Revisiting the structural and stratigraphic setting of the Teena Zn–Pb deposit and implications for mineralisation processes

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Introduction

The Teena deposit in northern Australia is an example of a sediment-hosted stratiform lead–zinc (SHMS) deposit. It is located ~10 km west of the McArthur River mine (HYC; **Figure 1**) in the Northern Territory. The deposits occur within the ca 1640 Ma Barney Creek Formation of the McArthur Group (**Figure 2**). The sediments are preserved within the Batten Trough, a north–south-orientated fault-bounded basin that forms part of the larger Isa Superbasin (Ahmad *et al* 2013). The Isa Superbasin hosts several world class shale-hosted lead–zinc deposits, including Mount Isa, Lady Loretta, George Fisher, Century, and Dugald River (Spinks *et al* 2021).

The eastern margin of the Batten Trough is bound by the Emu Fault. This a linear feature in the geology and topography that can be traced for around 150 km north–south. The Batten Trough is divided into smaller sub-basins that formed in response to north–south-directed extension. These sub-basins are believed to have controlled local facies variations and stratigraphic thickening; they subsequently became the preferred sites for the emplacement of mineralisation due to the thicker and more favourable stratigraphy, and presence of the fault network necessary to introduce the mineralising fluids (Blaikie and Kunzmann 2020, Hayward *et al* 2021).

The Batten Trough has undergone multiple deformation events that now obscure the original basin architecture. The most intense deformation event was the Isan Orogeny at ca 1600-1500 Ma. This saw the cessation of sedimentation with inversion of the Batten Trough. The main phase of deformation was marked by east–west directed shortening that resulted in reactivation of older faults and the development of short wavelength north–south-orientated folding (Blaikie and Kunzmann 2020).

The origin of the HYC deposit has been contentious for many years, with both epigenetic and synsedimentary models suggested. The fine-grained nature of the mineralisation at HYC initially led many researchers to favour a synsedimentary model (Croxford and Jephcott 1972, Large *et al* 1998). More recently, the documentation of carbonate replacement textures at HYC and Teena has seen a shift towards an epigenetic model (Spinks *et al* 2021, Magnall *et al* 2021). However, while the prevailing models have shifted, a central theme is the importance of active faulting in defining the basin architecture and presenting potential conduits for the mineralising fluids. This interpretation has implications for exploration tactics, with fault corridors seen as more favourable settings.

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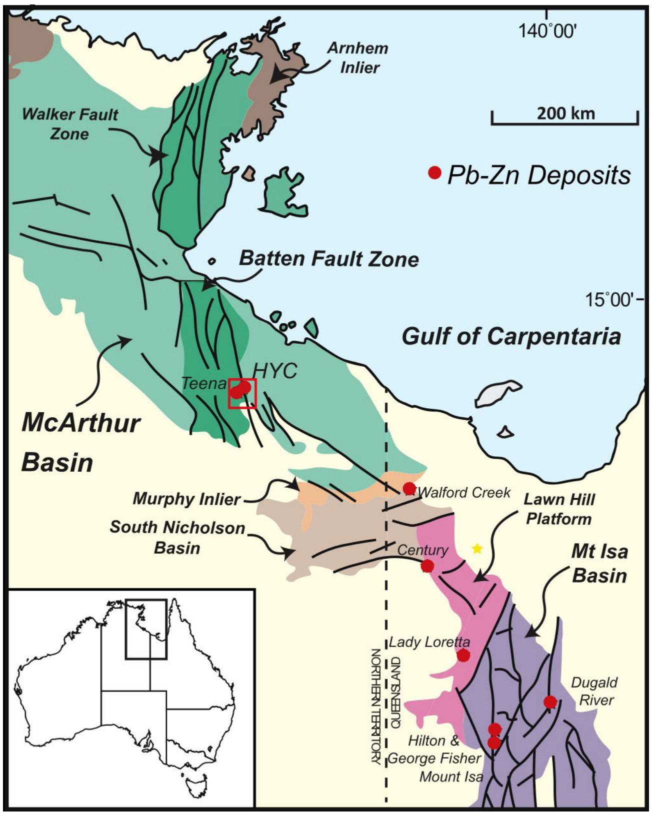

Figure 1. Simplified geological map of the Isa Superbasin with the location of the major stratiform Pb–Zn deposits. Modified from Hayward *et al* (2021).

