

Impact Sedimentation of the Tookoonooka and Talundilly Marine
Impact Structures, Australia: An Impact Reservoir Generated by
Cratering in a Petroleum Basin

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Abstract

Tookoonooka and Talundilly are two large meteorite impact structures buried in the sedimentary rocks of central Australia, and are among the largest impact structures known on Earth. They are shown to be a rare example of an ancient marine impact event and are also an extremely rare terrestrial example of a probable binary impact event. A preserved marine impact ejecta horizon, interpreted to span a vast area of the continent and corresponding to the extent of a Cretaceous epicontinental sea, is used to biostratigraphically constrain the impact age to the Barremian-Aptian boundary (125 +/- 1 Ma) in the Lower Cretaceous. Evidence is presented that the Wyandra Sandstone Member petroleum reservoir overlying the horizon is, in part, a binary impact tsunamiite.

Analyses of drill core, subsurface drilling data, and geological outcrops over >805,000 km² show that the base of the Wyandra Sandstone Member is an impact horizon: a widespread scour surface that is attributed to impact-related excavation and tsunami scour mechanisms. The impact horizon is underlain by seismites and overlain by very poorly sorted sediment with highly polymictic exotic clasts, imbricated pebbles, and intraformational cobble rip-up clasts. Exotic clasts are predominantly interpreted as impactoclasts, and include complex accretionary and armoured impactoclasts of vapour plume origin, shock-metamorphosed lithic fragments, and altered melt impactoclasts. Some lithic fragments resemble basement lithologies from the Tookoonooka and Talundilly target rock sequences.

The stratigraphy of the Wyandra Sandstone Member contains elements characteristic of impact tsunami deposition including ejecta entrained in high flow regime bedforms, pebble to boulder-sized clasts, >16m thick beds, and cyclic sedimentation of tsunami couplets, across five depositional realms. These elements are in stark contrast to the persistently low-energy nature of the ambient sedimentation and overlying quiescent marine shales, but are consistent with the intense seismicity, high energy seiche action and rapid deposition expected from a marine impact in a mostly enclosed basin. A dual impact source is indicated, based on sediment distribution patterns in combination with the proximity of the impact structures in age and location. The Wyandra Sandstone Member records both marine impact depositional processes as well as the waning of the event; the upper part of the Wyandra returns to background depositional energies and intense bioturbation and is conformably overlain by transgressive marine shales.

The Tookoonooka-Talundilly impact event may be an extreme prototype, as very few doublet craters, marine craters, impact tsunamiites, or economic impactites are individually known or preserved on Earth, yet this crater pair may represent all four. This impact crater pair provides a model for binary marine impact sedimentation and highlights the significance of ancient impact sediments to petroleum basins. Sedimentation patterns evidence a dual crater source even in a marine impact scenario where reworking and burial complicate the interpretation of depositional indicators; observations suggest that Tookoonooka-Talundilly may be the largest doublet crater discovered on Earth.

Thesis Declaration

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1. Contextual Statement

Impact cratering in sedimentary basins has the potential to create significant petroleum reservoirs. However, Australia has experienced few studies into the significance of meteorite impact events for hydrocarbon exploration. I hypothesized that impacts have created hydrocarbon traps or potential reservoirs in Australia's depositional basins, thus far unidentified, since only five confirmed or probable impact structures are known in petroleum basins of Australia compared to the many probable craters predicted by cratering rate estimations (Figure 1.1). Tookoonooka and Talundilly, two of these five, are buried in the Cretaceous sedimentary record of central Australia and are among the largest impact structures known on Earth. They were identified as the best potential case studies for this investigation due to their size, subsurface locations, Tookoonooka's confirmed impact status*, the availability of petroleum industry data, the proximity of producing fields, and their intriguing doublet crater potential. I hypothesized that these impact structures, possibly marine and apparently buried during a transgressive depositional regime, had remnant impact deposits preserved that may be associated with petroleum systems. As marine impact structures are statistically underrepresented on Earth despite expected cratering rates and are thus an under-studied realm of impact cratering, it was predicted that impact sedimentology research at these two structures could also prove insightful to the understanding of marine impact depositional processes. Thus the broad aims of this research were two-fold:

- 1) to improve the understanding of the effect of meteorite impacts, particularly marine impacts, on the sedimentological record, and
- 2) to further the understanding of impact-related structures and/or deposits in the context of hydrocarbon systems.

These were accomplished via the study of Tookoonooka and Talundilly in the Eromanga Basin of central Australia, which had experienced little sedimentological investigation; impact-related sediments outside the structures had never been identified, characterized, or correlated with the impact events.

This PhD thesis consists of three journal papers (two published and one prepared in manuscript format for submission), which methodically develop the line of investigation into the petroleum prospectivity of Tookoonooka and Talundilly's impact-related deposits. As little research had previously been done on the sedimentary record of these impacts, a search for impact ejecta was initiated in order to establish the age and thus the stratigraphic context of the impacts. Research could then progress to investigating the impact age-equivalent strata both proximal and distal to the craters. Finally, impact deposits could be characterized, and their petroleum association ascertained.

*Note: At the start of this PhD thesis research, Talundilly remained unconfirmed as an impact structure. Talundilly's impact origin (Gorter & Glikson 2012a) remains contentious. See Section 2.8 and Paper 3 for more detail.

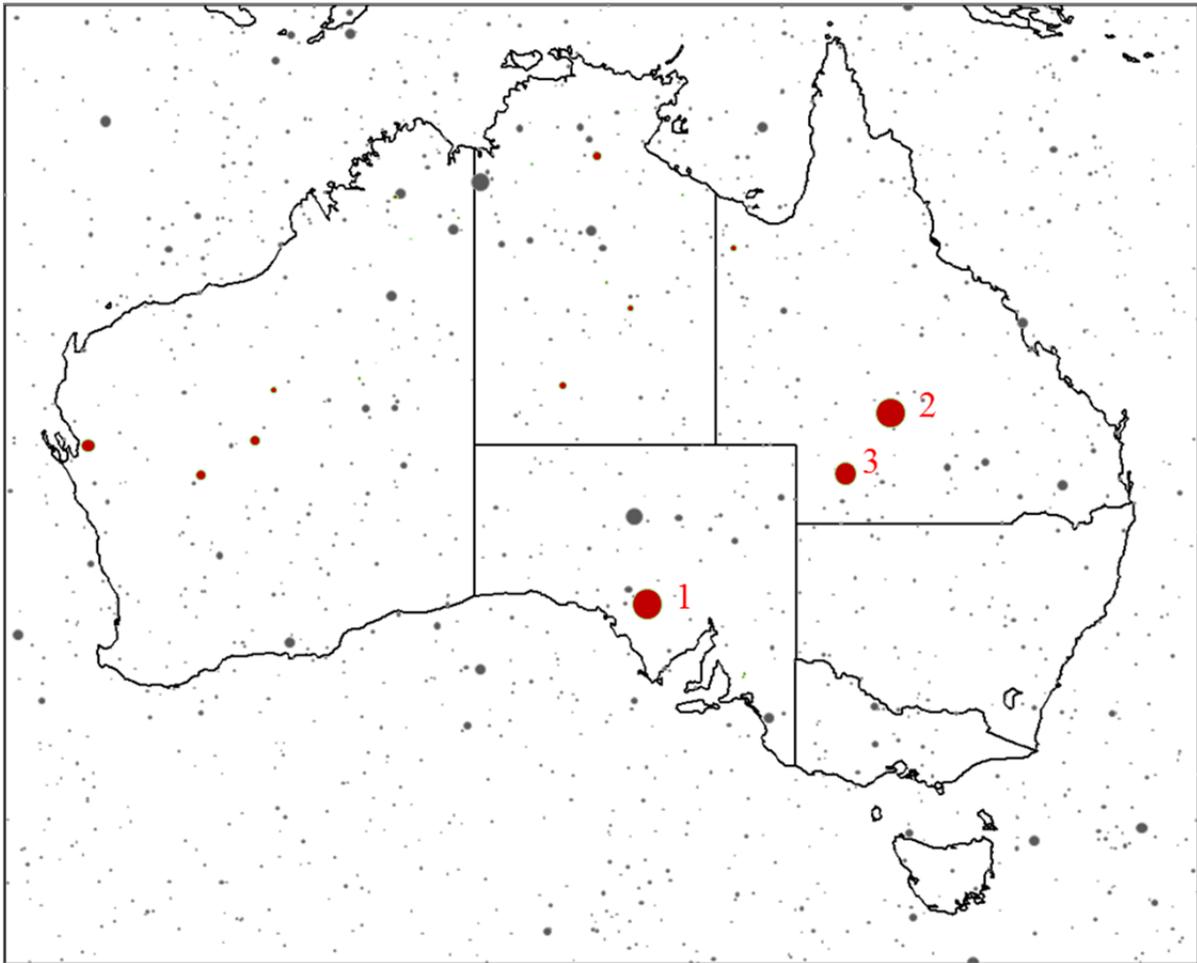


Figure 1.1 Probability map showing a possible cratering distribution over the last 541 Ma in the Australian region, based on estimates of Earth's cratering rate. See French (1998) for discussion on cratering rate uncertainties. Red circles indicate known impact structures in Australia, the largest being Acraman (1), Talundilly (2), and Tookoonooka (3), while grey circles show a possible undiscovered crater population according to impact frequency only in the last 541 Ma period. Only craters >5 km diameter are considered due to preservation potential. Craters >50km diameter are not considered, with the exception of known craters, due to the low frequency of large impacts within the specified time interval: cratering estimates suggest that with 3 large craters already discovered in Australia, statistically there are unlikely to be more with >50km diameter. Crater sizes are relative to each other but not to map scale. Note that many craters over 120 Ma and under 20 km diameter that were not buried have low preservation potential (Grieve, 1998). Map inspired by Mazur et al. (2000).

Investigations were done via drill core studies, field work, geological log interpretations and correlation, mapping, petrographic evaluation, and geochemical analyses. The research results presented in this thesis represent the culmination of analyses from 51 drill cores and 12 field locations covering an area of >525,000 km² of the Eromanga Basin in central Australia which spans 3 states and a territory (see Section 3 for method and location details). Locations reach a maximum distal extent of 23 crater radii from Tookoonooka. Over 20 Ma of stratigraphic record were reviewed in detail in the search

for impact sediments, and 1369 metres of drill core through impact-related deposits were logged.

The discovery of the Tookoonooka impact horizon in the Eromanga Basin, including evidence for its impact provenance, marine context and age, was made via core studies, petrographic evaluation and geochemical analyses (Papers 1 and 2). It was thought to be a shared Tookoonooka-Talundilly impact horizon, though at the time further support for Talundilly's impact origin had not yet been presented. Papers 1 and 2 thus necessarily focussed on the Tookoonooka impact structure (the only confirmed impact structure of the two). Paper 1 described the occurrence of impactoclasts, particularly accretionary and melt impactoclasts, from within the Tookoonooka impact structure and as a constituent of the ejecta outside the impact structure. This paper documented the discovery of an understudied type of impactoclast at 24 locations in the basin using geochemistry and petrography. Gaps in existing impact terminology were identified, and new terminology was proposed to establish the distinctive character of impact geology as independent of other geological realms (e.g. volcanology). Most notably, the impactoclasts described may signify a new type of marine impact indicator. The results of Paper 1 established the marine context of the impact(s) and the presence of preserved ejecta deposits outside the impact structures, and prompted a more formal analysis of ejecta provenance and the sedimentary context of the impact horizon, presented in Paper 2. The significance of classifying the impact structures as marine widened the scope of their potential influence on contemporaneous sedimentation.

Paper 2 confirmed the impact signature of the ejecta in parallel with a petrographic analysis of the ejecta-bearing sediments. The character of the impact horizon was described, confirming its stratigraphic position in 31 locations. The character of the impact horizon is an erosive surface with underlying seismites, often overlain by coarse polymictic sediment including accretionary, melt and lithic impactoclasts. The resolution of the shock-metamorphic impact signature allowed the age of the marine impact horizon to be biostratigraphically constrained to the Barremian-Aptian boundary in the Lower Cretaceous. The recognition of the impact horizon also established the connection of the impact event to the Wyandra Sandstone Member reservoir overlying this horizon. The results presented in Papers 1 and 2 established a foundation for the investigation of the overlying impact-related sedimentary succession, which is the focus of Paper 3.

Paper 3 presents the distillation of results from several extensive datasets covering more than 805,000 km², the bulk of the known extent of the Eromanga Basin: 25 corelogs (representing 931m of vertical section), map data compiled from 158 well locations, calibrated from the corelogs, and petrographic observations from 9 locations. Results of these sedimentological analyses show that a marine impact tsunamiite sequence overlies the impact horizon. The impact tsunamiite sequence and post-impact recovery deposits comprise a producing petroleum reservoir: the Wyandra Sandstone Member. Furthermore, Tookoonooka and Talundilly were established as a likely doublet crater based on significant though indirect evidence of sediment distribution patterns in

combination with probability calculations of terrestrial impact recurrence with regards to crater proximity and impact age uncertainty. Thus in Paper 3, the origin and stratigraphic architecture of a probable binary impact-generated tsunamiite reservoir is presented.

This research details the discovery of ejecta and a tsunamiite from an ancient marine impact event in the Cretaceous strata of Australia. The discovery constrains the age of impact, classifies Tookoonooka and Talundilly as marine impacts, and confirms the impact origin of the Wyandra Sandstone Member. The Wyandra Sandstone Member reservoir constitutes in part an impact tsunami sequence, a rarity in the ancient geological record. The Tookoonooka and Talundilly impacts occurred in a quiescent, transgressing epicontinental sea, which favoured preservation of the event in the sedimentary record of the basin. Rapid tsunami deposition also contributed to the preservation via quick burial of the ejecta. Tookoonooka and Talundilly represent a probable doublet crater, thus the Wyandra Sandstone Member exemplifies both a binary impact tsunamiite from large meteorite impacts and a superb example of a hydrocarbon reservoir originating from a marine impact event. This discovery is a prototype for binary marine impact sedimentation.

2. Literature Review

2.1 Meteorite Impact Structures

At least 184 confirmed impact structures are known on Earth (Earth Impact Database 2015), a modest number in comparison to the expected cratering rate on Earth and the heavily cratered surfaces of other planetary bodies in the solar system. The cratering record on Earth is biased towards younger and larger impact structures due to Earth's erosional processes, which gives perspective to cratering rate estimations (e.g. French 1998); however, while many of Earth's impact craters may have been erased, buried structures represent about 35% of the cratering record (Grieve 1991, 1998) and it is estimated that a significant proportion, perhaps 2/3 of the impact structures on Earth, have not yet been recognized due the dynamics of erosion, burial, and tectonism. Perhaps it is due to this realization that scientific research on terrestrial impact structures has only begun in recent decades to grow into its own field of study, and impact cratering appreciated not only as a major geological process, but also as a formidable influence on the Earth's biological history (French 2004, 1998).

Impact craters on Earth evolve in morphology according to crater size, resulting in at least three recognizable final crater forms: simple craters, central peak complex craters, and peak ring complex craters (Figure 2.1). The simple crater to central peak complex crater transition occurs around 2-4km crater diameter, whereas the transition to peak ring complex crater occurs around 25-30km diameter, depending on target material (cf. Melosh 1989; French 1998; Grieve 1998). Complex morphologies are driven by crustal rebound and gravitational instability. The "transient crater" refers to the original bowl-shaped crater which precedes crater modification (driven by gravitational collapse) for all impacts, and can be calculated from impact scaling laws (Equation 2.1). Cratering processes occur on "sub-geological" time scales of minutes to hours with rapid excavation, crater modification, uplift, and deposition.

$$D_f = 1.17 \frac{D_t^{1.13}}{D_c^{0.13}}$$

D_f = final crater diameter

D_t = transient crater diameter

D_c = simple-complex
craterform transition diameter

Assumptions: D_f applies to rim to rim diameter of a fresh, uneroded crater. D_c is 3.2km for Earth.

Collins et al. (2005) after
McKinnon & Schenk (1985)

(Equation 2.1)

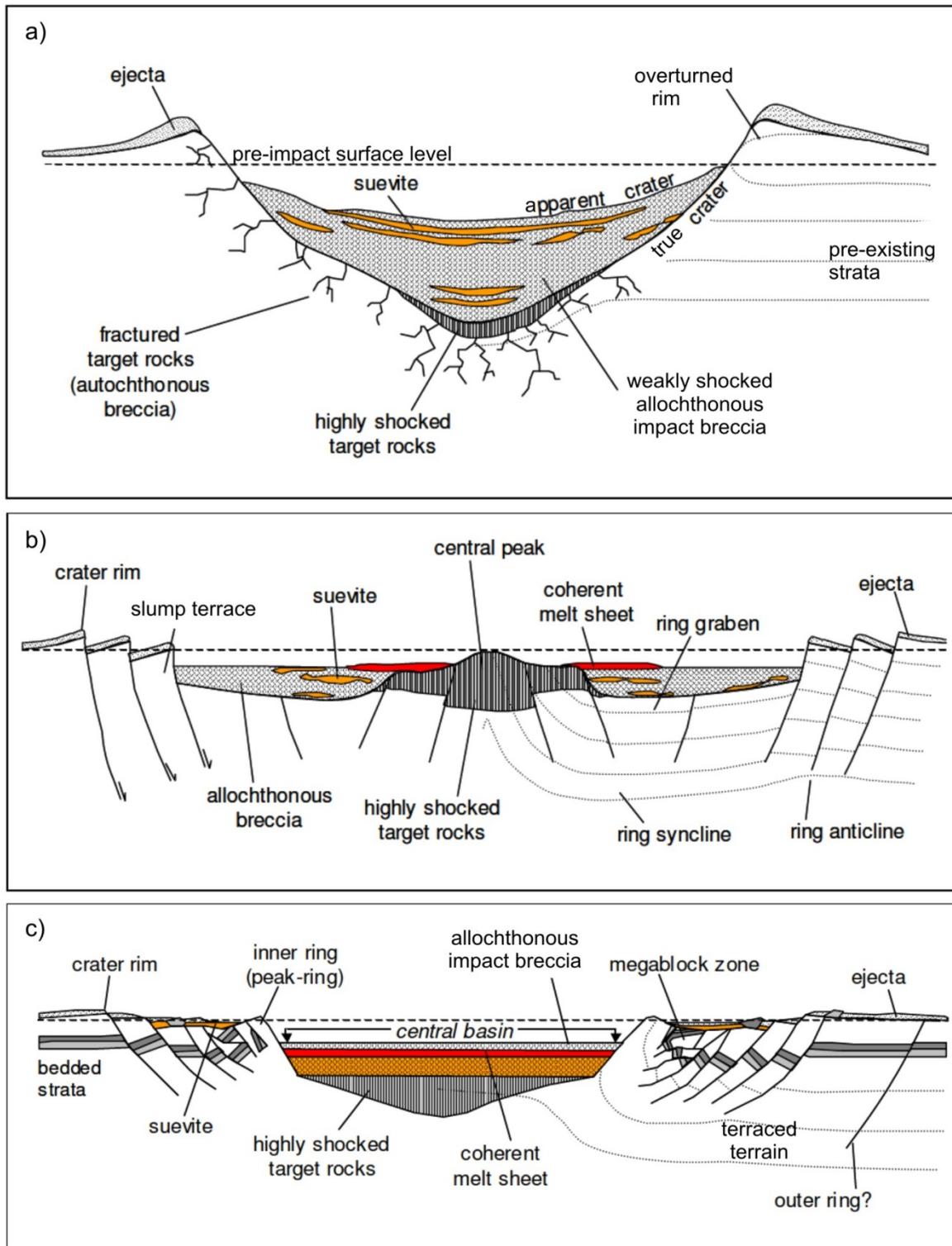


Fig. 2.1 Idealized cross-sections of a) simple, b) central peak complex and c) peak ring complex impact craters. Modified from Hawke (2004) after Grieve (1987) and Pösges & Schieber (1997).

While crater morphology and geophysical data can be used to identify likely impact structures, only petrographic or geochemical impact signatures can be used to confirm the impact origin of crater structures (Grieve & Pilkington 1996; Koeberl & Martínez-Ruiz 2003). Impact structures on Earth, variably affected by tectonism and erosion, require a standardized approach to crater size estimations (Turtle et al. 2005). Erosion levels can be estimated on a scale of 1-7, where 1 is a largely non-eroded crater and 7 is an eroded crater floor (Grieve & Pilkington 1996).

2.2 Binary Impacts and Doublet Craters

Up to 3-5 crater pairs on Earth have been identified as candidate doublets, craters formed near-simultaneously from the same impact event, most likely a binary asteroid originating from gravitational aggregates/rubble piles (Bottke Jr. & Melosh 1996a; Miljković et al. 2013; Richardson 2002). Doublet craters would be expected to represent 10% of all terrestrial impacts (Bottke Jr. & Melosh 1996a) based on the population of binary asteroids in the Near Earth Asteroid region, whereas *well-separated* doublet craters would represent ~2% (Miljković et al. 2013). For distinguishable craters in close proximity, shared ejecta blankets (see Section 2.4) would ideally point to a dual impact origin (Bottke Jr. & Melosh 1996b), however, for buried craters and marine craters (see Section 2.3), such evidence would be concealed or reworked. The probability of the dual origin of terrestrial crater pairs can be assessed based on a combination of crater separation, age uncertainty versus impact recurrence interval, and impactor diameter (Miljković et al. 2013), the latter of which can be calculated from theoretical asteroid velocities, impact angle, type of asteroid, crater diameter and impacted water depth (Collins et al. 2005).

2.3 Marine Impacts

Marine impact structures are statistically under-represented according to expected oceanic cratering rates (Dypvik & Jansa 2003; Dypvik et al. 2004; Ormö & Lindström 2000): only 43* (~23%) of the confirmed impacts on Earth are probable marine (Appendix 1), compared to an expected 70% based on Earth's ocean surface area. However, subduction/recycling of oceanic crust results in the erasure of marine craters over geological time spans, and questions also remain as to how the terrestrial crater size-frequency distribution is affected by the Earth's ocean cover (Davison & Collins 2007). Marine impact structures vary widely in their features, governed by variables such as impacted water depth, impactor diameter, as well as the strength, porosity, and saturation of the target material. They differ in their morphology from "dry target" (subaerial) craters, with subdued rims and resurge channels evidencing the erosive influence of a water column after impact (Ormö & Lindström 2000; Dypvik & Jansa 2003; Baldwin et al. 2007; Gault & Sonett 1982). Crater-fill breccias of unusual thickness are another defining feature of marine craters (e.g. Poag et al. 2002; Jansa 1993). Marine craters are believed to lack the melt volumes produced by their counterparts formed on land (Ormö & Lindström 2000), although ejecta may be more often preserved by burial in marine impact scenarios due to favourable sedimentation rates in marine environments.

The nominal water depth required to form a marine crater and control cratering processes have been modelled, as has impact tsunami propagation (Glimsdal et al. 2010; Matsui et al. 2002): a large crater radius to water depth ratio, e.g. $d > 2H$, where d =impactor diameter and H =water depth (Shuvalov 2008), applies to large craters formed in a shallow sea such as Chicxulub, Mjølner, Tookoonooka and Talundilly (Appendix 1). This ratio results in a well-defined crater and a temporarily dry seabed. Violent resurge into the crater (Simonson et al. 1999) precedes a radially propagating tsunami and is associated with rim collapse in un lithified sediments (Goto 2008; Dypvik & Jansa 2003) and ejecta/water curtain collapse (Ormö & Lindström 2000). Inside the crater, slumping, debris flow and turbidite processes contribute to resurge deposits (e.g. Lindström et al. 1996; Poag 1997; Ward et al. 1995). Outside the crater, impact-generated tsunamis manifest various marine depositional processes depending on impact location and depositional water depth (Goto 2008). The resurge and tsunamis of shallow marine impacts cause strong sediment mixing and transport, significant suspension of seafloor sediments, and extreme alteration of the seabed (Glimsdal et al. 2010); evidence of the latter manifests as a basal unconformity of impact deposits proximal to craters, as observed at Chicxulub (Albertão et al. 2008; Goto et al. 2008), Ames (Mescher & Schultz 1997), Kärđla (Suuroja & Suuroja 2006), Lockne (von Dalwigk & Ormö 2001; Lindström et al. 2008) and Manson (Izett et al. 1998). Complex stratigraphic architecture and multiple erosion surfaces in sedimentary sequences generated by varied depositional processes have been described from marine impact deposits (Dypvik & Jansa 2003; Goto 2008).

*Twenty to twenty-six impact structures were categorized as having impacted marine environments in previous compilations (Dypvik & Jansa 2003; Ormö & Lindström 2000; Abels et al. 2002), prior to this research. However, a focussed literature review (Appendix 1) has resulted in the addition of 17-23 impact structures to this classification.

2.4 Impact Deposits: Ejecta, Impact Signatures, Sedimentation Processes, and Related Nomenclature

Impact ejecta layers (cf. Montanari & Koeberl 2000) have been observed in sedimentary units spanning the geological record, although as of 1998 (Grieve), only 16 impact events were known from the stratigraphic record. Only a fraction of the confirmed terrestrial impact structures have ejecta preserved; due to terrestrial erosion processes, ejecta are usually only observed at younger craters or where sedimentary burial has enabled preservation. Classifications of impactites and terminology relating to ejecta have been proposed by a number of authors including Stöffler & Grieve (2007), French (1998), Melosh (1989), Montanari & Koeberl (2000), King & Petruny (2003), and Bron (2010, this volume). Various melt products, spherules and tektites (cf. French 1998; Stöffler 1984; Montanari & Koeberl 2000; Osinski et al. 2008), comminuted lithic fragments (cf. Stöffler & Grieve 2007), and accretionary clasts (cf. Bron 2010, this volume) are associated with impact ejecta deposits. More detail of impact clast terminology, as well as their parallels to volcanic products, is provided in Paper 1 Background.

Melosh (1989) discussed the distribution of ejecta volumes based on radial limits. For a given crater, approximately 50% of the ejecta volume lies within a continuous ejecta blanket within two crater radii (2Rc) of the crater centre (i.e. 1Rc from the crater rim), and 90% lies within 5Rc (Figure 2.2). Between 2Rc and 5Rc lies a discontinuous ejecta blanket, which becomes increasingly thinner and ray-like with distance from the crater. Ejecta are considered proximal within 5Rc and distal beyond 5Rc (Figure 2.2). The scale of the continuous ejecta blanket may be tens to hundreds of metres thick depending on crater size, in contrast to distal ejecta which have an atmospheric transport component resulting in fallout layers (typically $\leq 1\text{mm}$) at regional to global extents. It must be noted that these theoretical distributions in the terrestrial realm are most applicable to fresh, non-aquatic impact sites where minimal erosion and reworking have occurred.

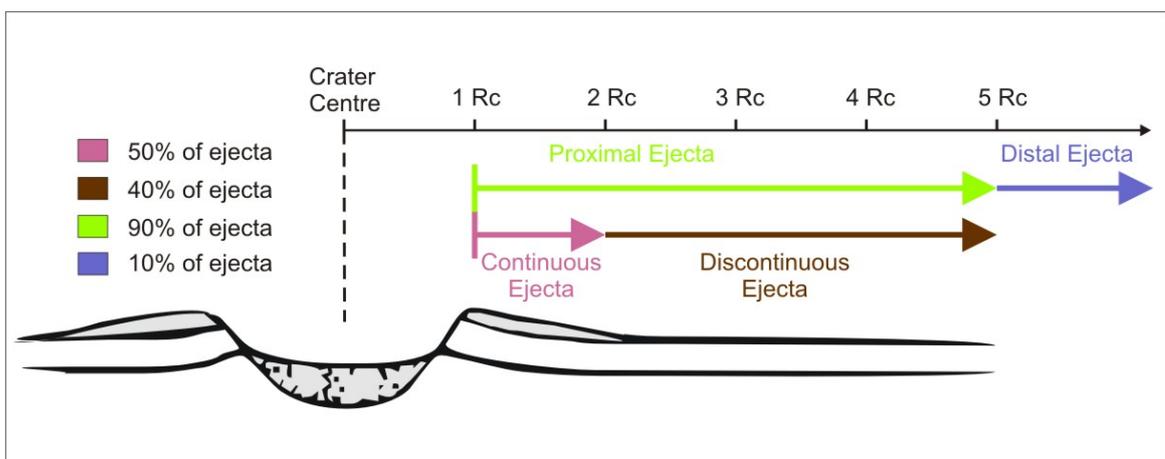


Fig. 2.2 Classification and distribution of ejecta volumes with respect to crater radius (Rc). Compiled after Melosh (1989).

McGetchin et al. (1973; Equation 2.2) and Hörz et al. (1983; Equation 2.3) described empirical relationships of continuous ejecta distribution as a function of crater radius. McGetchin et al. (1973) estimated the thickness of ejecta layers based on nuclear and explosion cratering, laboratory cratering experiments, terrestrial meteorite craters, and lunar estimates, whereas Hörz et al. (1983) described distal fining of ejecta based on studies of the Bunte Breccia at the Ries crater. Collins et al. (2005; Equation 2.4) describe ejecta thickness as a simple relationship between transient crater diameter and range:

$$t = 0.14R^{0.74} \left(\frac{r}{R}\right)^{-3.0} \quad S_{MP} = 2.6 \times 10^3 \left(\frac{r}{R_D}\right)^{-5.6 \pm 1.3} \quad t_e = \frac{D_{tc}^4}{112r^3}$$

t = thickness of ejecta layer
r = radial distance from crater centre
R = transient crater radius

Assumptions: applies to ballistic ejecta only, corrections for orogenic thickening must be applied

McGetchin et al. (1973)
(Equation 2.2)

S_{MP} = mean grain size
r = radial distance from crater centre
R_D = final crater radius

Assumption: applies to primary ejecta only; does not include bulking material ripped up from the pre-impact surface

Hörz et al. (1983)
(Equation 2.3)

t_e = ejecta thickness
D_{tc} = transient crater diameter
r = range

Assumptions: applies to primary ejecta only (thus minimum thickness); maximum thickness is at the transient crater rim

Collins et al. (2005)
(Equation 2.4)

Impact theory (Melosh 1989), lunar studies (Oberbeck 1975) and ejecta observations (Hörz et al. 1983) also show that around 2/3 of ejecta deposits actually derive from the substrate, i.e. ambient deposits of the pre-impact surface, via scour.

Diagnostic indicators of the impact origin of ejecta include geochemical anomalies, such as PGE enrichments, and shock metamorphic features (cf. French 1998; French & Koeberl 2010). The latter may take the form of microscopic planar deformation in minerals, the presence of high temperature/pressure mineral polymorphs, and diaplectic glasses. Microscopic planar deformation includes planar deformation features (PDFs) and planar fractures (PFs), although it is contested whether the latter can be considered an impact indicator in isolation (French & Koeberl 2010). The unique impact origin of “toasted” quartz, which is a brownish-colored texture of quartz reported from impact sites, has also been investigated by Whitehead et al. (2002). The effects of shock metamorphism have been recognized in numerous minerals in impact- and experimentally-shocked rocks (reviews in Grieve et al. 1996; Stöffler 1972; Stöffler & Langenhorst 1994). Measurements of orientations of PDFs in quartz can be made microscopically on a universal stage; 15 crystallographic orientations are considered typical (cf. Stöffler & Langenhorst 1994; Ferrière et al. 2009). Occurrence of suites of PDF orientations have been further applied to impact shock pressure calibration (Grieve et al. 1996; Stöffler & Langenhorst 1994; Grieve & Robertson 1976). It is recognized that

different target materials, such as crystalline or unconsolidated/porous sedimentary rocks, may influence the suite of shock effects present at a given impact site. Hence, classifications have been proposed for the progressive stages of shock metamorphism in different target lithologies (Stöffler & Grieve 2007).

Many high energy depositional mechanisms have been invoked to explain sedimentation at impact sites, regardless of the impact target material (i.e. crystalline bedrock, sedimentary rock, or water). Depositional processes, especially proximal to impact structures, are not fully understood and are highly complex, owing to the fact that impact events likely represent the highest depositional energies possible and go beyond the known realms of “normal” sedimentary processes. Hörz et al. (1983) describe breccia of the 24-km diameter Ries crater as being “among the most poorly sorted materials known” on Earth, with grainsize varying over 8 orders of magnitude. Impact deposits may be influenced by ballistic sedimentation, base surge, debris flows, and, specific to targets with high water content, resurge, tsunamis, and turbidites. Nuclear explosions and explosive volcanism, which give the closest comparisons to impact-scale deposition, produce ejecta deposits emplaced by base surge mechanisms (Melosh 1989; Fisher & Schmincke 1984), although ballistic sedimentation is thought to be the more dominant process at impact sites (Oberbeck 1975; Melosh 1989). Impacts also produce vapour plumes which can be analogued with volcanic ash clouds, although the mechanics of the large-scale vapour plumes are poorly understood (Melosh 1989), as are their unique products (cf. Bron 2010, Paper 1 of this thesis). At marine impact sites, water content drives sedimentation processes (see Section 2.3 above). Fluidized ejecta flow around Martian craters is also theorized to be driven by substrate water content (Barlow 2005; Osinski 2006; Melosh 1989) which may parallel the water proportion in ejecta of the shallowest marine craters. Hence, the field of impact sedimentation has many unanswered questions and is a new and evolving field of research.

2.5 Tsunami Sedimentation

Tsunamis are generated from four different mechanisms: earthquakes, slope failures, volcanism, and meteorite impacts (Dawson & Stewart 2007). Reports of ancient tsunamiites from the rock record, particularly *impact* tsunami deposits, are uncommon and impact tsunamiites are the least understood (Dawson & Stewart 2007, 2008; Scheffers & Kelletat 2003; Dypvik & Jansa 2003). Tsunami deposits typically exhibit:

- unusually coarse poorly-sorted sediment with exotic and polymictic clasts including rip-ups;
- erosional or sharp basal contacts;
- seismites (liquefaction features, rip-up, injectites, soft-sediment deformation);
- both muddy suspension deposits and organic terrestrial debris, often capping the deposit;
- sedimentary structures spanning the flow regime due to rapidly shifting current flow velocities, although absence of sedimentary structure is also common;
- coarse-grained, clast-supported basal carpet
- a lack of bioturbation;
- bidirectional flow indications corresponding to inflow and outflow;
- tsunami couplets;
- multiple fining-up sequences;
- landward-fining;
- an overall tabular or sheet-like geometry with lateral continuity.

(Dawson & Stewart 2007; Shiki et al. 2008a; Morton et al. 2007; and Nanayama & Shigeno 2006). Research indicates that tsunami depositional processes are complex and varied, imitating features of other sudden, high-energy marine and coastal processes (Dawson & Stewart 2008). The search for specific indicators to distinguish tsunami-generated sediments is a growing area of research (Shiki et al. 2008a).

Impact tsunamis differ from tsunamis generated from other mechanisms in scale, depositional and erosive potential, and entrained impact debris such as meteoritic or shock signatures in the tsunamiites (e.g. Sugawara et al. 2008; Goto 2008; Albertão et al. 2008; Dypvik & Jansa 2003). The staggering variety of tsunami-related deposits from the Chicxulub impact alone (see Goto 2008 for a review) gives pause to the enormous task of defining the character of impact tsunami deposition, despite observed sediment thickness, cyclicity and current reversal trends. Only 13 marine impact structures have been associated with tsunami or potential tsunami deposits (Appendix 1). Kamensk-Gusev was the first confirmed marine doublet crater on Earth (Masaitis 1999; Masaitis et al. 1980; Bottke Jr. & Melosh 1996a; Miljković et al. 2013) and recent work has paired Lockne with Målingen (Alwmark et al. 2014; Ormö et al. 2014a). Kara-Ust Kara is also a possible marine doublet (Masaitis 1999; Masaitis et al. 1980; Bottke Jr. & Melosh 1996a;). Kamensk-Gusev and Kara-Ust Kara most likely had associated tsunamis, but distal deposits have not been discovered to date (Masaitis, pers. comm. 2014).

2.6 The Petroleum Prospectivity of Impacts

Generally, impact-related features are considered favourable zones for the localization of hydrocarbons and ore minerals (Masaitis 1989, 2005; Grieve & Masaitis 1994; Reimold et al. 2005). Approximately 25% of proven impact structures are associated with economic deposits. Of those 25%, about two-thirds are being actively exploited (Grieve & Masaitis 1994; Hawke 2004). In North America, studies of impact structures in hydrocarbon-producing basins have shown that they are excellent targets for oil and gas, with 11 out of the 26 known impact structures formed in North American basins associated directly with commercial petroleum fields (Donofrio 1997, 1998; Table 2.1).

Donofrio (1981) examined the impact breccias at four exposed impact sites in North America and showed that three could make productive reservoirs. Another example from the southeastern Mexican oil fields shows a carbonate breccia and overlying ejecta layer (dolomitized seal) have been stratigraphically correlated to the Chicxulub impact of Cretaceous-Paleogene boundary age. This unit of the Cantarell oil field is responsible for 1.3 million barrels of daily oil production (Grajales-Nishimura et al. 2000). Donofrio (1998) reported on the commercial success rate of hydrocarbon exploration in confirmed impact structures in American petroleum provinces as 53% (i.e. percentage of producing wells), with up to 86% drilling success rate (i.e. percentage of drilled wells with hydrocarbon shows), which makes impact-related reservoirs an attractive target by commercial standards, and possibly one of the most under-appreciated plays of hydrocarbon-producing regions.

