From source to trap. Geophysical insights into base metals mineralisation in the southern McArthur Basin

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Introduction

The ca 1815–1450 Ma southern McArthur Basin contains sedimentary sequences from four vertically stacked and unconformity-bound superbasins (**Figure 1**; Rawlings 1999, Jackson *et al* 2000, Ahmad *et al* 2013). These superbasins evolved in response to far-field plate boundary processes, which influenced periods of extension and crustal shortening across the basin. Extension and shortening events varied in their orientation and intensity, and resulted in the development of a complex fault and depositional architecture.

This abstract discusses results from the interpretation and modelling of new and historical geophysical data from across the southern McArthur Basin. We summarise the tectonic evolution of the basin, which was derived from integration of our geophysical and structural interpretation into the geodynamic framework of the North Australian Craton. We also discuss implications of new geophysical modelling results for understanding Zn-Pb-Ag mineralisation within the basin, with a focus on metals source regions, fault and sub-basin architecture, and tectonic triggers for fluid migration.

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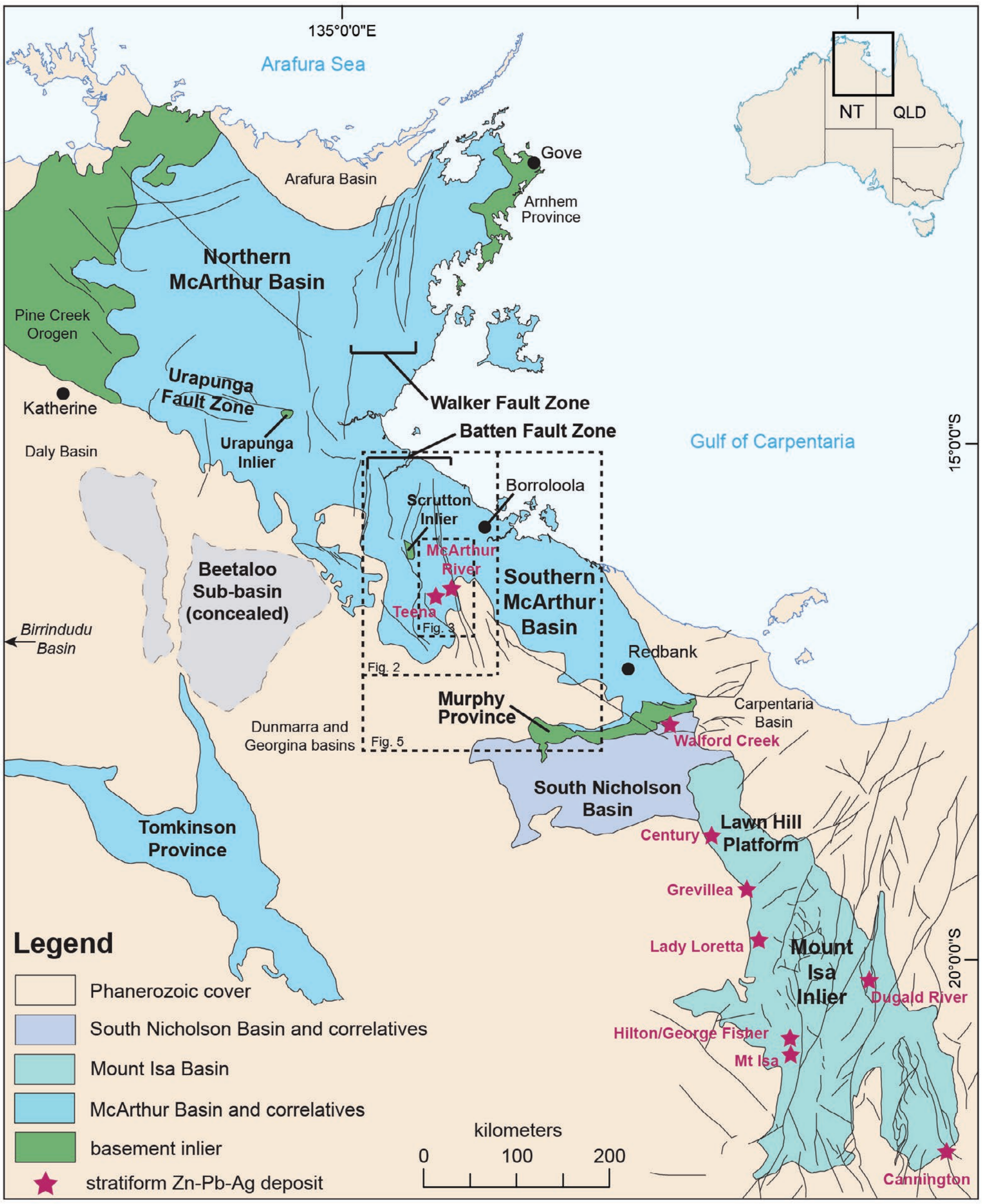

