Towards a revised stratigraphy for the Neoproterozoic and probable early Cambrian in the central Amadeus Basin, Northern Territory

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Revisions to the Neoproterozoic to early Cambrian stratigraphy of the central Amadeus Basin have resulted from mapping by Northern Territory Geological Survey (NTGS) in southern HENBURY[3] in 2015. Many of the revisions relate to the identification of the formal Neoproterozoic stratigraphy from the northeastern and northern Amadeus Basin in areas previously mapped as broad informal units in HENBURY. These revisions include recognition of the Loves Creek and Johnnys Creek formations (Bitter Springs Group) replacing all outcrops previously identified as undivided Bitter Springs Formation. The basal unit of Bitter Springs Group, the Gillen Formation, is apparently not exposed in HENBURY. The recently defined Wallara Formation (formerly 'Finke beds') also crops out locally. All exposures of *Inindia beds*, which are widespread in the south in the first edition of HENBURY (Ranford *et al* 1963), are now recognised as largely Aralka Formation together with its constituent Limbla Member, as well as Areyonga Formation and rarely as Pioneer Sandstone.

At this stage the most significant outcome from NTGS mapping in southern HENBURY is a new stratigraphy for the previously undivided *Winnall beds*. *Winnall Group* is herein defined and comprises: Breaden, Gloaming, Froud, Liddle and Puna Kura Kura formations. The Puna Kura Kura Formation includes a conglomeratic interval referred to as the Chookla Member. It is likely that Pertatataka Formation will soon be included in Winnall Group.

The revisions to the stratigraphy of HENBURY are summarised in **Figure 1** where they are compared with the

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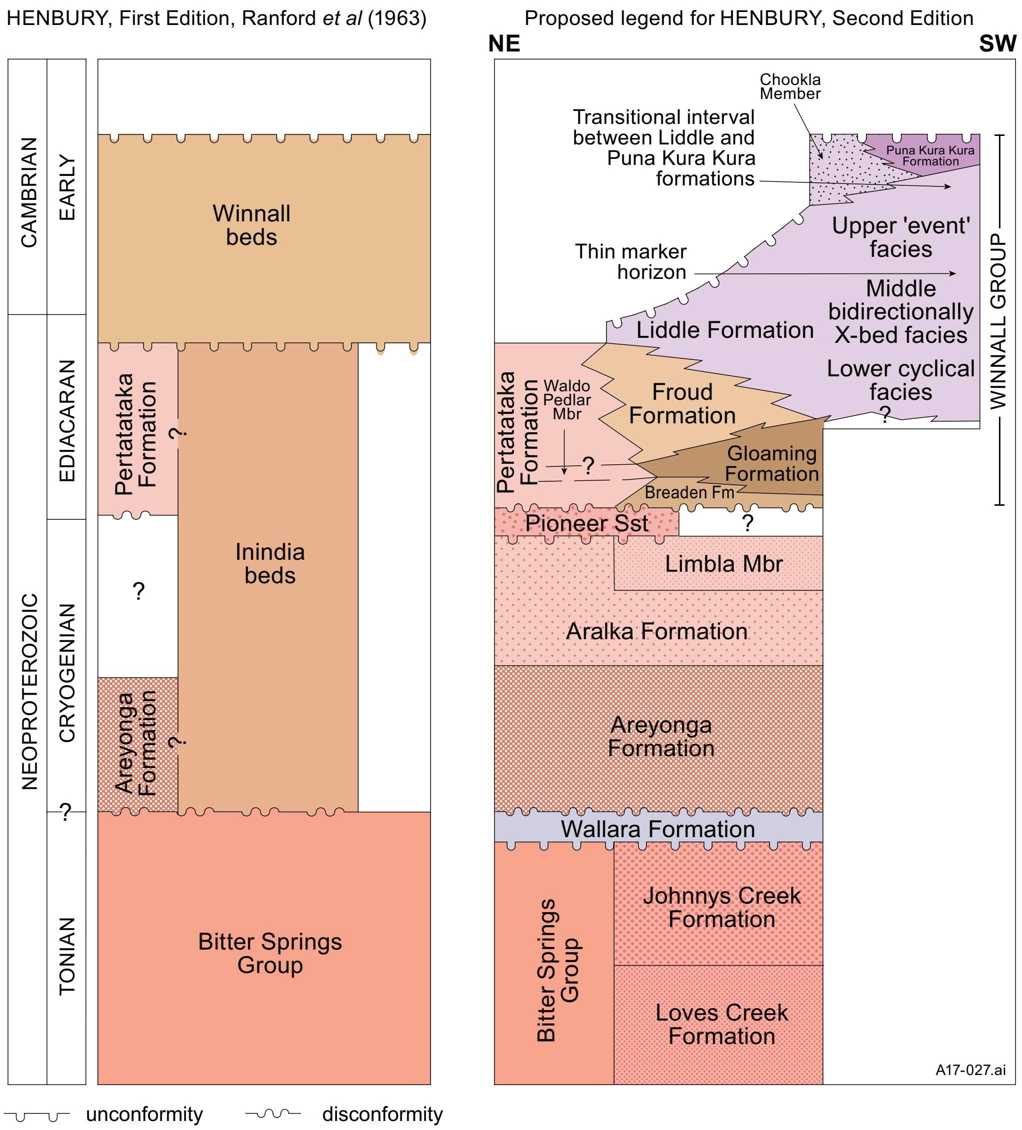