Table 2.1 Estimate of hydrocarbon resource potential associated with proven impact structures

Name	Location	Hydrocarbon Accumulation	Estimated Resource in Place (MMBOE)
Boltysh ³	Ukraine	oil shale	32,985
Chicxulub ¹	Mexico	oil & gas	32,500
Red Wing Creek ^{1,2}	USA	oil & gas	147
Viewfield ^{1,2}	Canada	oil & gas	76
Ames ^{1,2}	USA	oil & gas	60
Sierra Madera ^{1,2}	USA	gas	45
Steen River ^{1,4}	Canada	oil & gas	17
Middlesboro ^{1,2}	USA	oil	16
Newporte ¹	USA	oil sands	15
Avak ^{1,2}	USA	gas	8
Calvin ¹	USA	oil	5
Marquez ¹	USA	oil & gas	1
Cloud Creek ^{5,6}	USA	oil & gas	?
Eagle Butte ⁴	Canada	oil & gas	?
Kärdla ⁷	Estonia	seeping oil	?
Mjølner ⁸	Norway	gas	? untested gas potential
Obolon ³	Estonia	oil shale	?
Rotmistrovka ³	Estonia	oil shale	?
Siljan ^{9,10}	Sweden	oil & shale gas	? commercial oil
Gosses Bluff ¹¹	Australia	gas shows	? proximal commercial gasfields but limited potential in structure
Tookoonooka ^{12,13}	Australia	oil shows	? proximal commercial oilfields
Talundilly	Australia	gas shows	? proximal commercial gasfields
Haughton ¹⁴	Canada	Hydrocarbon residues or bitumen may indicate presence of migrated or target sequence hydrocarbons	0
Yallalie* ¹³	Australia		? proximal oil & gas prospects but limited potential in structure

Data from: ¹Donofrio (1998); ²Hawke (2004); ³Grieve & Masaitis (1994); ⁴Mazur et al. (2000); ⁵Stone & Therriault (2003); ⁶Reimold et al. (2005); ⁷Suuroja (2002); ⁸Tsikalas et al. (2002); ⁹Vlierboom et al. (1986); ¹⁰Arslan et al. (2013); ¹¹Tingate et al. (1996); ¹²Gorter (1998); ¹³Hawke & Dentith (2006); ¹⁴Parnell et al. (2007). “?” indicates unknown resource volumes. *Yallalie is considered a highly probable impact structure.

Mazur et al. (2000) consider the breccia infill, the rim uplift, and the central uplift of impact structures as potential areas to collect hydrocarbons, and production currently occurs from these traps in North American craters. A crater may also form its own restricted basin (Castaño et al. 1997; Donofrio 1998), which has raised the question of craters as favourable source rock depocentres and hydrocarbon maturation zones. Craters have been shown to have lingering, late post-impact hydrothermal systems which are capable of geologically instantaneous hydrocarbon maturation or thermal alteration over thousands of years, and up to a million years in the largest known impact structures (Vlierboom et al. 1986; Arslan et al. 2013; Naumov 2002; Parnell et al. 2007; Ames et al. 1998). Hydrothermal alteration is most pervasive in shallow marine target craters

(Naumov 2002). Other possible traps not currently identified as producing anywhere in the world but with upside potential include those formed by reef growth on crater rims and sediment draping over the buried and subsiding impact structure (Mazur et al. 2000), impact breccia pinch-outs, ejecta deposits or post-impact sedimentation against the inner crater walls and the raised crater rim (Donofrio 1998) (Figure 2.3, Table 2.2). However, few considerations have been made of the unique traps potentially formed at marine impact structures.

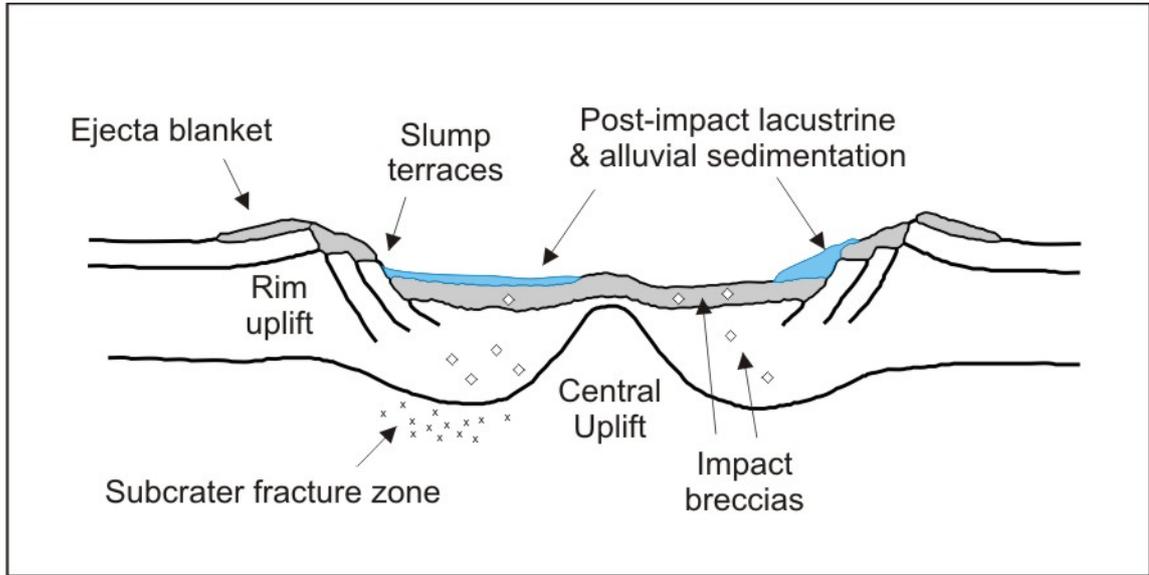


Fig. 2.3 Potential impact-related stratigraphic and structural petroleum plays
Modified after Donofrio (1998).

Table 2.2 Potential impact-related stratigraphic and structural petroleum plays

Trap Type	Potential Impact Plays
Structural	Central uplift
	Listric-faulted slump terraces
	Rim uplift
	Subcrater fracture zone
Stratigraphic	Seismic breccias (beyond crater)
	Impact breccias (within crater)
	Ejecta blanket
	Drapeover
	Lacustrine crater fill
	Alluvial fans from crater highs
	Rim reef growth

Sources: Mazur et al. (2000), Donofrio (1998), Grajales-Nishimura et al. (2000).

2.7 The Petroleum Prospectivity of Impact Structures in Australia

Australia's impact record is extensive: 27 meteorite impact craters & subsurface structures have been confirmed, and a further 22 possible impact structures have been identified (Haines 2005; Earth Impact Database 2015). Australia's crater collection is mainly due to the well-exposed landmass and its stable cratonic areas, and can be compared to the limited discoveries on the densely-forested South American, African, and Asian continents. Of the 49 structures identified in Australia, at least 9 are located in petroleum basins (Table 2.3). However, impact structures in Australia have been inadequately tested with regard to their resource potential (Hawke & Dentith 2006). Hawke (2004), Gorter (1998), and Hawke & Dentith (2006) reviewed the petroleum potential of Australian impact structures located in known petroleum basins (Table 2.3). These reviews highlight the gaps in knowledge regarding the known Australian impact structures in petroleum basins; in-depth work is necessary on most of these structures to adequately assess their economic potential. Gosses Bluff, though relatively well-studied and located in a petroleum basin (Milton et al. 1996a, 1996b; Tingate et al. 1996) is exhumed below the level of the crater floor, and what remains of the eroded central uplift lacks a hydrocarbon seal. Its petroleum prospectivity is also limited by diagenetic effects in potential reservoirs and poor timing with respect to hydrocarbon migration in the basin (Tingate et al. 1996). Yallalie similarly lacks an adequate seal, although hydrocarbon residues suggest a history of oil migration at the structure (Hawke & Dentith 2006). Woodleigh, Mulkarra, Bedout, Gnargoo and Mercury have seen only a limited amount of exploration or testing. Tookoonooka is considered the most prospective impact structure with regards to hydrocarbon potential (Hawke & Dentith 2006) although exploration has been sparse to date (see below). Producing oilfields are located beyond the crater rim.

Table 2.3 Impact structures in petroliferous areas of Australia

Name	Location	Hydrocarbon Shows
Confirmed & Probable Impact Structures		
Gosses Bluff	Amadeus Basin, NT	Yes
Talundilly	Eromanga Basin, QLD	Yes (but poor data coverage to date; proximal gasfields)
Tookoonooka	Eromanga Basin, QLD	Yes (and proximal oilfields)
Woodleigh	Carnarvon Basin, Northwest Shelf, WA	No (but poor data coverage)
Yallalie	Perth Basin, WA	No (but hydrocarbon residues present)
Possible/Speculative Subsurface Geophysical Anomalies		
Bedout	Canning Basin, Northwest Shelf, WA	Unknown
Gnargoo	Carnarvon Basin, Northwest Shelf, WA	Unknown
Mercury	Carnarvon Basin, Northwest Shelf, WA	Unknown
Mulkarra	Eromanga Basin, SA	No (but poor data coverage)

2.8 The Tookoonooka and Talundilly Impact Structures

Tookoonooka (27°07'S, 142°50'E) and Talundilly (24°50'S, 144°30'E) are two large subsurface anomalies in the Eromanga Basin of central Australia that were recognized by petroleum exploration in the 1980s (Gorter et al. 1989; Longley 1989). The structures and surrounds are in a petroleum exploration area, and thus they were initially identified by seismic exploration but saw limited exploratory drilling. Tookoonooka and Talundilly are about 303 km apart, buried under almost one kilometre of flat-lying sediments near the centre of the basin in southwest Queensland (Figure 2.4). Due to uncannily similar seismic structures and stratigraphic placement, they were interpreted to be of related origin (Longley 1989; Gostin & Therriault 1997; Gorter 1998; Haines 2005).

The impact origin of subsurface structures is notoriously difficult to investigate due to inaccessibility and paucity of data. Tookoonooka was confirmed as an impact structure through the identification and measurement of shock metamorphic features in quartz grains in drill core from the structure's buried central uplift subsequent to drilling (Gorter et al. 1989; Gostin & Therriault 1997). Shock evidence of Talundilly's impact origin was only recently presented from a non-central drillhole in the buried structure (Gorter & Glikson 2012a), but microscopic analyses were done on allochthonous rather than autochthonous rocks and are not considered conclusive (i.e. Talundilly's impact origin should be proven from in-situ rocks of the crater structure). Heidecker (2012) also questioned the impact origin of the microstructures, though Gorter & Glikson (2012b) successfully refuted this criticism. Though highly probable to be an impact structure based on other merits (geophysical characteristics and apparently simultaneous stratigraphy with Tookoonooka; Gorter 1998), Talundilly awaits more sampling opportunities.

Crater diameter estimates are 66 km for Tookoonooka (Gostin & Therriault 1997) and 84 km for Talundilly (Gorter & Glikson 2012a), which could make them two of the largest ten meteorite impact structures on Earth. Talundilly and Tookoonooka are the second and third largest impact structures in Australia, respectively. Tookoonooka's final crater diameter of 66 km (Gostin & Therriault 1997) was a recalculation of an earlier estimate of 55 km from seismic data (Gorter et al. 1989). Talundilly was initially estimated to have a 95 km diameter from seismic data (Longley 1989). A Talundilly crater diameter cited by Bevan (1996) and Gorter (1998) of 30 km was not thoroughly discussed by those authors. However, the latest estimate of 84km (Gorter & Glikson 2012a) may be generous based on current crater scaling standards (cf. Turtle et al. 2005). Both structures are central peak complex craters. The structures were partially preserved by burial; Gostin and Therriault (1997) estimated the Tookoonooka crater erosion level at 5 (cf. Grieve & Pilkington 1996), although this estimate was unlikely to have taken into account the morphology of marine impact structures as outlined in Section 2.3 above. Both events were large enough to excavate significant thicknesses of target material, down to basement lithologies (Gorter et al. 1989; Gostin & Therriault 1997; Longley 1989).

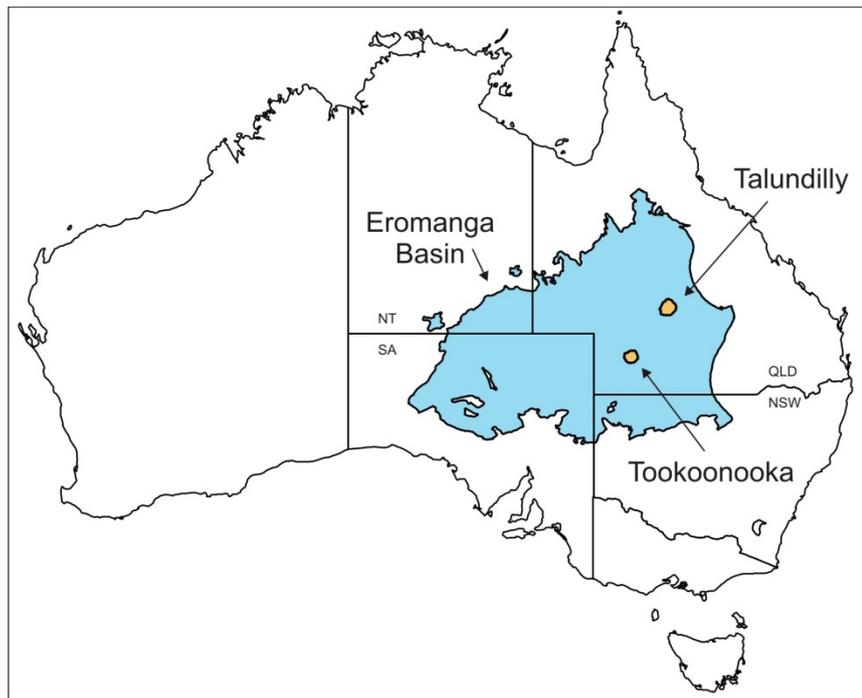


Fig. 2.4 Map of the Eromanga Basin in Australia with locations of Tookoonooka (proven) and Talundilly (probable) Impact Structures

The sedimentology of the Tookoonooka and Talundilly impact events has not been extensively investigated to date. At the start of this PhD research, ejecta had never been discovered (Haines 2005) and impact deposits outside the impact structures had not been identified. Impact-related sedimentary deposits within the structures had not been adequately analysed or classified. Early estimates of the Tookoonooka and Talundilly impact ages were based on seismic stratigraphic interpretations correlated to the palynostratigraphy of the area. The age of the Tookoonooka structure was variously dated at about 128 Ma between palynostratigraphic units PK2.1 and PK2.2 (Gorter et al. 1989; Gostin & Therriault 1997), and 112-115 Ma (Gorter 1998), within the Lower Cretaceous. Bron (2010, Paper 1 of this thesis) and Bron and Gostin (2012, Paper 2 of this thesis) constrained the impact age to the base of the Wyandra Sandstone Member, biostratigraphically dated at the Barremian-Aptian boundary (125 ± 1 Ma), based on the first presence of an impact signature in the stratigraphy. Based on their similar seismic stratigraphic positions, Tookoonooka and Talundilly were initially speculated to be the result of the same impact event (Gorter 1998; Haines 2005). However, more definitive evidence of their binary impact origin was lacking. This thesis presents sedimentological and petrographic evidence and a probability assessment in evidence of their doublet status. A common impact horizon for Tookoonooka and Talundilly is discussed (Paper 3 of this thesis).

2.9 The Stratigraphic Context of Tookoonooka and Talundilly: Target Sequence, Eromanga Basin Stratigraphy and Lower Cretaceous Paleoenvironment

Tookoonooka and Talundilly have slightly different target strata at their respective impact sites. Underlying their Eromanga Basin sequences, the Tookoonooka target sequence contains Permian-Triassic Cooper Basin sediments in addition to Thargomindah Shelf

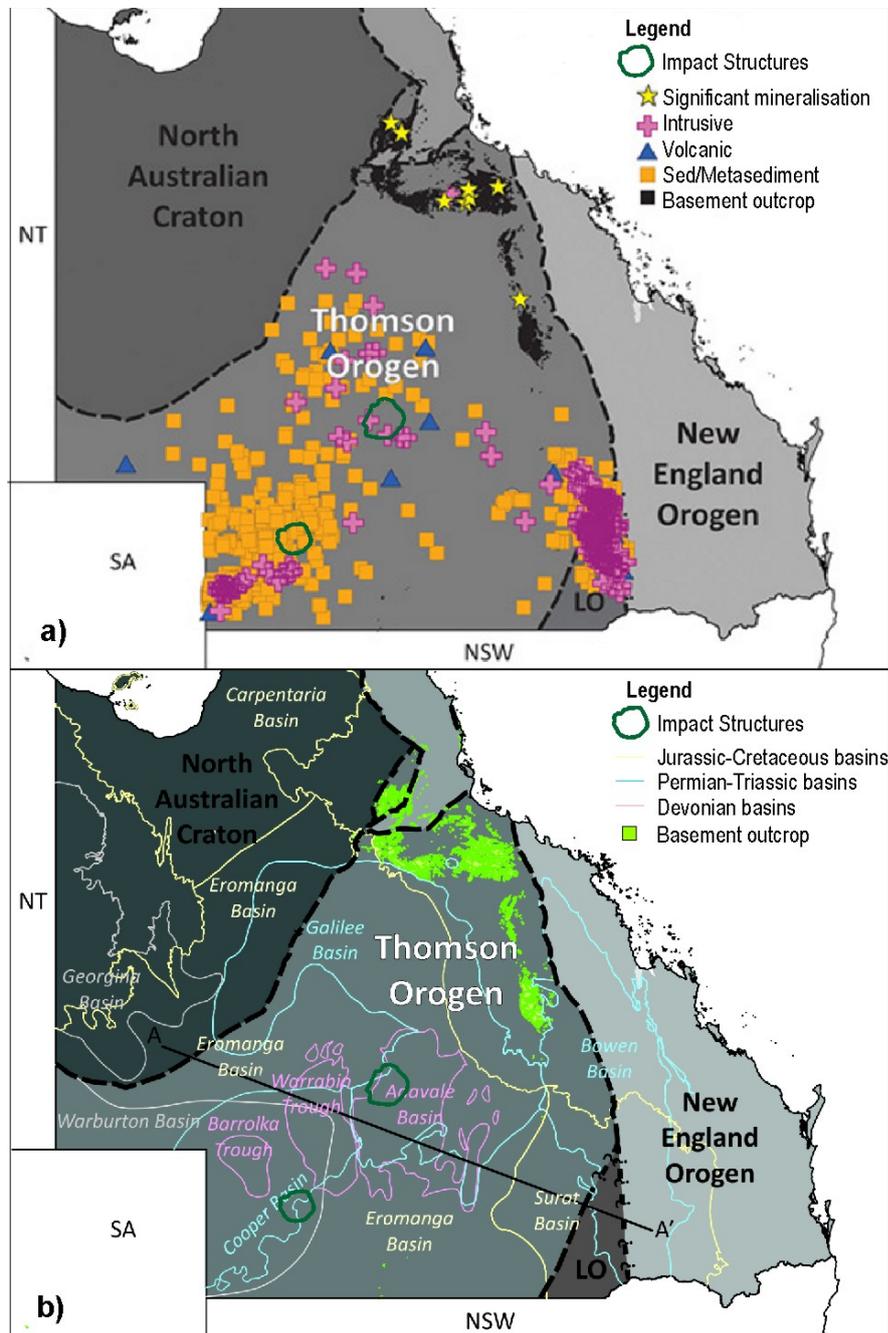


Fig. 2.5 Target sequence elements of Tookoonooka and Talundilly. Maps of Queensland, Australia, with locations of Tookoonooka and Talundilly impact structures, showing (a) known basement lithologies of the Thomson Orogen and (b) extents of sedimentary basins. Modified from Purdy et al. (2013).

metasedimentary basement of the Thomson Orogen, while Talundilly's target sequence contains Carboniferous-Triassic Galilee Basin sediments, Devonian Adavale Basin sediments, and basement of the Maneroo Platform of the Thomson Orogen (Figure 2.5).

The Eromanga Basin is a vast sedimentary basin of Jurassic-Cretaceous age covering 20% of the Australian continent (Krieg & Rogers 1995), spanning three Australian states and one territory (Figures 2.4, 2.5b). It is one of several epeiric, interconnected basins forming the Great Australian Superbasin which extends up to Indonesia (Jell et al. 2013). The stratigraphy of the Eromanga Basin in Australia has been reasonably well-documented. Work has been done on the sparse, deeply weathered southern and southwestern basin margin outcrops (Forbes 1986; Wopfner et al. 1970; Ambrose & Flint 1982; Krieg 2000; Alley & Pledge 2000; Alley & Sheard 1996; Krieg et al. 1991; Rogers & Freeman 1996; Forbes 1966; Hawke & Cramsie 1984; Greenfield et al. 2010; Morton 1982, among others), and knowledge of the buried sediments in the rest of the basin comes mainly from petroleum exploration and widely spaced stratigraphic wells (e.g. Draper 2002; Cotton et al. 2006; Day et al. 1983; John & Almond 1987; Exon & Senior 1976; Moore & Pitt 1984, 1985; Senior et al. 1975, 1978). The flat-lying nature of the sediments indicates that the paleobasin has experienced negligible tectonism since its inception.

The stratigraphic context of the Tookoonooka and Talundilly Impacts is the Cadna-owie Formation (Figure 2.6). The Cadna-owie Formation is comprised of very fine- to fine-grained, quartzose to sublamine sandstones with common siltstone interlaminae and thin interbeds (Day et al. 1983; Exon & Senior 1976; Senior et al. 1975). The sandstone matrix is calcareous in part and the siltstone may be carbonaceous (Draper 2002). The sedimentation of the Cadna-owie Formation is laterally uniform, with a siltier lower unit and a sandier, slightly coarser upper unit (Draper 2002; Cook et al. 2013). The formation has an average thickness of 60 m (Exon & Senior 1976; Senior et al. 1975), but is more typically 75-100 m thick in the centre of the basin (Moore & Pitt 1984, 1985). The Cadna-owie Formation records the transition to paralic and shallow marine environments as a very extensive, shallow epeiric sea transgressed the non-marine basin; Eromanga Basin sediments pre-dating the Cadna-owie Formation are largely fluvio-lacustrine (e.g. Exon & Senior 1976). Prior to deposition of the overlying Walumbilla Formation (Figure 2.6), basin sediments were predominantly quartz-rich (with sublamine components) and mature (Exon & Senior 1976; Day et al. 1983). No volcanism has been reported in the basin from this geological time (Harrington & Korsch 1985; McDougall 2008; Wiltshire 1989). The presence of glauconite and marine palynomorphs (e.g. Alley & Lemon 1988; Day 1969; Day et al. 1983; Senior et al. 1975; Ludbrook 1966; Price 1997) is strongly evident of a marine influence during deposition. Glacial indications have been described from the southern basin margin areas only (Alley & Frakes 2003; De Lurio & Frakes 1999; Frakes et al. 1995). The Cadna-owie Formation was likely deposited in restricted marine cold-water conditions in a low relief high-latitude basin with poor sediment supply. The Cadna-owie Formation is an important aquifer within the basin (Alexander & Boulton 2006).

The Wyandra Sandstone Member (Figure 2.6), stratigraphically assigned to the uppermost part of the Cadna-owie Formation in central Queensland (e.g. Draper 2002; Cook et al. 2013), is a coarser-grained, cleaner sandstone unit than the lower and upper Cadna-owie Formation units as described above. The unit was first named by Senior et al. (1975), and defined as a widespread, well-sorted, thin, medium- to coarse-grained quartzose sandstone with scattered carbonate cement and pebbles and no known fossils (Senior et al. 1975, 1978; Exon & Senior 1976). Though the Wyandra Sandstone Member occupies the uppermost part of the Cadna-owie Formation as originally defined, for clarity all references to the Cadna-owie Formation in this thesis will pertain to the Cadna-owie Formation deposits underlying the Wyandra Sandstone Member. The Wyandra Sandstone Member is a major regional aquifer and a producing petroleum reservoir (Senior et al. 1975; Root et al. 2005; Alexander & Boulton 2006). The provenance and regional extent of the Wyandra Sandstone Member has never been investigated, and it has been interpreted by some to be a transgressive beach sand (Senior et al. 1975).

Overlying the Wyandra Sandstone Member, the Walumbilla Formation (or Bulldog Shale, as it is known laterally in the southern parts of the basin) is a dark grey, fossiliferous and carbonaceous marine shale. The Bulldog Shale in South Australia has a maximum known thickness of 340 m (Moore & Pitt 1985). The Walumbilla Formation is known to be greater than 450 m thick in the centre of the basin, thinning to only 30 m in the far northwest of the basin in Queensland (Moore & Pitt 1985). The Walumbilla/Bulldog shales form a thick regional hydrocarbon seal (Alexander & Boulton 2006).

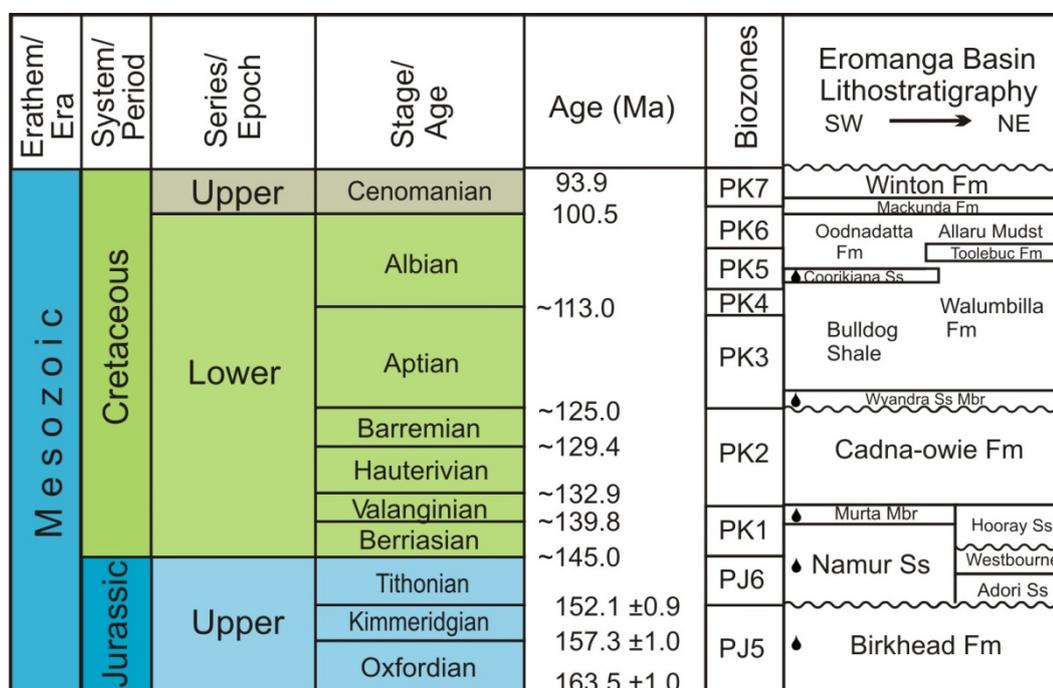


Fig. 2.6 Stratigraphy of the Eromanga Basin: stratigraphic context of the Tookoonooka and Talundilly impacts. Oil drops indicate known reservoirs in the basin. Stratigraphic chart after Cohen et al. (2013), Gradstein, Ogg & Smith (2004), Price (1997) and Gallagher et al. (2008).

2.10 Summary

Buried impact craters, marine craters, and doublet craters are all under-represented in the terrestrial cratering record as well as in the scientific literature. Ancient tsunami deposits are similarly under-represented in the literature. The sedimentation processes associated with marine impacts, including impact tsunami deposition, are not well understood, due in part to the small representation of marine impact structures in Earth's crater record. However, ejecta deposits for all crater types are in themselves rarely described, as few have been recognized in the stratigraphic record. As such, limited comprehensive investigations have been undertaken into the distribution and regional characterization of terrestrial impact ejecta.

The petroleum prospectivity of impact structures and resource assessments of Australia's impact structures have had minor attention in the research literature, although their potential is significant as exemplified by the scale of other economic impactites on Earth.

There are many gaps in the existing knowledge of the Tookoonooka and Talundilly impacts, which include the existence, character and distribution of impact deposits, constraint of the impacts' ages, Tookoonooka and Talundilly's paleoenvironmental context, their petroleum prospectivity, and evidence of their binary impact origin.

3. Methodology and Datasets

This research investigates the stratigraphic context of the Tookoonooka and Talundilly meteorite impact structures, which are concealed in the Cretaceous sedimentary record of central Australia. Concealment is a substantial challenge to data collection for the study of buried impact structures, but data exists for this investigation in the form of petroleum industry datasets and subsurface data from widely-spaced stratigraphic drill holes, water and mineral wells. Datasets span a large area of the continent, with data repositories at the geological surveys of Queensland, South Australia, New South Wales and the Northern Territory, in addition to petroleum industry and Geoscience Australia databases.

Outcrop exposures also exist at paleo-basin margins in central Australia. However, accurate data collection from field investigations is complicated by:

- poor vertical successions in low relief outcrops;
- locally diachronous contacts and hiatuses (Krieg & Rogers 1995);
- thinning due to basement onlap;
- deep weathering;
- regolith cover;
- the destruction of original depositional character by regolith processes (e.g. ferruginous induration and silcretization);
- glacial signatures at the southwestern basin margin (De Lurio & Frakes 1999; Alley & Frakes 2003) and
- poor intraformational age constraint due to the effects of deep weathering on microfossil preservation (Alley & Sheard 1996) and lack of fossils from marginal marine paleoenvironments.
- reworking and mixing of exposed strata in basin margin paleoenvironments coupled with the above resulting in “undifferentiated Mesozoic” units on existing maps

Such complications have plagued scientists throughout the history of geological mapping in central Australia, rendering study and characterization of the Jurassic-Cretaceous sedimentary succession challenging: “One of the greatest difficulties in surface mapping the Cretaceous of the Great Artesian Basin is the scarcity of measurable sections. The low relief, usually low angle of dip, and absence of sections of any representative thickness renders their designation only partially adequate to describe the complete unit” (Ludbrook 1966 p.14). Thus, while fieldwork provided integral insight into the context of the impact environment, it was considered supplemental to the subsurface basin analyses.

Methods of investigations for the three papers in this thesis (Section 4) are described within each individual publication/manuscript and include:

- core logging;
- field data collection;
- sedimentological evaluations;
- petrographic analyses;
- geochemical analyses;
- impact shock measurements;

- map compilation;
- datamining;
- stratigraphic correlations and
- binary cratering calculations.

As such, this chapter aims to describe only the approach applied to initial thesis data collection and the definition of the study area, which follows in sequential order.

3.1 Impact Target Sequence.

A reconnaissance of the impact target sequences of Tookoonooka and Talundilly was undertaken to become familiar with possible excavated formations and lithologies. This was done by reviewing both basin literature and drill cores from continuously cored stratigraphic wells closest to the impact structures.

3.2 Study Area and the Search for Impact Ejecta.

A search for impact ejecta was undertaken with the aim to identify the record of the impact event(s) in the stratigraphy and thereby constrain the time window of impact(s). A search area was identified based on theoretical ejecta distributions (cf Section 2.4). At the onset of this research, it was unknown whether the Tookoonooka and Talundilly impacts occurred into a non-marine or marine paleoenvironment, with prior work placing the time of impact(s) sometime within the broad context of the Cretaceous marine transgression (see discussions on impact timing and stratigraphy in Sections 2.8-2.9). Thus, as a starting point, the extents of a theoretical “dry” ejecta blanket were calculated based on rules of thumb for terrestrial limits of continuous ejecta blankets and proximal ejecta (Melosh 1989) and ejecta deposit thicknesses (Equation 2.2; McGetchin et al. 1973); see Figure 3.1. The latter assumes the following:

- ejecta distribution is governed by ballistic ejecta processes only;
- a continuous ejecta blanket of uniform thickness is formed (in reality, the ejecta blanket is discontinuous and ray-like beyond $2R_c$);
- ejecta thickness does not take compaction of sediments into account;
- a non-marine impact scenario.

The green circle on Figure 3.1 represents the extent of nominal ejecta thickness, taken to be 1m (uncompacted), which is a conservative bed thickness recognizable within the vertical resolution limitations of Formation Evaluation logs. It was hoped that ejecta deposits, if discovered, would have a unique log signature and thus correlate readily across the basin. Calculations are provided in Appendix 2.

A search priority was thus applied to core viewing and datamining (Figure 3.1):

1. Well data within $1-2R_c$ (theoretical continuous ejecta blanket, containing 50% of ejecta volumes)
2. Well data within $3.68R_c$ of Tookoonooka and $3.78R_c$ of Talundilly (theoretical limit of log-resolvable ejecta beds)
3. Well data within $5 R_c$ (theoretical extent of proximal ejecta)

- Data beyond 5Rc (distal, pending character of ejecta). Note: After discovery of ejecta at the base of the Wyandra Sandstone Member and interpretation of the impact event as marine, the data search was expanded to a more distal extent from the impact structures in an attempt to study the various depositional realms and trace the limit of distribution (as detailed in Paper 3 of this thesis).

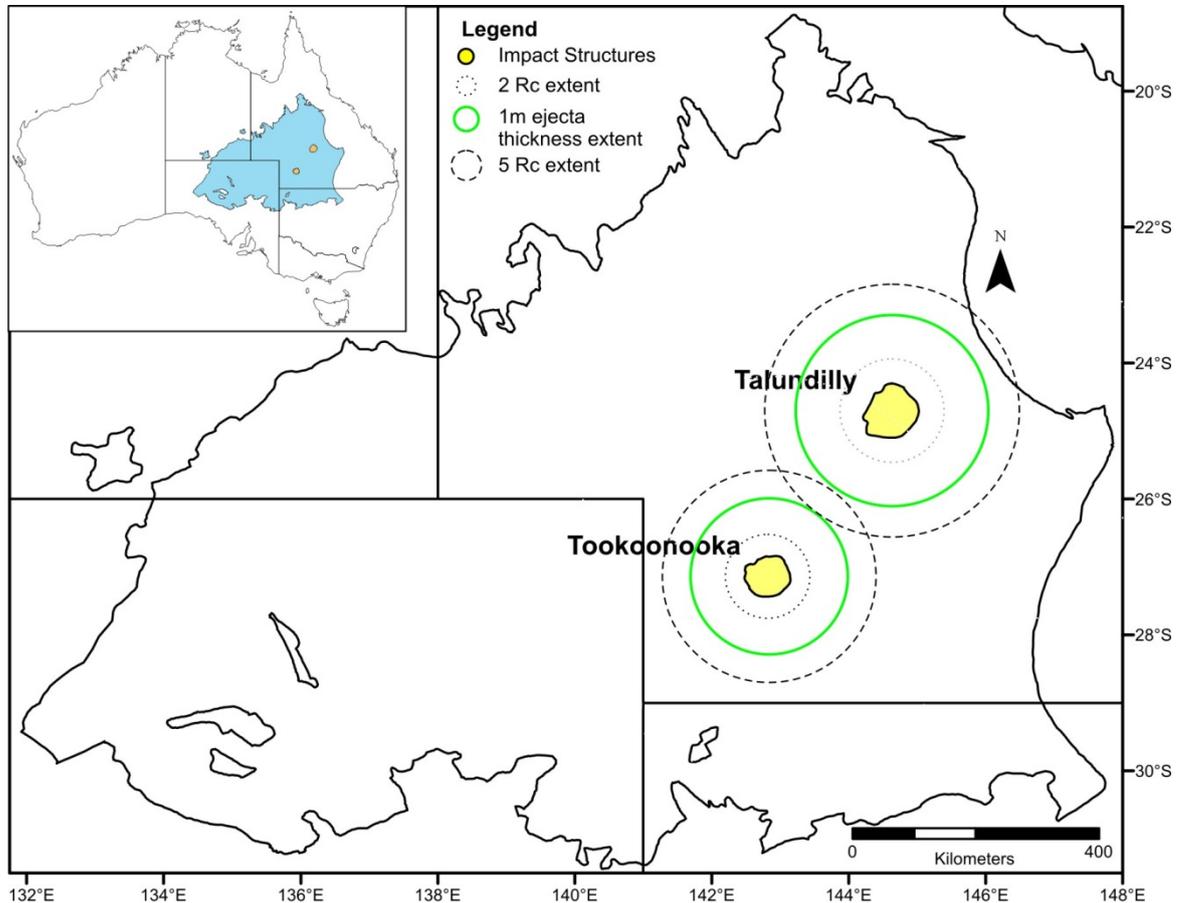


Fig. 3.1 Map of the Eromanga Basin showing extents of theoretical ejecta distributions with respect to crater radius (Rc) and nominal ejecta thickness used in data collection. Inset map shows the location of the Eromanga Basin within Australia. The bulk of ejecta volumes are expected proximally (within 5Rc of each crater centre) and the theoretical limit of the continuous ejecta blanket is ~2 Rc (see Section 2 and Figure 2.2). “1m ejecta thickness extent” is calculated from Equation 2.2.

3.3 Data Collection and Review

A review of formations and lithological descriptions for the targeted study area (Figure 3.1; Figure 2.6) and targeted depths/formations of interest (Cadna-owie and Walumbilla Formations) was undertaken to identify candidate impact deposits based on typical characteristics of impactites. Data were sought from State Geological Surveys and petroleum companies in the form of cores, drill cuttings, well completion reports, formation evaluation logs, mudlogs, maps, existing data analyses and field reports. Data used in this study are listed in Appendix 3. Data collection took three forms:

- Core analyses – detailed sedimentological observations to identify and classify impact deposits and their sedimentary context. The entire Cadna-owie Formation

to upper Walumbilla Formation interval was reviewed in all available continuously-cored stratigraphic wells, representing up to 300m of strata over more than 20 Ma of stratigraphic record. All known core samples of the Wyandra Sandstone Member were examined. 51 drill cores were viewed at the South Australian government, Queensland government, and Santos Ltd core libraries. Twenty-seven lithological logs were made over intervals of interest. Core and outcrop observations cover an area >525,000 km², shown in Figure 3.2. Core logs cover 1369 m of vertical section. Cores were described but not logged where core was discontinuous.

