An integrated study of the McArthur River mineral system: From geochemistry, geophysics and sequence stratigraphy to basin-scale models of fluid flow

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Introduction

In 2016, CSIRO embarked on a project with the Northern Territory Geological Survey to improve understanding of sediment-hosted base metal mineralisation in the southern McArthur Basin. The project has taken an integrated approach that includes 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. This abstract reports on the insights gained from numerical modelling, focusing on the integration of information from other areas of the project that have helped to refine and improve the numerical models.

Geological background and conceptual model for mineralisation

The southern McArthur Basin contains 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). Significant base metal mineralisation in the basin includes the ca 1640 Ma McArthur River and Teena Zn-Pb-Ag deposits, located on the eastern side of the Batten Fault Zone (**Figure 1**). These deposits occur in the Barney Creek Formation, a succession dominated by dolomitic siltstones deposited in fault-bounded sub-basins that formed during north–south extension (McGoldrick *et al* 2010, Kunzmann *et al* in press). Mineralisation occurred by reaction of an oxidised basinal brine with anoxic sediments of the Barney Creek Formation 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 returning to the surface via the Emu Fault, a long-lived structure that forms the eastern boundary of the Batten Fault Zone (**Figure 1**; Cooke *et al* 1998, Large *et al* 1998, Williford *et al* 2011).

Previous numerical modelling studies

Previous numerical modelling of the McArthur River mineral system suggested that the required fluid circulation could be driven by thermal or thermohaline convection. In this case, fluids descend down the Tawallah Fault on the western side of the Batten Fault Zone and migrate through a siliciclastic aquifer unit where they leach metals from the underlying volcanics, before returning to the surface via the Emu Fault and depositing metals on the seafloor (Garven *et al* 2001, Yang *et al* 2004, Yang 2006).

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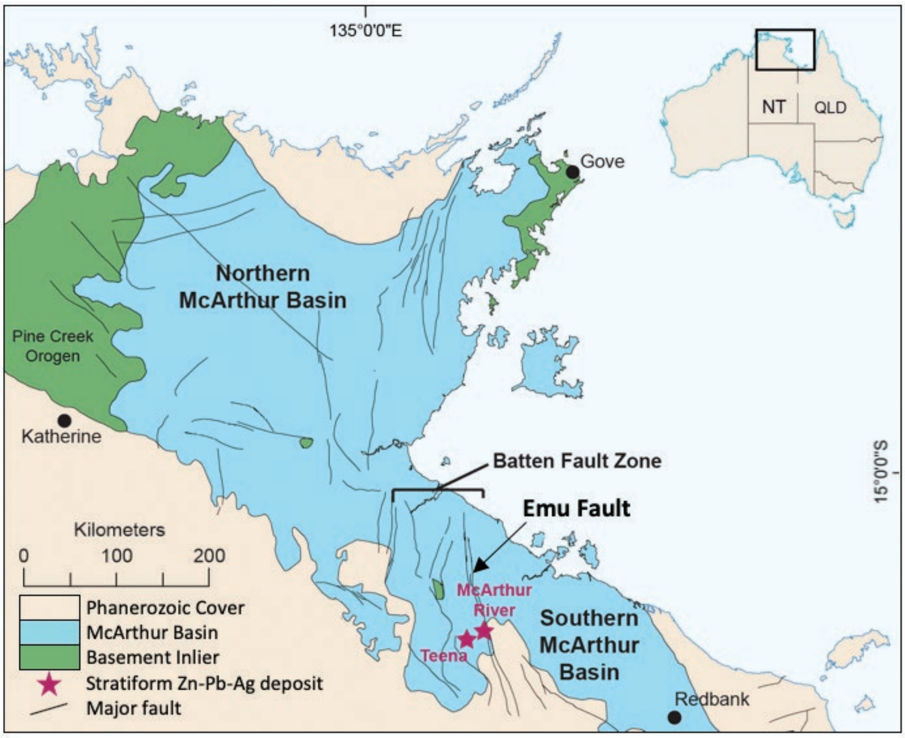

Figure 1. Location map of the McArthur River and Teena deposits.

None of these modelling studies considered the effect of deformation on fluid flow. Given the tectonically active setting of the mineralisation, a primary focus of the present numerical modelling effort has been to explore the interaction and competition between thermal convection and deformation-driven flow in this mineral system.