Figure 1. Comparative diagram showing proposed revisions to the Neoproterozoic and early Cambrian stratigraphy in HENBURY relative to the *First Edition* geological map by Ranford *et al* (1963).

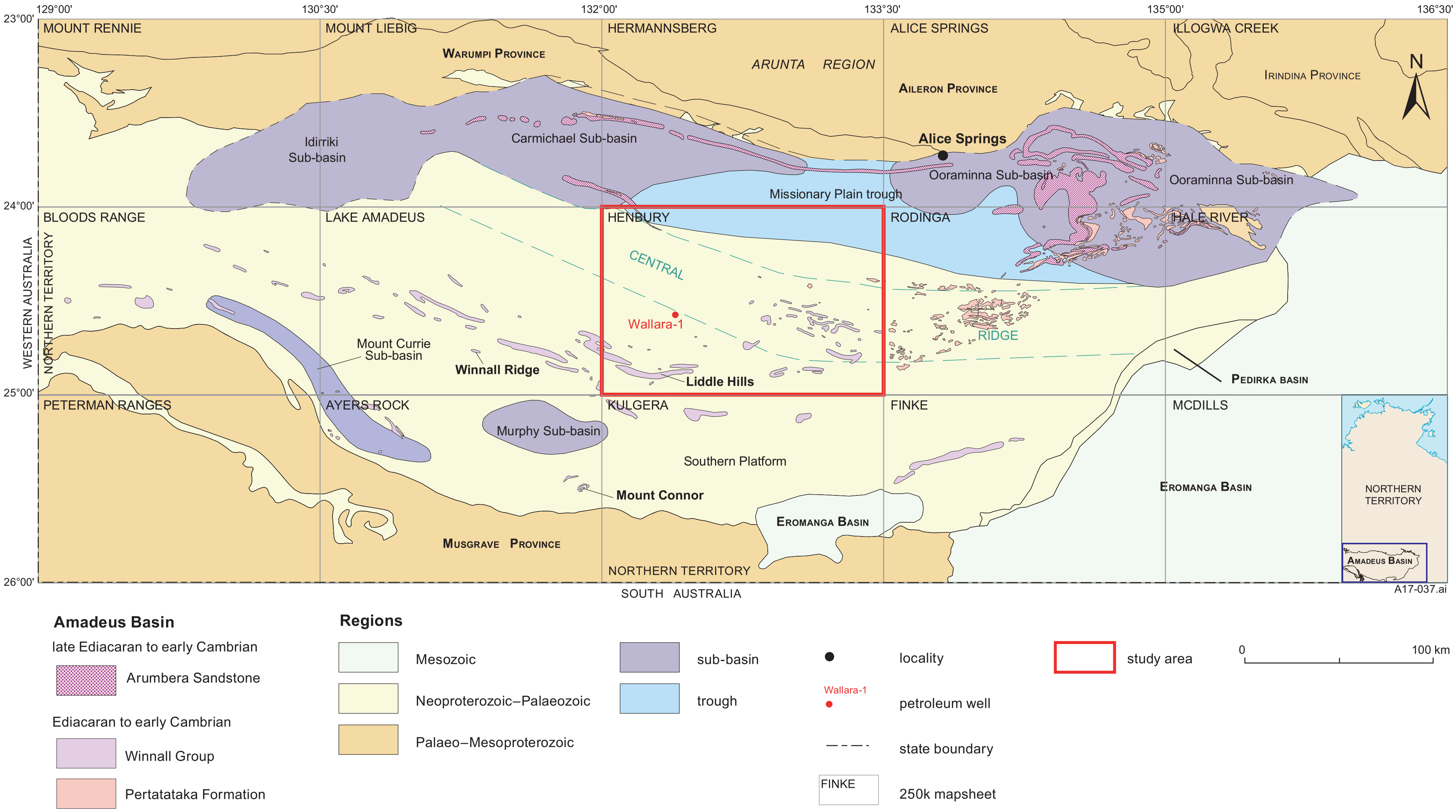

Figure 2. Regional geological setting of the Amadeus Basin in the Northern Territory. Late to post-Petermann Orogeny basin architecture is shown (after Edgoose 2013, and slightly modified after Marshall *et al* 2007), together with the distribution of the former Winnall beds (now Winnall Group) and probable partially correlative Pertatataka Formation and Arumbera Sandstone. Outcrop geology is derived from NTGS 1:2.5M geological regions GIS dataset. The location of the Wallara 1 well (53J 230787mE 7275207mN in HENBURY) is shown.

published stratigraphy of Ranford *et al* (1963). Some issues of correlation yet to be resolved with respect to the Winnall Group and its constituent formations are briefly discussed.

Regional geological context

The Amadeus Basin is discontinuously exposed over an area of about 170 000 km^2 in central Australia (**Figure 2**). The contemporary extent of the basin is structurally controlled to the north and south where it is juxtaposed with basement of the Arunta Region and Musgrave Province respectively. It is overlain to the west by the Canning Basin (not shown in **Figure 2**) and to the east by the Eromanga Basin. The Amadeus Basin has a protracted history. This traditionally extends from deposition of the Heavitree Formation and Dean Quartzite in the early Cryogenian (>820 Ma) to molasse sedimentation of the Pertnjara and Finke groups during the 450–300 Ma Alice Springs Orogeny. Up to 14 km of succession is accumulated locally. The history of the basin will likely be extended to include an earlier rift phase, but can currently be divided into two main depositional intervals. The first comprises sedimentation up to the late Neoproterozoic/early Cambrian 580–530 Ma Petermann Orogeny, including orogenic molasse deposited during and in response to this event. The second phase extends until the close of Alice Springs Orogeny molasse deposition. The development of the basin was also punctuated by a number of significant epeirogenic and erosional episodes, and includes a number of additional unconformities and time breaks of varying regional significance.