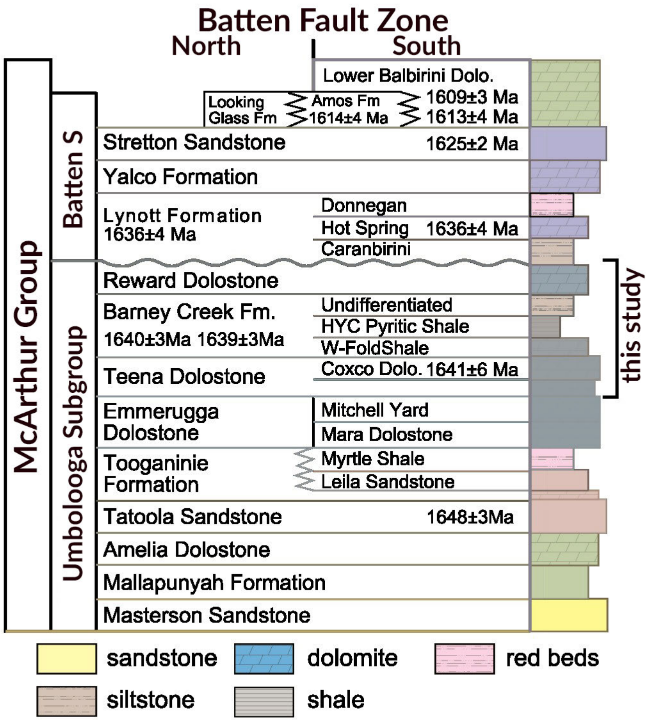

Figure 2. Stratigraphy, lithology, and geochronology of the McArthur Group in the Batten Fault Zone. Stratigraphy modified from Ahmad *et al* (2013).

In this context, we revisit the evidence for active faulting during the formation of the Teena deposit and consider what role faults have played in the emplacement of the Teena mineralisation.

Teena geology

The Teena deposit is located in an east–west-trending syncline that overprints and preserves an earlier formed sub-basin (**Figure 3**). The geology of the Teena Deposit is described in detail by Hayward *et al* (2021).

The oldest unit observed is the Teena Dolostone, a carbonate-dominated unit divided into two facies. On the southern limb of the syncline, the Teena Dolostone is laminated and typically grades upwards into the overlying W-Fold Shale Member of the Barney Creek Formation. On the northern limb of the syncline, the Teena Dolostone is massive and is commonly brecciated (Teena Breccia). There is generally a sharp or disconformable contact between the massive Teena Dolostone and the overlying Barney Creek Formation.

The W-Fold Shale Member forms the basal part of the Barney Creek Formation. It occurs as a sequence of interbedded siltstones and fine sandstones and often has a distinctive nodular texture. It is variably red and green in colour. A shale-dominated middle facies has been defined containing laminated carbonates and minor lead–zinc mineralisation. The thickest W-Fold unit occurs within the center of the syncline, and thins to the north and south.

The W-Fold Shale Member grades upwards into the HYC Pyritic Shale Member, which has a lower unit of fine siltstones with laminated and nodular carbonate and very little pyrite. The main mineralisation at Teena is hosted by this facies. This grades upwards into the middle HYC Pyritic Shale Member, a monotonous sequence of dolomitic, pyritic, dark shales and siltstones. The pyrite content decreases up section and is transitional with the Upper HYC Pyritic Shale Member.

The Barney Creek Formation is then overlain by the Reward Dolostone Formation, a more thickly bedded carbonate unit with minor interbedded dolomitic siltstones.

The Caranbirini Member of the Lynott Formation is the youngest unit preserved in the area. It comprises dark monotonous shales and siltstones, which can be difficult to differentiate from the upper Barney Creek Formation. In places, an unconformity marks the base of the Caranbirini Member where it can rest directly on Barney Creek Formation or the Teena Dolostone.

New observations from Teena

Hayward *et al* (2021) suggested that the Teena sub-basin developed as a half graben controlled by a series of east–west-orientated faults along the northern limb of the Teena Syncline (Jabiru and Bald Hills Faults). These faults later acted as conduits for the mineralising fluids. While this is possible, we present several new observations that are not necessarily consistent with this model.

Teena–Barney Creek contact

Along the northern limb of the syncline, the contacts between the Barney Creek Formation and the Teena Dolostone vary from gradational to sharp but are rarely faulted (**Figure 4**). All the units of the Barney Creek Formation can be seen in contact with Teena Dolostone. Based on these observations, we suggest that this surface is better interpreted as an unconformable stratigraphic contact and that the relationships can be accounted for by onlap of the various units onto the Teena Dolostone surface.