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 (CSIRO and INL 2018). Fluid flow is driven by changes in fluid pressure caused by deformation, and by density variations associated with the temperature gradient (ie 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**). The Tawallah Fault, which forms the western boundary of the Batten Fault Zone and was included in previous modelling studies, is not represented in this model; instead, we explore a scenario where an east-dipping aquifer intersects the seafloor to the west of the Emu Fault. 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 is not intended to reflect the complex fault and depositional architecture of the area (cf Blaikie and Kunzmann 2019); rather it represents the key features relevant to this study of fluid flow in the Batten Fault Zone, with geological units corresponding to those used in previous modelling studies. 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 Barney Creek Formation being below storm wave base (Bull 1998, Schmid 2015, Kunzmann *et al* in press). The initial fluid pressure gradient is hydrostatic. The base of the model is subject to a fixed heat flux of 100 mW/m^2. 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 (eg 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

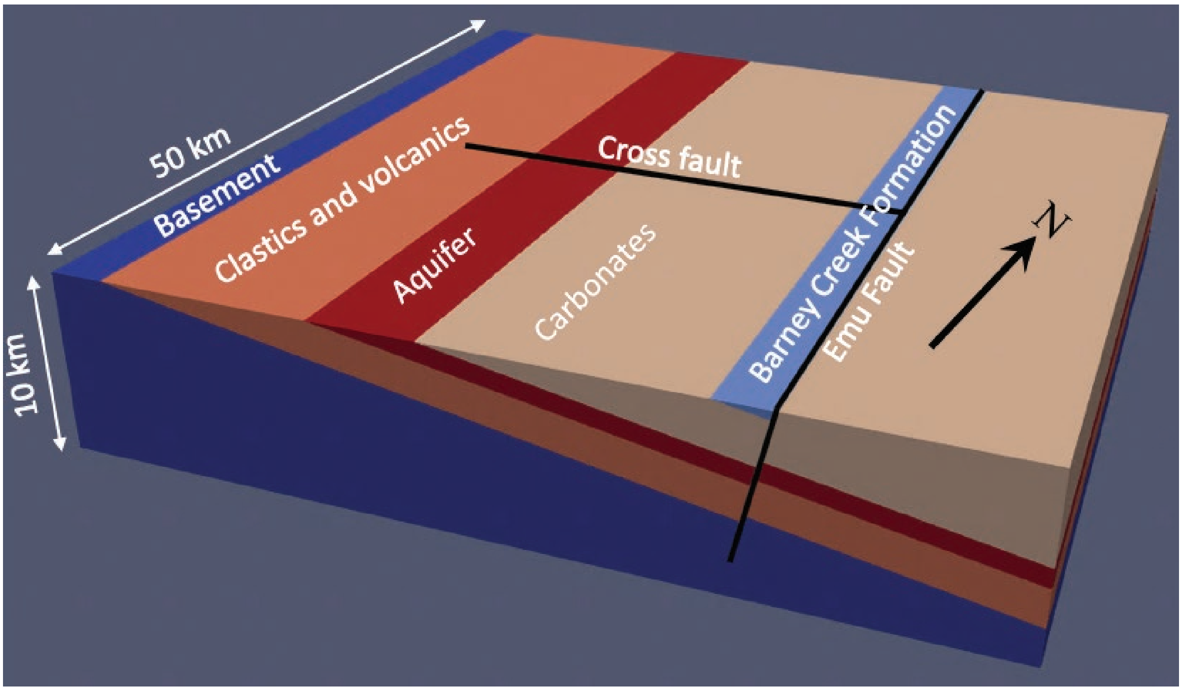

Figure 2. Geometry of the numerical models.

model. However, geochemical and petrographic studies conducted in this project support a diagenetic origin (Spinks *et al* 2019) whereby mineralisation occurred tens to hundreds of metres below the seafloor. This implies that the mineralising fluid moved laterally out of the Emu Fault into the adjacent Barney Creek Formation, 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 (eg Barnicoat *et al* 2009).