Figure 1. Regional geological map of McArthur and Mount Isa Basins showing location of major stratiform Zn-Pb-Ag deposits (after Ahmad *et al* 2013).

Regional scale geophysical modelling

Recent acquisition and modelling of gravity data across the Batten Fault Zone and southern McArthur Basin has provided new insight into the 3D architecture of the region. Both solid geology and structural interpretations of Proterozoic stratigraphy were completed, with most regions mapped down to formation scale (eg Blaikie and Kunzmann 2018). This allowed the lateral extent of major lithological units to be defined, as well as constrained 2D forward models of the Batten Fault Zone. Interpretations were also integrated with the detailed sedimentological evaluation and sequence stratigraphic framework developed by Kunzmann *et al* (2019) for the middle McArthur Group. This allowed observations of different depositional cycles, and shifting of depocentres to be placed in context of the structural framework.

Seven cross-sections were forward modelled and define the current 3D architecture of the region, including the nature of major basin controlling structures. The cross-sections were located along 500 m spaced gravity profiles, which were acquired along six east–west and one north–south traverse during the Batten Fault Zone gravity survey conducted in late 2017 (CSIRO 2018). **Figure 2** shows a 3D rendering of all cross-sections. The sections highlight the architecture of the fault zone, including regional scale folding, nature of major faults, and variations in the preserved thickness of stratigraphy.

Of significance for Zn-Pb-Ag mineralisation, forward modelling suggests that an anomalously thick sequence of mafic volcanics are preserved within the Tawallah Group in several regions of the Batten Fault Zone. The largest of these volcanic units has a strong spatial association to known mineralisation, including the McArthur River and Teena deposits. The volcanic unit is interpreted to be a thick accumulation of either or both of the Settlement Creek Dolerite and Gold Creek Volcanics. These units have experienced extensive potassic metasomatism and base metals depletion (eg Pietsch *et al* 1991, Haines *et al* 1993, Rawlings *et al* 1993); they have previously been interpreted as the source of base metals in the region (Cooke *et al* 1998, Huston *et al* 2006). Geophysical modelling has also identified regions of granitic basement within the Batten Fault Zone. Granitic clasts are recognised within several siliciclastic units of the Tawallah Group. These granites may represent a secondary source of metals, which were leached directly from the basement, or from clasts preserved within the Tawallah Group.

Recognition of anomalously-thick mafic volcanics within the Tawallah Group and felsic volcanics within the basement provides significant evidence of crustal pre-conditioning for base metals mineralisation; this implies that the source of base metals was located relatively close to major deposits discovered in the region. Modelling also recognises a number of aquifer and basement tapping faults, which would have provided a pathway for metal rich fluids to ascend.

Modelling sub-basin architecture

The McArthur Group was deposited during intermittent periods of extension and minor crustal shortening, which formed a complex array of sub-basins and palaeohighs. Forward models of the Batten Fault Zone were constructed at a regional scale, and although they model major sub-basin bounding faults, they do not focus on sub-basin architecture (less than 5 km scale). Integration of high-resolution geophysical data with the sequence stratigraphic framework developed by Kunzmann *et al* (2019) allowed more detailed geophysical models of sub-basin architecture to be constructed (eg Blaikie *et al* 2018, Blaikie and Kunzmann 2018).

