the model was allowed to establish convection without deformation, then north-south extension or shortening was applied at a range of strain rates. Figure 5 shows the effect of this deformation on the maximum vertical fluid flux in the Emu fault, with positive values indicating upward flow. This figure illustrates that extensional deformation tends to reduce the rate of convective upwelling but does not completely override it for the range of strain rates shown in Figure 5. Further simulation results (not shown here) have shown that overriding the upward convective flow requires unrealistically high strain rates. Conversely, the results shown in Figure 5 indicate that crustal shortening (inversion) enhances the rate of upward flow. We conclude that convection would have continued during extensional deformation, while the inversion event would have temporarily enhanced the upward flow.

SUMMARY AND CONCLUSIONS

A multi-disciplinary study of the southern McArthur Basin has provided new insights into the McArthur River mineral system. New 3D numerical models demonstrate the complex 3D nature of convective fluid flow in this mineral system. Geochemistry and petrography support a diagenetic origin for the mineralisation, implying low permeability at the top of the Emu Fault which is consistent with stratigraphic and sedimentological analysis of the BCF. Numerical modelling confirms that such a permeability scenario would result in upwelling fluids being diverted out of the Emu Fault into the BCF. Structural and stratigraphic interpretations of the basin suggest a dominantly extensional setting for the BCF, while a short-lived inversion event may have occurred around the time of mineralisation. Numerical models suggest that the convective flow (and therefore mineralisation) would have continued during extensional deformation, unless the deformation occurred at an extremely high strain rate, while inversion would have enhanced the upward convective flow. These results indicate that it is not necessary to invoke inversion to explain upward flow of mineralising fluids in this system, although the inversion event may have enhanced mineralisation in areas of convective upwelling.

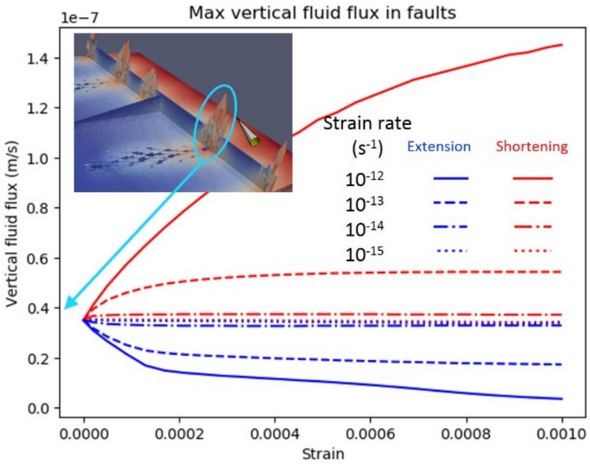

Figure 5. Effect of deformation on convection: Maximum vertical fluid flux in the faults as a function of strain rate.

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