Detailed stratigraphic analysis of the Barney Creek Formation provides an explanation for diversion of fluids out of the Emu Fault before reaching the seafloor. The known mineralisation is hosted by dolomitic and organic-rich siltstones of the HYC Pyritic Shale Member in the lower Barney Creek Formation. Within this member, a third-order maximum flooding surface is developed as organic-rich black shale and silty shale (Kunzmann *et al* in press). 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 fluid to be diverted laterally into the more permeable underlying siltstones where it deposited metals.

The effect of different permeability scenarios in the Emu Fault is illustrated in **Figure 3**. The left column in **Figure 3** shows the case where the Emu Fault has high permeability all the way to the seafloor. Note the pattern of thermal convection in the Emu Fault, with hot fluid exiting through the top of the model (**Figure 3a**, **3g** and **3i**). The convection is three-dimensional (**Figure 3d**), with exchange of fluids between the aquifer and faults facilitating transfer of metals from the source to the site of deposition. There is minimal movement of fluid from the Emu Fault into the Barney Creek Formation (**Figure 3e**). The right side of **Figure 3** shows the case where the Emu Fault has lower permeability than the Barney Creek Formation in the top 300 m of the model. The black shale is not represented explicitly in this model, but the Barney Creek Formation 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 Barney Creek Formation (**Figure 3d** and **3f**), which is 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, 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 Barney Creek Formation, 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 (McLellan *et al* 2004, Oliver *et al* 2006) that could override convective upwelling. Conversely, inversion would be expected to drive upward flow, enhancing the convective upwelling. 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 4** 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 4**. 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 4** 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 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. Structural and stratigraphic interpretations of the basin suggest a dominantly extensional setting for the Barney Creek Formation, 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 although it is not necessary to invoke inversion to explain upward flow of mineralizing fluids in this system, the inversion event may have enhanced mineralisation in areas of convective upwelling.