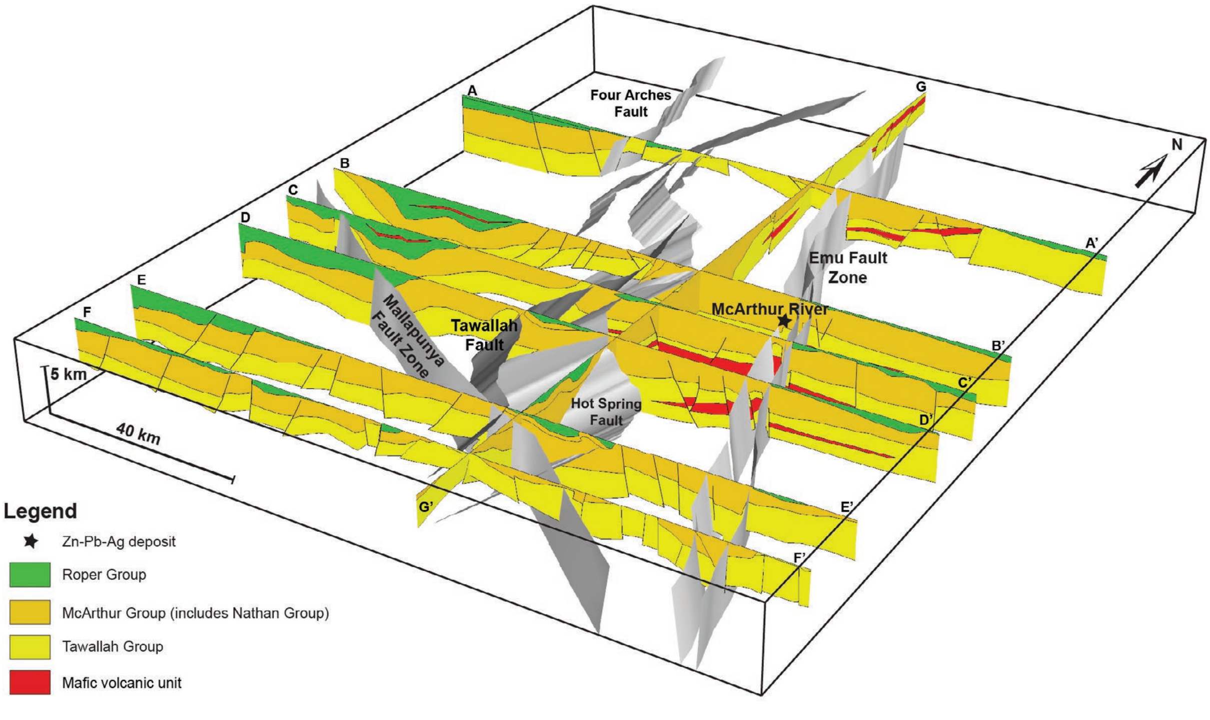

Figure 2. 3D rendering of forward modelled geological sections with surfaces for major faults overlain.

Two styles of sub-basins in the Batten Fault Zone are recognised from the interpretation of geophysical data (**Figure 3**; note: Barney Creek Formation may not be preserved in all sub-basins). North–south trending transtensional sub-basins developed between segments of the north–northwest-trending Emu Fault Zone (eg Glyde sub-basin. **Figure 3**; Type 1); and approximately east–west-trending sub-basins developed adjacent to east–west-trending normal and north–northwest-trending transfer faults located between the Hot Spring Fault and Emu Fault Zone (eg Teena sub-basin. **Figure 3**; Type 2).

These sub-basins are too small for detailed modelling on the regional scale cross-sections; however, many have high-resolution geophysical data acquired over them plus a number of drillholes to constrain interpretations. **Figure 4** shows the 3D architecture of the Glyde sub-basin, determined from forward modelling of gravity and magnetics, and interpretation of AEM data. Interpretation and modelling show thickening of the Barney Creek Formation between the Emu Fault Zone and Cowdreys Fault, with the greatest thickening of the formation occurring adjacent the Emu Fault Zone (**Figure 4**).

Tectonic evolution of the southern McArthur Basin

The structural and solid geological interpretation, and forward modelling of the potential field data, highlight the nature and overprinting relationships of major fault systems, regional scale folding and variations in the preserved thickness of stratigraphy within the Batten Fault Zone. This has allowed a synthesis of the basins depositional and structural evolution to be developed.