Teena breccias

The Teena Dolostone is commonly brecciated on the northern limb of the syncline. The breccias are predominantly monomict (clasts dominantly Teena Dolostone) and clast

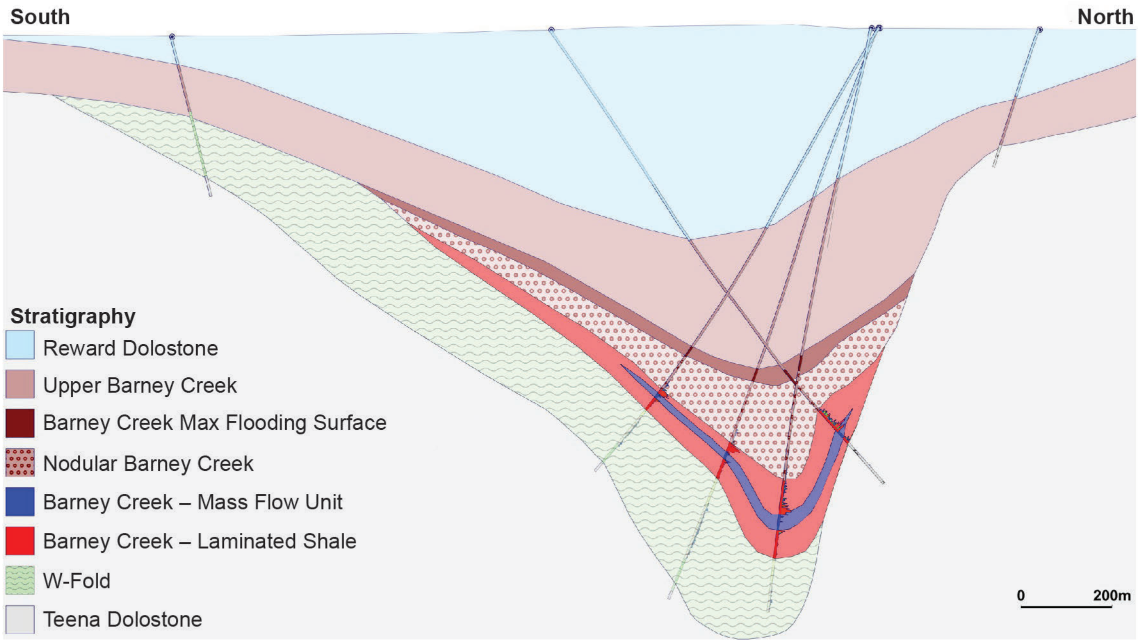

Figure 3. North–south cross-section of the Teena Deposit. The detailed stratigraphic subdivisions are provided in the legend.