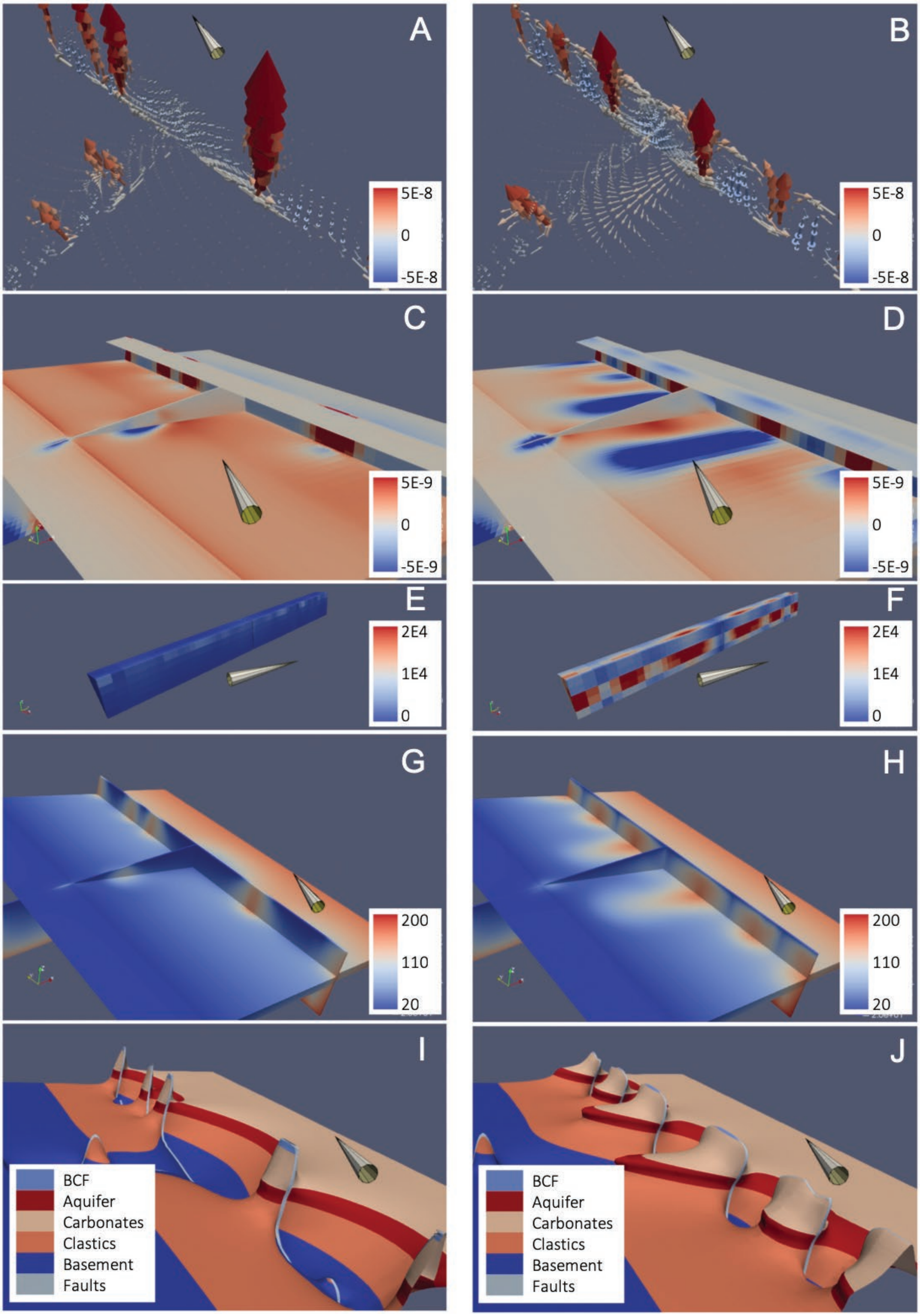

Figure 3. Convection without deformation. **Left side**: Emu Fault has high permeability throughout. **Right side**: Emu Fault has low permeability in top 300 m. Cone indicates North. (**a–b**) Fluid flow vectors. Arrows scaled with magnitude of fluid flux. Colours represent vertical component of fluid flux (m s^{-1}). (**c–d**) Horizontal component of fluid flux in aquifer, faults and Barney Creek Formation (m s^{-1}). Blue = west northwest, red = east southeast. (**e–f**): Time-integrated fluid flux in Barney Creek Formation (m^3/m^2). Vertical exaggeration x10. (**g–h**) Temperature in aquifer and faults (°C). (**i–j**) 120°C isosurface coloured by geological units.

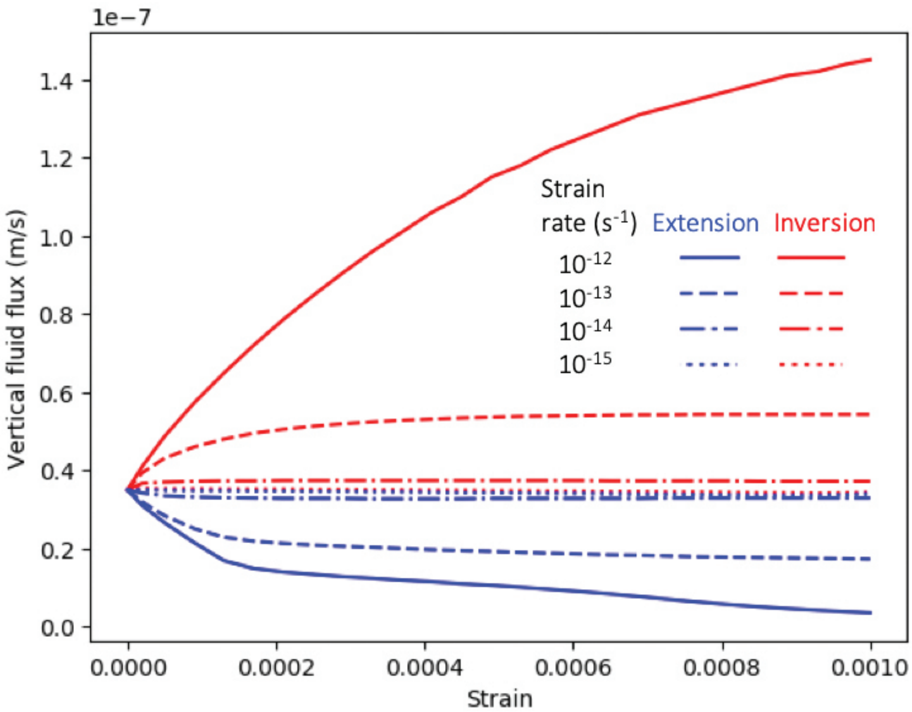

Figure 4. Effect of deformation on convection: Maximum vertical fluid flux in the faults as a function of strain rate.

Acknowledgements

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