NTGS mapping in the Amadeus Basin commenced in the central part of the basin in HENBURY[3] where nearly all stratigraphic units are exposed. This coincides with the transition in Cambrian lithofacies from more siliciclastic in the west to dominantly carbonate-bearing successions in the east. The major components of the post Petermann Orogeny architecture of the basin are the Southern Platform, Central Ridge, and the Missionary Plain Trough. The latter connects the Carmichael/Idirriki sub-basins in the northwest with the Oraminna Sub-basin in the northeast; these sub-basins fall just outside the northern boundary of HENBURY (**Figure 2**).

Winnall Group

The Winnall beds were named after Winnall Ridge in LAKE AMADEUS by Ranford *et al* (1965) who nominated a type area in the Liddle Hills in southwestern HENBURY (**Figure 2**). The mapped distribution of the unit in the Amadeus Basin is shown in **Figure 2**. It is re-defined as Winnall Group comprising the newly defined Breaden, Gloaming, Froud and Liddle formations; together with Puna Kura Kura Formation and its constituent Chookla Member (**Figure 1**). Historically the Winnall beds were considered a correlative of the Pertatataka Formation (eg Wells *et al* 1970), although Haines *et al* (2010) suggested Winnall beds post-dated the Pertatataka Formation. Under the newly defined Neoproterozoic stratigraphy of the central Amadeus Basin presented here, the Pertatataka Formation is considered to be a correlative of at least part of the Winnall Group (see discussion below). It is therefore likely that Winnall Group will be redefined to include Pertatataka Formation.

At Winnall Ridge, Ranford *et al* (1965) described four informal units (1–4) of repeated siltstone and interbedded silty sandstone, with sandstone. NTGS mapping has recognised Breaden, Gloaming and Froud formations mainly in the east (**Figure 1**), and Liddle and Puna Kura Kura formations, together with Chookla Member, mainly in western HENBURY. In central HENBURY, Froud Formation has a transitional upper contact with Liddle Formation. Liddle Formation is apparently incomplete in this area, and Puna Kura Kura Formation is missing altogether. In eastern HENBURY, the upper units of the group are apparently missing.