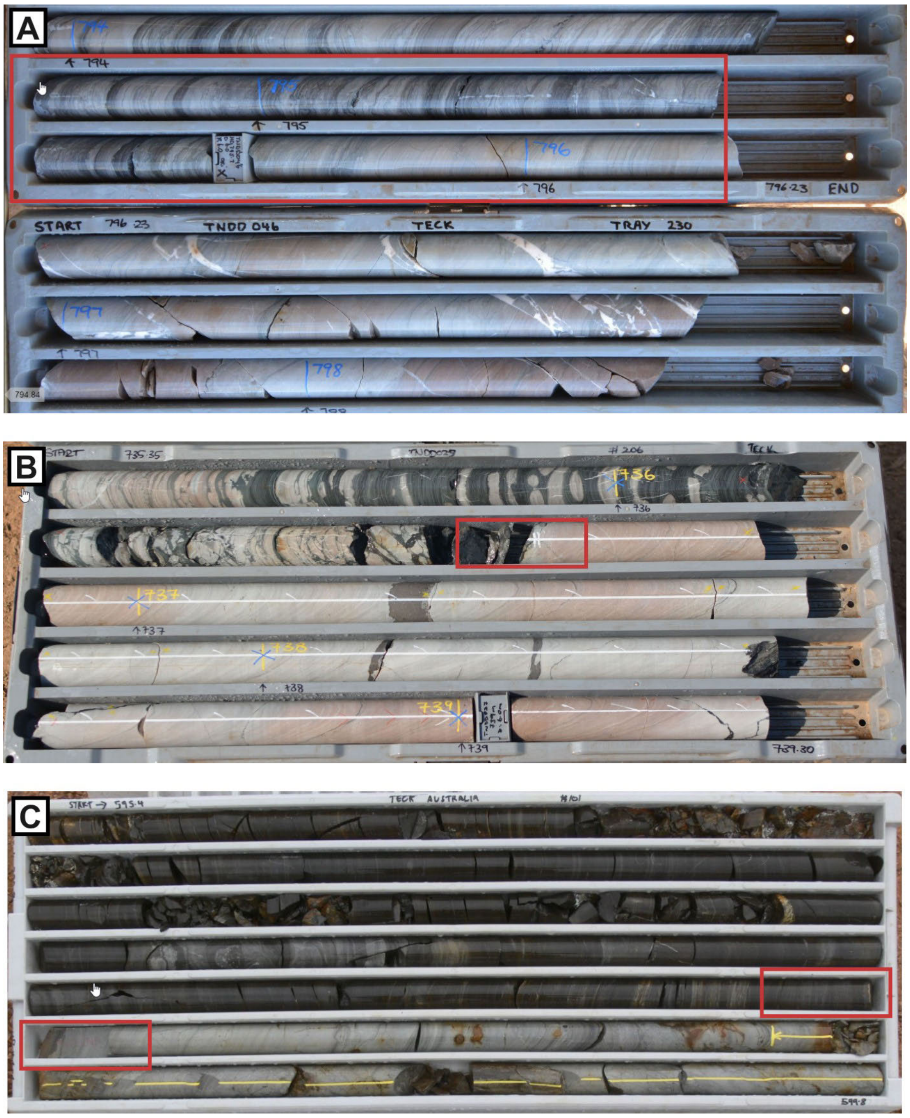

Figure 4. Typical contacts between the Barney Creek Formation and the Teena Dolostone along the northern limb at Teena. The contacts are shown by the red box on each image. (**a**) Gradational contact between the Teena Dolostone and the W-Fold Shale Member (TNDD046: 794–798.5 m). (**b**) Disconformable contact between the W-Fold Shale Member and the Teena Dolostone (TNDD027: 735.35–739.8 m). (**c**) Disconformable contact between the Barney Creek shales and the Teena Dolostone (Teena 8: 595.4–599.8 m).

or matrix supported. The matrix material is a dark grey to black, fine-grained dolomite (**Figure 5**); and the clasts are generally angular to sub-rounded. Breccia bodies vary in thickness from tens of centimetres to hundreds of meters. Marine-cemented veins are commonly truncated along clast boundaries.

Similar breccias have been observed in the Teena Dolostone at Boko and Berjaya (**Figure 5**). Gianfriddo *et al* (2022) also describes similar breccias at Rosie Creek, located ~120 km north of Teena.

Detailed pXRF analysis was completed on the breccia clasts and matrix from Teena drillholes (**Figure 6**). They all have a similar geochemical signature (with clasts typically having a lower aluminium content), which is distinct from the geochemistry of the Barney Creek Formation. In some localities, a thin carbonate unit can also be observed at the top of the breccia interval (Teena Breccia Cap). This unit is then overlain by Barney Creek Formation. This suggests that the Teena breccias formed prior to the deposition of the main Barney Creek units with minimal infiltration of shale material into the breccia matrix.

Neptunian dykes are also common within the Teena Dolostone. At Berjaya, there are examples of neptunian dykes within breccia intervals. The neptunian dykes have the same black matrix material overlying marine cements (**Figure 5**). This suggests that the neptunian dykes developed at a similar time to the breccias, ie during the formation of the Teena Dolostone. The observation of marine-cemented neptunian dykes truncating the Teena breccias indicates that the breccias are of synsedimentary marine origin.

Based on these observations, we suggest that a regional tectonic event caused instability in the Teena Dolostone and the subsequent formation of breccias and neptunian dykes before the deposition of the Barney Creek Formation. This is consistent with the observations of McGoldrick *et al* (2010) who documented neptunian dykes and breccias at this same stratigraphic level.

New observations from Boko

The Boko Syncline, located ~10 km west of Teena, is the extension of the Teena Syncline. In 2020, Teck Australia completed four diamond drillholes in the Boko Syncline. This included a north–south-orientated section to constrain the northern boundary or limb of the syncline (**Figure 7**). This section showed marked thinning of the Barney Creek member northwards; Teena Dolostone was brecciated on