The Tawallah Group (ca 1710–1790 Ma) was deposited during at least two extensional events, separated by a mild period of inversion (**Figure 5a–c**). These events were driven by subduction roll-back and collisions along the southern and eastern margins of the North Australian Craton (Betts and Giles 2006). North–south-directed extension at

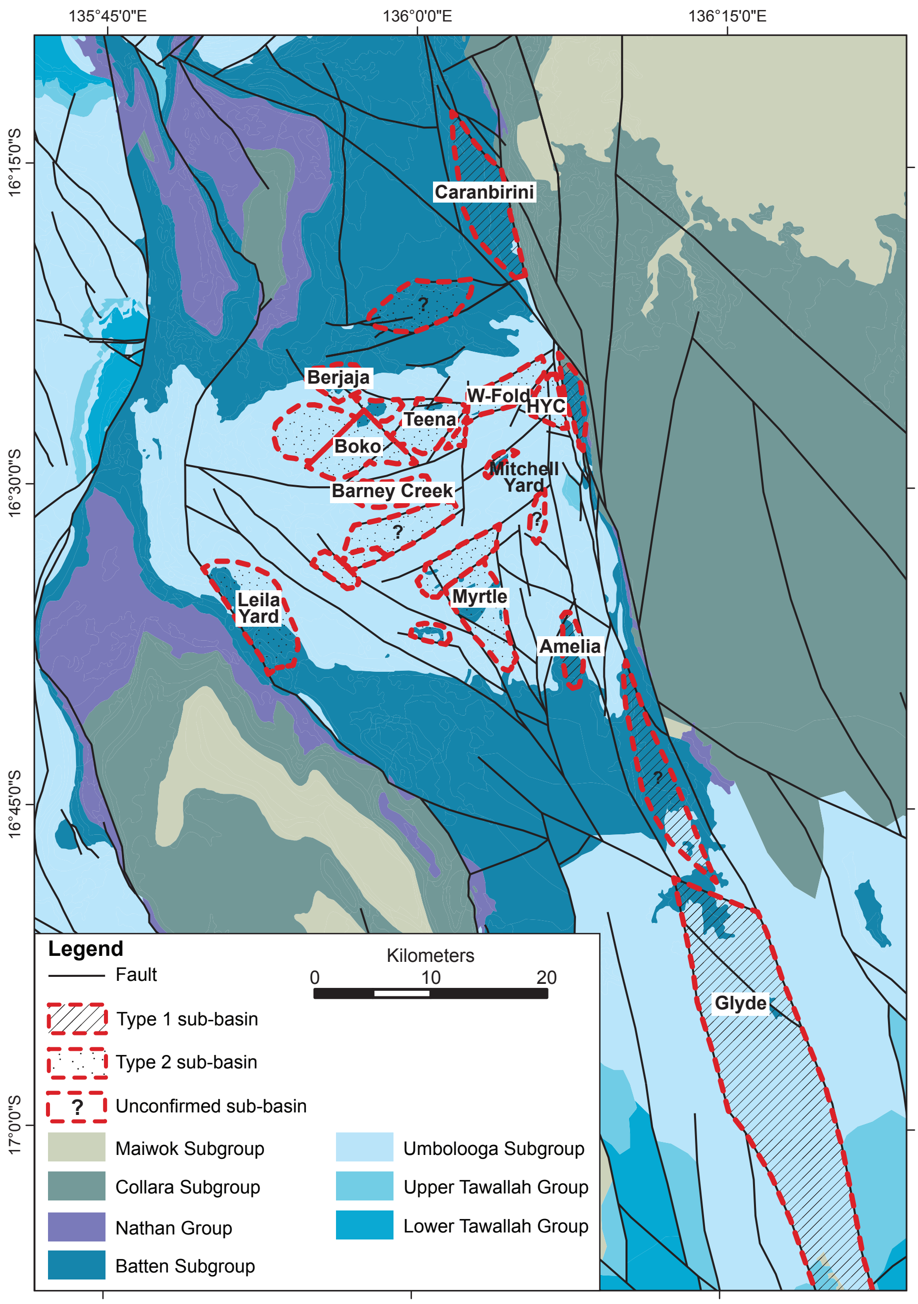

Figure 3. Map of geophysically defined, and previously interpreted (eg McGoldrick *et al* 2010) sub-basins in the central Batten Fault Zone.

ca 1760–1740 Ma caused the reactivation and development of northwest normal and northeast to north–northeast strike-slip faults (**Figure 5a**). A minor, east–west-directed inversion event is recognised at ca 1740 Ma (**Figure 5b**; Bull and Rogers 1996), which caused reverse movement along north–northeast faults. Northwest–southeast extension between ca 1730–1690 Ma caused development of north–northeast to northeast normal faults and strike-slip movement along northwest faults (**Figure 5c**).