Breaden Formation comprises thin-, and planar-bedded, or ripple cross-stratified siltstone. It is locally chertified to form finely banded 'ribbon-like' chert. The unit is commonly weathered and capped with ferricrete or silcrete.

Gloaming Formation comprises alternating thin- and medium-bedded, internally planar-parallel laminated, flaggy to fissile sandstone showing cyclicity on the scale of <5 m. Beds are arranged in thick, planar cross-stratified sets that show good lateral persistence. The sandstone comprises fine- to medium-grained, generally well-sorted and well-rounded quartz arenite and subarkose. The unit is characterised by a high density of small-scale sedimentary structures including a range of ripple marks, desiccation features, weathered-out shale clasts, and current/streaming lineation.

Froud Formation comprises thinly bedded, grain-size laminated sandstone. Up-succession, it becomes very thinly bedded and fissile with a good parting. It is also increasingly finer-grained, well sorted and well rounded up-succession. It is locally interbedded with more medium-bedded, medium-grained and moderately sorted and rounded, quartz arenite transitional to the overlying Liddle Formation. Froud Formation is distinguished from the underlying Gloaming Formation on the basis of: (1) maturity of composition (ie quartz arenite and feldspathic-quartz arenite as opposed to arkose); (2) colour variation (grey, or grey-green as opposed to the dark red-brown/chocolate brown); (3) absence of a wide range and abundance of small-scale sedimentary structures (restricted to rare ripple marks, a well-developed streaming or current lineation and locally abundant slump structures). Froud Formation thickens progressively eastward while the Gloaming and Liddle formations apparently thin. While remaining a cleanly-washed, winnowed quartz arenite with a well-developed parting lineation, the Froud Formation also takes on a combination of sedimentary characteristics from both Gloaming and Liddle formations, and includes thinly, planar-bedded, internally laminated, flaggy to fissile medium grained quartz arenites.

Liddle Formation sandstones are divided into three informal lithofacies (lower, middle and upper) in the Liddle Hills in southwestern HENBURY on the basis of bedding thickness and corresponding outcrop characteristics, and sedimentary structures. The more regional extent of these informal facies is as yet unknown. The lower lithofacies is cyclical with thinly, planar-parallel bedded sandstone overlain by medium to thickly bedded, low-angle cross-bedded sandstone; the middle lithofacies is bidirectionally cross-bedded; and the upper lithofacies is an 'event' facies comprising small-scale trough and festoon cross-bedded sandstone with abundant ripple marks and weathered-out shale clasts. Generally recessive fine-grained, very thinly to thinly, planar-parallel bedded and laminated, fissile reddish-brown and grey-green sandstone overlies the ridge-forming interval of Liddle Formation. It may be possible to define these rocks as a discrete unit but pending further work to the west in LAKE AMADEUS, they are included as uppermost Liddle Formation. These sandstones may be transitional to Puna Kura Kura Formation, but the field relationships seen so far are ambiguous.

Puna Kura Kura Formation comprises well-sorted and well-rounded subarkose or quartz arenite. Bedding characteristics vary up-succession suggesting changing conditions of sedimentation. Initially the sandstone is thin- to medium-bedded, with tabular non-tangential angular cross-beds in simple bed sets. Bedding rapidly thickens up-succession and outcrop appears massive before another rapid transition, this time to medium-bedded then predominantly thinly bedded sandstone. These latter sandstones are planar-parallel and apparently continuously bedded suggesting that any cross-stratification is low-angle. A similar cyclicity is repeated up-succession. Weathered-out shale clasts are common in the more thin- and medium-bedded units, particularly near the base of the formation, and are commonly associated with ripple-marks. Sandstones of the Puna Kura Kura Formation are locally trough cross-stratified. Surficial calcrete formation suggests intervals of calcareous-cemented sandstone, which are locally associated with interbedded fissile to flaggy, very thinly to thinly bedded, micromicaeous arkose. *Chookla Member* (of Puna Kura Kura Formation) is conglomeratic and is generally exposed as residual rounded pebbles, cobbles and small boulders of quartz arenite, subarkose and vein quartz without matrix. Coarsely-grained to granular, poorly-sorted and poorly-rounded sandstone is locally exposed. Relict clay indicates a significant original feldspar content suggesting that these sandstones are arkosic. A similar composition is inferred for the matrix to the conglomerate.