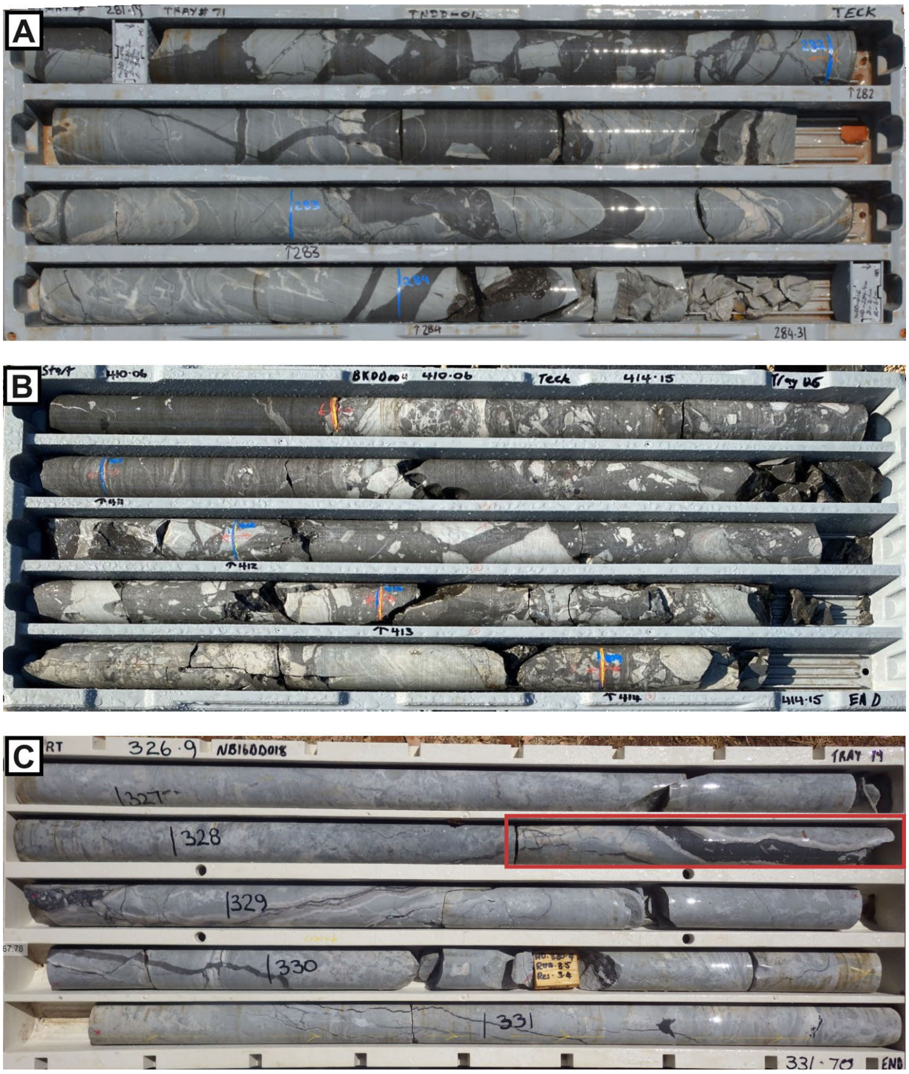

Figure 5. Examples of the Teena Breccia from the Teena area. (**a**) Matrix supported Teena Breccia in the northern limb of Teena (TNDD016: 528.19–284.31 m). (**b**) Matrix supported Teena Breccia beneath the Barney Creek Contact at Boko (BKDD004: 410.6–414.15 m). (**c**) Neptunian dyke with black dolomite matrix infill after the marine cements (NB16DD018: 326.9–331.7 m).

the northern limb; and there was no evidence for faulting, with shallow bedding dips consistent with the modelled contacts. From these observations, we interpret that the Barney Creek Formation is thinning onto a basement of brecciated Teena Dolostone. This setting is similar to that observed at Teena but with no significant sulfide mineralisation.

Revision of the Teena stratigraphic and structural model

Based on these new observations from Teena and Boko, a revised model is proposed (**Figure 8**). Towards the end of the deposition of the Teena Dolostone, a widespread tectonic event disrupted the unit, resulting in the formation of the Teena breccias and neptunian dykes over a broad area. The event was immediately followed by a major marine transgression and the deposition of the Barney Creek Formation. There is no evidence for substantial faulting during the deposition of the Barney Creek Formation. The thickness changes observed can instead be accounted for by onlap of the Barney Creek Formation onto Teena Dolostone.

While this model does not require active faulting, it appears likely that faulting accompanied the Teena tectonic event and influenced the distribution of the breccias and seafloor bathymetry. However, based on the drilling to date, it is not possible to constrain the location or the nature of these structures; they remain enigmatic as they have not been constrained by drilling.

Later inversion has modified the initial geometries making it more difficult to define the original architecture. The northern limb of the Teena Deposit is near vertical in places, and the degree of parasitic folding and deformation increases markedly towards the Barney Creek–Teena Dolostone contact. This may reflect preferential deformation along a strong rheology contrast.

Implications for deposit models

Previous models have relied heavily on faults to act as both conduits for mineralisation fluids and controls of the distribution of sub-basins (Large *et al* 1998, Hayward *et al* 2021, Spinks *et al* 2021). While this is possible, our observations suggest that the main period of faulting occurred before the deposition of the Barney Creek Formation and that there was little fault movement following deposition of the Teena Dolostone. The sub-basin geometries possibly reflect an uneven Teena Dolostone bathymetry and onlap on the Barney Creek Formation. Later deformation has then preserved this stratigraphy in synclines. This folding may be in response to a deeper fault architecture but this has not been defined to date.