Deposition of the ca 1670–1600 Ma McArthur Group and the ca 1600–1575 Ma Nathan Group occurred predominantly within a sag basin, which experienced short-lived periods of extension and inversion in response to deformation occurring at the margin of the North Australian Craton. A broadly north–south-directed period of extension occurred during deposition of the middle McArthur Group (ie during Barney Creek Formation; **Figure 5d**). This event compartmentalised the basin, causing significant deepening of sub-basins in some areas, and uplift and erosion in others (McGoldrick *et al* 2010 ,Kunzmann *et al* 2019). We speculate that a minor compressional event at ca 1640 Ma caused syn-depositional uplift along extensional faults resulting in an influx of breccias into previously developed sub-basins. The timing of this event is coincident with the Riversleigh Event on the Lawn Hill Platform (eg Bradshaw *et al* 2000), which has been correlated to the accretion of the Warumpi province (eg Hollis *et al* 2013; Scrimgeour *et al* 2005) on the southern margin of the craton at ca 1640 Ma (Betts and Armit 2011; Gibson *et al* 2017). Alternatively, if collision of the Warumpi province occurred at ca 1130 Ma as proposed by Wong *et al* 2015, then the ca 1640 Ma deformation recognised in the north Australian basins may be related to intraplate instability associated with broader scale plate reorganisation, which triggered a reversal in plate motion (eg Idnurm 2000).

The Isan Orogeny, driven by orogenesis at the margins of the North Australian Craton, caused significant uplift and erosion across the southern McArthur Basin. Initially, sedimentation of the upper McArthur and Nathan groups continued during the onset of the earliest phase of the orogeny. Sedimentation had ceased by ca 1570 Ma, with minor east–west folding and reverse faulting along extensional basin faults occurring during the late first stage of the orogeny (**Figure 5e**). The late Isan Orogeny caused reverse movement along north–northwest to north–northeast faults, which resulted in significant uplift and erosion, particularly in the north of the Batten Fault Zone (**Figure 5f**).

During the Mesoproterozoic, renewed basin development caused the widespread deposition of the Roper Group across the region (**Figure 5g**). Following this period of deposition, northeast–southwest-directed crustal shortening caused thrust faulting and folding in the Batten Fault Zone (**Figure 5h**; Rogers 1996, Keele and Wright 1998, Rawlings *et al* 2004). Timing of this event is not well constrained but is thought to be after the ca 1313 Ma (Collins *et al* 2018) emplacement of the Derim Derim Dolerite dykes and sills.

Tectonic triggers of fluid migration

Zn-Pb-Ag mineralisation within the McArthur Basin occurred when fluids from aquifers at depth (ie Tawallah Group; Polito *et al* 2006) flowed upward into a suitable trap at or near the surface. Although extensional conditions are favourable for formation of suitable metal traps, such as restricted sub-basins in the case of the McArthur Basin, they are not conducive to mineralisation because fluids will largely tend to migrate downward (Sheldon and Schaubs 2018). However, compressional stresses associated with a short-lived, ca 1640 Ma compressional event provide a