2. Fieldwork – assess presence and thus lateral continuity of distal impact deposits, and confirm large-scale features and deposit geometry at outcrop scale, as well as to assess paleoenvironmental context of the impacts. 12 field sites in South Australia, Queensland, and New South Wales were studied and lithological logs and/or outcrop descriptions were recorded. Only qualitative data was recorded at basin margin sites where correlations were low confidence due to poor intraformational age constraint, insufficient vertical exposures, or deep weathering that affected preservation of original sedimentary textures. Combined core and outcrop observations cover an area >525,000 km², shown in Figure 3.2. Wyandra Sandstone Member-equivalent deposits were interpreted at four field locations.
3. Datamining – to bridge gaps in drill core coverage in central parts of the basin and improve data resolution for mapping the distribution of the impact deposits (n.b. tsunami sequence is usually below seismic resolution). Lithological logs (from core and outcrop observations) and palynological data were used as calibrations to extrapolate interpretations to subsurface petroleum and mineral well datasets and field records from South Australia, New South Wales, the Northern Territory and Queensland governments, Santos Ltd. and Magellan Petroleum. All data used was checked for consistency: the data required corrections for formation depths, formation naming conventions (see Table 6.1), grainsize scale and metric conversions, as the well database spans four states and over a century of drilling. Combined data represent 158 locations covering an area of >805,000 km² out to a maximum extent of 23 Rc from crater centres (Figure 3.3). While Formation Evaluation logs were used as supplementary data, it must be noted that the log signature of the impact deposits was not consistent: while the base of the Wyandra Sandstone Member *can* be evident by the sudden increase in porous sand content (due to ejecta), it is often masked by the mud content of altered impactoclasts and sedimentary lithic volumes. Cobbles and boulders of Cadna-owie Formation scoured or ejected from the substrate by impact-related processes are evident in the Wyandra Sandstone Member in full-hole core, but cannot be differentiated from the underlying Cadna-owie Formation in log signatures. Thus correlations were done holistically using all available well data.

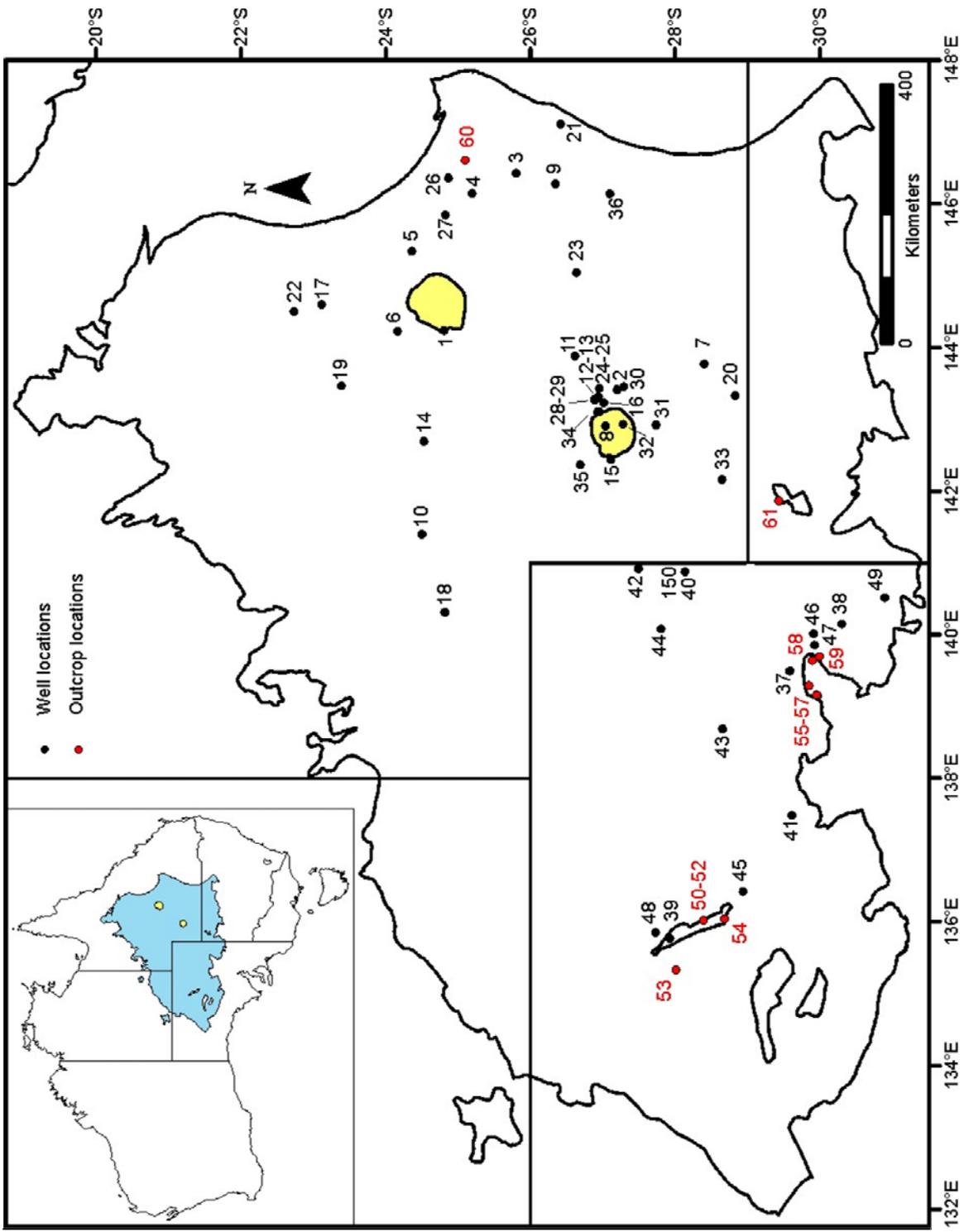


Fig. 3.2 Map of the Eromanga Basin, showing Tookoonooka and Talundilly Impact Structures and locations of cores and outcrop analysed in this thesis. These locations represent an areal extent of >525,000 km².

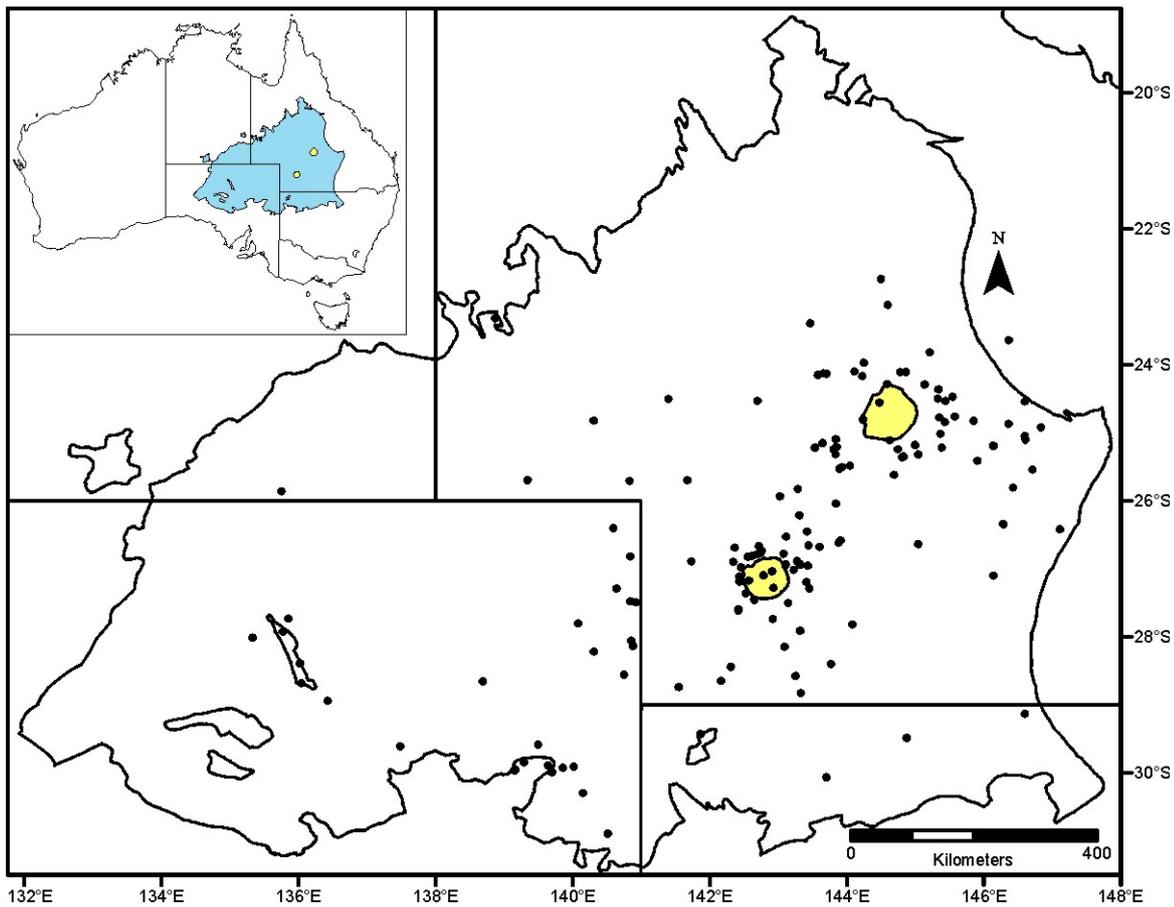


Fig. 3.3 Map of the Eromanga Basin, showing Tookoonooka and Talundilly Impact Structures and locations of all data analyzed in this thesis, including points from datamining. Datapoint locations represent an areal extent of >805,000 km².

3.4 Confirmation of an Impact Signature

Evidence of impact can be demonstrated via identification of geochemical or petrographic signatures such as shock metamorphic features or exotic elemental, mineralogical and isotope anomalies. Analyses to test the impact signature of the proposed impact deposits for this study included measurements of shocked quartz via universal stage microscopy as well as geochemistry and standard petrography. These analyses required sampling of the impact deposits, thin section preparation, and use of specialized analytical equipment, described in Papers 1 and 2. Locations at which shock-metamorphosed quartz was measured are shown in Figure 3.4. Note that due to limited rock material available for sampling, dilution of impact signatures in reworked sediments across the vast basin and the limitations inherent in universal stage microscopy, statistical datasets of shock measurements were generally unfeasible.

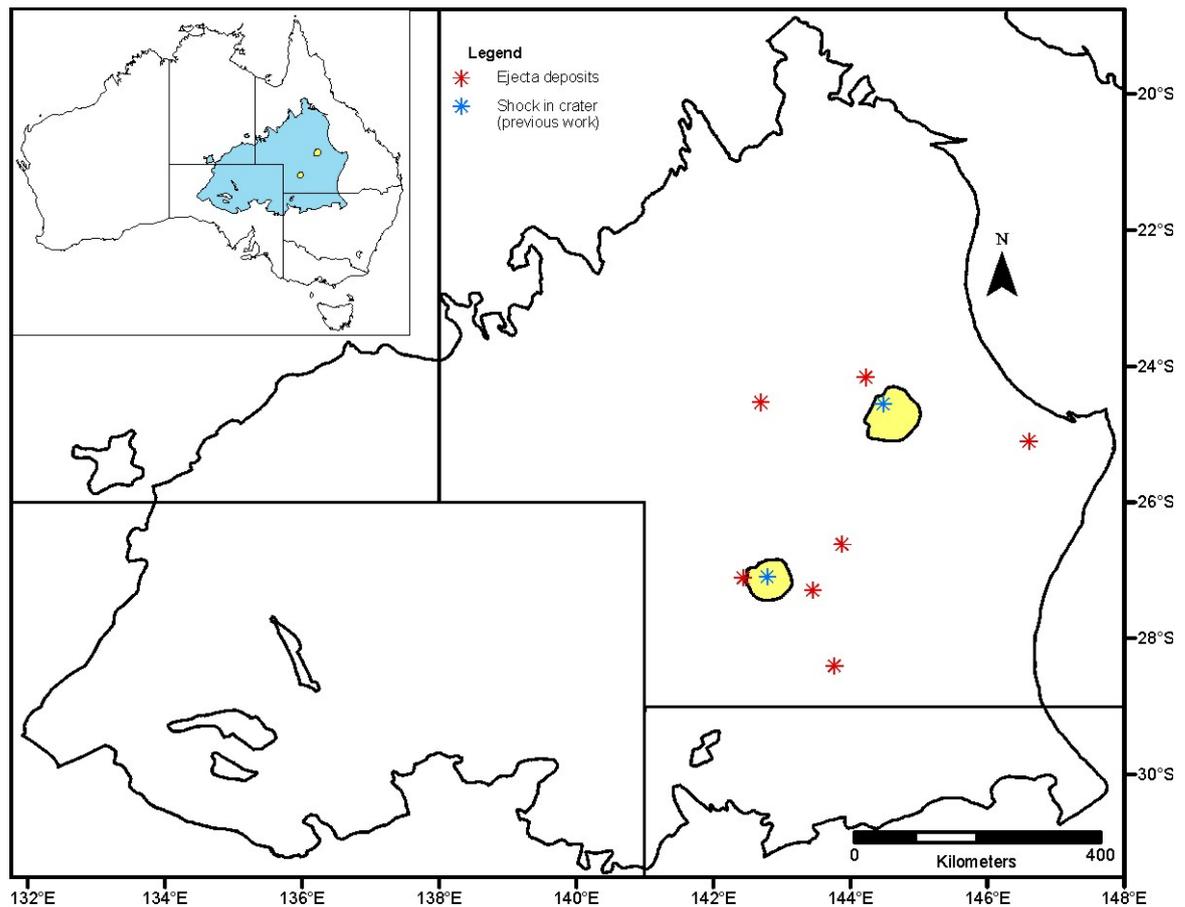


Fig. 3.4 Map of the Eromanga Basin, showing Toookoonooka and Talundilly Impact Structures and locations of ejecta deposits where impact shock measurements were made. Inset map shows the location of the Eromanga Basin within Australia.

3.5 Summary

Numerous investigations were done in the course of this PhD research. Challenges faced in the development of thesis analyses were mainly related to data coverage, as this was predominantly a subsurface study over a large regional area utilizing extensive databases across the breadth of the Eromanga Basin and multiple state boundaries. However, the methodical approach to the ejecta search was successful, which enabled the identification of the impact horizon and subsequent investigations of the impact deposits via sedimentological evaluations, stratigraphic correlation, mapping, petrographic analyses and geochemical analyses. Detailed methods are described in individual papers in the following section.

4. Papers

Paper 1: Bron K.A. 2010. Accretionary and melt impactoclasts from the Tookoonooka impact event, Australia. In R.L. Gibson and W.U. Reimold (Eds.), *Large Meteorite Impacts and Planetary Evolution IV* (Chapter 15). Geological Society of America Special Paper **465**. Boulder: Geological Society of America, 219-244.

Paper 2: Bron K.A. and Gostin V., 2012. The Tookoonooka marine impact horizon, Australia: Sedimentary and petrologic evidence. *Meteoritics and Planetary Science* **47(2)**, 296-318.

Paper 3: Bron K., (text in manuscript). A Tsunamiite Petroleum Reservoir formed from a Binary Meteorite Impact?

Note: unpublished data related to this paper are included in Appendix 4

Supplementary abstracts and posters completed during this PhD research are included in Appendix 5.

Statement of Authorship

Title of Paper	Accretionary and melt impactoclasts from the Tookoonooka impact event, Australia.
Publication Status	<input checked="" type="radio"/> Published, <input type="radio"/> Accepted for Publication, <input type="radio"/> Submitted for Publication, <input type="radio"/> Publication style
Publication Details	Bron, K.A., 2010. Accretionary and melt impactoclasts from the Tookoonooka impact event, Australia. Chapter 15. In Large meteorite impacts and planetary evolution IV: Geological Society of America special paper 465, edited by Gibson R.L. and Reimold W.U. Boulder: Geological Society of America. pp. 219-244.

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author (Candidate)	Katherine Bron		
Contribution to the Paper	Conceptualized work, performed analyses on all samples, interpreted data, wrote manuscript, acted as corresponding author with publisher.		
Signature		Date	24 Sep 2014

Name of Co-Author			
Contribution to the Paper			
Signature		Date	

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Accretionary and melt impactoclasts from the Tookoonooka impact event, Australia

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ABSTRACT

The Tookoonooka impact structure is a subsurface structure of the Eromanga Basin in Australia. Impact ejecta have recently been discovered in the stratigraphy proximal to the structure. The ejecta includes accretionary and armored impactoclasts. They are observed at multiple locations in drill core across central Australia, spanning 375,000 km² within possible impact tsunami deposits. Typical characteristics of the accretionary impactoclasts include a distinctive brownish-gray color, flattened shapes, concentric zonation, and a variety of morphologies with and without obvious nuclei. Some complex accretionary impactoclasts include melt components. Apparent diameters of these impactoclasts in drill core are commonly less than 2 cm, but may be up to 9 cm. They occur in a variety of depositional contexts, including clast-supported breccia-conglomerate layers and “floating” within massive and planar-bedded sandstones. Microscopic and geochemical investigations reveal that they are pervasively altered. Many resemble the types of accretionary lapilli recognized from hydroclastic volcanic environments, which implies the presence of significant water at the time of impact. Tookoonooka is interpreted to have been a marine (likely paralic to shallow) impact event. It is proposed that hydroclastic types of accretionary impactoclasts at impact sites may be an indicator of wet or marine targets. Complex forms of accretionary impactoclasts may also lead to new understanding of impact vapor plume processes. The impactoclasts studied at Tookoonooka are consistent with an impact origin of the candidate ejecta. The consistent first occurrence of the impactoclasts at the base of the Wyandra Sandstone Member stratigraphically constrains the Tookoonooka impact age to 125 ± 1 Ma in the Lower Cretaceous.

INTRODUCTION

The Tookoonooka impact structure (27°07'S, 142°50'E) is a buried structure of the Eromanga sedimentary basin in central Australia (Fig. 1). The structure and surrounds are in a petroleum exploration area, and thus the structure was initially identified by seismic exploration but saw limited exploratory drilling in the

1980s (with no hydrocarbon shows). The structure's impact origin was confirmed by Gorter et al. (1989) and Gostin and Therriault (1997) with the discovery and measurement of planar deformation features (PDFs) in shock-metamorphosed quartz in drill core from the central uplift. The diameter of the final crater has been estimated at ~66 km (Gostin and Therriault, 1997), making Tookoonooka the tenth largest confirmed impact crater on Earth

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Bron, K.A., 2010, Accretionary and melt impactoclasts from the Tookoonooka impact event, Australia, in Gibson, R.L., and Reimold, W.U., eds., Large Meteorite Impacts and Planetary Evolution IV: Geological Society of America Special Paper 465, p. 219–244, doi: 10.1130/2010.2465(15). For permission to copy, contact editing@geosociety.org. ©2010 The Geological Society of America. All rights reserved.

at this time, and the second largest in Australia. The structure is buried under almost 1 km of sediments near the center of the largely tectonically inactive basin. Toookoonooka is part of a possible binary impact event (Gorter, 1998): Talundilly is a second subsurface structure of unconfirmed impact origin, located some 300 km to the northeast of Toookoonooka in Queensland (Longley, 1989; Fig. 1), and it has a similar stratigraphic position (Gorter, 1998). Estimates of the Toookoonooka impact age are based largely on seismic stratigraphic interpretations as they relate to the palynostratigraphy of the area. The age of the Toookoonooka structure has been variously dated at ca. 128 Ma between palynostratigraphic units PK2.1 and PK2.2 (Gorter et al., 1989; Gostin and Therriault, 1997), and 112–115 Ma (Gorter, 1998), within the Lower Cretaceous (Fig. 2). Based on these estimates, the timing of the impact is thought to have occurred during the deposition of the Cadna-owie or Walumbilla Formations, during the time of a marine transgression into the basin. The Cadna-owie is a fine-

grained, nonmarine to paralic silty sandstone, whereas the Walumbilla is a dark marine shale. The Wyandra Sandstone Member, at the top of the Cadna-owie, is a coarser-grained, cleaner sandstone unit. No volcanism has been reported in the basin from this geological time, and prior to the approximate time of impact, the sedimentation was predominantly quartz rich and mature (Exon and Senior, 1976). The Toookoonooka structure is preserved, though little-explored due to its subsurface position; Gostin and Therriault (1997) estimated the crater erosion level at 5 (cf. Grieve and Pilkington, 1996). The sedimentology of this impact has not been well investigated to date, though Toookoonooka ejecta was recently located in the sedimentary succession (Bron and Gostin, 2008) and is the subject of ongoing research.

This paper aims to report and describe the occurrence of Toookoonooka impactoclasts, particularly accretionary and melt impactoclasts, from within the crater structure and as a constituent of the ejecta outside the crater.

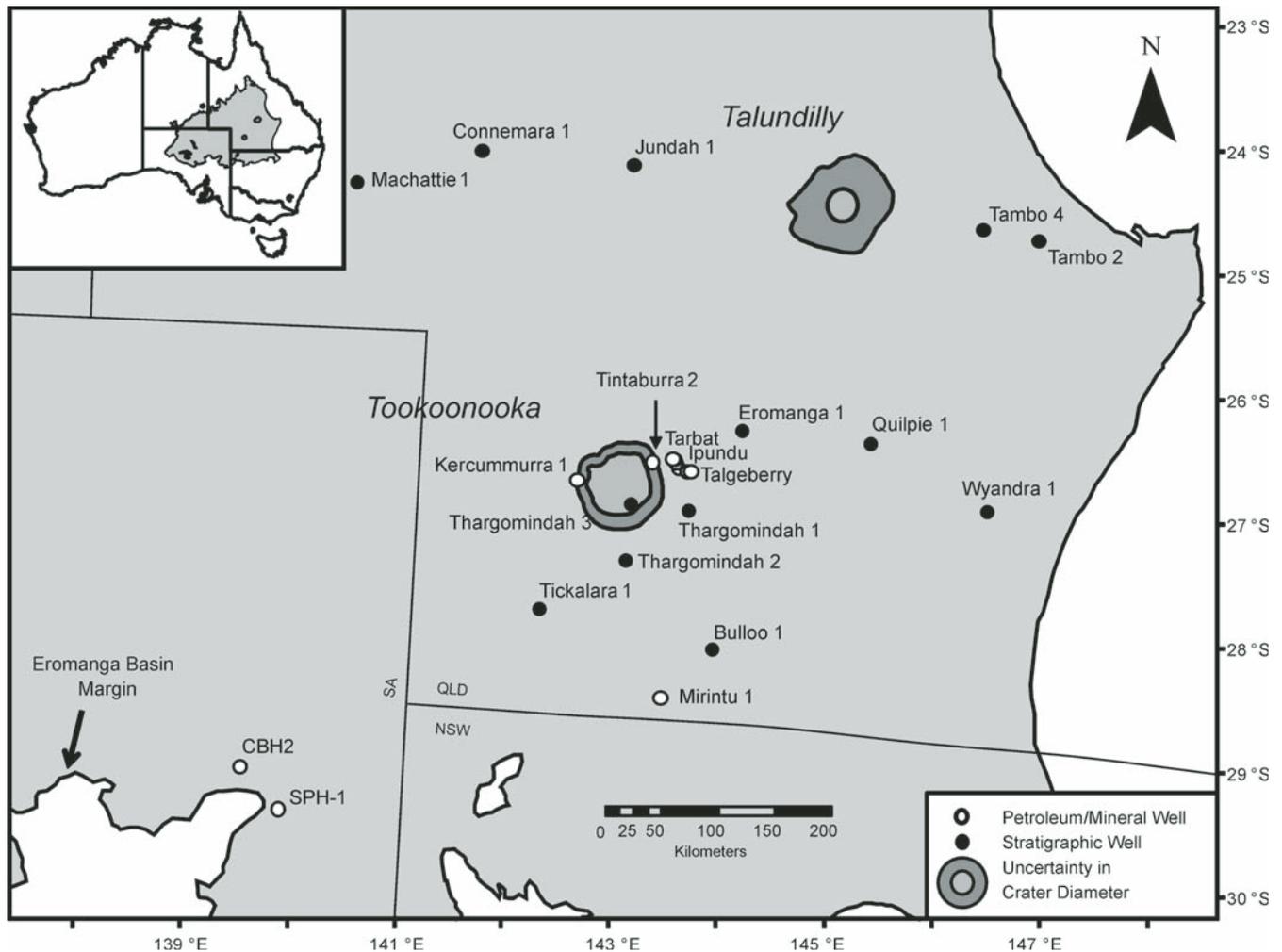


Figure 1. Map of the Eromanga Basin of central Australia showing the locations of Toookoonooka impact structure and Talundilly possible impact structure and wells where impactoclasts have been recorded. Positional data are from Geoscience Australia; crater diameter estimates are from Gorter et al. (1989), Gorter (1998), Gostin and Therriault (1997), and Longley (1989).

BACKGROUND: IMPACT TERMINOLOGY AND VOLCANIC TERMINOLOGY AS IT APPLIES TO IMPACT PROCESSES

The field of impact geology is young. Traditionally, many impact structures and their ejecta were mistaken for being of volcanic or pyroclastic origin. Indeed, there are important parallels between volcanism and impact mechanisms that give rise to similar rock types, and some impact rock descriptions and terminology are drawn from volcanology. The processes of large-scale impacts such as vapor plume formation (the hot gas and ejecta cloud rising above the crater in the early stages of the impact, presumed to be the source and/or dispersal mechanism of accretionary particles and distal ejecta) and plume-related sedimentation have not been extensively documented, owing to the fact that they remain largely speculative and unwitnessed. Current knowledge draws on observations from nuclear detonations, laboratory experimentation, and volcanism, none of which attains the energy levels of large impacts. Melosh (1989) contrasted vapor plumes from smaller impacts (similar to the energy levels of volcanism and nuclear explosions) and larger “atmospheric blowout” impacts; Bosumtwi’s 10.5-km-diameter crater was considered to be the known minimum limit for the formation of atmospheric blowout plumes. The Tookoonooka impact, at ~66 km diameter, would thus theoretically be well beyond the realm of volcanic energy

scales. Volcanic terminology employs arbitrary size criteria that seem irrelevant for impact debris when considering these vastly different scales of energy and mechanisms at play. However, this terminology has been used in some impact literature in lieu of a comprehensive compilation on the size ranges and distribution of “impact pyroclasts.” Volcanic terminology has also been used where no nomenclature equivalents exist for the impact realm. The relevant nomenclature to this paper draws from both volcanology and impact geology and is summarized next.

Impact terminology (e.g., Stöffler and Grieve, 2007; French, 1998; Melosh, 1989) is evolving as the understanding of impact mechanisms and their effect on rock characteristics improves. “Impactite” is a collective term for all impact-metamorphosed rocks, including shocked rocks, impact breccia, and melt rocks (French, 1998; Stöffler and Grieve, 2007).

“Pyroclastic,” by definition, refers to rock materials or particles that are volcanic or explosive in origin (Neuendorf et al., 2005). Fisher and Schmincke (1984) defined pyroclastic rocks as being composed of fragments that originate from volcanic eruptions. They differentiated between two main types of eruptions: those caused by expansion of gases initially contained within the magma (thus pyroclastic or magmatic eruptions), and those caused by vaporization of abundant external water in contact with hot magma or lava (hydroclastic eruptions). I believe that this distinction also has bearing on the pyroclastic-like rocks

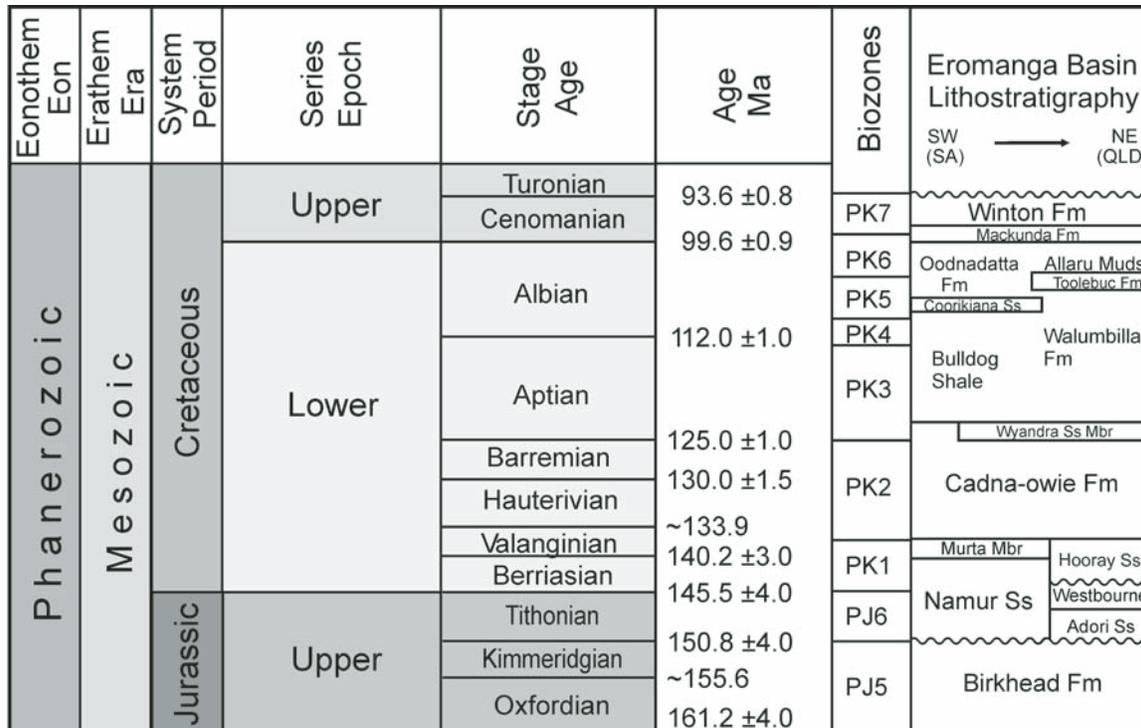


Figure 2. Stratigraphic context of the Tookoonooka impact. Previous estimates have put the impact timing between 112 and 133 Ma. This author constrains the timing to 125 ± 1 Ma at the Barremian-Aptian boundary. Stratigraphic chart is after Gradstein et al. (2004), the 2009 International Stratigraphic Chart, Price (1997), Draper (2002), and Gallagher et al. (2008).

originating from impact processes. Pyroclasts may include lithic, melt-derived, and accretionary clast types.

“Impactoclast” has been recently defined (Stöffler and Grieve, 2007) as a “rock fragment resulting from impact-induced comminution of rocks. It may display variable degrees of shock metamorphism.” By this definition, it is applicable only to impact-derived lithic fragments, and it is not the impact equivalent of a volcanic pyroclast.

Pyroclastic materials between 2 and 64 mm in size are termed “lapilli,” whereas clasts that exceed the 64 mm limit are termed “bombs” and “blocks.” Neuendorf et al. (2005) specified that lapilli may be either solidified or still viscous when they land, and thus they have no characteristic shape. However, various shapes of glassy aerodynamic bombs were described by Macdonald (1972).

“Lapillistone” is defined as lithified accumulations of lapilli containing greater than 75% lapilli (Fisher and Schmincke, 1984).

“Accretionary lapilli” are a special type of lapilli-sized particle that form predominantly in eruption clouds from the aggregation of moist ash. Mechanisms of formation may also include rain falling through dry eruption clouds (Fisher and Schmincke, 1984) or agglomeration of particles within laterally expanding, turbulent wet ash clouds associated with base surges (Fisher and Waters, 1970; Schmincke et al., 1973; “ground clouds” of Schumacher and Schmincke, 1991) or by rain drops and grains rolling downslope through fresh ash deposits (Reimer, 1983a). They were defined by Neuendorf et al. (2005, p. 5) as “spheroidal pellets, mostly between 1 mm and 1 cm in diameter, of consolidated or cemented ash.” For more detailed discussions of the formation, internal structure, and occurrence of accretionary lapilli, see Schumacher and Schmincke (1995, 1991), Gilbert and Lane (1994), and Reimer (1983a). They are primarily thought to be formed by the accretion of ash around particles (or nuclei) in a turbulent volcanic plume or ash cloud with high moisture content. In impact terms, they would be formed in the impact vapor plume by accretion and adhesion of grains, and could likely exhibit much larger size ranges than noted for volcanic clasts given the energy scale contrast between volcanism and impacts.

Reimer (1983a) distinguished between two predominant types of accretionary lapilli that have been observed forming in modern volcanic environments (type A and type B; Table 1). Type A includes moist mud balls or irregularly shaped aggre-

gates that often deform and flatten into mud cakes upon impact with the ground. Type B pertains to compact, brown, dry pisolites, which usually exhibit a concentrically banded outer zone (“coating”). Reimer attributed their brown color to a possible enrichment of ferrous minerals, which has been observed in examples from the ancient rock record. A subordinate type C was also recognized: spherical or roller-shaped clasts restricted to the vicinity of the volcano, where clasts accrete by rolling downslope through fresh ash.

Accretionary lapilli have been recognized in association with a number of impact events worldwide, including the Ries (Graup, 1981; Newsom et al., 1990), Alamo (Warme et al., 2002; Morrow et al., 2005), Sudbury (Addison et al., 2005), Popigai (Masaitis, 2003), Chicxulub (e.g., Alegret et al., 2005; Pope et al., 1999; Salge et al., 2000), and Bosumtwi (Koeberl et al., 2007; Petersen et al., 2007). Typical characteristics of impact-produced accretionary lapilli include concentric zonation (rims or crusts, mantles, and nuclei or cores), inclusions of lithic rock fragments or grains (which may have shock features), a fining-outward texture, and a spherical to subspherical shape. Impact-derived accretionary lapilli may also exhibit geochemical anomalies suggesting a meteoritic signature (e.g., Chicxulub: Salge et al., 2000). Pope et al. (1999) described an accretionary block originating from the Chicxulub impact that is 4.5 m in diameter, which attests to the energy-scale difference between impacts and volcanism; Gilbert and Lane (1994) predicted maximum volcanic accretionary lapilli sizes of 20 mm. For clarification, this discussion will use the same terminology as Warme et al. (2002), i.e., “crust” for the outer rim or shell; “mantle” for the main body of the lapilli consisting of accreted particles; and “nucleus” where an inner core is present.

“Armored lapilli,” a variety of accretionary lapilli exclusive to hydroclastic deposits as defined by Fisher and Schmincke (1984), contain crystal- or rock-fragment nuclei coated by rinds of fine to coarse ash. In volcanic deposits, they range in diameter from 3 mm to 10 cm or more, depending somewhat on the size of the nucleus. For these clasts to form, the presence of abundant water or vapor is necessary for the cohesion of a plastered rim of wet ash on solid nuclei. In hydroclastic deposits, a second unusual type of accretionary clast has also been observed: flattened lapilli- to bomb-size clasts composed entirely of ash without cores. These are interpreted to have been sticky and wet “blobs” of ash when deposited (Fisher and Schmincke, 1984).

TABLE 1. THE TWO MAIN TYPES OF ACCRETIONARY LAPILLI OF REIMER (1983a)

	Type A	Type B
Shape	Spherical to irregular, frequently flattened or deformed	Spherical, compact
Size (diameter)	Several mm up to 15 cm	Modern samples only 1 mm, ancient samples up to 2 cm
Characteristics	Uncoated, moist	Coated, brown, dry
Frequency	Most common in modern volcanic environments	Most common in ancient rocks (better preserved)

Revised Terminology

From these definitions, it is clear that the available terminology falls short on a few points. For one, there is no clear impact analogy for “pyroclast.” Similarly, impact terminology (e.g., Stöffler and Grieve, 2007) currently excludes clasts of an accretionary nature and their lithified counterparts: impact-derived accretionary lapilli are not a subset of impactoclasts by current definition, nor can lapillistone be regarded as an impactite, as accretionary clasts are not strictly shock-metamorphosed or fragmented. No singular term in the impact realm refers collectively to lithic fragments, melt clasts, and accretionary particles (Table 2). The application of volcanic terminology and volcanic environments of formation to impact-generated “pyroclasts” seems loosely applicable, and yet the use of pyroclastic terms (e.g., impact pyroclasts, accretionary lapilli, bombs) for many connotes volcanic origin, and this breeds confusion. Furthermore, impact geology’s discovery and documentation of impact “pyroclasts” is still in its infancy, and impact processes will likely be found to form a number of types of “pyroclasts” not seen in the volcanic realm.

Another problem is that volcanic terminology (e.g., ash, lapilli, bombs, and blocks) follows arbitrary size criteria, assumed to be somewhat based on size distributions of volcanic debris. Such terms seem problematic and extraneous when considering the immensely different ranges of rock volumes and energies potentially involved in impact processes and clast creation (compared to volcanism). Until a size classification more relevant to impact materials can be derived, it is suggested that size-based terminology be avoided. Hence, a clean foundation of terminology is required.