Given the relatively early timing of the faulting, it is difficult to envisage that faults acted as the primary

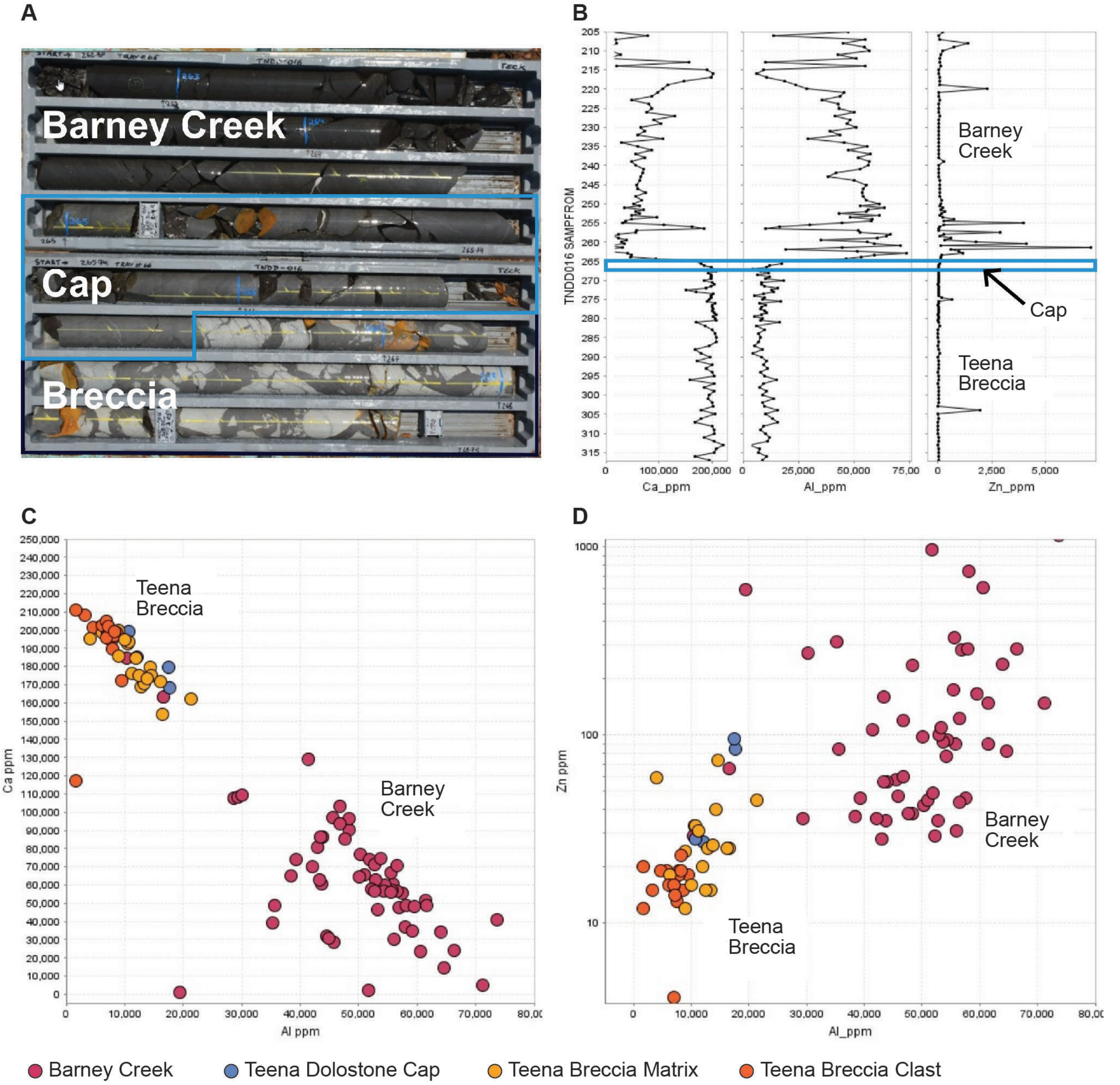

Figure 6. Geochemistry of the Teena Breccia in TNDD016. (**a**) Core tray photograph showing the Teena Breccia overlain by the Teena Cap unit. This is overlain by the Barney Creek Formation. (**b**) Downhole plot of the pXRF data for TNDD016. The Teena Cap unit has a signature like the breccia unit and is distinct from the Barney Creek Formation. (**c**) Al vs Ca plot of the pXRF data. The breccia and cap units can be clearly differentiated from the Barney Creek. The cap unit does tend towards higher Al value. (**d**) Al vs log Zn plot. Again, the breccia and cap units can be differentiated from the Barney Creek Formation, which has higher Zn values particularly in the basal interval above the contact with the Teena Cap.