Liddle and Puna Kura Kura formations are interpreted to broadly correlate with units 2 and 4 of Ranford *et al* (1965) at Winnall Ridge. The poorly exposed fine-grained, thinly bedded sandstone and silty-sandstone that is apparently transitional between Liddle and Puna Kura Kura formations (see above) is interpreted to correlate with unit 3 at Winnall Ridge. In the Liddle Hills, unit 1 is poorly outcropping and apparently <6 m thick. These correlations suggest that Breaden, Gloaming and Froud formations of Winnall Group may be missing at Winnall Ridge and further west in the Amadeus Basin. Puna Kura Kura Formation may correlate with the former Eninta Sandstone. This was originally mapped in northwestern HENBURY by Ranford *et al* (1963), but was subsequently included in Arumbera Sandstone by Warren and Shaw (1995).

Pertatataka Formation is predominantly red and green shale and siltstone, with local minor conglomerate. Its mapped distribution in the Amadeus Basin is shown in **Figure 2**. In the western-central to eastern Amadeus Basin, Preiss *et al* (1978) described three informal members: siltstone; sandstone including quartzite; and shale, siltstone and sandstone. In the northeastern Amadeus Basin, Pertatataka Formation includes two defined sandstone members. Waldo Pedlar Member is typically thinly planar-bedded, and well-laminated with locally abundant and varied sedimentary structures suggesting shallow water to intertidal sedimentation. These sedimentary structures include: trough cross-stratification; long wavelength, low amplitude straight crested, bevelled slightly sinuous crested, asymmetric, bidirectional and interference ripple marks; flute casts; parting lineation; current lineation; and probable rivularites. Cyclops Member comprises thinly, rhythmically bedded or well-laminated flaggy sandstone. Further descriptive details of these and other Neoproterozoic units in the northeastern Amadeus Basin can be found in Normington *et al* (in prep).

Ranford *et al* (1963) mapped minor, scattered exposure of Pertatataka Formation in HENBURY. In far central-eastern HENBURY, these outcrops are silicified coarsely-grained quartz arenite and are retained as Pertatataka Formation. Exposures in central-western HENBURY previous defined as Pertatataka Formation are now mapped as Winnall Group.

Some issues of correlation

Neoproterozoic stromatolite biostratigraphies for Australia are given by Grey *et al* (2011) and for the Amadeus Basin by Grey *et al* (2012) and Allen *et al* (2015). These provide broad temporal constraints for carbonate-rock bearing units of the Amadeus Basin. They also assist to discriminate between units where lithological constraints are ambiguous in areas of poorly exposed, weathered outcrop. Grey (2005) has determined an acritarch biostratigraphy for the Pertatataka Formation. A biostratigraphy is not currently available for Winnall Group.

Poor biostratigraphic or chronostratigraphic control largely precludes establishing lithostratigraphic correlation of Neoproterozoic and earliest Cambrian siliciclastic units of the Amadeus Basin on a precise temporal basis. Two alternative possible correlations between Winnall Group and other units of the Amadeus Basin are shown in **Figure 3**. Importantly, possible correlations between Winnall Group in HENBURY and immediately to the south, for example at Mount Connor, in AYERS ROCK (**Figure 2**), are ambiguous (CJ Edgoose, NTGS, *pers comm* 2015). In this context, it is noted that Neoproterozoic/earliest Cambrian basin architecture and Petermann Orogeny-aged structures may have had a significant influence on the distribution of Winnall Group and its constituent stratigraphic units. This is being investigated as part of the current Amadeus Basin solid geology interpretation project by NTGS.

Winnall Group largely comprises different successions in the east and west of HENBURY. These successions locally overlap in central HENBURY where the eastern succession largely underlies the western. Winnall Group may therefore be informally divided into lower and upper successions comprising Breaden, Gloaming and Froud formations; and