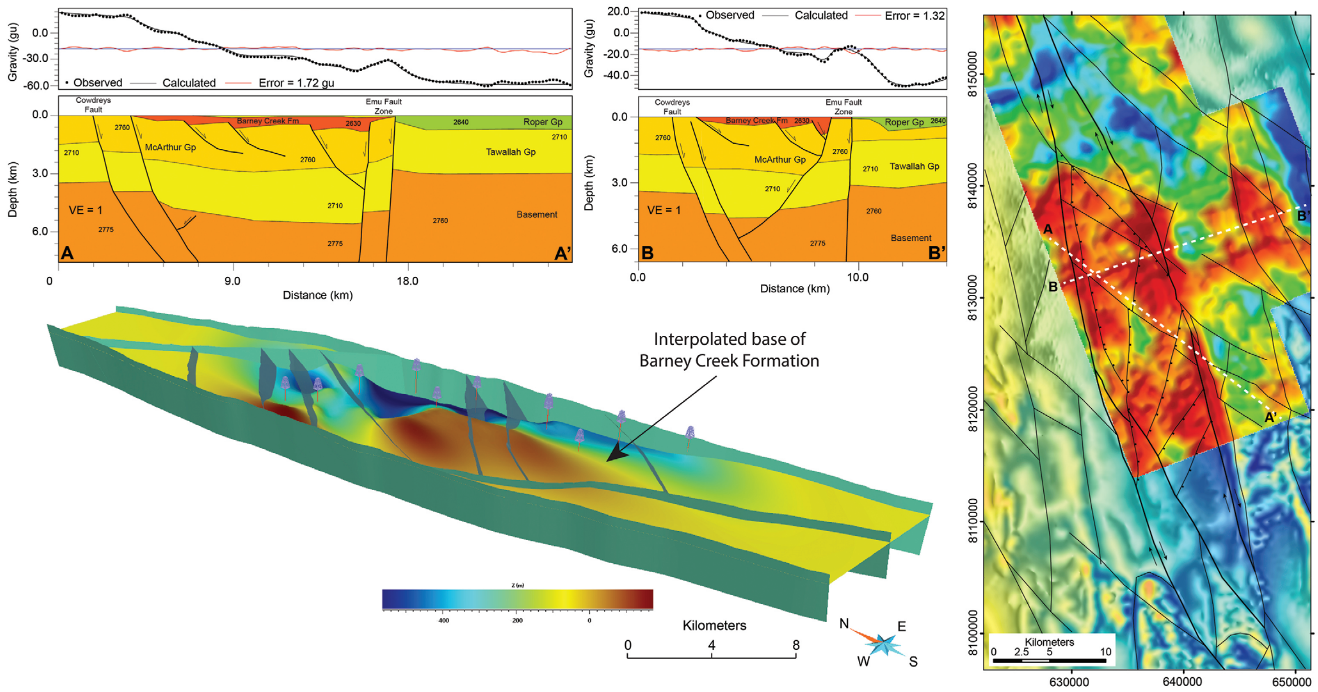

Figure 4. Architecture of the Glyde sub-basin determined from geophysical interpretation and modelling. (**a-b**) Forward modelled cross-sections of the Glyde sub-basin. **c**) Falcon gravity data (acquired by Armour Energy 2013) overlain with interpreted faults. (**d**) 3D model of the Glyde sub-basin showing location of wells, major faults and an interpolated surface for the base of the Barney Creek Formation.

mechanism to drive metal rich fluids upward and into the host stratigraphy.

Syn-depositional deformation associated with crustal shortening was first documented by Hinman (1995) at McArthur River where inversion of extensional structures and an influx of mass-flow breccias into the HYC sub-basin was interpreted. Folding and reverse faulting was recognised largely in close proximity to the Emu Fault Zone, but is also observed in other regions of the Batten Fault Zone (Hinman 1995, Rogers 1996). The onlap of strata of the upper Barney Creek Formation onto stratigraphy that was reversely faulted and incised during inversion indicates that sedimentation of the Barney Creek Formation continued during the onset of deformation (Hinman 1995). Recent evidence for a diagenetic