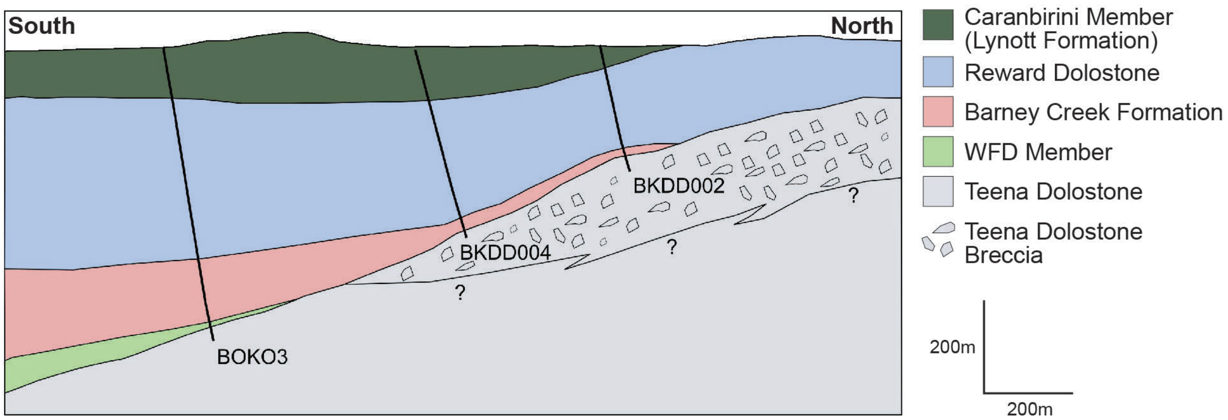

Figure 7. North–south cross-section of the Boko Syncline. W-Fold Shale Member (WFD Member) is differentiated but the remaining Barney Creek members are combined. The stratigraphic thickness to the south is constrained by other drilling off the section. The lateral distribution of the Teena Breccia is constrained in BKDD004 and BKDD002, but the thickness is unknown.