In light of these issues, it is proposed that the term “impactoclast” be broadened to clearly include accretionary and melt clasts (in addition to lithic fragments) that are interpreted to be deposited initially by fallback and fallout impact processes. The term could then be used as an umbrella term for all impact-derived clasts and fragments, analogous to “pyroclast.” Subdivisions (Table 2) proposed are simply “lithic impactoclast,” “melt impactoclast,” and “accretionary impactoclast,” the latter

of which would replace the use of (impact-derived) accretionary lapilli. Armored impactoclasts are an accretionary subtype, and melt impactoclasts would have subtypes of existing terminology such as tektites and impact glass. This terminology also eliminates size criteria inherent in volcanic terminology. Under this revised terminology, lapillistone will be referred to as impactoclastic deposits, with indications of clast abundance stated.

METHODOLOGY

Drill cores from 33 wells (15 petroleum wells and 18 stratigraphic wells) in the Eromanga Basin of southwest Queensland and northern South Australia were selected for study based on proximity to the Tookoonooka impact structure or completeness of core sampling. Drill core locations were chosen from: within the crater structure; within the theoretical continuous ejecta blanket limit for Tookoonooka (i.e., within two crater radii; cf. French, 1998); and from more distal locations. The cores were studied in detail macroscopically to determine the distribution, characteristics, and occurrences of impactoclasts across the basin within the interpreted Tookoonooka ejecta. Clasts within this ejecta were compared to clasts in the crater fill in core from the Thargomindah-3 stratigraphic well. Petrographic microscopy was used to analyze impactoclasts in finer detail.

An electron microprobe and scanning electron microscope (SEM) were employed to confirm geochemical trends within thin sections, and specifically within accretionary impactoclasts. A Cameca SX51 electron microprobe (with a Gresham ultrathin window energy dispersive spectrometer [EDS] detector and four wavelength dispersive spectrometer [WDS] detectors) was used at Adelaide Microscopy at the University of Adelaide. The microprobe was operated at a 15 kV accelerating voltage, 20 nA beam current, and 40° take-off angle, and utilized Astimex and Cameca international mineral standards. Standard PAP ZAF corrections were used. Average detection limits for Mg, Al, Si, K, Ca, Ti, and S were better than 500 ppm; Fe, Na, Co, and Ni were under 600 ppm; Mn was better than 1000 ppm; and Cu and Zn were under 1200 and 2000 ppm, respectively.

TABLE 2. COMPARISON OF VOLCANIC AND IMPACT TERMINOLOGY FOR DIFFERENT CLAST TYPES

Types of clast	Volcanic terminology*	Impact terminology	
	Pyroclasts	Current [†]	Proposed
		Clasts of impact origin [§]	Impactoclasts
Lithic fragments	Cognate/accessory or accidental ash, lapilli, or bombs	Impactoclasts	Lithic impactoclasts
Melt clasts	Essential/juvenile ash, lapilli, or bombs	Impact melt clasts, impact glass, tektites, and possibly highly shocked impactoclasts	Melt impactoclasts Subtypes: tektites, etc.
Accretionary clasts	Accretionary lapilli	Accretionary lapilli [#]	Accretionary impactoclasts Subtype: armored impactoclasts

Notes: Pyroclasts are subdivided by grain size: ash consists of particles <2 mm, lapilli are fragments 2–64 mm, and bombs/blocks are >64 mm.

*Volcanic terminology cf. Fisher and Schmincke (1984), Fisher (1997), Macdonald (1972). Terms may vary depending on interpreted origin of the clasts.

[†]Current impact terminology (cf. Stöffler and Grieve, 2007).

[§]There is currently no collective term to refer to all clasts of impact origin.

[#]“Accretionary lapilli” is not included in Stöffler and Grieve (2007) but has been used in some impact literature.

The SEM used was a Philips XL30 instrument at Adelaide Microscopy (operating a field emission electron gun at 1–30 kV). Backscattered electron (BSE) images were recorded at 15 kV, with a spot size of 5 units.

RESULTS

Of the 33 wells studied, the drill cores from 24 (Fig. 1) contain good examples of clasts interpreted to be impactoclasts. In other wells, their presence was less obvious, either due to the finer-grained nature or more distal location of the deposits, the degree of alteration, or the integrity of the core. In all cases, the base of the Wyandra Sandstone marks the first appearance of these unusual clasts in the sedimentary basin; no such clasts exist below this unit in the finer-grained sediments of the Cadna-owie Formation. The following sections will describe the characteristics (macroscopic, microscopic, and geochemical), occurrences, and distribution of these impactoclasts in the wells studied.

Characteristics of the Tookoonooka Impactoclasts

In Thargomindah-1, within two crater radii of the center of the Tookoonooka structure, rimmed, elongate, light-brown clasts of very fine-grained material up to 2.2 cm in length were observed in a breccia-conglomerate layer at the base of the Wyandra Sandstone (705.08 m; Fig. 3A). Another layer at ~704.5–704.6 m contains larger clasts up to 5 cm in apparent diameter, the largest of which is subspherical and concentrically zoned with no apparent nucleus, and exhibits dark-colored aerodynamic flanges on its outer crust (Fig. 3B). These were the first clasts of their kind discovered outside the crater, and they are interpreted to be impactoclasts. Similar clasts are present at the same stratigraphic position across the basin. Overall, the impactoclasts exhibit the characteristics listed in Table 3, but various sizes and shapes are detailed in Table 4, Figure 4, and Figure 5.

The most distinctive examples of melt impactoclasts observed exhibit a dark red-brown-purplish color. Larger examples show some of the classic aerodynamic shapes described from volcanic environments (e.g., Macdonald, 1972): Figure 4B (clasts marked “mi”) shows ribbon-shaped melt impactoclasts; Figures 4C and 4E show examples of fusiform shapes, and Figure 5F shows an example of a drop shape. Overall, the melt impactoclasts appear to be heavily altered. White, glossy, speckled mineralization is interpreted to be zeolite alteration, or kaolinization of vesicular fill material within melt components. These textures are apparent within the centers of clasts in Figures 4C, 4F, 4H, and 5A.

A large portion of the impactoclasts observed is interpreted to be accretionary impactoclasts that exhibit the following range of characteristics:

- generally tan to light-brown in color;
- massive *or* concentrically zoned, many of which appear in hand sample to lack nuclei;
- fining outward with very fine-grained outer crust (when concentrically zoned);

- may be armored;
- nuclei may be discrete melt clasts, lithic fragments, or accretionary clasts;
- consistently rounded to subrounded (few angular or broken clasts are observed);
- pervasive alteration: clay and carbonate rich;
- various degrees of accretionary complexity: variability in crustal development (i.e., concentric zonation), mantle thickness, and types of nuclear clasts;
- apparent diameters in core: commonly <1.5 cm, maximum 9 cm;
- apparent shapes: subspherical through ellipsoidal (e.g., Fig. 4F) and elongate shapes are most prevalent, though irregular (e.g., Fig. 4G) and aerodynamic forms (fusiforms, e.g., Fig. 3B; drops, e.g., Fig. 4H; and almonds, e.g., Fig. 5A) are also present; and
- inclusions of quartz and feldspar grains within the mantles.

Examples in Figures 4A and 4B (clast labeled “ai”) are more classic forms of accretionary clasts. They are light brown-gray, spherical to subspherical, and have well-formed nuclei. Nuclei are relatively coarser-grained than the mantles. The example in Figure 4B has an off-center, ovate nucleus. The accretionary impactoclast in Figure 4D is similar to these clasts, but is slightly flattened, larger (3.75 × 2.25 cm), and has a flattened accretionary nucleus. The shape of the nucleus appears to be primary, as the degree of flattening of the impactoclast cannot account for the thinness of the nucleus.

Both the A and B accretionary clast types of Reimer (1983a; Table 1) have been observed, as well as gradations; type A is predominant in an elongate form, though concentric layering may be more prevalent than this type implies. As much of the concentric layering is often only obvious microscopically, the abundance of zoned or coated clasts cannot be accurately estimated. Quantification of the absence of nuclei was not attempted here; however, the sheer number of accretionary impactoclasts without apparent nuclei indicates that a portion of these are non-nucleated types. Irregularly shaped, massive varieties are interpreted to have formed as mushy, sticky wet ash “blobs” as described from hydroclastic deposits by Fisher and Schmincke (1984) or the “irregular-shaped aggregates” of Reimer (1983a). These represent the largest observed accretionary clasts. An example is shown in Figure 4G, which has an apparent diameter of 9 cm.

In Thargomindah-3, within the crater fill, similar impactoclasts were observed within the “diamictite” zone (for Thargomindah-3 stratigraphy, see Young et al. [1989]). Accretionary impactoclasts in this drill core have compact aerodynamic shapes (subspherical and lozenge shapes). Various melt and lithic clasts have thin accretionary outer layers and are thus the armored variety of accretionary impactoclasts. Figures 5A–5G show a range of impactoclasts observed in Thargomindah-3; all clasts except for the example in Figure 5F are armored. The clasts in Figures 5A and 5G bear a strong resemblance to the clasts in Figures 4F and 4H. Armored impactoclasts, particularly the lithic nuclei type, are more common in this core than outside the

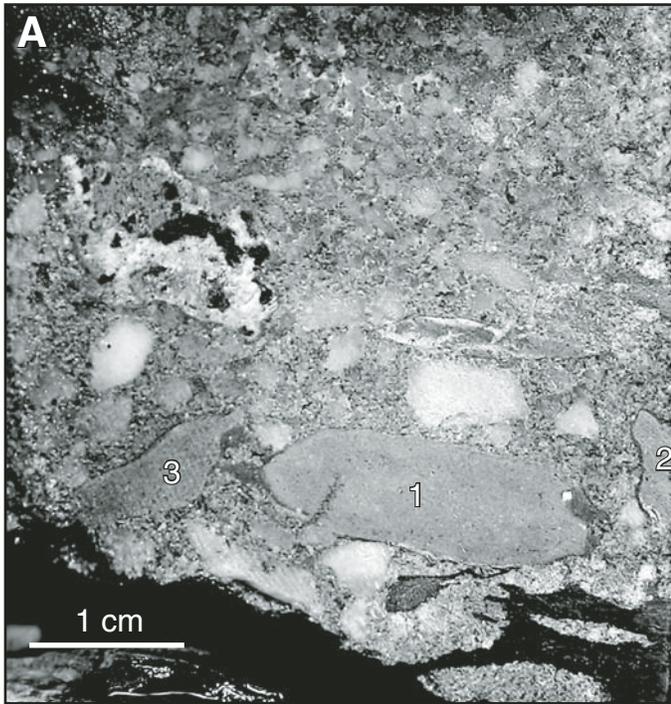


Figure 3. (A–B) Breccia-conglomerate layers in the Wyandra Sandstone of Thargomindah-1 drill core containing accretionary impactoclasts. (A) Basal 5 cm of the Wyandra Sandstone, showing at least three tan-light brown accretionary impactoclasts, the largest of which is elongate and 2.2 cm in length. (B) Three views of a large, light-brown fusiform accretionary impactoclast with concentric zonation and aerodynamic dark gray flanges. Clast is 5 cm in apparent diameter.

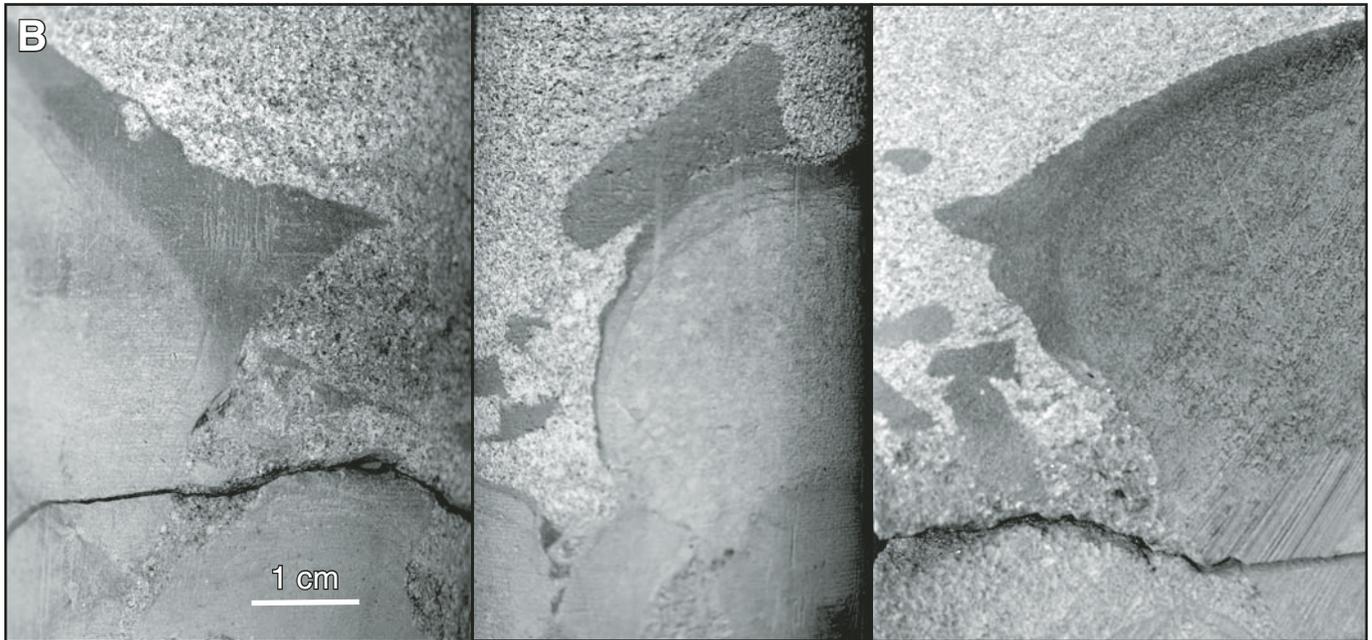


TABLE 3. CHARACTERISTICS OF TOOKOONOOKA MELT AND ACCRETIONARY IMPACTOCLASTS

Characteristic	Observations
Type	A wide range of interpreted impactoclasts, including accretionary and armored
Abundance	Macroscopically, accretionary impactoclasts without distinct nuclei are most common, followed by melt impactoclasts
Size*	Commonly <1.5 cm, maximum 9 cm (but may be much larger)
Shapes	Various: subspherical, elongate to ellipsoidal, irregular, and aerodynamic forms (e.g., fusiform, almond and lozenge shapes, drop shapes, and ribbon shapes; cf. Macdonald, 1972)
Alteration	Pervasive: clay and carbonate rich; probable zeolite in the melt components

*Size refers to apparent diameter of clasts in drill core. Most cores are 4.8 cm in width and thus larger clast sizes cannot often be differentiated and measured; as a result, maximum clast size may be much larger than indicated.

TABLE 4. OCCURRENCE OF TOOKOONOOKA ACCRETIONARY AND MELT IMPACTOCLASTS OBSERVED IN DRILL CORES ACROSS THE EROMANGA BASIN

Well name	Approximate distance from Tookoonooka (Rc*)	Impactoclast shapes ¹ observed (not exhaustive) in drill cores	Comments	Example figure number
Thargomindah-3	< 1 Rc	Immature fusiform, subspherical, almond, elongate/flattened, possible ribbons, irregular, drops	Some impactoclasts exhibit flanges. Lithic and melt nuclei common. Occurrence of accretionary impactoclast bed.	Fig. 5
Ipundu-6	< 2 Rc	Elongate, subspherical, fusiform	-	-
Ipundu North-1	< 2 Rc	Elongate	-	-
Kercummurra-1	< 2 Rc	Elongate, subspherical, irregular	Mostly small (<1 cm)	-
Talgeberry-1	< 2 Rc	Elongate, subspherical, possible ribbon fragments	Abundant small impactoclasts (cm-scale)	-
Talgeberry-2	< 2 Rc	Elongate, almond, irregular, possible ribbon	-	-
Tarbat-6	< 2 Rc	Elongate, subspherical/ovate	Small (1 mm to 1 cm), predominantly kaolinized	Fig. 7B
Tarbat-8	< 2 Rc	Elongate	-	-
Thargomindah-1	< 2 Rc	Elongate, subspherical, fusiform, irregular without apparent nuclei	-	Figs. 3, 8
Thargomindah-2	< 2 Rc	Ovate, elongate, irregular, drop, subspherical, almond	-	Figs. 4F, 4H
Tintaburra-2	< 2 Rc	Subspherical, elongate, irregular	-	-
Eromanga-1	< 4 Rc	Irregular without apparent nuclei, fusiform, possible cow-dung, almond, elongate, drops, subspherical	-	Fig. 4G
Bulloo-1	< 5 Rc	Ribbons, spherical, subspherical, immature fusiform, elongate, almond	Some nuclei are flattened. Some nuclei are accretionary clasts. Occurrence of accretionary impactoclast bed.	Figs. 4A, 4B, 4D, 6B, 7A, 7D
Tickalara-1	< 5 Rc	Immature fusiform, irregular, subspherical, elongate	-	-
CBH-2	> 5 Rc	Elongate	-	-
Connemara-1	> 5 Rc	Irregular, immature fusiform, subspherical, elongate, possible ribbons and drops	-	-
Jundah-1	> 5 Rc	Melt ribbon, elongate, subspherical, fusiform, almond	-	Fig. 7C
Machattie-1	> 5 Rc	Fusiform, ribbons, elongate, ovate	Sparse	Fig. 4E
Mirintu-1	> 5 Rc	Irregular, fusiform, elongate, subspherical	-	Fig. 4C
Quilpie-1	> 5 Rc	Irregular without apparent nuclei, elongate, irregular, subspherical	-	-
SPH-1	> 5 Rc	Elongate	Rare, small (<1 cm)	-
Tambo-2	> 5 Rc	Subspherical	Very small (mm-scale), kaolinized	-
Tambo-4	> 5 Rc	Elongate	-	-
Wyandra-1	> 5 Rc	Spherical, subspherical, elongate, irregular	Occurrence of accretionary impactoclast bed.	Fig. 6A

Notes: Drill cores are from both Queensland and South Australia government core libraries, and include stratigraphic, petroleum, and mineral wells. Occurrences are all within the Wyandra Sandstone Member. "n" indicates not applicable.

*Rc - Crater radii. Tookoonooka original crater diameter is estimated at 66 km; therefore 1 Rc = 33 km, from the crater center to the crater rim.

¹Shapes cf. Macdonald (1972) for pyroclastic lapilli and bombs.

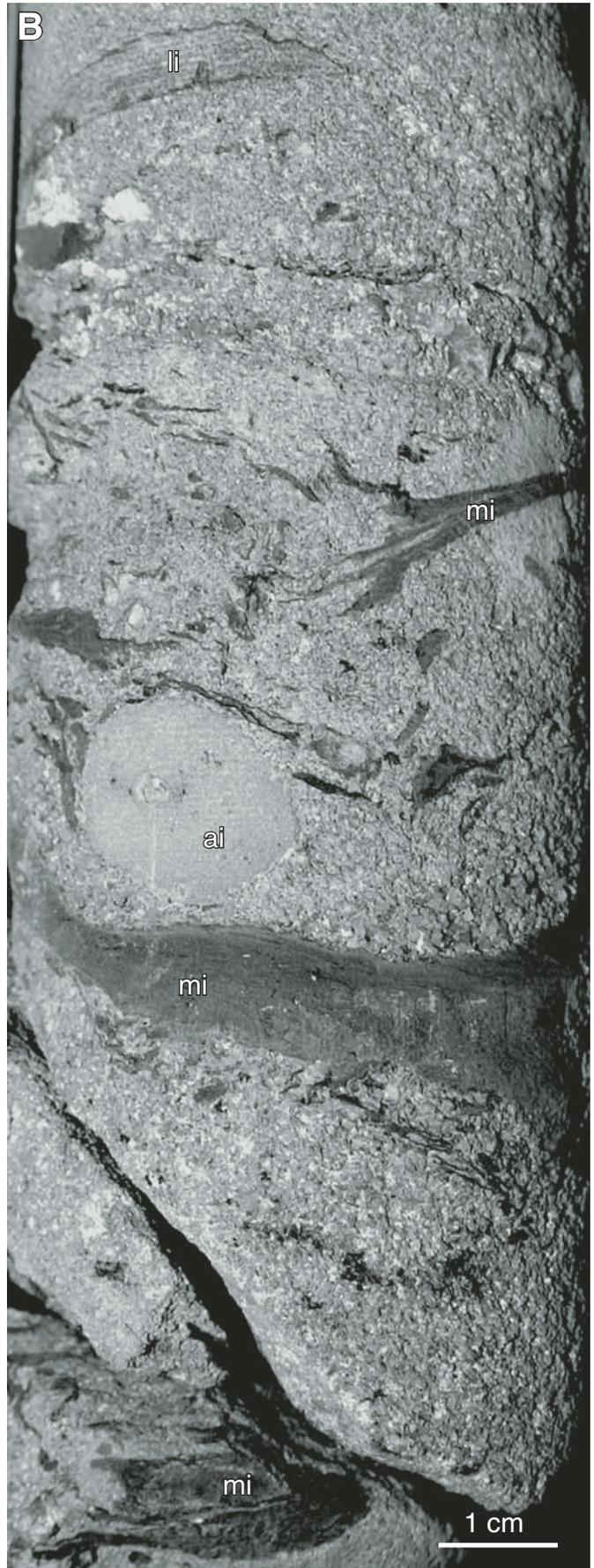
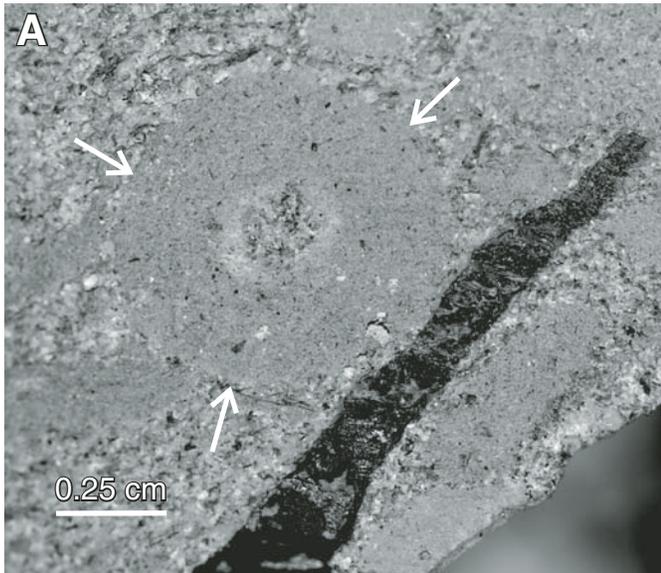


Figure 4 (continued on following pages). (A–H) Variety of shapes, types, and occurrences of Tookoonooka accretionary and melt impactoclasts in drill core across the Eromanga Basin. Arrows indicate extent of outer crust. (A) Accretionary impactoclast in clast-supported bed in Bulloo-1. Clast is 0.75 cm in apparent diameter. Crust is not obvious at this scale. Thin, dark clast beside impactoclast is a coal fragment. Other accretionary impactoclasts of the same color as the mantle of the larger example (but elongate and without nuclei, 1 cm or less in length) are also visible. (B) Accretionary impactoclast (ai) in Bulloo-1, ~1.5 cm in apparent diameter. Clast was deposited with a number of ribbon-shaped impactoclasts (mi; probably of altered melt compositions) and lithic impactoclasts (li).

crater structure. The armored types with green lithic nuclei (e.g., Fig. 5C) are of special note because the green clasts are identical to the metasedimentary basement rock observed at total depth in Thargomindah-1, which should resemble the presumed base of the target rock sequence. The nucleus of the clast in Figure 5E is also metasedimentary (quartzite).

Accretionary impactoclastic deposits occur in a few isolated beds (± 15 cm thick) in Thargomindah-3, Bulloo-1, and possibly Wyandra-1 (Figs. 6A–6B). In Bulloo-1, the proportion of accretionary impactoclasts in a 13-cm-layer deposit is $\sim 77\%$ of the rock. In these deposits, accretionary impactoclasts are mostly elongate, flattened, and subspherical shapes 1 cm or less in

length. Many do not exhibit obvious nuclei or crusts macroscopically. Clasts are often imbricated.

Occurrence and Distribution

Impactoclasts as described here occur within and outside of the crater structure (Table 4). Outside of the crater structure, they occur in a wide range of sedimentary contexts, from gravel and pebble breccia-conglomerate layers with high lithic content to rare accretionary impactoclastic deposits to “floating” within fine- to coarse-grained (usually planar-bedded or massive) sandstones. Accretionary impactoclasts, often occurring with

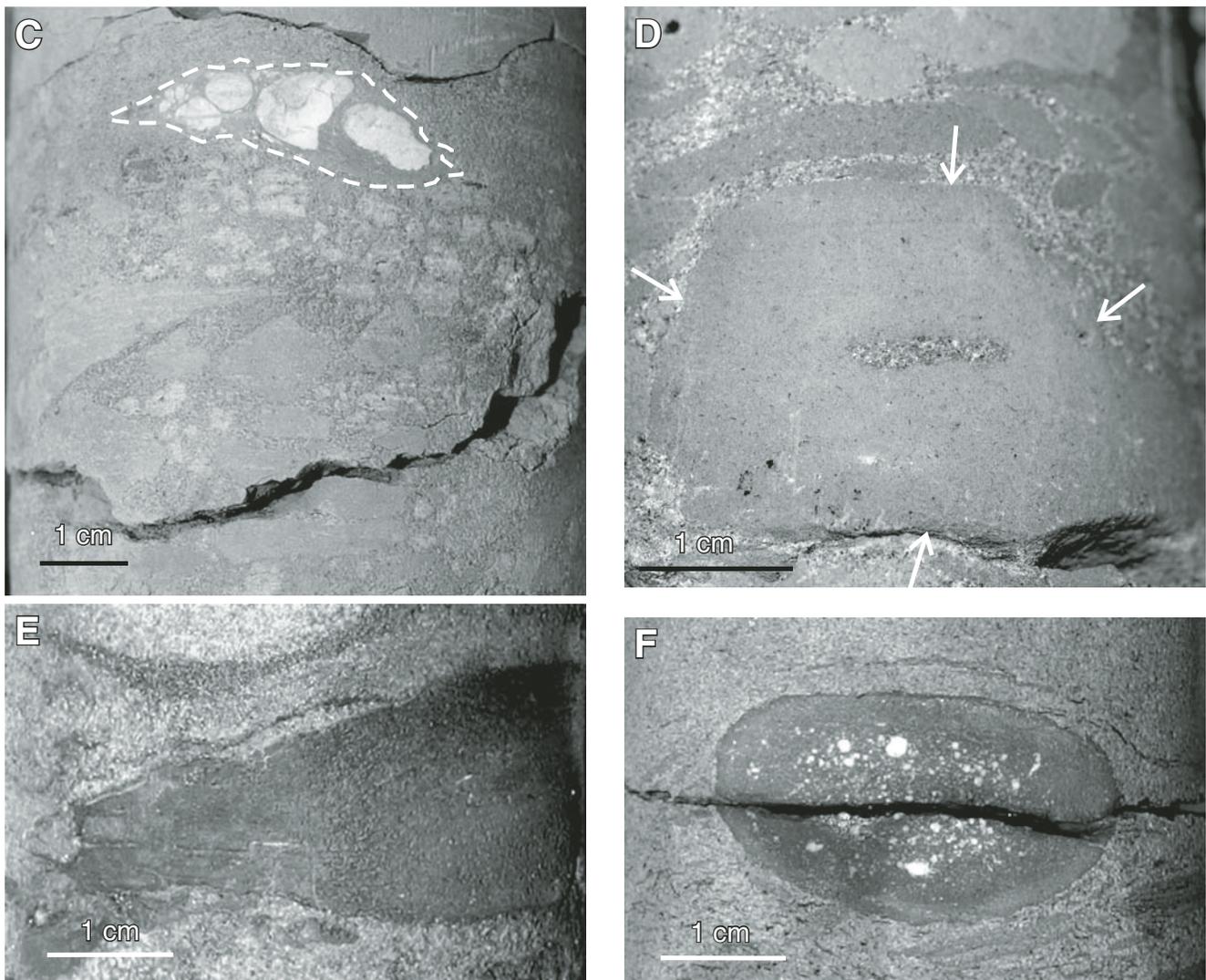


Figure 4 (continued). (C) A reddish-brown, fusiform, melt impactoclast (indicated by dashed line) deposited with accretionary and lithic impactoclasts within breccia-conglomerate in Mirintu-1. The clast is 3.3 cm in length and exhibits flow texture and likely altered, filled vesicles. (D) Accretionary impactoclast within accretionary impactoclastic bed in Bulloo-1. A subtle, darker-gray crust is visible. (E) Dark reddish-brown part of a fusiform melt impactoclast, from Machattie-1. (F) Ellipsoidal armored impactoclast, 3.5 cm in width, with an altered red-brown melt clast nucleus. Melt is likely partially altered to zeolite (glossy white specks). Thin crust is light-brown.

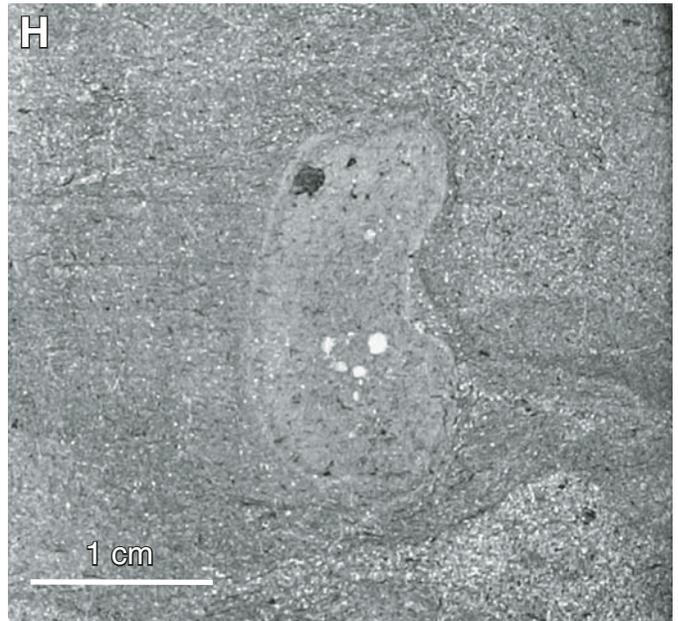


Figure 4 (*continued*). (G) Large, light-brown, extremely fine-grained, amorphous accretionary impactoclast from Eromanga-1 with no visible nucleus or crust. (Note: lineations on clast are not internal bedding features but are a mechanical relic of drill-coring.) Note imbricated accretionary and lithic impactoclasts deposited below. (H) Light-brown impactoclast from Thargomindah-2 similar to F with melt nucleus and crust, but drop/bean-shaped, ~2 cm in length.

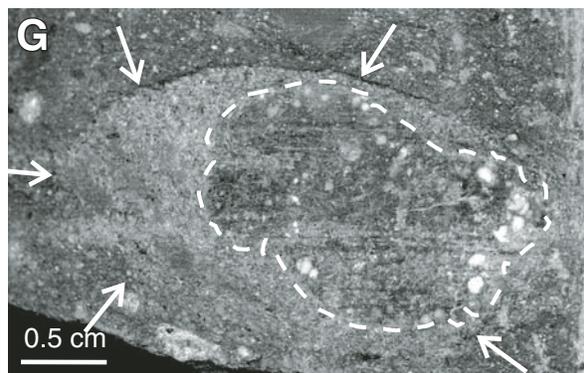
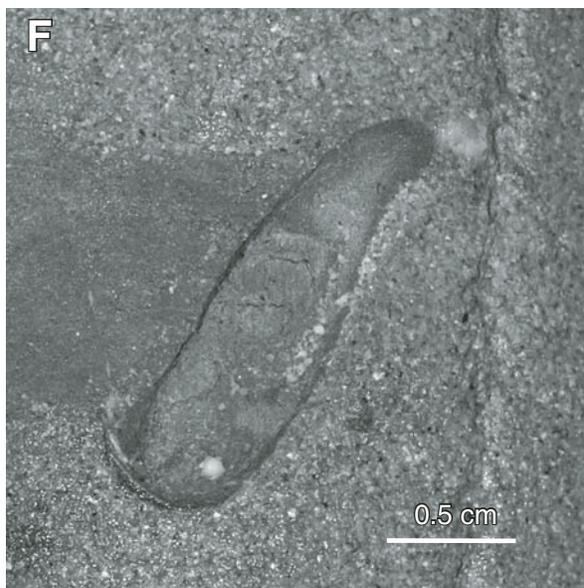
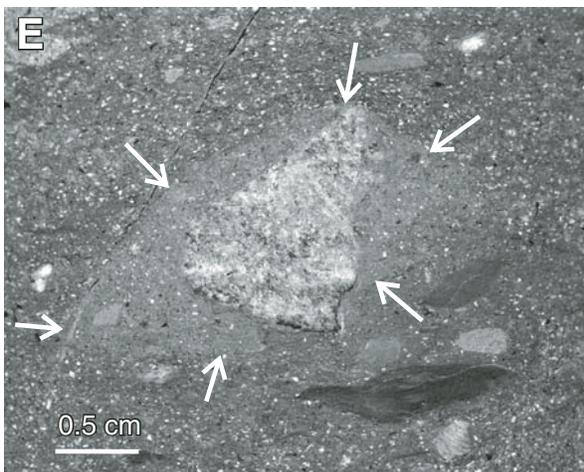
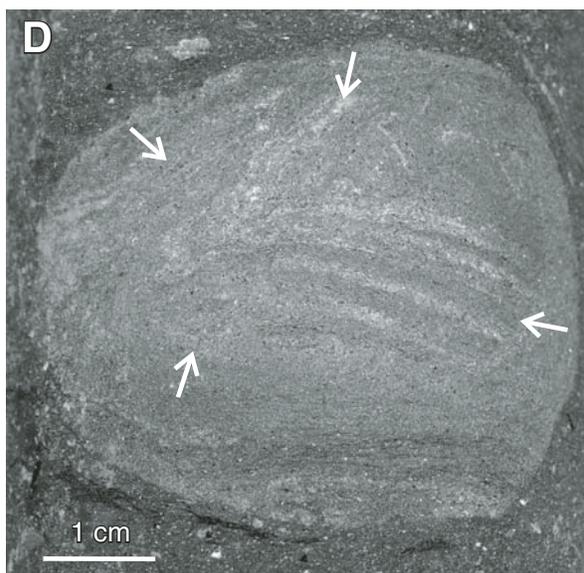
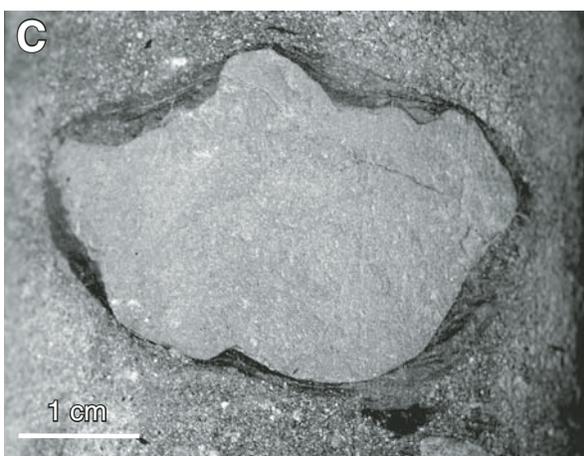
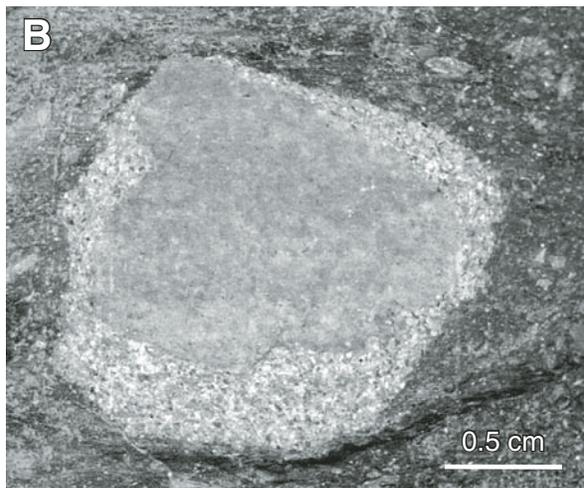
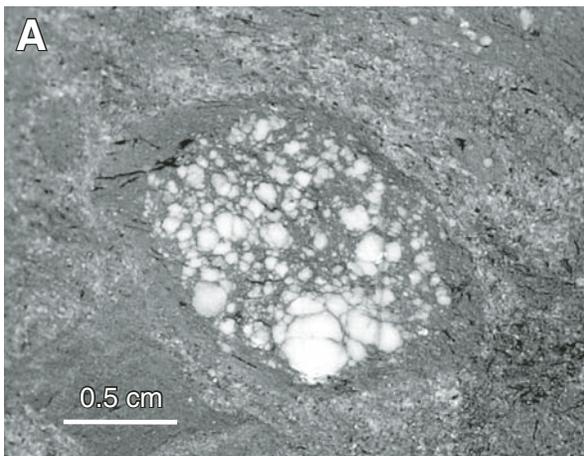




Figure 6. (A–B) Examples of accretionary impactoclastic deposits observed in drill core. (A) Clay-rich Wyandra-1 core. Accretionary impactoclasts are mostly light-brown. Note imbrication in this sample showing flow direction from right to left. (B) Bulloo-1 core. Accretionary impactoclasts are mostly light-gray-beige in color, with some light-brown and medium-gray. Of particular interest is bidirectional imbrication of the clasts in this core sample, implying changing flow directions during deposition.