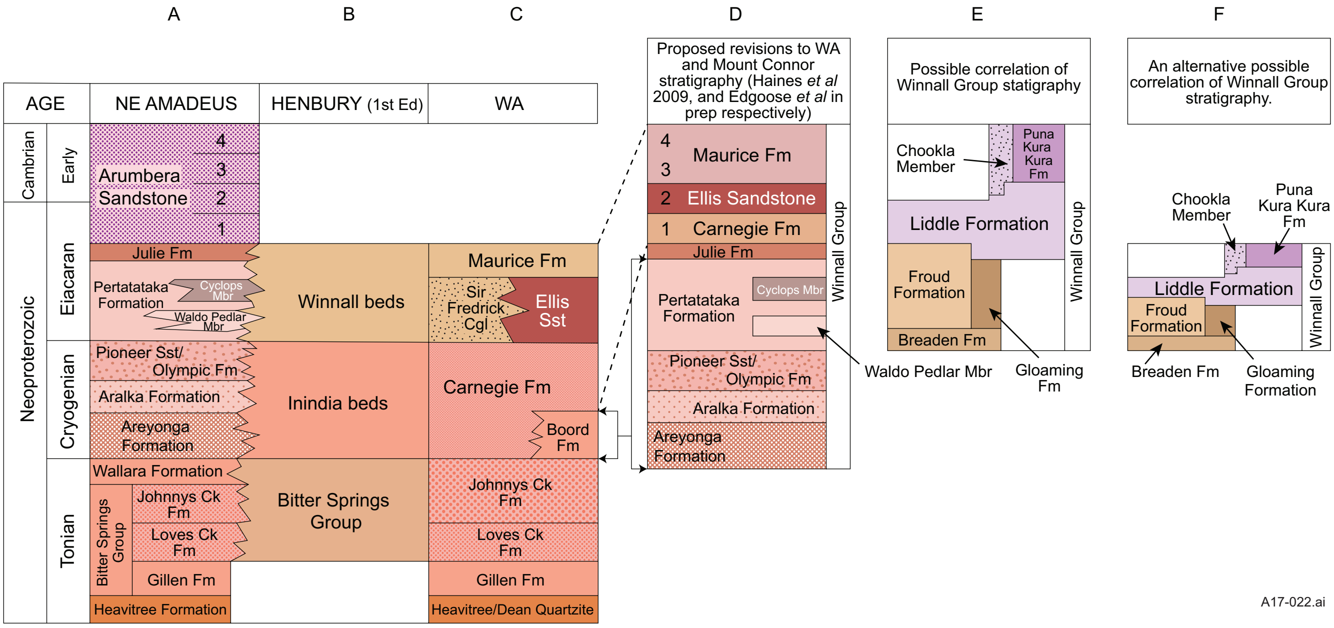

Figure 3. A comparison between the Neoproterozoic to early Cambrian stratigraphy of: (A) the northeastern Amadeus Basin, Northern Territory; (B) the central Amadeus Basin from the *First Edition* HENBURY; (C) Western Australia; (D) proposed revisions to the stratigraphy in Western Australia (Haines *et al* 2012) and at Mount Connor in AYERS ROCK (Edgoose *et al* in prep); (E and F) two alternative correlations for Winnall Group. While these do not cover all possibilities, correlation between lower Winnall Group and Pertatataka Formation, and between upper Winnall Group and Arumbera Sandstone (E) seems most likely but has yet to be confirmed.

Liddle and Puna Kura Kura (including Chookla Member) formations respectively.

A working hypothesis is presented in **Figure 3**. Correlation between lower Winnall Group and Pertatataka Formation (**Figure 1**), and the eventual inclusion of Pertatataka Formation in Winnall Group seems likely. Correlation between Winnall Group in HENBURY and that exposed further west in LAKE AMADEUS was discussed above (see ***Winnall Group***). How Winnall Group correlates with Arumbera Sandstone (**Figure 2**) is more enigmatic. Puna Kura Kura Formation and Chookla Member may correlate with the former Eninta Sandstone, and with Quandong Conglomerate in the north of HENBURY. Haines *et al* (2010) working in the Amadeus Basin in Western Australia correlated lowermost Winnall *beds* (unit 1 of Ranford *et al* 1965) with Carnegie Formation; unit 2 with Ellis Sandstone and Sir Fredrick Conglomerate; and units 3 and 4 with Maurice Formation. Unit 1 was in turn correlated by Haines *et al* (2010) on lithostratigraphic and sedimentological grounds with Arumbera Sandstone rather than Pertatataka Formation.

While *upper* Winnall Group likely therefore correlates with Arumbera Sandstone (*cf* Haines *et al* 2010, 2012), a correlation between lower Winnall Group and Pertatataka Formation remains likely. The Julie Formation forms a distinct marker horizon between the Pertatataka Formation and the Arumbera Sandstone in the northeast of the basin. However, Julie Formation thins substantially westward to the north of HENBURY and then is absent still further to the west, before reappearing and thickening again in Western Australia. Thus, the absence of Julie Formation in HENBURY does not preclude the correlation of upper Winnall Group with Arumbera Sandstone.

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