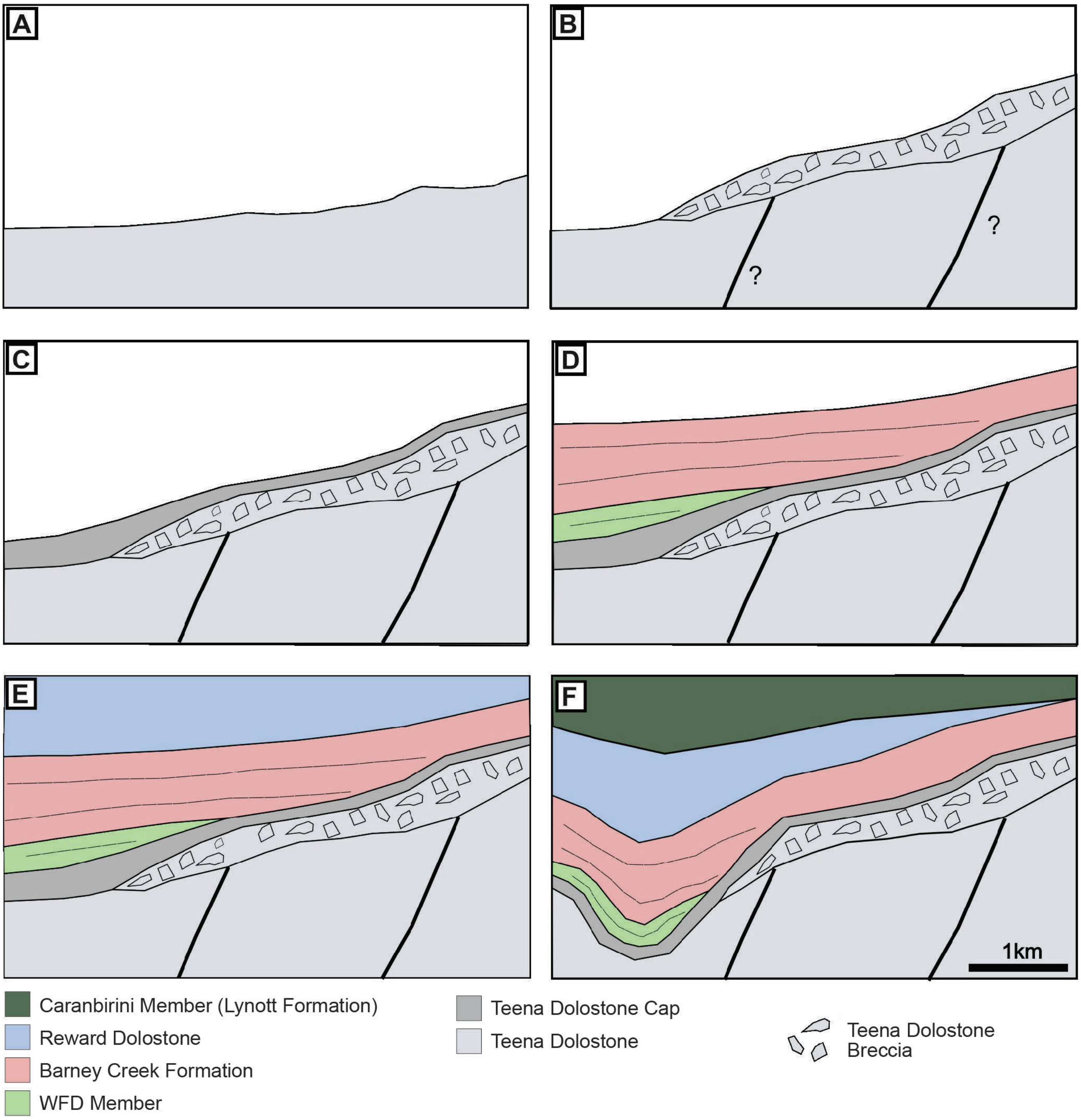

Figure 8. Geological model for the development of the Teena Syncline. (**a**) Teena Dolostone is deposited. (**b**) Tectonic event causes formation of the breccias and neptunian dykes on the seafloor. (**c**) Teena Cap unit is deposited in carbonate-dominated environment. (**d**) Onlap of the Barney Creek Formation. WFD Member is the deposited first and is more restricted in distribution. (**e**) Deposition of the Reward Dolostone. (**f**) Deposition of the Caranbirini Member following mild inversion. The timing of the different inversion events is poorly constrained, but the diagram preserves the relationships observed.

conduits for the ascent of fluids from kilometres depth. Rather a more subtle onlap surface may have been the principal control for trapping basin-derived fluids with later deformation obscuring the true nature of the contact.

Another observation is that, if faults act as conduits, there should be more mineralisation or alteration observed along these fault systems. However, mineralisation at Teena occurs in the centre of the syncline and not along the more northern limb, the inferred fluid conduit (Hayward *et al* 2021). Boko shares the same stratigraphic setting, including extensive breccias, but is not mineralised. Likewise, the Emu Fault can be traced for 150 km, but the only mineralisation discovered to date in this system occurs at HYC. Given these observations, it would seem likely that there is another critical control for mineralisation and that faults alone are a poor predictor of shale-hosted mineralisation. A bias may exist because the long and protracted deformation history of the basins has obscured subtle older features while emphasizing the youngest events.

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References

Ahmad M, Dunster JN and Munson TJ (2013). Chapter 15 - McArthur Basin: in Ahmad M and Munson TJ (compilers). '*Geology and mineral resources of the Northern Territory'. Northern Territory Geological Survey, Special Publication* 5.

Blaikie TN and Kunzmann M, 2020. Geophysical interpretation and tectonic synthesis of the Proterozoic southern McArthur Basin, northern Australia. *Precambrian Research* 343, 105728. https://doi.org/10.1016/j.precamres.2020.105728

Croxford NJW and Jephcott S, 1972. The McArthur lead-zinc-silver deposit, NT. *Proceedings of the Australasian Institute of Mining and Metallurgy* 243, 1–26.

Gianfriddo C, Bull SW and Andrews TM, 2022. The Rosie pyrite hydrothermal system in the McArthur Basin: tectono-sedimentary constraints on mineralization and alkali metasomatism in stratiform sediment-hosted sulfide deposits of northern Australia. *Mineralium Deposita* 57(3), 377–398. https://doi.org/10.1007/s00126-021-01069-w

Hayward N, Magnall JM, Taylor M, King R, McMillan N and Gleeson SA, 2021. The Teena Zn–Pb Deposit (McArthur Basin, Australia). Part I: Syndiagenetic base metal sulfide mineralization related to dynamic sub-basin evolution. *Economic Geology* 116(8), 1743–1768. https://doi.org/10.5382/econgeo.4846

Large RR, Bull SW, Cooke DR and McGoldrick PJ, 1998. A genetic model for the HYC deposit, Australia; based on regional sedimentology, geochemistry, and sulfide-sediment relationships. *Economic Geology* 93(8), 1345–1368. https://doi.org/10.2113/gsecongeo.93.8.1345

Magnall JM, Hayward N, Gleeson SA, Schleicher A, Dalrymple I, King R and Mahlstadt N, 2021. The Teena Zn–Pb deposit (McArthur Basin, Australia). Part II: Carbonate replacement sulfide mineralization during burial diagenesis—implications for mineral exploration. *Economic Geology* 116(8), 1769–1801. https://doi.org/10.5382/econgeo.4845

McGoldrick P, Winefield P, Bull S, Selley D and Scott R, 2010. Sequences, synsedimentary structures, and sub-basins: the where and when of SEDEX zinc systems in the southern McArthur Basin, Australia: in Goldfarb RJ, Marsh EE and Monecke T (editors). '*The challenge of finding new mineral resources: Global metallogeny, innovative exploration, and new discoveries'. Society of Economic Geologists, Special Publication* 15, 367–389.

Spinks SC, Pearce MA, Liu W, Kunzmann M, Ryan CG, Moorhead GF, Kirkham R, Blaikie T, Sheldon HA, Schaubs PM and Rickard WDA, 2021. Carbonate replacement as the principal ore formation process in the Proterozoic McArthur River (HYC) sediment-hosted Zn–Pb deposit, Australia. *Economic Geology* 116(3), 693–718. https://doi.org/10.5382/econgeo.4793