←
Figure 5. (A–G) Tookoonooka impactoclasts in drill core from Thargomindah-3 (within the crater fill). Most are examples of armored impactoclasts. (A) Almond-shaped armored impactoclast with altered red-brown melt clast nucleus (likely altered to zeolite). Thin accretionary crust is light-brown. (B) Irregular to subspherical armored impactoclast with light-brown melt clast nucleus and thin accretionary light-brown crust. (C) Subellipsoidal-shaped armored impactoclast with light-green-blue lithic fragment nucleus. Thin veneer of concentric layered crust is dark-brown. (D) Subspherical, armored impactoclast with sedimentary or metasedimentary lithic nucleus showing deformed bedding (arrows indicate extent of nucleus). Accretionary crust is tan-light-brown. (E) Almond-shaped armored impactoclast with lithic fragment nucleus (likely from metasedimentary basement rock). Accretionary crust is light-brown. Arrows indicate extent of outer crust. (F) Red-brown, drop-form melt impactoclast. (G) Subellipsoidal-shaped armored impactoclast with altered red-brown melt clast nucleus (indicated by dashed line). Accretionary crust is tan-light-brown (arrows indicate extent of outer crust).

ellipsoidal and elongate shapes, tend to be imbricated (up to sub-vertical orientations) in clast-supported deposits and oriented bed-parallel in planar-bedded deposits. Thus, they appear to have survived high-energy reworking processes intact.

Proximal locations to Tookoonooka have a greater frequency of clast-supported breccia-conglomerates, whereas distal deposits are more commonly matrix supported and more “diluted” regarding interpreted primary ejecta concentrations. While

the base of the Wyandra Sandstone marks the first appearance of these impactoclasts, they are found to occur throughout the Wyandra. Distally-fining trends may also occur: proximal locations that exhibit abundant, predominantly cm-scale accretionary impactoclasts can be compared to radially distal locations with similar, abundant, though mm-scale, clasts.

The presence of the impactoclasts at the same stratigraphic interval in drill cores (Table 4) across the basin equates to some

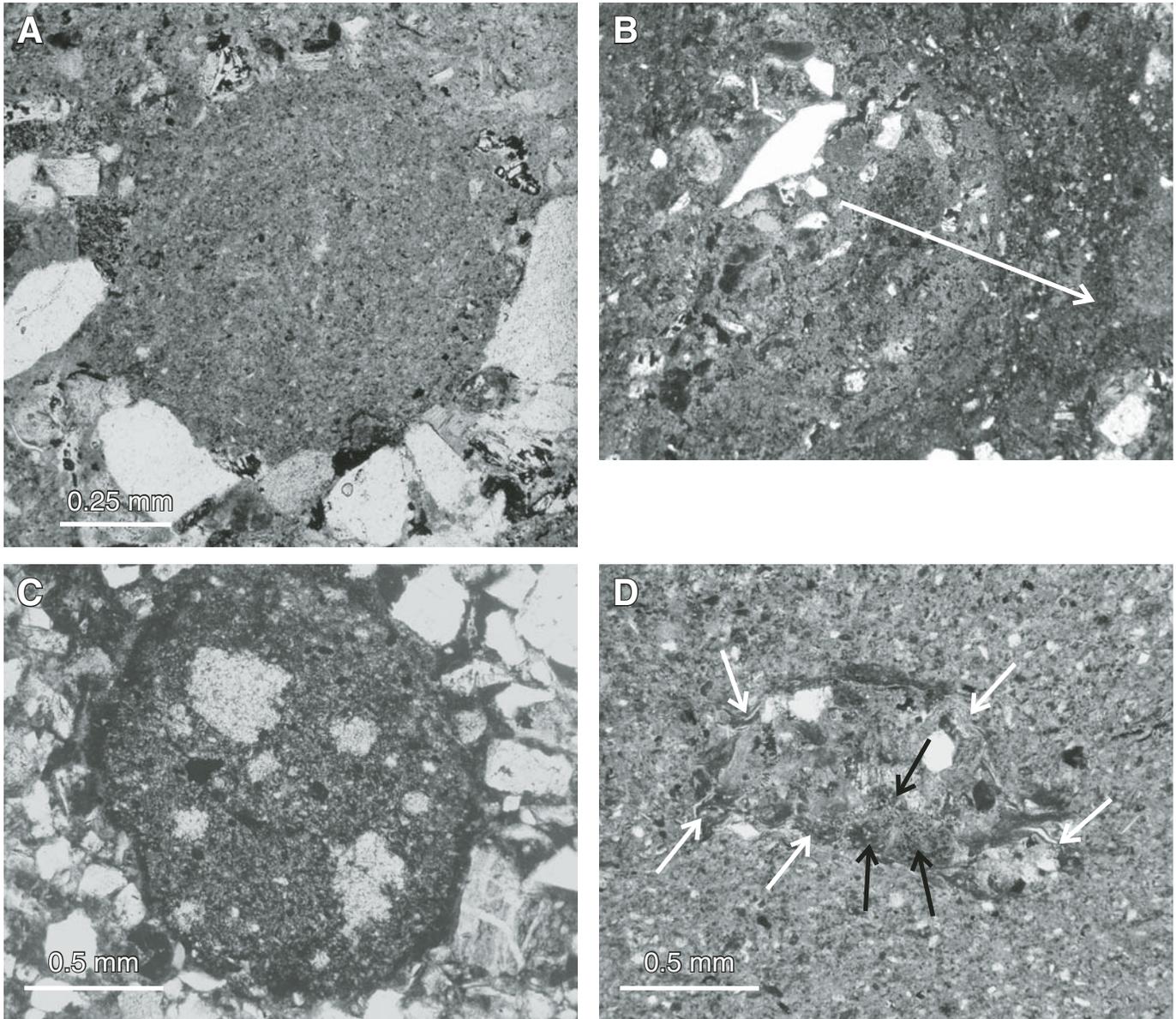


Figure 7. (A–D) Thin section photographs of accretionary impactoclasts. (A) Subspherical, light-brown accretionary impactoclast with no apparent nucleus from Bulloo-1. (B) Detail of a subspherical, brown, 4-mm-diameter accretionary impactoclast from Tarbat-6. Clast exhibits good concentric zonation, and an accretionary nucleus with coarse-grained fragments. Arrow shows direction of fining-outward toward crust. Field of view is 2 mm wide. (C) Subspherical, brown accretionary impactoclast from Jundah-1, with medium-grained altered inclusions within the mantle. (D) Thin section photograph of nucleus of a complex accretionary impactoclast. Nucleus is fusiform shaped, with a melt crust (white arrows). Nucleus contains an agglomeration of altered melt and lithic clasts and mineral grains (black arrows indicate melt clasts). The accretionary impactoclast is brown in color and occurs within an accretionary impactoclastic deposit in Bulloo-1.

375,000 km² of areal extent in central Australia. This correlates roughly to the presumed extent of the Eromanga Basin in the mid-Cretaceous.

Microscopic Characteristics

Petrographic observations reveal that the impactoclasts are more complex than they at first appear in hand sample. Melt clasts

exhibit microscopic flow textures, and dull-colored “mud clasts” with subtle concentric structure or seeming homogeneity in hand sample display marked concentric zonation and fining-outward textures typical of accretionary clasts in thin section (Figs. 7 and 8). In some cases, “ghost” nuclei can only be seen in thin section. Generally, the impactoclasts are heavily altered, appearing to have undergone multiple diagenetic phases: clay, carbonate, goethite, and multiple overgrowths on mineral inclusions are common.

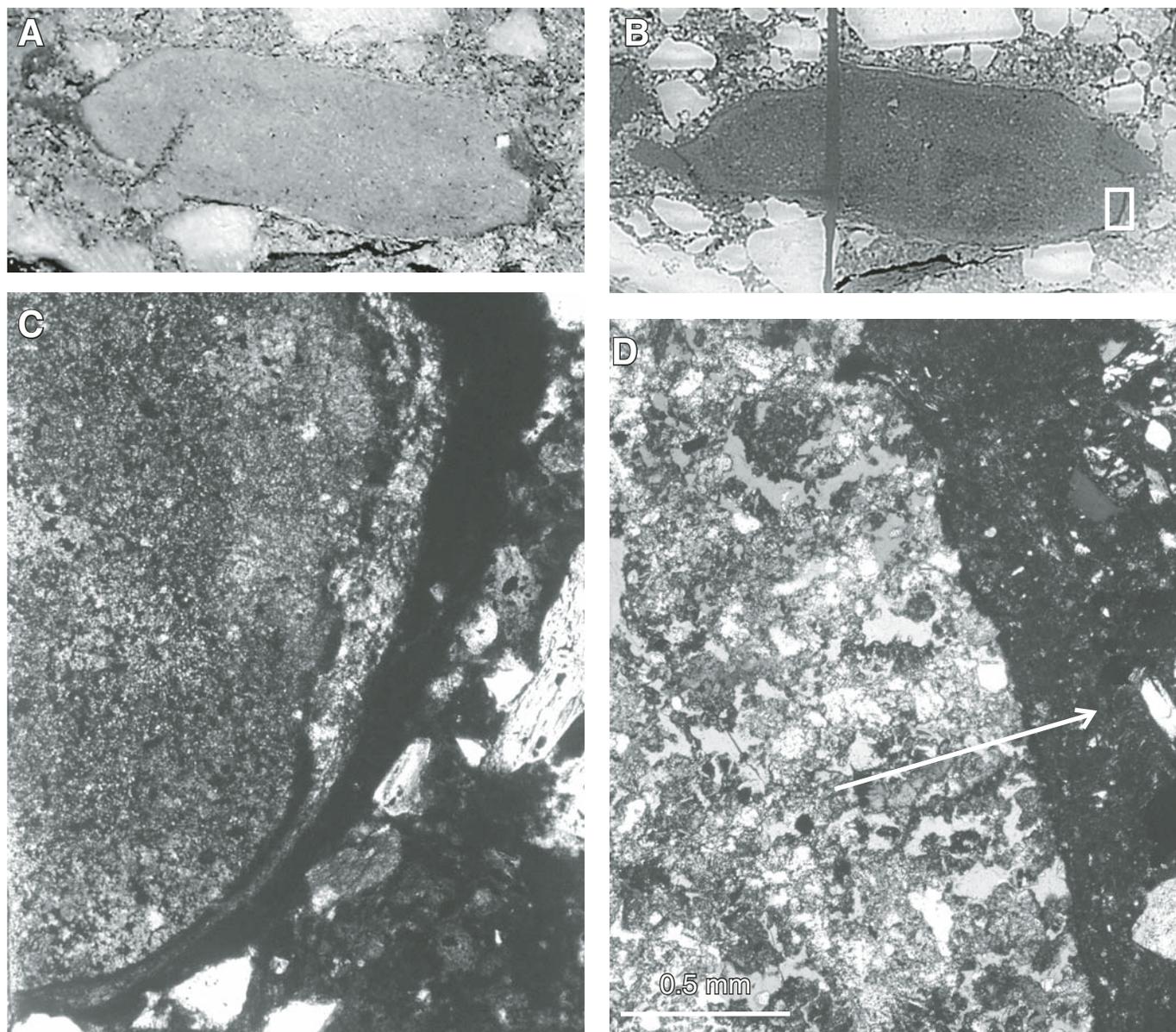


Figure 8 (continued on following page). (A–G) Microscopic analysis of AI#1 from Thargomindah-1. Microscopic characteristics include concentric zonation of crust, complex inclusions, and diagenetic carbonate-rich mantles with poikilotopic matrix. (A) Hand sample view. AI#1 is 2.2 cm in length, and dull light-brown in color. Aerodynamic flanges (dark patches on left and right edges of clast) and concentric zonation are subtle. (B) Thin section view, showing more marked concentric zonation. (C) Detail of lower right corner of clast as indicated in B, showing good concentric structure of crust. (D) Crossed polarizers. Concentric zonation of crust is defined by both fining-outward texture and color variation. Arrow indicates direction from mantle to outer crust.

Microscopically, the crusts of the accretionary impactoclasts are color-banded, implying chemical variability, and they have entrained grains in their outer crusts (e.g., Figs. 7B, 8C, and 8D). The mantles are composed of a largely massive, brownish, carbonate-rich matrix exhibiting poikilotopic fabric under crossed polarizers (Figs. 8D and 8E). Mantles may appear fine grained and homogeneous (e.g., Fig. 7A), or they may exhibit angular inclusions (e.g., Fig. 7C). Accretionary impactoclasts from Thargomindah-1 have fine-grained inclusions of quartz and feldspar (predominantly plagioclase, with rare K-feldspar, both heavily altered) within their mantles; however, the inclusions are complex, with multiple overgrowths. Most of the quartz grains exhibit partially dissolved grain boundaries, which are then enveloped in euhedral quartz overgrowths, which may in turn be overgrown by calcite (Figs. 8F and 8G). The degree of alteration and very fine-grained size of the quartz grains make detection of possible shock features difficult within these clasts. The altered feldspar

inclusions are enveloped in colorless calcite crystal overgrowths. In some cases, pyritic overgrowths are also present. The carbonate and pyrite phases (and likely the euhedral quartz) are interpreted to be the result of multiple stages of postdepositional diagenesis. Although it is clear that these clasts have experienced extensive alteration, the primary accretionary zonation (and in some cases, ghost nuclei) is still apparent beneath the diagenetic overprint.

Other accretionary impactoclasts show complexity within their nuclei. One rare example is spherical, 6.5 mm in diameter, and exhibits an almond- or fusiform-shaped accretionary nucleus enveloped in a fairly uniform accretionary mantle. The nucleus is 1.4 mm across, includes fine-grained melt and lithic particles, and has a flow-textured crust suggestive of melt (Fig. 7D).

Rare spherules (~0.3 mm in diameter) have also been found in thin section (e.g., Figs. 9A and 9B). These are interpreted to be possible devitrified and replaced silicate glass spherules or coated glass spherules (a volcanic example of the latter was noted

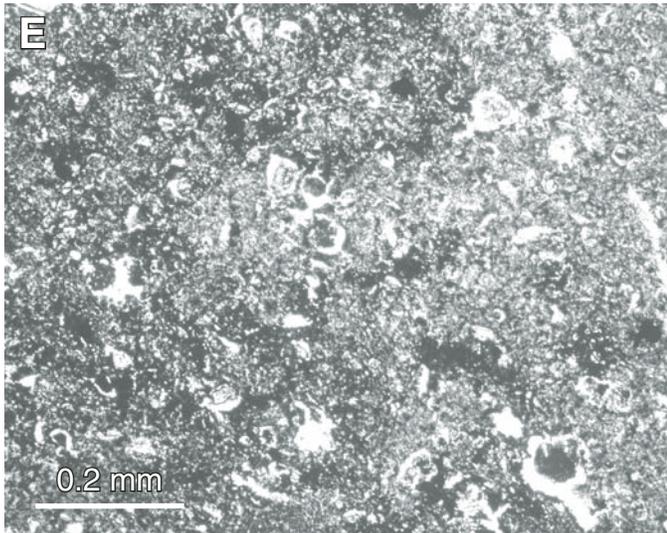


Figure 8 (continued). (E) Crossed polarizers. Massive, brownish poikilotopic matrix of carbonate-rich mantle with numerous complex inclusions. Light-colored crescent shapes are calcite overgrowths on quartz or feldspar grains. (F–G) Extremely fine-grained quartz inclusions within the mantle showing numerous diagenetic stages. Primary quartz grains (q) are partly dissolved then overgrown by euhedral quartz (o). These are enveloped in calcite (c) and sometimes pyrite. F and G are in cross-polarized and plane-polarized light, respectively.

by Reimer, 1983b). The example shown is composed of microcrystalline quartz. A subtle outer rim is visible and is believed to be an original structure rather than a relic of diagenesis. A microprobe transect of the spherule (Fig. 9C) is discussed later herein.

Geochemical Analyses

Electron microprobe analyses of two pebble-sized accretionary impactoclasts (Fig. 10, referred to as AI#1 and AI#2) in a breccia-conglomerate in Thargomindah-1 were conducted to investigate complex inclusions within the mantles, the major element composition and trace elements present, the nature of the chemical differentiation in the concentrically zoned crust, and variability between the two clasts. In total, 108 analysis points (of mantle, crust, nucleus, and inclusions) were taken within the two accretionary impactoclasts. Selected analytical data are presented in Tables 5 and 6.

Analyses of inclusions within the mantles of the accretionary impactoclasts (examples from AI#1 are included in Table 5) confirm petrographic observations that the bulk of the larger accreted grains (within the mantles) was originally quartz and feldspar. BSE images show the pervasiveness of alteration associated with some of these inclusions in AI#1. Figure 11A shows a subrounded feldspar grain with dissolution in the core of the grain. On the left of the grain, there is a remnant of crystalline calcite overgrowth, which has in turn been overgrown and largely replaced with a pyritic envelope. Figure 11B shows another altered grain of albite feldspar (rectangular), which has been partially replaced by mica and carbonate. A thick crystalline calcite overgrowth surrounds the grain, and both the calcite and feldspar are partly replaced by two species of pyrite (light-colored minerals in the image). Figure 11C shows a quartz shard enveloped in a euhedral quartz overgrowth. This grain and two small euhedral apatites (light gray, on the left of the quartz grain) are enclosed in a calcite overgrowth.

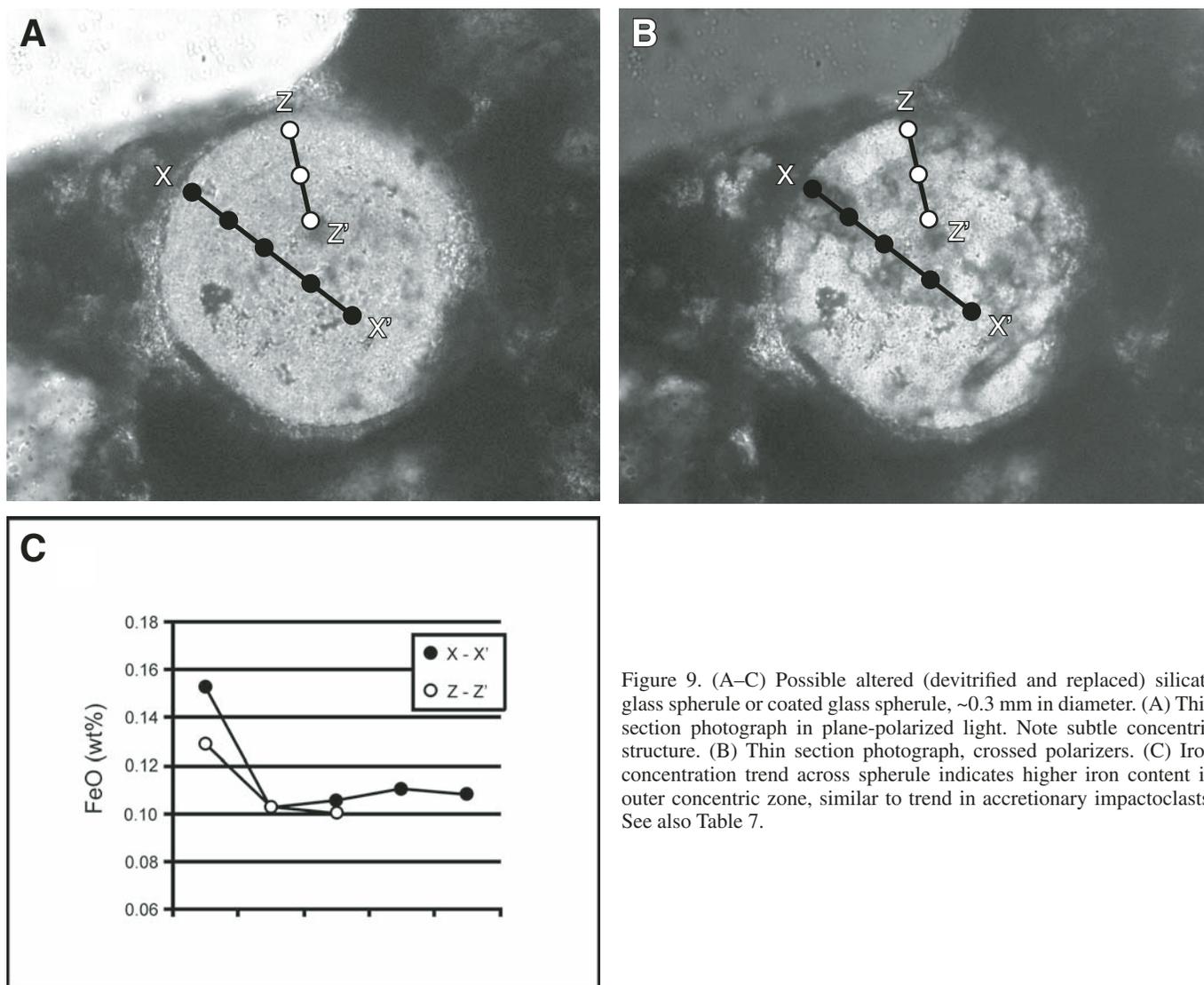


Figure 9. (A–C) Possible altered (devitrified and replaced) silicate glass spherule or coated glass spherule, ~0.3 mm in diameter. (A) Thin section photograph in plane-polarized light. Note subtle concentric structure. (B) Thin section photograph, crossed polarizers. (C) Iron concentration trend across spherule indicates higher iron content in outer concentric zone, similar to trend in accretionary impactoclasts. See also Table 7.

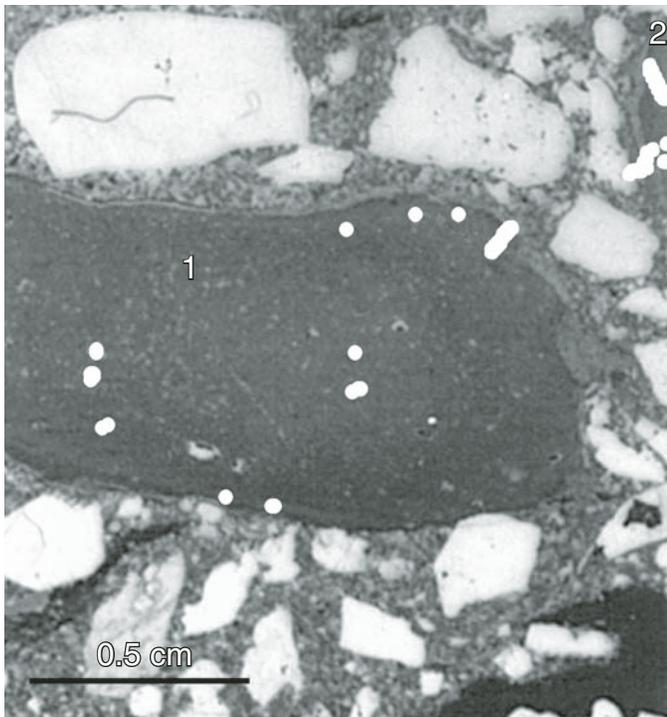


Figure 10. Thin-section photograph showing all points within two accretionary impactoclasts (indicated by white circles) analyzed geochemically by electron microprobe. Points analyzed include crust, mantle, and nucleus points.

Microprobe transects across the two clasts reveal strong geochemical trends that are consistent across both clasts (Figs. 12–14; Table 5). A calcium carbonate phase with generally less than 5 wt% FeO content dominates the mantles. The carbonate phase has negligible Mg content, whereas MnO_2 can attain over 5 wt% at high CaO levels (~60 wt%). A plot of MnO_2 versus CaO shows distinctly positive correlation, confirming that the Mn is associated with the carbonate phase. The crusts of the clasts are generally aluminosilicate rich, iron rich, and carbonate poor. Iron concentration in the crust attains levels of 36 wt% FeO, and CaO versus SiO_2 is negatively correlated, hinting at diagenetic carbonate replacement of aluminosilicate phases. The FeO versus SiO_2 plot shows negative correlation for crust sample points. This may indicate a diagenetic overprint where aluminosilicate phases saw some diagenetic replacement by an iron-rich carbonate phase (siderite) that was successively altered under oxidizing conditions to goethite.

In transects of both clasts, a distinct enrichment in iron exists in the outer crust. An overlay of the FeO trend across the concentric crustal layers of AI#2 shows that iron content varies with the crustal morphology (Fig. 15; Table 6). SO_3 wt% values are negligible for these analysis points (iron is associated with the Al-Si phase of the crust and not with random grains of pyrite, which are also present in these clasts). A microprobe transect across the microcrystalline quartz spherule (Fig. 9C; Table 7) also indicates

a minor iron enrichment in the outer concentric zone relative to the inside of the spherule.

The ghost nucleus in AI#1 was also investigated by microprobe, and sufficient original material exists to confirm the nucleus to be a grain of albite feldspar; surrounding data points indicate, however, that this grain was partly altered to chlorite and calcite (Table 5).

DISCUSSION

The observed impactoclasts span a wide range of types, shapes, and sizes. For the most part, they resemble their volcanic equivalents. However, there are some differences. Some definitions of accretionary lapilli (based on volcanic observations) do not account for any viscosity of clasts on deposition. The amorphous, irregular, and flattened shapes of many of the accretionary impactoclasts described here and their particle-entrained crusts clearly imply a certain degree of pliability on deposition. Similarly, aerodynamic flanges on pyroclasts are well recorded for volcanic glasses, but not for accretionary bodies as seen here.

The interpretation that many of the Tookoonooka accretionary impactoclasts were pliable or spongy on deposition and yet have survived high-energy reworking processes intact may seem contradictory, particularly in light of Reimer's (1983a) observation that more viscous type A accretionary lapilli are more commonly seen in modern environments yet are rarely preserved, whereas the harder, drier "pisolites" (type B) are the most common in the ancient record. Preservation of mud-rich clasts in a high-energy environment implies a hardened outer crust, possibly "baked" (ceramic-like). Warne et al. (2002) suggested a quicklime-portlandite-calcite reaction series for the formation and quick solidification of pliable Alamo accretionary impactoclasts from a carbonate-rich target material. Gilbert and Lane (1994) suggested mineral salt precipitation commencing before deposition as a mechanism to enable accretionary lapilli to survive ground impact, which may be more applicable to Tookoonooka's silicate-rich target sequence. It is possible that the presence of abundant water in the impact and depositional environment may also be a key factor in creation and preservation of the viscous types. The high-water-content vapor plume could make accreting mud-rich clasts pliable without melting. Schumacher and Schmincke (1995) described irregular-shaped aggregates forming when condensed moisture in the vapor plume exceeds 25% (i.e., above the water content threshold for regular accretionary lapilli). Deformation in flight (and on impact with the ground if they are still hot) would be prevalent. Temperature heterogeneities in the turbulent vapor plume may allow some baking during flight, though shattered accretionary impactoclasts (from impact with the ground if they are brittle) are not obvious here. Rapid burial (e.g., by debris flow or tsunamiite) may also have favored preservation. It should be noted that little tectonism has affected this basin since deposition of these sediments; thus flattened shapes are not due to tectonic deformation. High-angle imbrication of flattened accretionary impactoclasts commonly

TABLE 5. REPRESENTATIVE ELECTRON MICROPROBE ANALYSES FROM ACCRETIONARY IMPACTOCLASTS NO. 1 AND NO. 2

Data point	Al*	Na ₂ O (wt%)	MgO (wt%)	Al ₂ O ₃ (wt%)	SiO ₂ (wt%)	SO ₃ (wt%)	K ₂ O (wt%)	CaO (wt%)	TiO ₂ (wt%)	MnO ₂ (wt%)	FeO (wt%)	Co (wt%)	Ni (wt%)	Cu (wt%)	Zn (wt%)	Total (wt%)	Comments/interpretations
Inclusions																	
Th1-A11-m4	1	0.77	-	17.59	63.34	-	15.51	0.07	-	-	0.08	-	-	-	-	97.53	Mantle inclusion: very angular Kspar grain
Th1-A11-m3	1	-	0.11	-	-	-	-	59.29	-	5.38	0.59	-	-	-	-	65.59	Calcite overgrowth on Kspar grain above
Th1-A11-m5	1	-	-	-	97.70	-	-	0.13	-	0.10	0.08	-	-	-	-	98.24	Mantle inclusion: qtz grain
Th1-A11-m6	1	-	-	-	-	-	-	55.67	-	6.98	0.90	-	-	-	-	63.82	Calcite overgrowth on qtz grain above
Th1-A11-m7	1	9.81	-	19.61	67.84	-	-	-	-	-	0.40	-	-	-	-	97.95	Mantle inclusion (see Fig. 11A): albite grain
Th1-A11-m8	1	-	-	-	-	136.66	-	0.10	-	-	61.11	-	-	-	-	198.05	Pyrite overgrowth on albite grain above (see Fig. 11A)
Th1-A11-m1	1	0.10	-	34.86	43.06	0.09	-	0.11	-	-	0.12	-	-	-	-	78.54	Mantle inclusion: mineral/lithic fragment altered to kaolinite
Th1-A11-m2	1	0.10	0.33	34.69	42.59	-	-	-	-	-	3.80	-	-	-	-	81.69	Pyrite inclusion in crust
Th1-A11-c7	1	-	-	-	-	132.19	-	0.32	-	-	58.70	0.130	0.081	0.128	-	191.81	Mantle inclusion: albite grain
Th1-A11-t1-21	1	11.80	-	20.24	69.29	-	-	0.42	-	-	0.08	-	-	-	-	101.91	
Mantle																	
Th1-4R-t1-52	1	-	0.18	-	-	-	-	50.03	-	4.52	0.62	-	-	-	-	55.97	Carbonate
Th1-4R-t1-54	1	-	0.38	2.57	3.97	2.42	0.09	41.61	-	2.78	4.94	-	-	-	-	58.92	Carbonate
Th1-4R-t1-58	1	-	0.30	2.52	5.09	-	0.56	42.33	1.38	3.73	1.39	-	-	-	-	57.69	Carbonate
Th1-A11-t1-19	1	-	0.14	0.18	0.29	-	-	51.07	-	4.38	1.10	-	-	-	-	57.29	Carbonate
Th1-A12-t2-15	2	-	0.15	0.31	1.23	-	0.06	54.22	-	3.93	1.03	-	-	-	-	61.10	Carbonate
Th1-A12-t2-27	2	-	0.16	0.23	0.49	-	-	56.14	-	4.75	1.13	-	-	-	-	63.02	Carbonate
Th1-A12-m1	2	-	0.19	0.30	0.54	-	0.05	56.77	-	5.28	1.24	-	-	-	-	64.37	Carbonate
Crust†																	
Th1-4R-t2-72	2	1.78	2.68	19.28	33.14	-	0.14	0.23	0.08	0.16	30.17	-	-	-	-	87.75	-
Th1-A11-c1	1	0.16	5.35	21.89	36.11	-	1.84	0.76	1.57	0.25	20.49	-	-	-	-	88.67	-
Th1-A11-c2	1	0.25	4.59	19.38	32.65	8.60	1.75	9.51	1.70	0.16	9.59	-	-	-	-	88.37	-
Th1-A11-c6	1	0.17	4.56	17.87	26.61	-	0.80	0.37	0.74	0.14	34.92	-	-	0.218	-	86.55	-
Th1-A11-t1-13	1	0.21	7.95	7.56	18.80	-	3.19	23.80	0.13	1.18	3.43	-	-	-	-	66.29	-
Th1-A11-t1-5	1	0.31	0.10	0.25	4.31	-	0.05	52.75	-	4.22	0.84	-	-	-	-	62.61	-
Th1-A11-t1-1	1	0.31	2.35	15.67	45.93	0.11	0.38	0.48	0.14	0.13	25.57	-	-	0.243	0.273	91.76	-
Th1-A12-t2-1	2	0.85	2.64	20.62	37.75	-	0.91	0.33	0.09	0.16	26.43	-	-	-	-	90.09	-
Th1-A12-t2-2	2	0.12	3.19	20.05	29.31	-	0.30	0.41	0.15	0.15	32.97	-	-	-	-	86.84	-
Nucleus																	
Th1-A11-n3	1	9.84	-	20.81	64.46	-	-	2.22	-	-	0.12	-	-	-	-	97.69	Unaltered nucleus grain: albite feldspar
Th1-A11-n4	1	0.28	2.82	19.32	24.77	-	0.31	0.76	0.08	0.17	35.03	-	-	-	-	83.85	Altered part of grain (likely chamosite)
Th1-A11-n1	1	-	0.16	-	-	-	-	57.58	-	5.09	0.88	-	-	-	-	63.88	Calcite alteration/overgrowth

Notes: Accretionary impactoclasts #1 and #2 are from Thargomindah-1 drill core, at a depth of 705.08 m. Electron microprobe data show major-element (and in a few cases, trace element) variation in wt%. Raw data are presented here; totals do not take into account hydrous and hydroxide components of minerals (e.g., clays, goethite) within impactoclasts; carbon was not analyzed, and thus carbonates show low totals; oxide assumptions have not been corrected; results may be influenced by Fe³⁺ content. "-" indicates not detected; Kspar—K-feldspar; qtz—quartz.

*Al indicates the accretionary impactoclast that the data point resides in.
†Crustal points exhibit varying compositions and degrees of alteration. Carbonate, goethite, and clays may be present.

TABLE 6. ELECTRON MICROPROBE ANALYSIS (MAJOR ELEMENTS IN WT%) OF CONCENTRICALLY ZONED CRUST OF ACCRETIONARY IMPACTOCLAST NO. 2

Data point	Position	Na ₂ O (wt%)	MgO (wt%)	Al ₂ O ₃ (wt%)	SiO ₂ (wt%)	SO ₃ (wt%)	K ₂ O (wt%)	CaO (wt%)	TiO ₂ (wt%)	MnO ₂ (wt%)	FeO (wt%)	Total (wt%)
Transect a												
Th1-AI2-1	1	0.21	2.87	21.63	32.29	0.14	1.20	0.35	0.13	0.14	31.76	90.93
Th1-AI2-2	2	—	3.17	17.88	21.69	—	0.08	0.11	—	0.14	31.03	74.20
Th1-AI2-4	4	0.22	3.59	20.87	35.42	0.13	0.48	0.32	0.27	—	32.18	93.67
Th1-AI2-5	5	—	2.23	12.76	53.15	—	0.06	0.12	0.10	—	24.32	93.18
Th1-AI2-6	6	0.12	2.96	18.24	30.80	—	0.22	0.36	0.12	0.18	32.12	85.17
Th1-AI2-7a	7	0.10	3.42	20.04	27.11	—	0.12	1.30	—	0.28	34.89	87.50
Th1-AI2-7	8	0.12	3.19	19.74	29.04	0.09	0.19	0.75	0.08	0.17	33.33	87.10
Th1-AI2-8	10	—	0.14	0.25	0.36	—	—	54.87	—	4.46	0.81	60.99
Th1-AI2-9	11	—	0.20	0.53	1.05	—	0.09	53.55	—	4.73	1.15	61.41
Transect b												
Th1-AI2-c4	2	0.11	3.42	20.37	25.67	—	0.12	0.26	0.09	0.17	35.69	86.10
Th1-AI2-c3	3	—	—	37.32	45.10	—	—	—	—	—	0.44	83.07
Th1-AI2-c2	4	0.15	3.53	21.02	28.83	—	0.22	0.32	0.10	0.22	33.88	88.32
Th1-AI2-c1	9	0.14	1.67	15.23	55.13	—	0.45	0.29	0.22	0.11	17.04	90.34

Notes: Accretionary impactoclast #2 is from Thargomindah-1 drill core, at a depth of 705.08 m. Transects and position indicate radial location of data points on concentrically zoned structure (position 1 represents the outermost part of the crust, and position 11 represents the innermost analysis point within the mantle); see Figure 15. Crustal points exhibit varying compositions and degrees of alteration. Carbonate, goethite, and clays may be present. "—" indicates not detected.