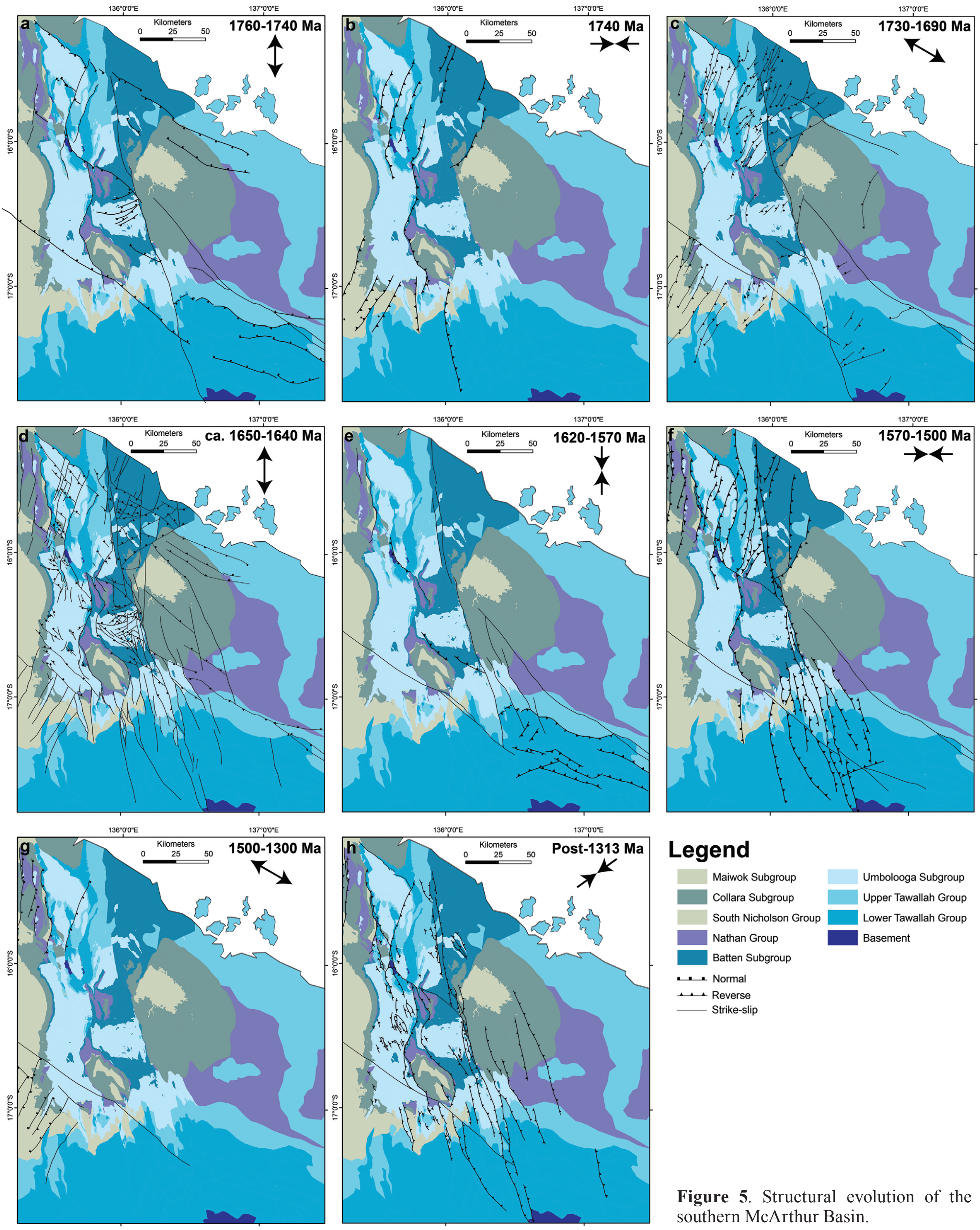

Figure 5. Structural evolution of the southern McArthur Basin.

origin of Zn-Pb-Ag mineralisation at McArthur River (Spinks *et al* 2018), which stratigraphically occurs in the lowermost Barney Creek Formation, suggests that mineralisation may have occurred tens to hundreds of meters below the sea floor. This means that fluid flow and mineralisation may have occurred at about the time the upper Barney Creek Formation was deposited (Kunzmann *et al* 2019), ie the proposed time of the onset of deformation at ca 1640 Ma.

Conclusions

Geophysical interpretation and modelling results from this study have important implications for understanding Zn-Pb-Ag mineralisation within the region. Modelling has recognised potential source rocks for metals in the form of anomalously thick sequences of mafic volcanics within the Tawallah Group. Modelling also identified potential fluid pathways in the form of sub-basin bounding faults that tap the basement and aquifers within the Tawallah Group.

A new synthesis for the structural and tectonic evolution of the southern McArthur Basin was developed from the integration of modelling results into the geodynamic framework of northern Australia. Results of this work led to a correlation between a short-lived compressional event occurring towards the end of deposition of the Barney Creek Formation and inversion on the Lawn Hill Platform. This event is thought to be driven either by deformation related to the accretion of the Warumpi province at ca 1640 Ma, or by broader scale tectonic instability due to a reversal in plate motion. This event may have provided the mechanism for pumping metal-bearing fluids up faults and leading to mineralisation within the basin.

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