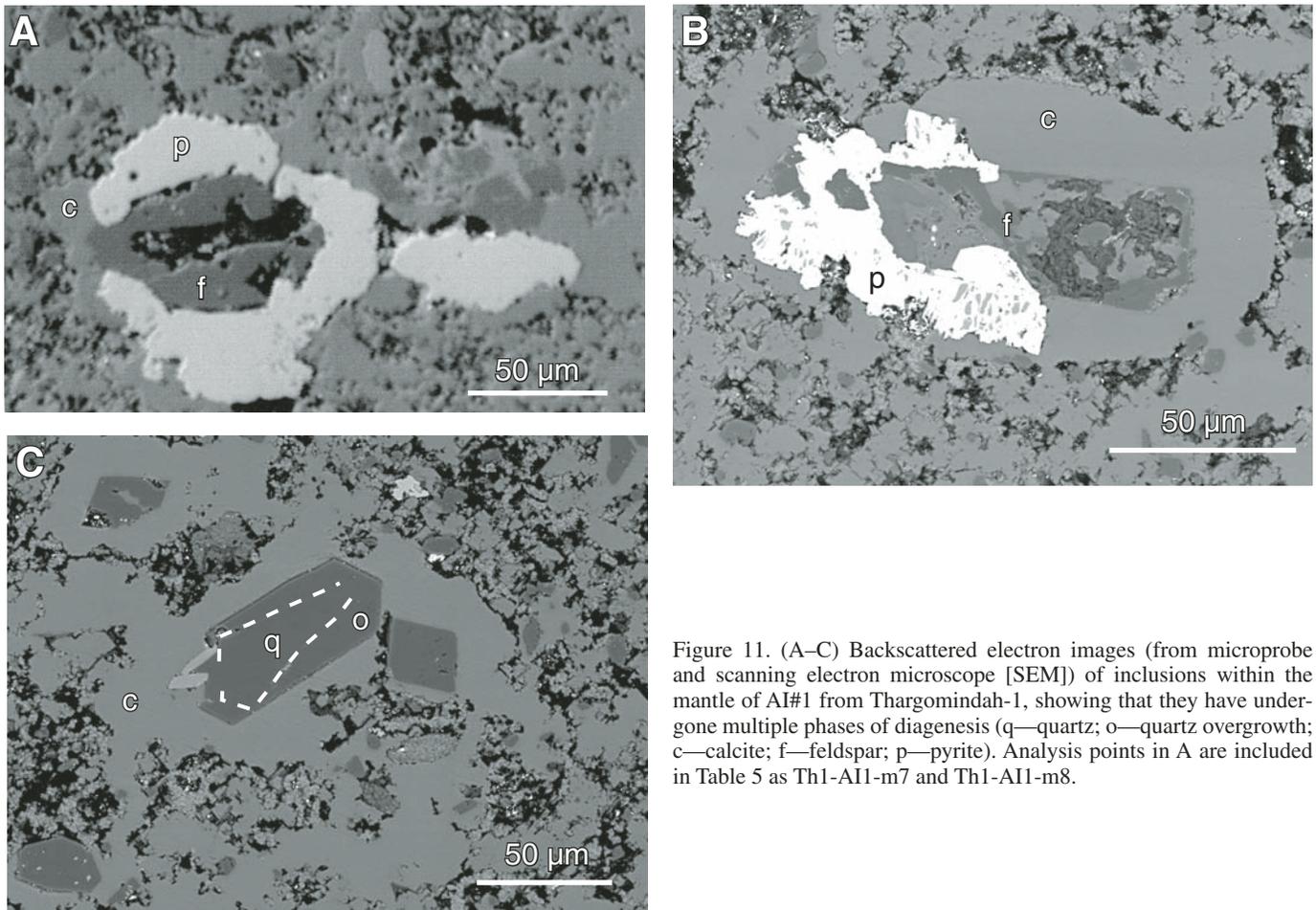


Figure 11. (A–C) Backscattered electron images (from microprobe and scanning electron microscope [SEM]) of inclusions within the mantle of AI#1 from Thargomindah-1, showing that they have undergone multiple phases of diagenesis (q—quartz; o—quartz overgrowth; c—calcite; f—feldspar; p—pyrite). Analysis points in A are included in Table 5 as Th1-AI1-m7 and Th1-AI1-m8.

observed in cores also rules out compaction by burial. Alternatively, perhaps the abundant, elongate accretionary impactoclasts were not pliable but represent type B accretionary lapilli: Schumacher and Schmincke (1991) recorded primary discoidal shapes of accretionary lapilli from pyroclastic-flow deposits that they believed occurred prior to crust formation and did not depend on ground impact or other mechanical deformation mechanisms. The nucleus in the accretionary impactoclast of Figure 4D may be evidence of this.

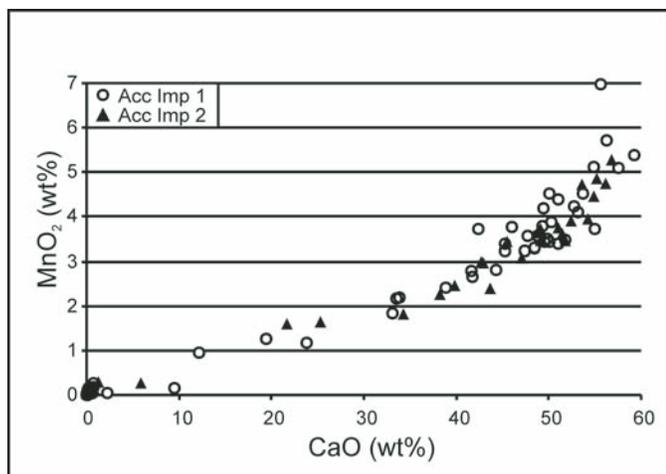


Figure 12. MnO_2 versus CaO for two accretionary impactoclasts (AI#1 and AI#2). MnO_2 versus CaO shows distinctly positive correlation. The carbonate phase prevalent in the mantles was found to have negligible Mg content, whereas MnO_2 can attain over 5 wt% at high CaO levels (~60 wt%). See also Table 5.

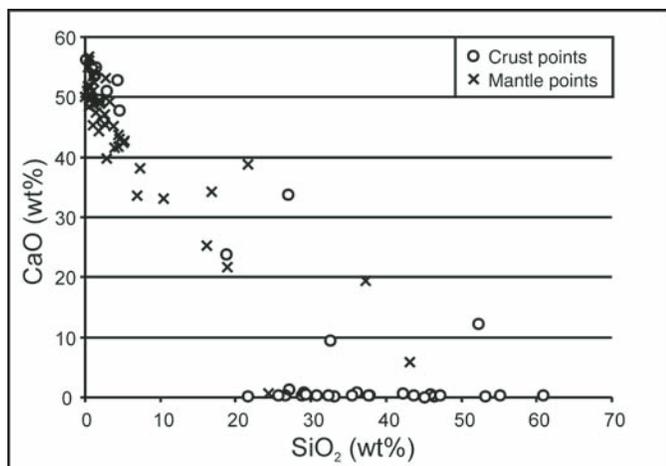


Figure 13. CaO versus SiO_2 for two accretionary impactoclasts (AI#1 and AI#2). Plot shows an inverse relationship between the carbonate phase and aluminosilicate phase. The carbonate phase dominates the mantles, whereas the crusts are consistently aluminosilicate rich and carbonate poor. See also Table 5. Note: SiO_2 points in mantle may have partly sampled larger inclusions.

An interesting category of pyroclastic rocks is those originating from hydroclastic eruptions, as described by Fisher and Schmincke (1984). The presence here of armored impactoclasts (as well as the flattened and amorphous impactoclasts without obvious nuclei) points to the presence of water in the pre-impact environment, and may be supporting evidence that Tookoonooka was a marine impact. The nature of impactoclasts originating from wet target impacts might thus be expected to more closely resemble the pyroclasts from hydroclastic volcanic processes, and we may be able to draw on this key distinction as evidence of the paleoenvironment at time of impact. A marine impact thus may preferentially form the armored and type A accretionary impactoclasts and aid in preserving them via high sedimentation rate of the ensuing impact tsunami waves. Tsunami transport at Tookoonooka could also partially account for the vast area of the basin across which these clasts are dispersed.

With the limited lateral “visibility” gained from drill core samples, and the complication of potential tsunami reworking, it is impossible to assess the lateral extent and primary depositional character of the accretionary impactoclasts in proximal ejecta (i.e., <5 crater radii; cf. French, 1998), although distally fining trends as discussed in the Occurrence and Distribution section may give subtle indications. Indeed, distribution trends (e.g., for Laacher See; cf. Schumacher and Schmincke, 1991) of impactoclasts would only be meaningful for nonmarine impacts, given tsunami mixing. Tsunami redistribution may also explain the absence of expected accretionary impactoclastic deposits in the impactite sequence, although localized pockets may be present in Bulloo-1, Wyandra-1, and Thargomindah-3 (Fig. 6). In all three wells, the ±15-cm-thick beds present are thinner than the

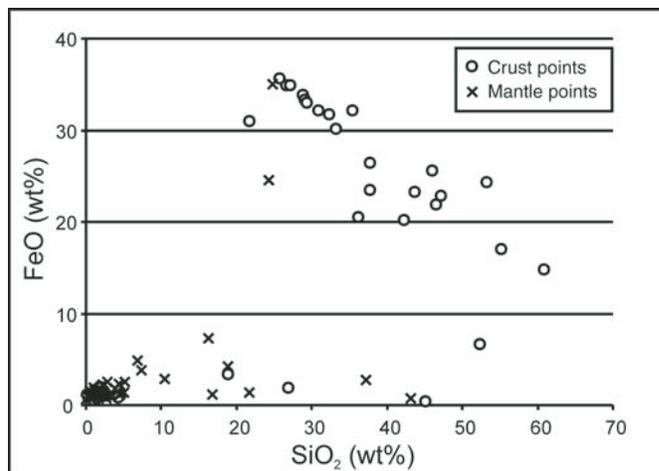


Figure 14. FeO versus SiO_2 for two accretionary impactoclasts (AI#1 and AI#2). Plot shows that the crusts are iron rich and the mantles are iron poor. Iron concentration in the crust attains levels of 36 wt% FeO . This plot also shows negative correlation for crust sample points that may indicate a diagenetic overprint. See also Table 5. Note: Two high- FeO points in mantle are not sulfides.

TABLE 7. ELECTRON MICROPROBE ANALYSIS (MAJOR ELEMENTS IN WT%) OF MICROCRYSTALLINE QUARTZ SPHERULE FROM THARGOMINDAH-1 DRILL CORE

Data point	Position	Na ₂ O (wt%)	MgO (wt%)	Al ₂ O ₃ (wt%)	SiO ₂ (wt%)	SO ₃ (wt%)	K ₂ O (wt%)	CaO (wt%)	TiO ₂ (wt%)	MnO ₂ (wt%)	FeO (wt%)	Total (wt%)
<u>Transect X-X'</u>												
Th1-4R-s1	1	—	—	0.34	96.46	—	—	—	—	—	0.15	97.11
Th1-4R-s2	2	0.06	—	0.22	97.42	—	—	—	—	—	0.10	97.92
Th1-4R-s3	3	—	—	0.26	96.49	—	—	—	0.07	—	0.11	97.03
Th1-4R-s4	4	—	—	0.35	94.36	—	—	—	—	—	0.11	94.93
Th1-4R-s5	5	—	—	0.37	93.75	—	—	—	—	—	0.11	94.33
<u>Transect Z-Z'</u>												
Th1-4R-s6	1	0.06	—	0.35	96.45	—	—	—	—	—	0.13	97.14
Th1-4R-s7	2	0.10	—	0.45	96.92	—	—	—	—	—	0.10	97.63
Th1-4R-s8	3	—	—	0.35	97.19	—	—	—	—	—	0.10	97.73

Notes: Transects and positions indicate radial location of data points on spherule (position 1 represents the outer part of the grain); see Figure 9C. "—" indicates not detected. Spherule is from Thargomindah-1 drill core at a depth of 705.04 m.

occurrence of accretionary impactoclastic deposits (lapillistone) in the Alamo Breccia (maximum 1 m thick; Warme et al., 2002) for a crater of potentially similar magnitude (Morrow et al., 2005). This may indicate that the beds seen here are only fragments as opposed to autochthonous units, or that more syndepositional erosion has occurred.

Another significance of the armored impactoclasts here is that it implies the presence of melt particles in the accretionary cloud/vapor plume (in the case of armored impactoclasts with melt nuclei) that has not previously been noted from impact sites. Melosh (1989) theorized that the impact vapor plume may

capture droplets of impact melt ejected from the crater during vapor plume expansion. The marked presence of melt nuclei in these clasts of the Tookoonooka ejecta testifies to this process. Furthermore, the variety of impactoclasts present here suggests limited interaction between accretionary and melt processes (and in fact, one might expect to see the whole range of clasts from melt to accretionary rather than just the end members): some hybrid clasts observed resemble indistinct concentrically zoned melt particles, while others, accretionary impactoclasts, have subtle flow textures on their outer crusts. Yet other rare accretionary impactoclasts have small accretionary clasts within their

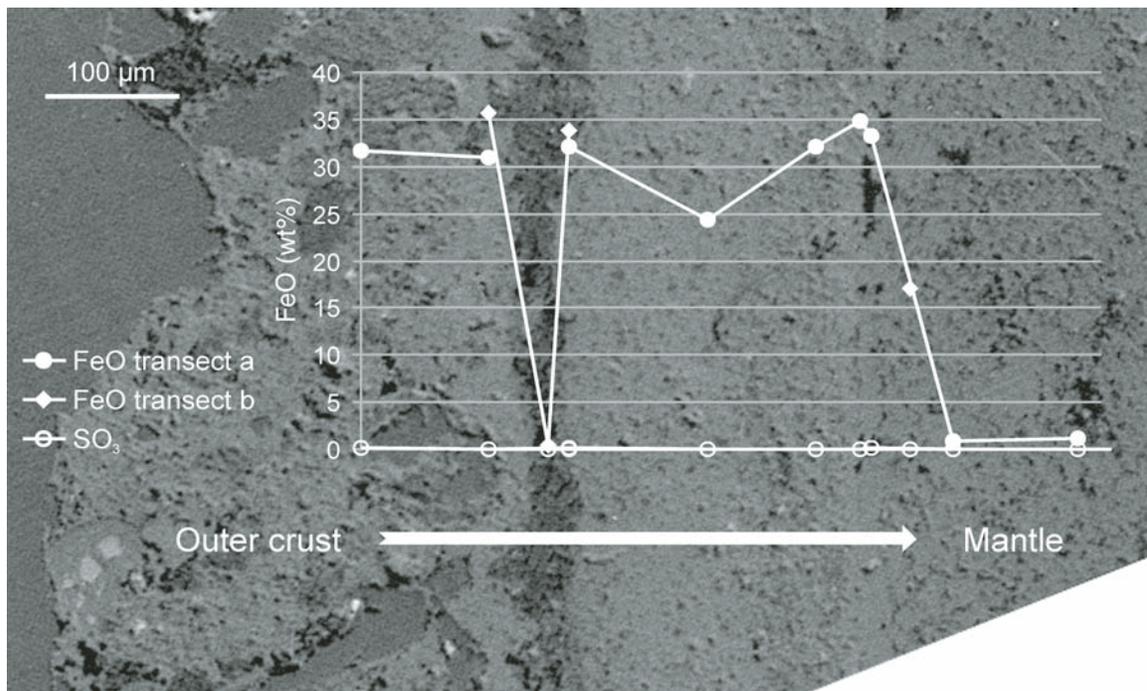


Figure 15. FeO trend across crust of AI#2, showing FeO variance with crustal morphology. The background picture is a backscattered electron image. Particle-entrained outer crust is on the left; mantle is to the right. See also Table 6. Note: SO₃ is negligible for these points. Two transects (a and b) were made to duplicate some data points.

nuclei or melt crusts on their nuclei, implying that turbulence and reworking occurred in the vapor plume (Fig. 16). The complexity of the impactoclast in Figure 7D suggests multiple transits between accretionary and melt zones. To the author's knowledge, melt clast nuclei and melted-rim nuclei in accretionary impactoclasts have not been observed at other impact sites to date, though examples of accretionary impactoclasts from the Bosumtwi (Koeberl et al., 2007, their fig. 3C) and Popigai (Masaitis, 2003) impacts exhibit glass particle inclusions.

Another perspective of the armored impactoclasts and non-nucleated accretionary impactoclasts is that they may merely represent "simpler" varieties of accretionary impactoclasts. Varieties with thicker mantles and crusts and multiple concentric layers would then be more mature forms (Fig. 17), indicative of more time spent in the vapor plume. Gilbert and Lane (1994) considered that re-entrainment of lapilli and rigorous turbulence in the volcanic plume could create larger lapilli and greater concentricity. Equally, the reworked and hybrid accretionary impactoclasts described here could be considered more complex varieties. The higher incidence of armored impactoclasts with lithic nuclei in the crater fill (e.g., in Thargomindah-3) than outside the crater structure could indicate either early fallback from the plume (hence the "simpler" varieties), or that the relative weight of the armored types precludes their deposition further from the crater (e.g., transport away from the crater in a horizontally moving ash cloud, as some accretionary lapilli formation models suggest; e.g., Schumacher and Schmincke, 1995, their fig. 1). However, the deposition of accretionary impactoclasts within the crater structure is likely due to both fallback and tsunami resurge processes.

Other considerations regarding the formation mechanisms of accretionary impactoclasts are the evolution of the vapor plume and the duration of the impact vapor plume before plume collapse. Two observations are worthy of note: accretionary impactoclasts are not reported from distal impact ejecta layers, which could be an indication of height within, or time phase of, the plume at which these clasts form. Secondly, accretionary impactoclasts (lapilli) from the Alamo impact were not likely deposited in the earlier units of the Alamo Breccia, but higher in the post-impact depositional sequence; Warme et al. (2002) interpreted lapilli fallout to begin only after deposition of primary ejecta. This possibly implies that formation of accretionary impactoclasts only occurs in later (post-blowout? lower-temperature?) plume stages. Reimer (1983a) observed that the formation of (volcanic) type A accretionary lapilli can continue for up to 2 days, and that type B accretionary lapilli started to fall 2 hours after a volcanic eruption; for how long could the vapor plume (and hence accretionary impactoclast formation period) from a large impact last? It is unknown how long it takes accretionary impactoclasts to form, but the duration of the plume (and hence re-entrainment and reworking potential) could affect the resultant size ranges and internal structures of the accretionary impactoclasts. Reimer's observations would also suggest that these clasts indeed fall out well into the tsunami depositional phase. Some workers have interpreted accretionary lapilli to form from volcanic base-surge mechanisms (see Background section), but these accounts are rare; it is unknown what proportion of accretionary impactoclasts could form by this mechanism.

The iron concentration trend in the accretionary impactoclast crusts may partly represent a diagenetic overprint, but it is

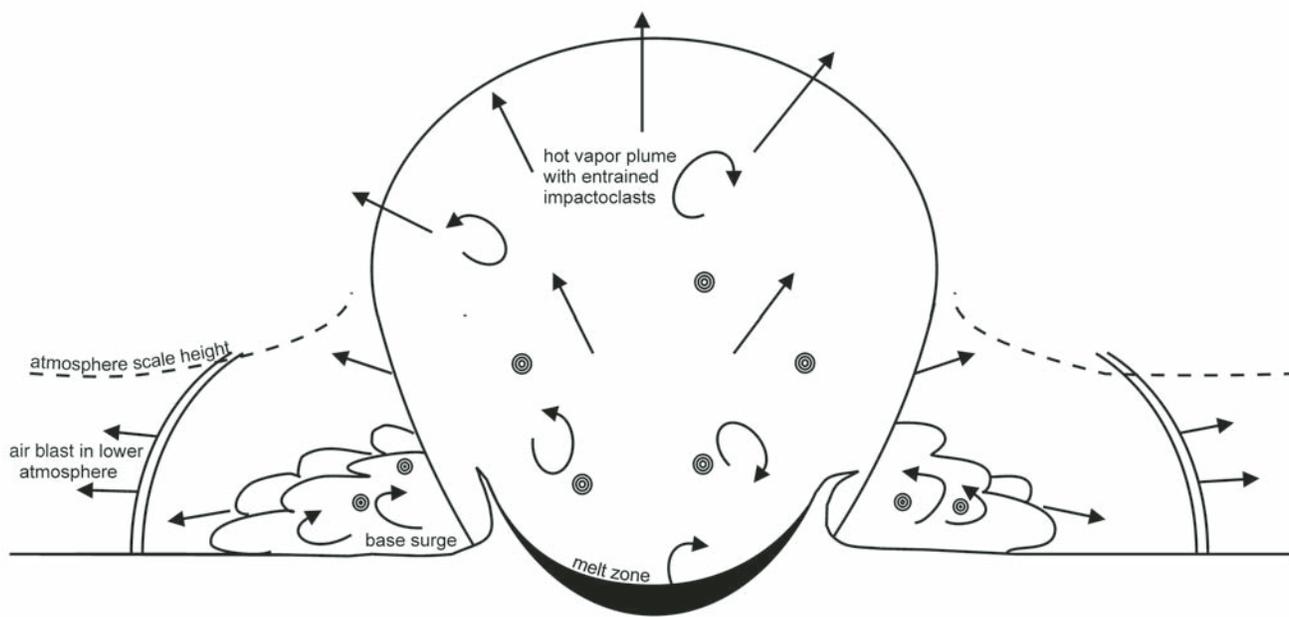


Figure 16. Impact vapor plume (atmospheric blowout type after Melosh, 1989), showing likely mechanisms for Tookoonooka accretionary impactoclast formation.

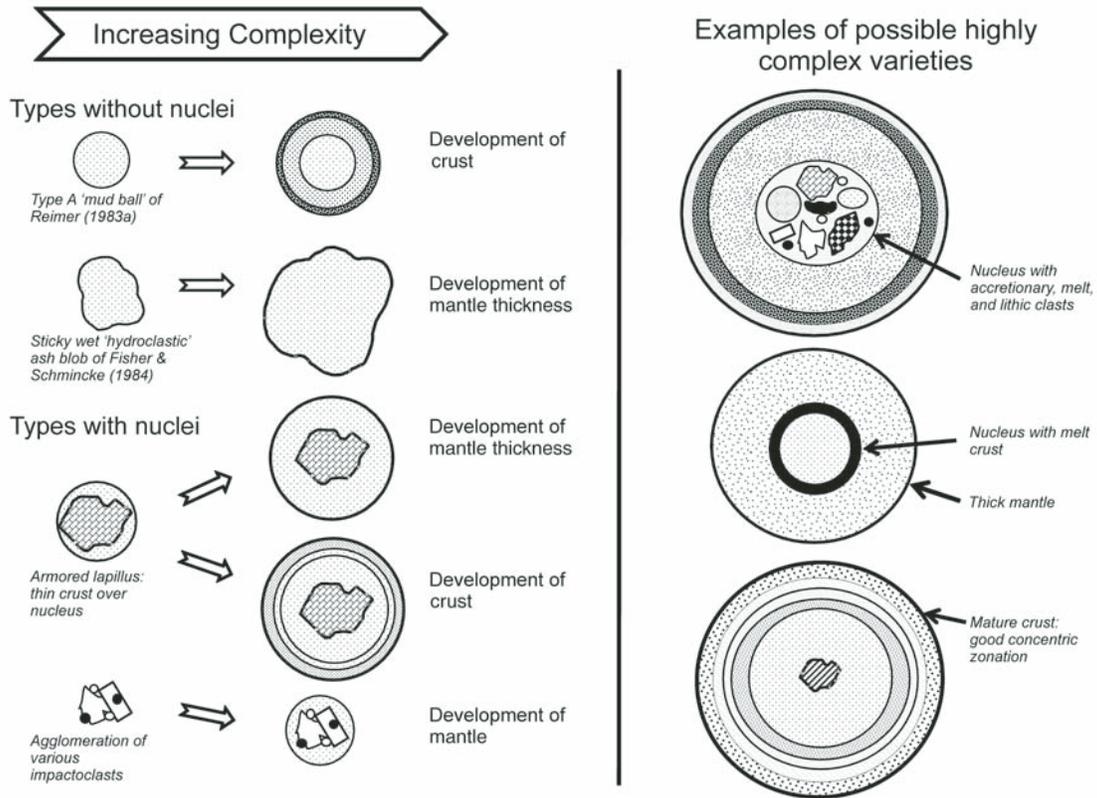


Figure 17. Development of complex accretionary impactoclasts.

believed that the major control on the crustal chemical variation is the original composition of the concentric layers. Otherwise, the iron content would be more pervasive in the mantles, and the diagenetic effect would be more localized: it is surely not coincidental that all accretionary impactoclasts observed across such a large extent of the basin are consistently light brownish to brownish-gray in color. Furthermore, Reimer (1983a) recognized a type of brown accretionary lapilli (type B, Type 1) that was considered to be characterized by ferrous enrichment.

The base of the Wyandra Sandstone consistently marks the first occurrence of impactoclasts across the basin. Thus, the timing of the Tookoonooka impact event can be stratigraphically constrained to 125 ± 1 Ma, at the base of the PK3 palynological zone and the Barremian-Aptian boundary in the Lower Cretaceous (Fig. 2).

CONCLUSIONS

Accretionary impactoclasts have not been widely recognized in impact rock classifications and literature to date. While found to be associated with some impact events, they have only been described from a handful. The clasts described from deposits in and around the buried Tookoonooka impact structure in central Australia are unusual within the context of the predomi-

nantly siliciclastic Eromanga sedimentary basin. They exhibit many of the characteristics of previously described accretionary impactoclasts (impact-derived accretionary lapilli) and volcanic pyroclasts, even though they are pervasively altered. With no contemporaneous volcanism at this time in the basin, the clasts are undeniably linked to the Lower Cretaceous Tookoonooka impact event. Similarity of impactoclast types between the crater fill and the interpreted ejecta (external to the crater structure) also implies a common source.

The accretionary impactoclasts observed display a range of complexity, shapes, and sizes, but they have similar geochemical properties. Some resemble the types of clasts described from hydroclastic volcanic deposits: armored lapilli (with lithic and melt clast nuclei) and irregular-shaped accretionary clasts without nuclei. Most of the accretionary impactoclasts appear to have been pliable on deposition or deformed prior to deposition. Accretionary impactoclasts exhibit an iron trend across their concentric layers that may be due to ferrous enrichment associated with their mode of formation, and widespread carbonate-phase diagenetic alteration. Melt nuclei within armored impactoclasts and rare hybrid (melt-accretionary) clasts imply some communication between melt and vapor plume processes.

The impactoclasts are found in drill cores across a vast area of subsurface central Australia, covering $\sim 375,000$ km², roughly

corresponding to the known extent of the paleo–Eromanga Sea in the late Lower Cretaceous. They are believed to have been dispersed partially by impact tsunamis. These impactoclasts provide further evidence of: impact provenance for interpreted ejecta within the Wyandra Sandstone; a “first occurrence” of Tookoonooka ejecta in the sediment record of the Eromanga Basin at the base of the Wyandra Sandstone, and thus a stratigraphically constrained age of 125 ± 1 Ma for the Tookoonooka impact event; and a marine target for the Tookoonooka impact.

It is proposed that the presence of “hydroclastic” types of accretionary impactoclasts at other impact sites may be indicative of wet targets, and that the further study of accretionary impactoclasts may lead to an increased understanding of impact vapor plume processes. This paper includes revised terminology for the ongoing study of these clasts.

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The Tookoonooka marine impact horizon, Australia: Sedimentary and petrologic evidence

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Abstract—Ejecta from the large subsurface Tookoonooka impact structure have been found in the Lower Cretaceous strata of the extensive Eromanga Basin of central Australia. Observations from 31 wells spanning 400,000 km² of the basin provide compelling evidence for the presence of a marine impact horizon of regional extent. Drill core was examined to determine the sedimentary context of the Tookoonooka impact event, the presence of ejecta, and the nature of the impact horizon. The base of the Wyandra Sandstone Member of the Cadna-owie Formation is an unconformity commonly overlain by very poorly sorted sediment with imbricated pebbles, exotic clasts, and occasional boulders. The basal Wyandra Sandstone Member is bimodal: a fine sand mode reflects an ambient sediment contribution and a coarse mode is interpreted to be impact-derived. Wells Thargomindah-1 and Eromanga-1, within four crater radii of Tookoonooka, contain distinctive clast-supported breccia-conglomerate beds at the base of the Wyandra Sandstone Member. Clasts in these beds include altered accretionary and melt impactoclasts, as well as lithic and mineral grains corresponding to the Tookoonooka target rock sequence, including basement. Petrographic evidence includes shock metamorphosed quartz and lithic grains with planar deformation features. These breccia-conglomerates are in stark contrast to the underlying, laterally persistent, unimodal Cadna-owie sediments and overlying shales deposited in an epeiric sea. The base of the Wyandra Sandstone Member is therefore interpreted to be the Tookoonooka impact horizon. The timing of the impact event is confirmed to be the Barremian-Aptian boundary, at 125 ± 1 Ma. The Wyandra Sandstone Member preserves both impact ejecta and postimpact marine sediments.

INTRODUCTION

Tookoonooka and Talundilly are two subsurface anomalies in the Eromanga Basin of central Australia that were recognized by petroleum exploration in the 1980s (Fig. 1). Tookoonooka and Talundilly are some 300 km apart, buried under almost 1 km of flat-lying sediments near the center of the basin in southwest Queensland. The impact origin of subsurface structures is notoriously difficult to investigate due to inaccessibility and paucity of data. Tookoonooka was confirmed as an impact structure through the identification and measurement of shock metamorphic features in quartz grains (Gorter et al. 1989; Gostin and Therriault 1997)

from the structure's buried central uplift. However, Talundilly has not been adequately drilled to date, and remains a possible impact structure.

Tookoonooka is the second-largest known impact structure in Australia, and possibly the tenth largest in the world (Earth Impact Database, 2011). It was estimated to have a final crater diameter of 66 km (Gostin and Therriault 1997), which is a recalculation of an earlier estimate of 55 km from seismic data (Gorter et al. 1989). Talundilly was estimated to have a 95 km diameter from seismic data (Longley 1989). A Talundilly crater diameter cited by Bevan (1996) and Gorter (1998) of 30 km, while it may be more accurate according to more recent crater-scaling techniques (cf. Turtle et al.

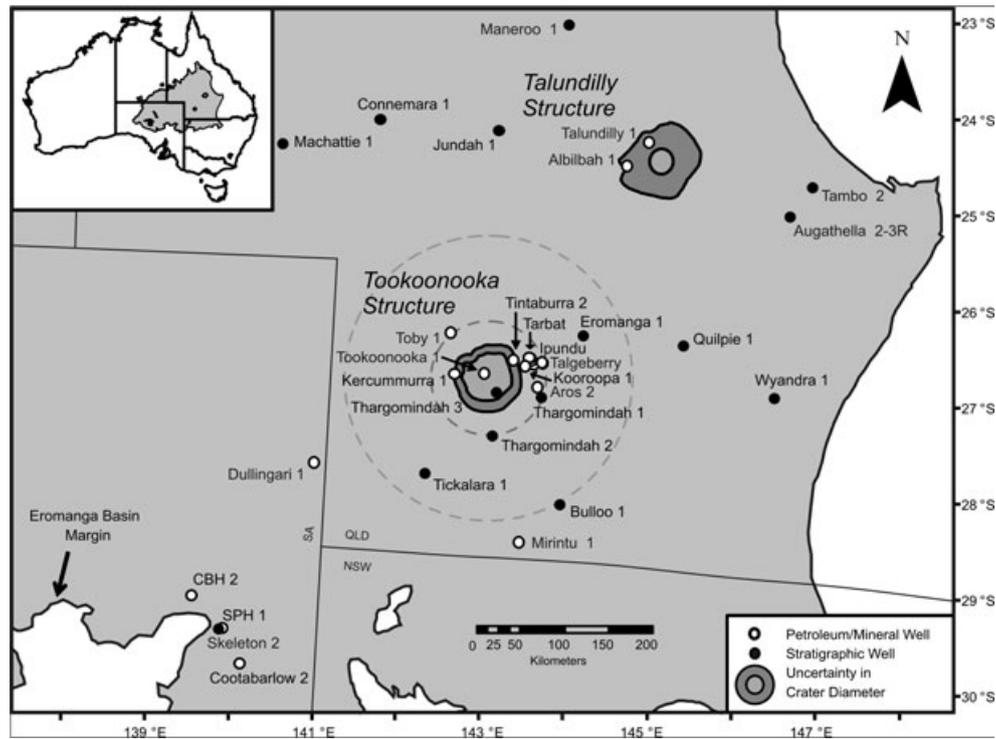


Fig. 1. Map of the Eromanga Basin of central Australia with the locations of Tookoonooka impact structure, Talundilly structure, and wells studied. Modified after Bron (2010). Dashed concentric circles around Tookoonooka indicate theoretical 2Rc and 5Rc limits.

2005), was not thoroughly discussed by those authors, and no new data exist. Based on their similar stratigraphic positions, the two structures are thought to be the result of a binary impact event (Gorter 1998; Haines 2005). From palynology and seismic stratigraphic interpretations, the age of the impact event has been variously estimated at approximately 128 Ma between palynostratigraphic units PK2.1 and PK2.2 (Gorter et al. 1989; Gostin and Therriault 1997), and between 112 and 115 Ma (Gorter 1998), within the Lower Cretaceous (Fig. 2). Bron (2010) constrained the impact age to 125 ± 1 Ma based on a first presence of impactoclasts in the stratigraphy. The Tookoonooka structure was partially preserved by burial; on an erosion level scale of 1–7, where 1 is a largely uneroded crater and 7 is an eroded crater floor (cf. Grieve and Pilkington 1996), Gostin and Therriault (1997) estimated the crater erosion level at 5. Both events probably excavated basement lithologies (Gorter et al. 1989; Longley 1989; Gostin and Therriault 1997).

The sedimentology of the Tookoonooka/Talundilly impact event has not been extensively investigated to date. No ejecta layer has previously been reported (Haines 2005), although impactoclasts originating from the Tookoonooka impact have recently been described (Bron 2010). This discovery prompted a wider search

for impact-related sediments at the same stratigraphic horizon across the basin. This paper aims to: investigate the nature of the impact horizon, provide further evidence of the occurrence of Tookoonooka ejecta in the basin sediments, confirm stratigraphic age constraints of the impact, and better constrain the paleoenvironment at time of impact. As Talundilly's impact origin is as yet unconfirmed, this article will essentially focus on Tookoonooka as the source of interpreted ejecta, although it is recognized that a Talundilly component may exist if the two causative events were coeval.

BACKGROUND

Eromanga Basin Sequence

The Eromanga Basin is a sedimentary superbasin of Jurassic-Cretaceous age covering 20% of the Australian continent (Krieg and Rogers 1995). The stratigraphy of the Eromanga Basin (Fig. 2) has been well documented: work has been done on the deeply weathered southern and southwestern basin margin outcrops, and knowledge of the buried sediments in the rest of the paleobasin comes mainly from petroleum exploration and widely spaced stratigraphic wells. The flat-lying nature of the

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	Biozones	Eromanga Basin Lithostratigraphy	
Phanerozoic	Mesozoic	Cretaceous	Upper	Cenomanian	93.6 ± 0.8	PK7	Winton Fm	
			Lower	Albian	99.6 ± 0.9	PK6	Mackunda Fm	
					112.0 ± 1.0	PK5	Oodnadatta Fm, Allaru Mudst, Toolebur Fm	
				Aptian	112.0 ± 1.0	PK4	Coonkiana Ss	
					112.0 ± 1.0	PK3	Bulldog Shale, Walumbilla Fm	
				Barremian	125.0 ± 1.0	PK2	Wyandra Ss Mbr	
				Hauterivian	130.0 ± 1.5		Cadna-owie Fm	
				Valanginian	~133.9		PK1	Murta Mbr
				Berriasian	140.2 ± 3.0			Hooray Ss
			Jurassic	Upper	Tithonian	145.5 ± 4.0	PJ6	Namur Ss, Westbourne, Adori Ss
	Kimmeridgian	150.8 ± 4.0			PJ5	Birkhead Fm		
	~155.6							
	Oxfordian	161.2 ± 4.0						

Fig. 2. Stratigraphy of the Eromanga Basin. Modified after Bron (2010).

sediments indicates that this paleobasin has experienced negligible tectonism since its inception. As the basin spans three Australian states and one territory (Fig. 1), a comprehensive literature review is not attempted here. The following paragraphs give reference to details of the formations investigated.

The stratigraphic context of the Toookoonooka impact is the Cadna-owie Formation (herein referred to as “the Cadna-owie”; Fig. 2). The Cadna-owie is comprised of very fine- to fine-grained, quartzose to sublamine sandstones with common siltstone interlaminae and thin interbeds (Senior et al. 1975; Exon and Senior 1976; Day et al. 1983). The sandstone matrix is calcareous in part and the siltstone may be carbonaceous (Draper 2002). The sedimentation of the Cadna-owie is laterally uniform, with a siltier lower unit and a sandier, slightly coarser upper unit (Draper 2002). The formation has an average thickness of 60 m (Senior et al. 1975; Exon and Senior 1976), but is more typically 75–100 m thick at the center of the basin (Moore and Pitt 1984, 1985). The Cadna-owie records the transition to a paralic or shallow marine environment as a very extensive, shallow epeiric sea transgressed the nonmarine basin; Eromanga Basin sediments predating the Cadna-owie are largely fluvio-lacustrine (e.g., Exon and Senior 1976). No volcanism has been reported in the basin from this geological time (Harrington and Korsch 1985; Wiltshire 1989; McDougall 2008). The presence of glauconite and marine palynomorphs (e.g., Day 1969; Senior et al. 1975; Day et al. 1983; Alley and Lemon 1988) is strongly evident of a marine influence during deposition. Glacial indications

have been described from the southern basin margin areas (Frakes et al. 1995; De Lurio and Frakes 1999; Alley and Frakes 2003). The Cadna-owie was probably deposited in restricted marine cold-water conditions in a low-relief, high-latitude basin with poor sediment supply.

In contrast, the Wyandra Sandstone Member (herein referred to as “the Wyandra”; Fig. 2), stratigraphically assigned to the Cadna-owie Formation in central Queensland (e.g., Draper 2002), is a coarser grained, cleaner sandstone unit than the lower and upper Cadna-owie units as described above. The unit was first named by Senior et al. (1975), and defined as a thin, widespread, well-sorted, medium- to coarse-grained, quartzose sandstone with scattered carbonate cement and pebbles and no known fossils (Senior et al. 1975, 1978; Exon and Senior 1976). Although the Wyandra occupies the uppermost part of the Cadna-owie as originally defined, for clarity, all references to the Cadna-owie in this article will pertain to the Cadna-owie deposits underlying the Wyandra.

Overlying the Wyandra, the Walumbilla Formation (also known as the Bulldog Shale in southern parts of the basin; Fig. 2) is a dark gray, fossiliferous, carbonaceous marine shale. Prior to deposition of the Walumbilla Formation, basin sediments were predominantly quartz-rich (with sublamine components) and mature (Exon and Senior 1976; Day et al. 1983). The Bulldog Shale in South Australia has a maximum known thickness of 340 m (Moore and Pitt 1985). The Walumbilla Formation is known to be greater than 450 m thick in the center of the basin, thinning to only 30 m in the far northwest of the basin in Queensland (Moore and Pitt 1985).

Impact Ejecta

Impact ejecta layers have been observed in sedimentary units spanning the geological record (cf. Montanari and Koeberl 2000). Only a fraction of the 178 confirmed terrestrial impact structures (Earth Impact Database 2011) have ejecta preserved; due to terrestrial erosion processes, ejecta are usually only observed at younger craters or where sedimentary burial has enabled preservation. Twenty-seven impact structures are currently categorized as having impacted marine environments, and distinct marine impact sedimentation processes have been recognized (Dypvik and Jansa 2003; Dypvik and Kalleson 2010). Due to sedimentation rates in marine environments, it is likely that ejecta may be more often preserved by burial in marine impact scenarios.

Classifications of impactites and terminology relating to ejecta have been proposed by a number of authors including French (1998), Stöffler and Grieve (2007), Melosh (1989), Montanari and Koeberl (2000), King and Petruny (2003), and Bron (2010); terms proposed by these authors will be applied herein. Melosh (1989) discussed the distribution of ejecta volumes based on radial limits. For a given crater, approximately 50% of the ejecta volume lies within a continuous ejecta blanket within two crater radii (2Rc) of the crater center (or 1Rc from the crater rim), and 90% lies within 5Rc. Between 2Rc and 5Rc lies a discontinuous ejecta blanket. Ejecta are considered proximal within 5Rc and distal beyond 5Rc. It must be noted that these theoretical distributions in the terrestrial realm are most applicable to fresh, nonaqueous impact sites where minimal erosion and reworking have occurred.

Diagnostic indicators of the impact origin of ejecta include geochemical anomalies and shock metamorphic features (cf. French 1998; French and Koeberl 2010). The latter may take the form of microscopic planar deformation in minerals, the presence of high-temperature/pressure mineral polymorphs, and diaplectic glasses. Microscopic planar deformation includes planar deformation features (PDFs) and planar fractures (PFs), although it is contested whether the latter can be considered an impact indicator in isolation (French and Koeberl 2010). The unique impact origin of “toasted” quartz, which is a brownish-colored textural variety of quartz reported from impact sites, has also been investigated by Whitehead et al. (2002). The effects of shock metamorphism have been recognized in numerous minerals in impact shocked and experimentally shocked rocks (reviews in Grieve et al. 1996; Stöffler 1972; Stöffler and Langenhorst 1994). Measurements of orientations of PDFs in quartz can be made microscopically on a universal stage; 15 crystallographic orientations are considered typical (cf. Stöffler and Langenhorst 1994;

Ferrière et al. 2009). Occurrence of suites of PDF orientations have been further applied to impact shock pressure calibration (e.g., Grieve et al. 1996). It is recognized that different target materials, such as crystalline or unconsolidated/porous sedimentary rocks, may influence the suite of shock effects present at a given impact site. Hence, classifications have been proposed for the progressive stages of shock metamorphism in different target lithologies (Stöffler and Grieve 2007).

Tookoonooka Impactoclasts

Bron (2010) described the occurrence of accretionary and melt impactoclasts within the Wyandra. Similar to their volcanic equivalents (accretionary lapilli, melt lapilli, and bombs), a variety of melt morphologies and concentrically zoned accretionary clasts were recognized. Similar clasts have also been described from other impact sites around the world. Accretionary and armored impactoclasts up to 9 cm in diameter were observed in drill core across the Eromanga Basin (Bron 2010). Given their proximity to the Tookoonooka impact structure, their presence within the Tookoonooka crater fill, and the lack of contemporaneous volcanic evidence in the basin record, they were interpreted to be of Tookoonooka impact vapor plume origin. A new terminology was proposed to highlight the significance of these clasts to impact geology.

METHODOLOGY

Drill cores from 31 wells in southwest Queensland and northern South Australia were examined in the search for a Tookoonooka ejecta layer (Fig. 1). Emphasis was first placed on the most proximal wells to the Tookoonooka structure within the theoretical continuous ejecta blanket limit, followed by an expanded search to more distal wells. The cores were studied in detail macroscopically across the formations of interest (the Cadna-owie, the Wyandra, and the lower Walumbilla) to investigate the presence, sedimentary context, distribution, and characteristics of possible ejecta across the basin. Characteristics such as grain size, sorting, clast composition, texture, and physical and biogenic sedimentary structures were recorded. Clast-supported breccia-conglomerate beds were observed in many of the Wyandra cores studied; as these were expected to contain discernible primary ejecta (Bron 2010), they were the focus of a more detailed investigation.

Cores from two Geological Survey of Queensland (GSQ) stratigraphic wells were chosen for microscopic study: Thargomindah-1 and Eromanga-1 (Fig. 1). They were chosen for their proximity to Tookoonooka and the

Table 1. Point-counting data sets for three thin sections analyzed.

Thin section from well	Thargomindah-1	Eromanga-1	Eromanga-1
Stratigraphic interval	basal Wyandra	basal Wyandra	upper Cadna-owie
Total # points counted for volumetrics	573	1409	308
Total # grains analyzed	325	316	308
% volume grains—unresolved mineralogy	~1%	~1%	~3%
# detrital grains—mineralogy identified	320	309	305
# detrital grains—grain size measured ^a	301	305	294
# detrital grains—grain shape recorded	301	303	282

Point-counting results are presented in Tables 4 and 5.

^aGrain sizes in thin section are uncorrected with respect to comparative sieved equivalents.

presence of a clast-supported breccia-conglomerate (CSBC) bed at the base of the Wyandra. GSQ Thargomindah-1 is located about 64 km (1.9 Rc) east of the approximate Tookoonooka crater center, within the theoretical continuous ejecta blanket range of Tookoonooka, and 303 km from the center of Talundilly. GSQ Eromanga-1 is located 119 km northeast (3.6 Rc) of the Tookoonooka crater center and 219 km from the center of Talundilly. Both wells are within the theoretical proximal ejecta range of Tookoonooka. Petrographic microscopy was used to conduct point-counting of grains and search for shock metamorphic evidence within thin-sections of the CSBC beds. Data recorded were: detrital grain mineralogy, grain size, grain shape, optical properties, textures, and alteration. Standard point-counting procedures were used (cf. Tucker 1988). Over 300 grains were analyzed per thin section to obtain statistically significant results (Table 1). Grain size nomenclature utilizes the scales of Udden-Wentworth (as detailed in Folk 1980; Tucker 2001) and Blair and McPherson (1999). PDF orientations were measured using a four-axis universal stage and indexed (cf. Stöffler and Langenhorst 1994) utilizing the stereographic projection template of Ferrière et al. (2009). Thin sections of the Thargomindah-1 and Eromanga-1 CSBC beds were made at 705.08 m depth and 743.73 m depth, respectively.* For comparison with the ambient (i.e., interpreted preimpact) sedimentation, a thin section at 743.99 m depth in

Eromanga-1 within the upper Cadna-owie was also made; results of analyses were compared with those of the two basal Wyandra CSBC beds.

RESULTS

Sedimentological Observations

The Cadna-owie and Walumbilla Formations exhibit remarkably near-uniform character over vast distances (thousands of km; the breadth of the basin). They are fine- to very-fine-grained (sand or silt), well-sorted, and predominantly parallel-laminated. The dull-colored, beige-gray Cadna-owie (Fig. 3) is comprised of interlaminated sandstones and siltstones, and also displays ripple cross-lamination and pervasively burrowed, structureless beds. Rootlets, cm-scale coal beds, and wavy carbonaceous laminae also occur locally. Variations in the Cadna-owie across the study area are mainly in clay mineral content and degree of bioturbation. The ten meters of upper Cadna-owie directly underlying the Wyandra in Eromanga-1 are similar to the facies shown in Fig. 3B and are described in Table 2. Although interlaminations of siltstone and carbonaceous material are present, overall, the unit is sand-dominant. A sample was taken from this core interval to obtain an inventory of the grain mineralogies and microscopic characteristics present. The dark-gray, homogeneous Walumbilla shales exhibit a consistent character over hundreds of meters of depth, and are only interrupted by occasional shell hash deposits (usually molluscan).

The sedimentation style of the Wyandra is distinct from the underlying Cadna-owie and overlying Walumbilla Formations. It ranges from very poorly sorted beds containing common angular and irregular-shaped clasts, large rip-up clasts and imbricated pebbles to moderately well-sorted, very coarse-grained sandstone beds and laminated silt interbeds. Sedimentary structures such as massive bedding, graded bedding, trough cross-bedding, parallel lamination of coarse sediments, and possible hummocky and swaley cross-stratification

*For both GSQ Thargomindah-1 and GSQ Eromanga-1 wells, the depths inferred here for the base of the Wyandra Sandstone Member are different from those documented in the Stratigraphic Drilling Reports (Almond 1983, 1986), namely 732.74 m and 773.7 m, respectively. As the Wyandra was occasionally misinterpreted to be synonymous with the upper Cadna-owie in early wells (Draper 2010, personal communication), the base of the Wyandra was revised for GSQ Thargomindah-1 to approximately 705 m (QPED, 2009). We have placed the base at 705.08 m. As the depth pick for the base of the Wyandra in GSQ Eromanga-1 has not yet been revised (QPED, 2009) and the stratigraphic drilling reports for both wells have the same author, we adopt a similar interpretation for GSQ Eromanga-1 and place the base of the Wyandra at 743.73 m.

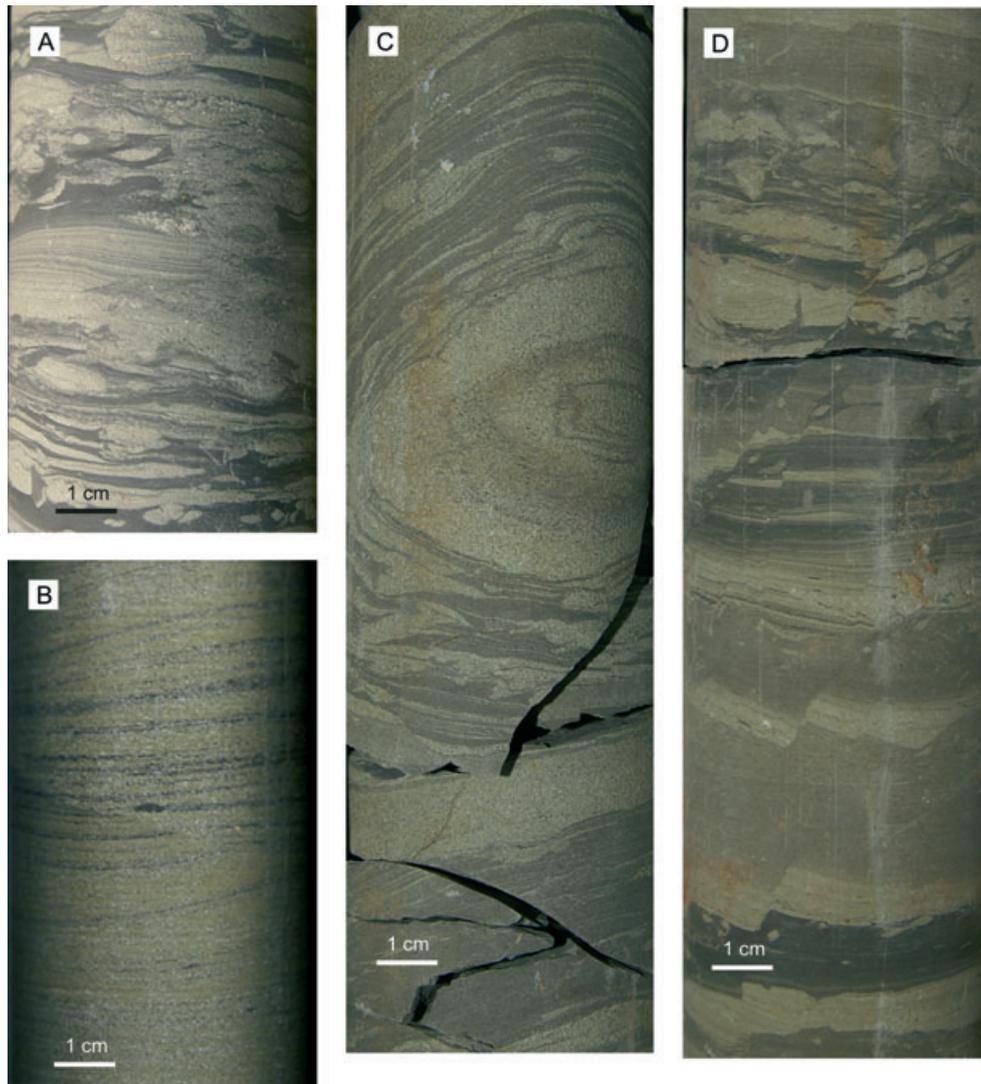


Fig. 3. Core photos of the Cadna-owie formation. A) and B) Typical Cadna-owie facies: deposits generally show only slight variance in the thickness or color contrast of the alternating siltstone and sandstone layers or degree of bioturbation. Deposits are often very dull-colored and rich in clay minerals. Upper Cadna-owie facies are very similar to the lower Cadna-owie, but generally have more sand content. A) The lower Cadna-owie in GSQ Maneroo-1, showing the obliteration of primary bedding structures by bioturbation. B) Unbioturbated, cross-laminated silty sandstone facies of the upper Cadna-owie in GSQ Thargomindah-1. C) and D) Deformation underlying the basal Wyandra contact in GSQ Jundah-1 well. C) Soft-sediment deformation. D) Soft-sediment deformation and microfaults in burrowed sediments.

(difficult to confirm in core width) are common in the Wyandra. Much coarser grained sediments distinguish the Wyandra: boulders and cobbles of amorphous- to aerodynamically shaped melt and accretionary impact-oclasts (as described in Bron 2010) and metamorphic lithic fragments (e.g., in Talgeberry-1) occur at and above the base of the Wyandra across the basin. The Wyandra is frequently punctuated by clast-supported and matrix-supported breccia-conglomerate beds (CSBC and MSBC beds, respectively; Fig. 4), which are not present in the Cadna-owie or Walumbilla. Of the 31 wells studied, 18 had CSBC layers present in the Wyandra with clasts

pebble-sized or larger (Fig. 1; Table 3). CSBC beds at the base of the Wyandra were observed in five wells (Tables 1 and 2; Figs. 4A–E).

Basal Wyandra CSBC beds at Thargomindah-1 (Figs. 4A and 4B) and Eromanga-1 (Fig. 4C) are similar to the character of other basal Wyandra CSBC beds (Table 2). Both are poorly sorted and composed of a range of highly angular fragments to rounded clasts. The basal Wyandra CSBC bed at Thargomindah-1 exhibits crude normal grading and directly overlies a thin black coal seam within the Cadna-owie. The basal Wyandra CSBC bed at Eromanga-1 is reverse-graded overall, with

Table 2. Summary of sedimentary observations for Cadna-owie and five basal Wyandra CSBC beds.

Well	Eromanga-1	Thargomindah-1	Eromanga-1	Talgeberry-1	Mirintu-1	Quilpie-1
Stratigraphic interval	upper Cadna-owie formation	basal Wyandra sandstone	basal Wyandra sandstone	CSBC beds		
Thickness	–	4.5 cm	7 cm	> 14.5 cm	8.5 cm	4 cm
Color	Med gray-beige	Light gray-beige	Light gray matrix	Med gray-beige	Light gray-beige	Beige-gray
Macroscopic texture	Fine- to very fine-grained, homogeneous, well sorted.	Clast-supported breccia-conglomerate. Max apparent grain size coarse pebble. Predominant grain size VCGR sand. Poorly sorted. Clasts lenticular to blocky and angular.	Max apparent grain size very coarse pebble. Poorly sorted. At base: matrix-supported. At top: very poorly sorted, clast-supported. Clasts very angular to irregular, blocky, and rounded shapes.	Max apparent grain size cobble. Very poorly sorted, becoming slightly better-sorted upward. Abundant brown-beige, lenticular to platy clasts and gray granules.	Max apparent grain size very coarse pebble. Poorly sorted. Clast shapes very angular and irregular.	Bed of pebble-sized mud clasts and granular quartz grains. Max apparent grain size coarse to very coarse pebbles. Very poorly sorted. Overlain by med-grained, massive sandstone, underlain by massive siltstone.
Composition	Mud-rich sandstone. Noncalcareous. Common plant fragments. Occasional coal clasts.	Polymictic clasts incl. abundant quartz, accretionary, and melt impactoclasts. Calcareous cement.	Polymictic clasts (mostly lithics), abundant calcareous cement.	Polymictic clasts. Abundant lithics incl. metasedimentary, accretionary impactoclasts, laminated siltstone clasts.	Polymictic clasts. Abundant lithics incl. metasedimentary, rip-ups, and possible melt impactoclasts.	Granules mostly quartz or quartz-rich. Pebbles are mud-rich, gray, and massive with no internal structure. Bed is clay-mineral rich.
Sedimentary structures	Parallel laminated. Ripple cross-lamination, thin carbonaceous laminations. Occasional rootlets. Burrowed.	Crudely normal-graded (subtly fining upward, but becoming more clast-supported upward), weak high-angle laminations and cross-laminations. Subvertically imbricated clasts. Bi-directional imbrication.	Overall reverse graded. At base: massive to very weakly laminated. At top: weakly imbricated.	Parallel laminated, defined by abundant, imbricated pebble-sized clasts. Normal (coarse-tail) graded.	High-angle bedding, imbrication of long angular clasts. Bi-directional imbrication.	No apparent grading. Large lenticular mudclasts flat-lying.

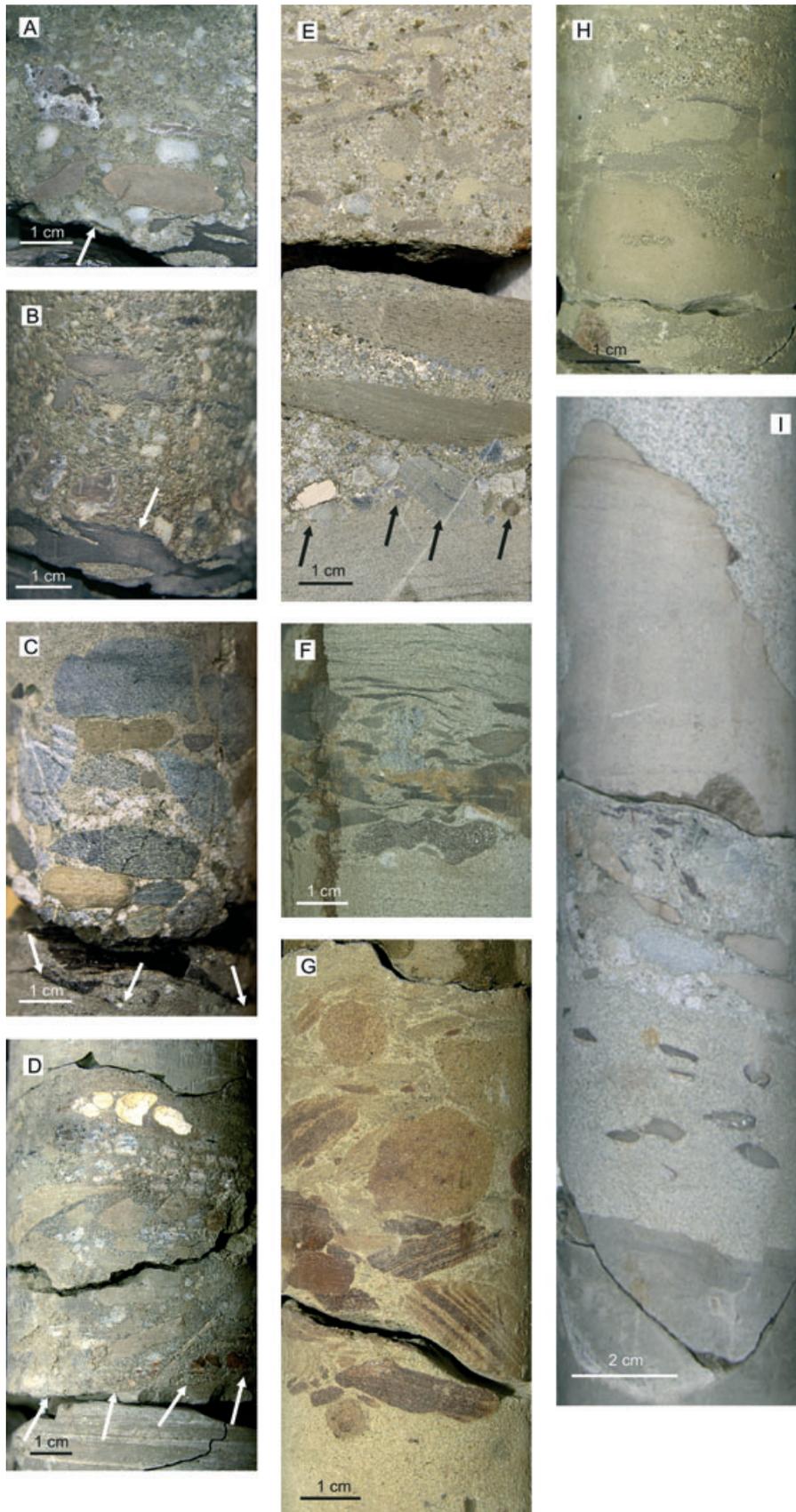


Fig. 4. Core photos of various breccia-conglomerate beds in the Wyandra from across the basin. Arrows indicate Cadna-owie-Wyandra contact. A)–E) Basal Wyandra CSBC beds. See Table 2 for details. F)–I) Wyandra CSBC and MSBC beds (nonbasal). A) and B) 4.5 cm thick bed at 705.08 m depth in GSQ Thargomindah-1 (2 core views). Bed overlies coal seam and erosional, angular basal Wyandra contact with flame structures. A) Tan-colored accretionary impactoclats are prominent. Modified after Bron (2010). B) Note imbrication of pebble-sized lithic and probable altered melt clasts, indicating flow direction from left to right. C) 7 cm thick bed at 743.73 m depth in GSQ Eromanga-1. Bed is strikingly polymictic, with coarse, angular, exotic clasts. Basal Wyandra contact is undulose, and underlain by bedded sandstone. D) 8.5 cm thick bed at Mirintu-1 with irregular-shaped and angular clasts. Basal Wyandra contact is sharp and cross-cuts underlying flat laminations at a low angle. E) Bed at Talgeberry-1 location. Sharp, undulose basal Wyandra contact is overlain with lithic, quartz, and probable altered melt clasts. Large dark rip-up clasts are probably of Cadna-owie origin. White line on lower right side of core is a scratch. F) MSBC bed within Wyandra at GSQ Maneroo-1, with rip-up clasts and amorphously shaped clasts of likely melt origin. Vertical dark stripe on left is a rust-colored stain on the core. G) Part of a 31 cm thick CSBC bed within the Wyandra in GSQ Wyandra-1. Mixing with local sediments is evident here, as many of the red stratified clasts appear to be locally derived rip-up clasts not seen in other wells. Some clasts show internal deformation. Imbrication is evident elsewhere in this layer. H) CSBC bed within Wyandra at GSQ Bulloo-1, which is part of a 16 cm thick bed of seeming mud clasts, interpreted by Bron (2010) as a possible accretionary impactoclast bed (note large accretionary impactoclast with nucleus). Bed shows bidirectional imbrication. I) An MSBC bed with floating pebbles is overlain by a very coarse-grained, 7–15 cm thick CSBC bed exhibiting imbricated impactoclats and a cobble-sized accretionary impactoclast described in Bron (2010), within the Wyandra at GSQ Eromanga-1. Beds overlie a dark, sandy siltstone bed deformed by microfaults.

maximum grain sizes of 1 cm near the base to 3.9 cm near the top, and overlies bedded fine-grained sandstone of the Cadna-owie. Exotic pebbles are the most distinctive feature of the beds in hand sample. In the Thargomindah-1 bed imbricated, polymictic clasts range from fractured and veined metamorphics that are blocky and angular to light-brown, clay-rich impactoclats that are lenticular to irregular in shape. Accretionary impactoclats up to 2.2 cm in length in this layer were geochemically analyzed by Bron (2010). The polymictic nature of the Eromanga-1 bed is also distinctive, with red, greenish, black, gray, and brown colors of sedimentary and volcanic lithic clasts. These beds are the lowermost of many breccia-conglomerate beds in the Wyandra at these two well locations. Shallower (younger) breccia-conglomerate beds in Eromanga-1 (e.g., Fig. 4I) contain some of the largest accretionary and melt impactoclats discovered in drill core in the basin thus far.

Basal Contact of the Wyandra

The basal contact of the Wyandra in the wells studied is consistently sharp, accompanied by a significant, sudden jump in grain size across the contact with the Cadna-owie (Table 3). Minimum average grain sizes above the contact are usually medium- to very coarse-grained sand, whereas the maximum observed grain size in Cadna-owie beds underlying the contact was fine-grained sand. The contact is erosional, angular, cross-cutting, and undulose at various locations (Figs. 4 and 5), and is often defined by flame structures (e.g., Figs. 4B, 5B, and 5D) or scours (e.g., Figs. 4E, 5C, and 5F). Rare occurrences of sandy paleosol and thin, minor coal seams in the Cadna-owie also underlie the Wyandra (e.g., Figs. 4B and 5A). In places, the contact truncates rootlets (Fig. 5E). The contact in Thargomindah-1 is erosional: it cross-cuts underlying coal laminations of the Cadna-owie and

variably exhibits cm-scale flame structures to incompletely ripped-up bedding (Figs. 4A and 4B). Apparent clasts within the coal are composed of the same sandstone matrix present above the contact, and may be filled scours, filled burrows, or minor sand injectites. Below the coal lies siltstone with rootlets, churned (highly burrowed) bedding, and soft-sediment deformation features. The contact in Eromanga-1 (Fig. 4C) appears more gradational than at Thargomindah-1, but this may be due to the similarity between the matrix material of the basal Wyandra CSBC bed and the underlying Cadna-owie sandstone, which is slightly coarser and cleaner at this location.

Deformation

Throughout the basin, microfaults and soft sediment deformation structures commonly underlie the Wyandra in the Hooray and Cadna-owie Formations (Figs. 3C and 3D). Convolute bedding appears to coincide with younger, more mud-rich sediments, and microfaults with older, more lithified sediments. These structures are, by contrast, very rare within the Wyandra; indeed, in places, their occurrence stops abruptly at the base of the Wyandra (e.g., Figs. 5A and 5F). It was also observed that some rip-up clasts within the Wyandra exhibit this deformation. In GSQ Thargomindah-3, located in the Tookoonooka outer crater structure, similar deformation is widespread; microfaults, sedimentary injectites (sandstone dykes), and soft sediment deformation structures are abundant in the crater fill.

Bioturbation

The Cadna-owie is frequently highly bioturbated, with churned bedding characteristic of abundant biological activity coupled with slow sedimentation rate (e.g., Figs. 3A and 5B). The Wyandra, in contrast, is

Table 3. Observations at 31 well locations.

Well name	Well type, location	Approx. distance from Tookoonooka (Rc) ^a	Approx. distance from Talundilly (Rc) ^a	Accretionary impactoclasts present in Wyandra?	CSBC beds present in Wyandra? ^c	Maximum grain size ^d within		Comments
						Wyandra	MSBC beds	
Thargomindah-3	strat, QLD	<1	>5	–	–	–	–	Wyandra not present
Aros-2	Petroleum, QLD	<2	>5	Yes	No	Cobble	Sharp, low angle	–
Ipundu 6	Petroleum, QLD	<2	>5	Yes ^b	Yes	Cobble	Sharp, angular, undulose	Wyandra not fully cored ^e
Ipundu North-1	Petroleum, QLD	<2	>5	Yes ^b	No	Pebble	Sharp, deformation, flame structures, angular	Wyandra not fully cored ^e
Kercummurra-1	Petroleum, QLD	<2	>5	Yes ^b	No	Pebble	n.d.	Base Wyandra not cored ^e
Kooropa-1	Petroleum, QLD	<2	>5	–	–	–	–	Wyandra not cored ^e
Talgeberry-1	Petroleum, QLD	<2	>5	Yes ^b	Yes, B	boulder	Sharp, undulose, erosional, cross-cutting	Wyandra not fully cored ^e
Talgeberry-2	Petroleum, QLD	<2	>5	Yes ^b	Yes	Cobble	Sharp, flame structures	Fig. 4E, Table 2
Tarbat-6	Petroleum, QLD	<2	>5	Yes ^b	Yes	boulder	n.d.	Fig. 5D
Tarbat-8	Petroleum, QLD	<2	>5	Yes ^b	Yes	Cobble	n.d.	Base Wyandra not cored ^e
Thargomindah-1	Strat, QLD	<2	>5	Yes ^b	Yes, B	Cobble	Sharp, erosional, flame structures in coal, deformation	Base Wyandra not cored ^e
Thargomindah-2	Strat, QLD	<2	>5	Yes ^b	Yes	Cobble	Sharp, undulose	Figs. 4A and 4B, Table 2
Tintaburra-2	Petroleum, QLD	<2	>5	Yes ^b	No	–	Angular, undulose, flame structures, deformation	Fig. 5B
Toby-1	Petroleum, QLD	2	>5	–	–	–	–	Wyandra not cored ^e
Eromanga-1	Strat, QLD	<4	<5	Yes ^b	Yes, B	Cobble	Undulose, erosional	Figs. 4C and 4I, Table 2
Tickalara-1	Strat, QLD	<4	>5	Yes ^b	Yes	Pebble	Sharp, undulose, erosional	–
Bulloo-1	Strat, QLD	5	>5	Yes ^b	Yes	Pebble	Sharp, erosional, cross-cuts rootlets	Figs. 4H and 5E
Connemara-1	Strat, QLD	>5	>5	Yes ^b	Yes	Pebble	Sharp, angular, erosional	Fig. 5C

Table 3. *Continued.* Observations at 31 well locations.

Well name	Well type, location	Approx. distance from Tookoonooka (Rc) ^a	Approx. distance from Talundilly (Rc) ^a	Accretionary impactoclasts present in Wyandra?	CSBC beds present in Wyandra? ^c	Maximum grain size ^d within Wyandra CSBC or MSBC beds	Basal Wyandra contact	Comments
Dullingari-1	Petroleum, SA	> 5	> 10	n.d.	No	–	n.d.	Wyandra not fully cored; base Wyandra not cored ^e
Jundah-1	Strat, QLD	> 5	< 4	Yes ^b	Yes	Pebble	Sharp	–
Mirintu-1	Petroleum, QLD	> 5	> 5	Yes ^b	Yes, B	Pebble	Sharp, erosional, cross-cuts rootlets, cross-cuts laminations at low angle	Wyandra not fully cored ^e Fig. 4D, Table 2
Quilpie-1	Strat, QLD	> 5	< 5	Yes ^b	Yes, B	Cobble	Sharp	Table 2
Wyandra-1	Strat, QLD	> 5	> 5	Yes ^b	Yes	boulder	Sharp, cross-cuts paleosol	Figs. 4G and 5A
Augathella-2-3R	Strat, QLD	> 10	< 4	n.d.	No	–	Sharp	–
CBH-2	Petroleum, SA	> 10	> 10	Yes ^b	Yes	Pebble	Sharp	–
Cootabar/low-2	Petroleum, SA	> 10	> 10	n.d.	No	–	Sharp	Wyandra may not be fully cored ^e
Machattie-1	Strat, QLD	> 10	> 5	Yes ^b	Yes	Pebble	Sharp, erosional	Fig. 5F
Maneroo-1	Strat, QLD	> 10	< 4	Yes—rare	Yes	Pebble	Sharp	Fig. 4F
SPH-1	Mineral, SA	> 10	> 10	–	–	–	–	Wyandra not present
Skeleton-2	Strat, SA	> 10	> 10	n.d.	No	–	n.d.	Wyandra not fully cored ^e
Tambo-2	Strat, QLD	> 10	< 4	Yes ^b	No	Pebble	Sharp	–

Drill cores are from stratigraphic, petroleum, and mineral wells from Queensland and South Australia government and Santos Ltd. core libraries; well locations are shown on Fig. 1. Stratigraphic well cores are 47.6 mm in diameter, petroleum well cores are usually 65 mm or 100 mm in diameter. “n.d.” indicates not applicable. “–” indicates not detected.

^aRc = Crater Radii, measured from crater center. Tookoonooka original crater diameter is most recently estimated at 66 km (Gostin and Therrault 1997), therefore 1 Rc = 33 km, or the distance from the crater center to the crater rim. Talundilly crater diameter is taken as 95 km as originally estimated, thus 1 Rc for Talundilly is 47.5 km.

^bObservations from Bron (2010).

^c“B” indicates that a basal Wyandra breccia-conglomerate layer is present.

^dMaximum grain-size is apparent grain-size within the context of drill core width. In stratigraphic well cores (4.76 cm in width), clast sizes larger than pebbles can often not be recognized; maximum clast size is restricted by the core width and may be larger than indicated.

^eDiscontinuous core, thus data may be incomplete.

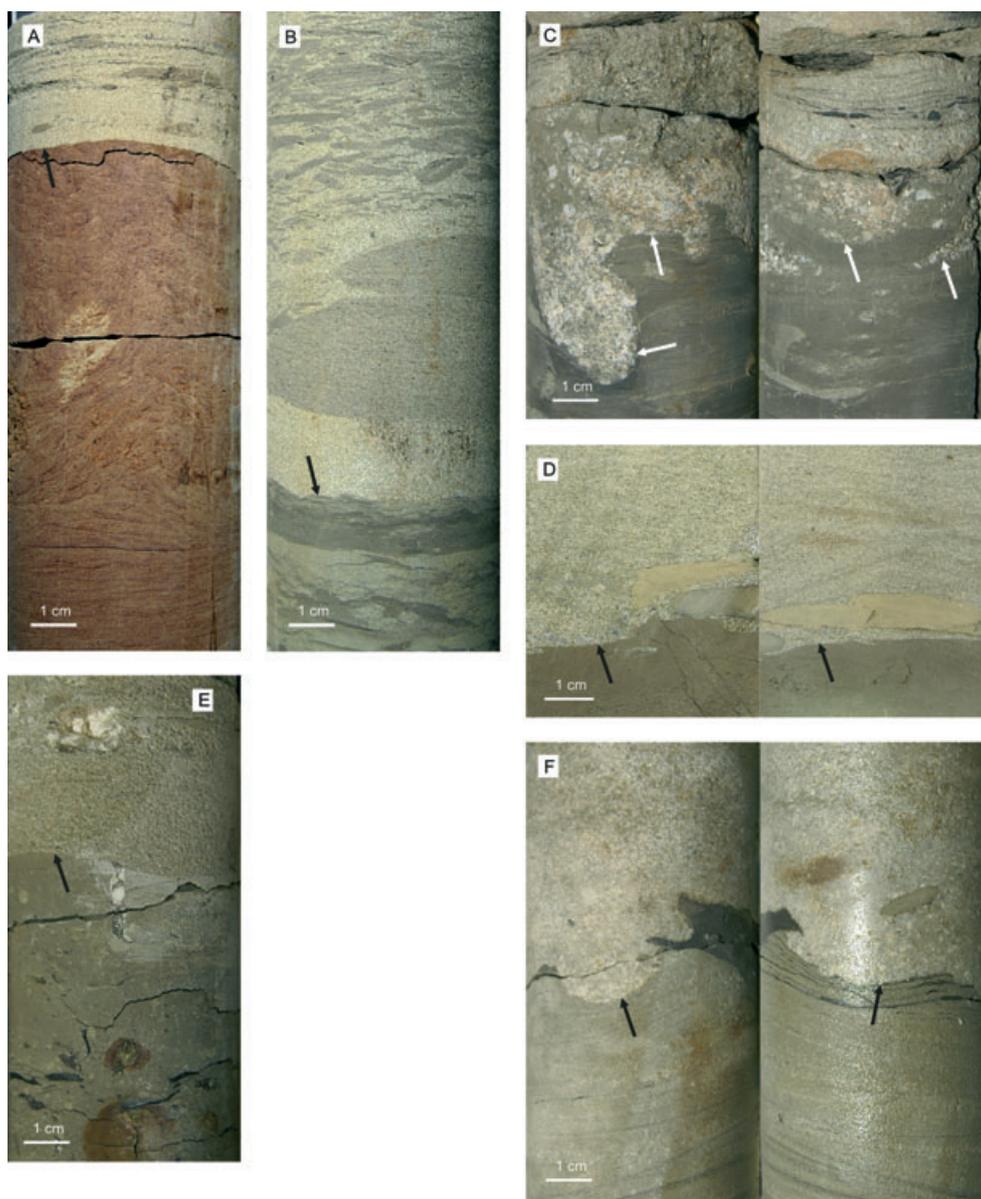


Fig. 5. Core photos showing the abrupt nature of the basal Wyandra contact (indicated by arrows). A) At GSQ Wyandra-1, gray Wyandra planar-bedded sandstone with floating pebbles sharply overlies red, convoluted sandstone bedding or sandy paleosol of the Cadna-owie. B) GSQ Thargomindah-2. Large rip-up clasts floating in sandstone above sharp undulose contact defined by minor flame structures and microfaults. The Cadna-owie below the contact is burrowed interbedded sandstone and siltstone. C) GSQ Connemara-1 (2 views of core). Scours filled with coarse lithic material define the erosional contact; dark, sandy, bioturbated Cadna-owie siltstone was partially ripped up by the scouring. D) Contact at Talgeberry-2 (2 views of core). Beige-gray Wyandra sandstone with floating, angular clasts (sedimentary lithics), overlying dark brown, silty, homogeneous mudstone of the Cadna-owie. Contact is sharp, and exhibits flame structures. E) GSQ Bulloo-1. Contact cross-cuts mudstone unit of the Cadna-owie with rootlets and burrows. Sparse, altered accretionary impactoclasts float in the sandstone above the contact. F) GSQ Machattie-1 (2 views of core). Fine-grained, cross-laminated sandstone of Cadna-owie underlies coarser, calcite-cemented Wyandra sandstone with floating pebbles and rip-up clasts. Contact is scoured, and cross-cuts underlying bedding, which exhibits minor deformation structures.

largely devoid of bioturbation; both sandstone beds and siltstone interbeds appear unaltered by burrowing activity. Across the study area, the base of the Wyandra typically marks an abrupt cessation of bioturbation and rootlets (e.g., Figs. 5B, 5C, and 5E).

Petrographic Results

Petrography of the Cadna-Owie

In the upper Cadna-owie sample from Eromanga-1, microscopic analyses (Table 1) revealed that clast compositions

Table 4. Summary of analyses and interpretations for three samples.

Well	Thargomindah-1	Eromanga-1	Eromanga-1
Stratigraphic interval	basal Wyandra CSBC	basal Wyandra CSBC	upper Cadna-owie
Depositional environment	High energy Marine	High energy Marine	Low energy, cold Marine
Metrics	Median grain size ^a (phi) Mean grain size ^b (phi) Mode or modes	0.17 (CGR sand) ^a 0.03 (CGR sand) Bimodal: 1) VCGR sand 2) FGR sand	2.46 (FGR sand) 2.41 (FGR sand) Unimodal: 1) VFGR sand
	Apparent sorting ^c (phi) Skewness ^a (phi)	1.74; poorly sorted -0.11; coarse-skewed ^a	0.74; moderately sorted -0.03; near-symmetrical
Classification ^d	Rock type	Sandy breccia-conglomerate Lithic arenite	Muddy sandstone
	Maturity ^e	Immature: angular and coarse clast content; poorly sorted; bimodal	Arkosic arenite Submature-mature: persistently FGR and well sorted
CSBC content comparison ^f	Quartz content	51:49 (mod mature) Prominent Qm and Qh volumes	30:70 (immature)
	Lithic content	Similar to Eromanga-1 r.e. L variety. Twice L volume of Cadna-owie.	-
	Impactoclast content	Basal CSBC bed has significantly greater volume and grain size range of Limp clasts than Eromanga-1 basal CSBC bed.	Four times L volume of Cadna-owie. Accretionary impactoclasts not prominent in basal CSBC bed. Other CSBC beds coarser than Thargomindah-1.

Note: Grain sizes are abbreviated as follows: VFGR = very fine-grained; FGR = fine-grained; MGR = medium-grained; CGR = coarse-grained; VCGR = very coarse-grained.

^aMedian and skewness are not useful metrics for bimodal samples but are shown here for comparative purposes.

^bM9 method was used to calculate mean grain size.

^cGrain size analyses by thin section give a value of *apparent* sorting: sediments may not be as poorly sorted visually as they appear in thin section (Tucker 2001). Values for CSBC beds indicate that they would probably still be poorly sorted visually, but Cadna-owie sample would be moderately well-sorted visually.

^dClassifications using: Blair and McPherson (1999), Pettijohn et al. (1987), and Tucker (2001).

^eThe application of maturity concepts is only moderately relevant here, as it applies mainly to sandstones and conventional sedimentation processes; it is used here for the sole purpose of contrasting the CSBC layers to the background sedimentation. Compositional maturity formula after Pettijohn et al. (1987): Q + Lch:F + L-Lch; volumetric data used in calculation.

^fSee Table 5 for mineral abbreviations.

Table 5. Petrographic results for three thin sections.

Well	Eromanga-1	Thargomindah-1	Eromanga-1	CSBC coarse	CSBC very		
Stratigraphic interval	Cadna-owie	Wyandra CSBC	Wyandra CSBC	grain fraction ^a	angular grain fraction ^a		
Grain size data (%)							
Very coarse pebble	n.d.	n.d.	n.d.	–	–		
Coarse pebble	n.d.	0.7	0.3	–	–		
Medium pebble	n.d.	1.3	1.3	–	–		
Fine pebble	n.d.	2.3	2.3	–	–		
Granule	n.d.	9.0	10.2	–	–		
Very coarse sand	n.d.	26.2	4.9	–	–		
Coarse sand	n.d.	9.0	3.9	–	–		
Medium sand	2.0	19.6	12.1	–	–		
Fine sand	22.8	24.6	42.0	–	–		
Very fine sand	59.2	6.0	19.0	–	–		
Coarse silt	12.2	1.3	3.6	–	–		
Medium silt	3.1	n.d.	0.3	–	–		
Fine silt	0.7	n.d.	n.d.	–	–		
Very fine silt	n.d.	n.d.	n.d.	–	–		
Total	100	100	100	–	–		
Grain shape data (%)							
Well-rounded	17.0	5.0	9.2	–	–		
Rounded	12.8	20.9	16.8	–	–		
Subrounded	28.0	25.3	19.5	–	–		
Subangular	32.3	23.9	18.8	–	–		
Angular	9.9	16.9	21.5	–	–		
Very angular	n.d.	8.0	14.2	–	–		
Total	100	100	100	–	–		
	Count or volume ^c	Count	Volume	Count	Volume		
Grain mineralogy data ^b (%)							
Q (undiff)	2.6	4.6	3.3	1.6	0.4	1	n.d.
Qi (undiff)	3.6	10.5	7.7	7.6	1.7	1	n.d.
Qiv	6.2	3.1	2.3	8.2	2.1	1,2	1,2
Qip	n.d.	3.4	3.0	2.2	0.9	1,2	1,2
Qm	1.6	15.4	20.8	3.2	6.0	1,2	1
Qh	n.d.	10.8	10.3	3.5	2.5	1,2	1
Total quartz	14.0	47.7	47.3	26.3	13.5	–	–
F (undiff or alt)	24.0	13.9	7.9	16.1	3.6	2	n.d.
Fp	12.0	4.3	2.4	2.8	0.6	n.d.	1,2
Fk	3.9	0.3	0.2	0.6	0.1	n.d.	n.d.
Total feldspar	39.9	18.5	10.5	19.6	4.4	–	–
L (undiff)	2.9	n.d.	n.d.	1.6	0.4	n.d.	n.d.
Lch	7.8	2.2	1.2	9.8	7.5	1,2	2
Ls other	n.d.	5.2	4.2	2.2	53.3	1,2	1,2
Lm	n.d.	0.6	1.2	1.3	4.0	1,2	n.d.
Li	8.4	7.1	4.0	5.4	8.9	1,2	n.d.
Lh	n.d.	0.9	0.7	n.d.	n.d.	1	n.d.
Limp	n.d.	8.3	25.5	6.3	1.4	1,2	1
Total lithics	19.2	24.3	36.8	26.6	75.5	–	–
Bio	10.1	3.1	1.7	7.6	1.8	1,2 minor	2
O and goeth	1.9	2.5	1.4	8.5	1.9	n.d.	n.d.
Mica	6.2	0.9	0.5	1.9	0.4	1,2 minor	1
Amph and pyroxene	3.9	n.d.	n.d.	1.9	0.4	n.d.	n.d.
Glauconite	0.3	0.6	0.4	0.6	0.1	n.d.	n.d.
Chlorite	0.6	0.6	0.4	0.3	0.1	n.d.	n.d.

Table 5. *Continued.* Petrographic results for three thin sections.

	Count or volume ^c	Count	Volume	Count	Volume		
Heavy minerals	0.6	n.d.	n.d.	1.6	0.7	2	2
Other	3.2	1.8	1.0	5.1	1.1	n.d.	n.d.
Total	100	100	100	100	100	–	–

Note: “n.d.” = not detected.

^aVery angular clast shapes and coarse-grained sand-coarse pebble grain sizes are present in CSBC beds, but absent in the Cadna-owie. 1 = observed in Thargomindah-1 CSBC bed; 2 = observed in Eromanga-1 CSBC bed.

^bDetrital grain mineralogy only; e.g., feldspar grains altered to clays, fine-grained mica, or carbonate are recorded as “F.” Abbreviations are as follows: “undiff” = mineralogy undifferentiated due to grain size or excessive alteration, etc.; “alt” = heavily altered; “Q” = quartz; “Qi” = igneous or common quartz, with “Qiv” (volcanic source) and “Qip” (plutonic source) distinguishable; “Qm” = metamorphic quartz; “Qh” = hydrothermal or vein quartz; “F” = feldspar; “Fp” = plagioclase; “Fk” = K-feldspar; “L” = rock fragment (lithic); “Lch” = chert of sedimentary or volcanic origin; “Ls” = sedimentary rock clast; “Lm” = metamorphic rock clast; “Li” = igneous rock clast; “Lh” = hydrothermal (vein) rock clast; “Limp” = melt and accretionary impactoclasts; “Bio” = carbonaceous material, organic debris, plant fragments, or bioclasts; “O and goeth” = opaques and iron oxy-hydroxides; “Amph” = amphibole. Heavy minerals include apatite, garnet, zircon, epidote.

^cFor Cadna-owie thin section, due to small grain-sizes, % count values are equivalent to % volume values.

are dominated by feldspar (40%), lithics (19%), and quartz (14%); data and analyses from point-counting are presented in Tables 4 and 5, and Figs. 6–7. Feldspars commonly display dissolution textures and heavy alteration. Of the lithic component, cherts and volcanic grains are prominent, whereas metamorphic, hydrothermal, melt, and accretionary clasts, and nonchert sedimentary lithic clasts are absent (Fig. 7D). Of the quartz grains, igneous grains are most common, few metamorphic quartz grains were observed, and no hydrothermal (vein) quartz is present (Fig. 7C). Organic material (plant debris), mica, altered amphibole, pyroxene, opaques, and bioclasts are present in decreasing amounts, in addition to accessory minerals (Table 5). The Cadna-owie is compositionally an arkosic arenite (Fig. 7A).

The Cadna-owie is unimodal, with a narrow, near-symmetrical grain size spread (Fig. 6A, Table 4). Ninety-eight percent of grains are less than medium-grained sand size, and approximately 5% of the grains are medium silt size or smaller, which implies that the rock is matrix-poor (e.g., Pettijohn et al. 1987). Texturally, the Cadna-owie is a muddy sandstone (Fig. 7B). Ten percent of the grains are angular (Table 5). This angular fraction is all fine-grained sand size or smaller, and is mainly comprised of feldspar.

Petrography of Basal Wyandra CSBC Beds

Point-counting revealed that the Thargomindah-1 and Eromanga-1 CSBC beds at the base of the Wyandra contain a similar variety of detrital clast compositions (Fig. 6, Tables 2 and 5). Volumetrically, the most common components are quartz and lithics, with lesser feldspar. Of the quartz grains, metamorphic species are predominant, followed by igneous and hydrothermal grains (Fig. 7C). Of the lithics in the Thargomindah-1 bed, altered melt and accretionary clasts, sedimentary clasts, volcanic clasts, chert,

and metamorphic clasts are present in decreasing order (Fig. 7D). Minor amounts of hydrothermal lithics are also present. Clasts interpreted to be devitrified and altered melt material, including rare microcrystalline quartz spherules, and accretionary impactoclasts account for about 8% of the grains (25% volumetrically). Some melt clasts exhibit flow-banding textures and aerodynamic shapes, and are described in more detail by Bron (2010). The melt clasts are relatively less altered than the volcanic lithics; the latter are often greenish in color and have a texture defined by feldspar laths. Accretionary impactoclasts in thin section often show distinctive concentric zoning, very fine-grained internal texture, and are usually tan to light gray in color. Of the lithics in the Eromanga-1 bed, nonchert sedimentary rock varieties are predominant, followed by volcanic, chert, and metamorphic grains (Fig. 7D). Altered melt clasts are also present. The CSBC beds have experienced significant diagenetic alteration, particularly the feldspar, volcanic lithic, and melt and accretionary components.

Grain size and grain shape analyses show that the two Wyandra CSBC beds are poorly sorted and distinctly bimodal (Table 4, Fig. 6). Clast sizes span from medium silt to coarse pebble. Coarse-grained sand to pebble-sized clasts account for 23–49% of the grains; this coarse fraction is dominated by lithics and quartz, particularly metamorphic and hydrothermal quartz, chert, accretionary impactoclasts, and sedimentary rock fragments. The angular to very angular fraction of the clasts (comprising 25–36% of the grains; Table 5) is dominated by quartz, feldspar, and lithic fragments. Amongst the very angular grains (8–14% of the grains), a grain shape that is not present in the Cadna-owie data set, quartz is predominant in both beds. These CSBC beds can be classified texturally as sandy conglomerate and conglomerate, respectively, and compositionally as lithic arenites (Figs. 7A and 7B).

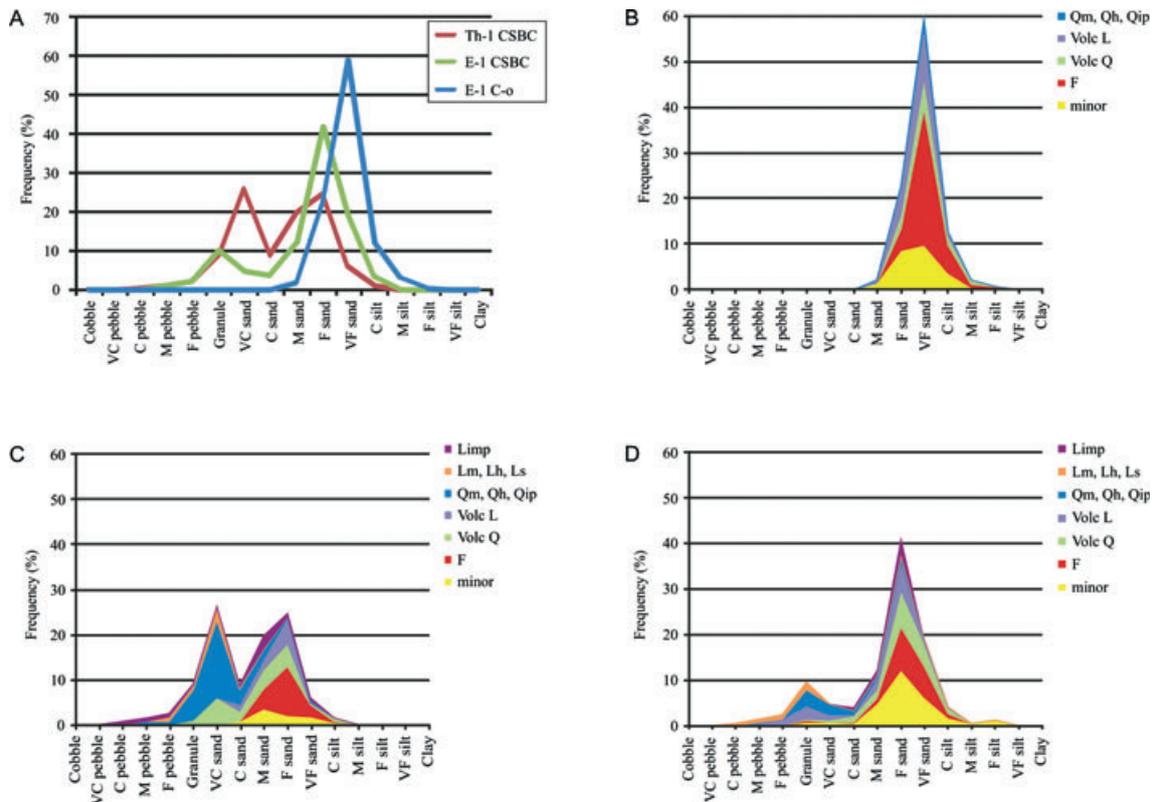


Fig. 6. Grain size distributions from thin section observations. See Table 5 for mineralogy abbreviations. A) Frequency (%) distribution versus grain size for 3 thin sections: Thargomindah-1 (Th-1) and Eromanga-1 (E-1) basal Wyandra CSBC beds, and Eromanga-1 Cadna-owie (C-o). See Table 1 for data set details. B–D) Frequency (%) distribution curves of grain sizes with stacked mineralogy for 3 thin sections. B) Eromanga-1 Cadna-owie. C) Thargomindah-1 basal Wyandra CSBC bed. D) Eromanga-1 basal Wyandra CSBC bed.

Shock-Metamorphosed Grains

Petrographic observations in the Thargomindah-1 and Eromanga-1 CSBC beds at the base of the Wyandra include shock-metamorphosed grains. Monocrystalline and polycrystalline quartz grains as well as quartz within lithic clasts exhibit PDFs and PFs. A brownish “toasted” appearance of quartz was also commonly observed. Shock data will be presented in a separate, forthcoming publication. Two shocked polycrystalline grains are illustrated in Fig. 8. Most shocked grains lie in the coarse-grained sand to fine pebble size fraction. No shock-metamorphosed grains were observed in the Cadna-owie analysis.

INTERPRETATIONS AND DISCUSSION

All sedimentary and petrographic observations suggest that the onset of Wyandra deposition indicates a sudden, regional change in sedimentation style, depositional energy, and sediment source. The consistency of the Cadna-owie sedimentation over time and area suggests a depositional environment of little change. The unimodality and mean grain size of the Cadna-owie suggest a degree of maturity

and grain recycling concomitant with poor sediment supply in a low-energy environment of regional extent. Similarly, in the Walumbilla, dark shales indicate a quiescent depositional environment, although in deeper marine conditions than the Cadna-owie. Shell hash indicates redeposition of broken shell into deeper water by occasional storm events. In contrast, a high-energy depositional environment of the Wyandra is indicated by scours, imbricated pebbles, and the predominance of high flow regime sedimentary structures. The Wyandra records the sudden, basin-wide appearance of a coarse and angular grain fraction absent in the Cadna-owie; the bimodality of CSBC beds at the base of the Wyandra confirms the presence of two grain populations (and thus two sources) when compared with the unimodal Cadna-owie (Fig. 6). The finer-grained mode of the CSBC beds mirrors the Cadna-owie mode, whereas the abrupt appearance of the coarser mode befits a catastrophic emplacement mechanism. In the absence of volcanism and significant tectonism in the flat-lying basin, this coarser mode is interpreted to derive from the Tookoonooka impact event. This coarser “impact” mode is more pronounced at Thargomindah-1 than at Eromanga-1: the

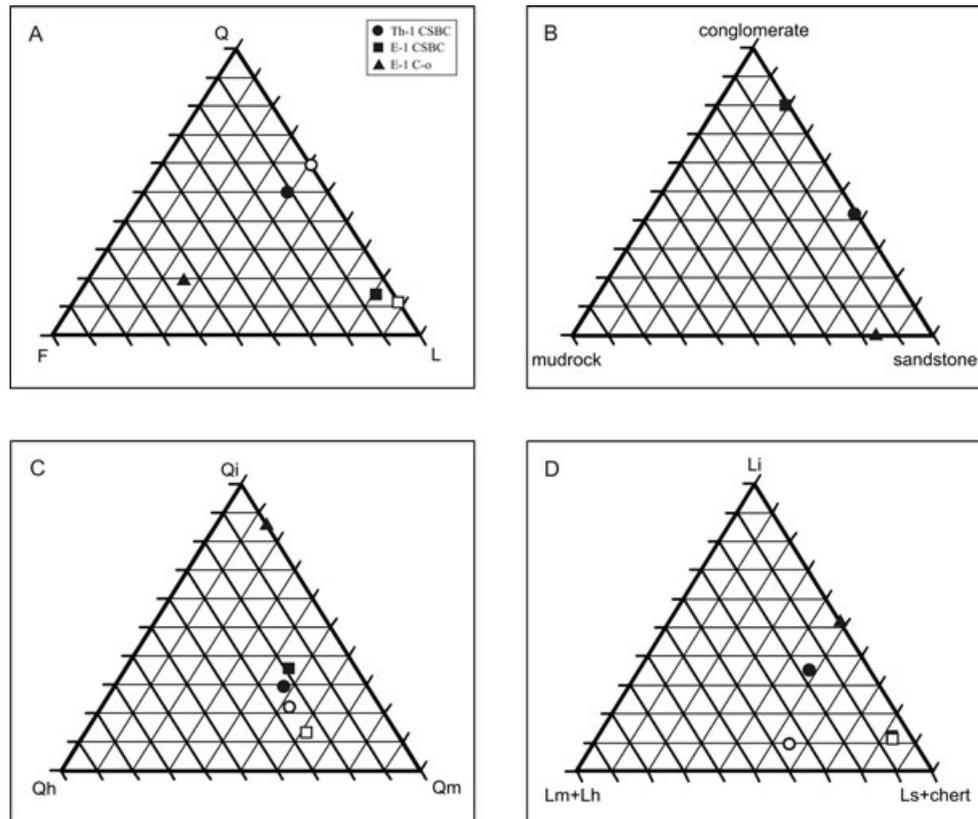


Fig. 7. Ternary plots for 3 thin sections, using volumetric data. Solid data points represent bulk volumes, white-filled data points represent Wyandra CSBC bed coarse fractions only (grain sizes not present in Cadna-owie, i.e., CGR sand to pebble size fraction). Classifications after Pettijohn et al. (1987) and Tucker (2001). See Table 5 for mineralogy abbreviations. A) Q-F-L plot for sandstone composition classification. Chert is included with lithic grains. B) Grain size plot for rock texture classification. C) Plot of quartz clast compositions. D) Plot of lithic clast compositions. Does not include melt and accretionary impactoclast grain population.

differences in the skewness, median, and mean grain sizes of the CSBC beds suggest that sediment transport occurred from Thargomindah-1 to Eromanga-1 (cf. Tucker 2001) and that dilution of ballistic ejecta (with ambient sediments) occurred distally; i.e., toward Eromanga-1 (cf. Melosh 1989). This is consistent with Tookoonooka as the possible source. As basal Wyandra CSBC beds record the first presence of this coarse material, they probably represent the least reworked Tookoonooka ejecta beds in the basin, and may record immediate postimpact sedimentary processes.

The abrupt Cadna-owie-Wyandra contact appears to be an unconformity across the entire basin. Additional observations by Dettman (1985) and Gallagher et al. (2008) in South Australia and at the Aros-2 well location (Fig. 1), respectively, support this view. Our observations of the erosional character of this contact and the sudden shift from a heavily burrowed Cadna-owie to a virtually unbioturbated Wyandra are basin-wide. Flame structures at the contact imply that rapidly deposited volumes of sediment caused sediment loading and water escape. Water escape structures are unexpected in the Cadna-owie's

depositional context, and thus evidence seismicity or the higher sedimentation rate of the Wyandra. Scouring observed at the contact may explain the absence of basal Wyandra CSBC beds at many of the locations studied. Although a regional Tookoonooka ejecta blanket may initially have existed, it is likely that at many locations, it was eroded by scouring or reworking subsequent to emplacement. Deformed rip-up clasts of likely Cadna-owie origin within the Wyandra are further evidence of this scouring. From these observations, we interpret that the Cadna-owie-Wyandra contact represents an event horizon of regional significance: the Tookoonooka event horizon.

The abundant deformation observed throughout the greater basin below the Cadna-owie-Wyandra contact in the Cadna-owie and Murta (Hooray) Formations (also observed by John and Almond 1987) may be another impact indication. Significant paleoslope, a common requirement for some of the deformation structures observed, is suggested by neither the flat-lying sediments of the Cadna-owie nor the scale of their lateral continuity in the basin. Rather, the soft-sedimentary deformation and microfaults, in addition to deformed rip-up clasts,

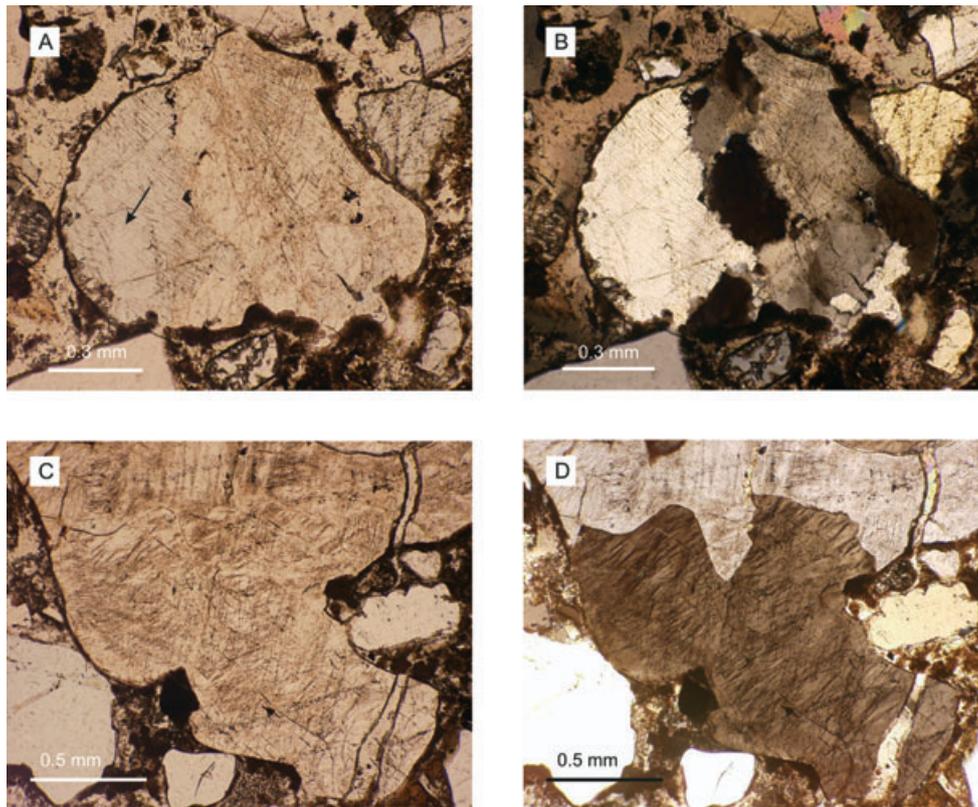


Fig. 8. Petrographic photos of two shocked grains within the Eromanga-1 basal Wyandra CSBC bed. Each grain is shown under both plain light (left) and crossed polars (right). A and B) A toasted, polycrystalline metamorphic quartz grain, exhibiting multiple sets of planar microstructures under the petrographic microscope. Universal stage measurements in various subcrystals indicate that up to three sets of PDFs are present per subcrystal, and include the following orientations: $\{10\bar{1}2\}$, $\{11\bar{2}2\}$, $\{21\bar{3}1\}$, and $\{11\bar{2}1\}$, the latter indicated by an arrow in the largest subcrystal. At least two sets of PFs are also present, with orientations of $\{51\bar{6}1\}$ and $\{11\bar{2}0\}$. C and D) Very irregularly shaped lithic clast with toasted appearance. Universal stage measurements in quartz crystals within this clast indicate that up to six sets of PDFs are present per crystal, and include only higher angle PDF plane orientations $\{10\bar{1}2\}$ and above, consistent with previous measurements made at Tookoonooka (Gostin and Therriault 1997). No basal $\{0001\}$ or $\{10\bar{1}3\}$ PDF orientations were observed in these two grains, which is consistent with observations at other sedimentary target impact sites (Grieve et al. 1996).

suggest that the quiescent sedimentation of the Cadna-owie was disrupted by a widespread seismic event that preceded or coincided with the onset of Wyandra deposition. They are interpreted to be impact seismites: the response of water-rich, ductile soft sediments, and partly lithified sediments to the passage of impact seismic waves through the sediment (cf. Shiki et al. 2000). We also interpret the presence of similar, likely time-equivalent deformation structures in the sediments of Tookoonooka's outer crater structure at Thargomindah-3, also observed by Young et al. (1989), to evidence impact-related fluidization and deformation.

Sediment Provenance

Clear differences in the composition of the Wyandra CSBC beds and the Cadna-owie sediments give provenance indications that are interpreted to signal the influx of

Tookoonooka impact ejecta (Figs. 6 and 7; Table 4). The Cadna-owie's sandstone composition suggests in part a mafic volcanogenic source. Volcanic lithics could only derive from recycled basement rock (Harrington and Korsch 1985) or contemporaneously from the distal eastern margin of Australia (Wiltshire 1989; McDougall 2008), the latter requiring an aeolian transport indication in the Cadna-owie given the basin's low relief and the ex-basin source. The Cadna-owie's slight negative skewness (Table 4) may suggest an aeolian component (cf. Tucker 2001). In contrast to the underlying Cadna-owie, the Wyandra CSBC beds are interpreted to be laden with impact ejecta.

The most compelling evidence of impact in the Wyandra CSBC beds is the presence of significant volumes of melt and accretionary clasts and shock metamorphosed grains. The melt and accretionary clasts clearly have a different origin than the volcanics discussed above. They

Table 6. Interpreted clast provenance from petrographic results: differentiation of an impact assemblage from the ambient sediments.

Clast mineralogy ^a	Cadna-owie “ambient” assemblage	“Impact” assemblage	Comments on source
Qiv	Y	Y	Both
Qip	n.d.	Y	–
Qm	Y	Y	Both
Qh	n.d.	Y	–
Fp	Y	Y	Both
Fk	Y	n.d.	–
Lch	Y	Y	Both sedimentary and volcanic origin. Minor in Thargomindah-1
Ls	Minor	Y	–
Lm	n.d.	Y	–
Li	Y	Y	Both. Minor in Thargomindah-1
Lh	n.d.	Y	–
Limp	n.d.	Y	Minor in Eromanga-1
Bio	Y	n.d.	Organics of diagenetic origin not included here
Mica	Y	Minor	–
Amph and pyroxene	Y	n.d.	–
Glauconite	Y	n.d.	–
Heavy minerals (e.g., apatite, garnet, zircon, barite)	Y	Y	Both

Notes: Y = present; n.d. = not detected.

^aSee Table 5 for mineral abbreviations.

are thought to provide substantive evidence of impact, and are thus termed melt and accretionary *impactoclasts* (cf. Bron 2010). The diagenetically altered nature of these clasts suggests chemical instability, which, in combination with their high energy mode of deposition, suggests that they experienced little reworking and quick burial. The nearby Tookoonooka structure is the likely source of these clasts. The presence of shocked grains in the Wyandra CSBC beds compared with an absence of shocked grains in the Cadna-owie represents diagnostic evidence of the arrival of impact-derived material at the base of the Wyandra. The association of the shocked grains with the coarser grain size mode of the Wyandra CSBC beds also indicates that CSBC material is from a different source than the Cadna-owie sediments.

The high proportion of lithics and quartz in the Wyandra CSBC beds clearly implies that the Wyandra CSBC beds are compositionally unrelated to the source of the considerable underlying thickness of Cadna-owie sediments. The Wyandra CSBC beds, particularly the coarse realm, are richer than the Cadna-owie in metamorphic, hydrothermal, chert, and sedimentary lithic clasts as well as metamorphic and vein quartz species (Figs. 7C and 7D). Many of the coarse lithic clasts observed in the Wyandra at numerous locations, particularly light green and greenish-blue metasedimentary clasts and veined grayish quartzite clasts, appear identical to basement

lithologies in the Tookoonooka central uplift (at Tookoonooka-1) and Thargomindah Shelf basement rocks at depth in Thargomindah-1. At least 7 wells from the Tookoonooka structure encountered similar basement lithologies at depth (QPED, 2009). The Tookoonooka impact event excavated Jurassic-Cretaceous Eromanga Basin sediments, metasedimentary basement rock of the Thargomindah Shelf, and possibly Permo-Triassic Cooper Basin sediments (Gorter et al. 1989; Longley 1989; Gostin and Therriault 1997). Thus, much of the lithic and quartz content in the Wyandra is interpreted to derive from this “fresh” source in the form of ejecta, and includes Tookoonooka basement material. Nearby wells beyond the crater structure indicate that, at present-day compaction, the average thickness of strata between the base of the Wyandra and the basement is approximately 450 m (QPED, 2009). Thus, the impact would have excavated this thickness of preimpact strata (target sequence) at a minimum. The enhanced quartz content is responsible for the compositional maturity of the Thargomindah-1 basal Wyandra CSBC bed relative to the Cadna-owie. The different proportion of quartz and lithics in the two basal Wyandra CSBC beds analyzed could be due to heterogeneous ejecta distribution.

As a result of our analyses, two distinct clast assemblages have emerged: a Cadna-owie (ambient sedimentation) clast assemblage and an interpreted impact

assemblage (Table 6, Figs. 6B–D). It is important to note that as the Cadna-owie sediments were part of the Tookoonooka target sequence and they were probably locally mixed with the ejecta (e.g., by ballistic sedimentation processes cf. Melosh 1989; impact tsunami scour, or postimpact sedimentary reworking), some overlap in the assemblages would be expected. From impactite terminology (cf. Stöffler and Grieve 2007), the basal Wyandra CSBC beds at Thargomindah-1 and Eromanga-1 could be classified as proximal, allochthonous, polymict impact breccia and basal Wyandra CSBC beds in wells beyond 5Rc could be considered distal air fall beds (with shocked and unshocked clasts). However, this classification refers to initial ejecta deposits and does not take into account reworking of ejecta by postimpact processes, or dispersal of ejecta by waves and currents in a marine impact scenario.

Distribution

The Wyandra breccia-conglomerate beds described appear concurrently across the basin at the same stratigraphic level. Their distribution corresponds to a spatial extent of about 400,000 km², and suggests a regionally instantaneous mechanism of deposition. This distribution correlates roughly with the presumed extent of the Eromanga Basin in the late Lower Cretaceous, and correlates with the occurrence of accretionary and melt impactoclasts within the Wyandra observed by Bron (2010). It is interpreted to be the known limit of the Tookoonooka impact deposits.

The Age of the Tookoonooka Impact Event

From the many indications discussed above, the basal contact of the Wyandra is considered to be the Tookoonooka impact horizon, corroborating the findings of Bron (2010). The base of the Wyandra is correlated with the base of the PK3 palynological zone and the Barremian-Aptian boundary by Gallagher et al. (2008). The timing of the Tookoonooka impact event is thus constrained to approximately 125 ± 1 Ma (Fig. 2). This provides a better constraint on the age of the Tookoonooka impact event than earlier estimates, and lies within the gross age range given by them.

Implications for the Impact Paleoenvironment and the Origin of the Wyandra Sandstone

Our observations of glauconite and bioturbation support previous work that indicates that Cadna-owie sedimentation occurred in a paralic to restricted shallow marine setting (summaries in Draper 2002; Krieg and Rogers 1995). These depositional environments appear to

have predominated prior to Wyandra deposition in the basin. However, our observations of occasional nonmarine sediments in the Cadna-owie, sometimes directly underlying the Wyandra, indicate the shallow nature of the epicontinental sea at time of impact, where shallow marine, marginal marine, swampy, and lagoonal environments coexisted. Paleogeographical reconstructions of the early to mid-Cretaceous imply that Tookoonooka was centrally located in the Eromanga Basin (Veevers 1984; Frakes et al. 1987; BMR, 1990), and that the Cretaceous Eromanga Sea covered a large part of central Australia by the time of impact. Interpretations by Bron (2010) regarding the origin of specific types of accretionary impactoclasts, which resemble hydroclastic volcanic accretionary lapilli, support a marine impact hypothesis. Thus, Tookoonooka was most likely a marine impact, and ejecta were deposited into a shallow sea and reworked in a marine environment before burial. Although the Wyandra has previously been interpreted to represent transgressive deposits (Senior et al. 1975; Exon and Senior 1976; Draper 2002), transgression cannot account for the sudden presence of the observed volumes of coarse sediments in the persistently fine-grained basin deposits of the time. As the Wyandra records a high energy of deposition and marine signature and occasionally overlies nonmarine sediments, this may indicate that the Wyandra was at least partially emplaced by impact tsunamis. Base surge mechanisms may have contributed to this deposition proximal to the crater.

Previous work implies that the geographical position of Tookoonooka in the Lower Cretaceous was ±65° latitude (Day 1969; Veevers 1984; Frakes et al. 1995; Klootwijk 2009). Near-freezing temperature mineralization in the Cadna-owie has been recorded from basin margin sites with an equivalent paleolatitude to Tookoonooka (De Lurio and Frakes 1999), and glacial lonestones in the Lower Cretaceous strata have been reported in the southwest of the basin (Frakes et al. 1995). Ice covering may have contributed to the low energy of the environment, and the potential for aeolian transport. In combination with a possibly semiarid climate (Fig. 7A), (cf. Tucker 2001), a suppressed weathering regime likely existed, evidenced by the presence of fresh feldspar in the Cadna-owie. Considerations of this paleoenvironment lead to new questions regarding how ejecta distribution was affected in a potentially ice-covered sea. For example, although much of the coarse material in the Wyandra is clearly impact-related, could air fall ejecta littered on distal ice have contributed to postimpact dropstones in the basin? Other considerations include how the impact affected the ice covering, the duration of impact-induced regional warming, and how impact mechanisms may have been affected by the presence of ice or frozen sediments, although the

thickness of the latter would have been minor relative to impact excavation depth.

Implications for Talundilly

A Talundilly ejecta contribution to the Wyandra will need to be considered if Talundilly is proven to be an impact coeval with Tookoonooka as has been speculated. However, there are at least four factors that could make the resolution of a Talundilly ejecta component in the CSBC beds problematic:

1. Heterogeneous distribution of ejecta lithologies almost always occurs at impact sites. There are two main reasons for this. First, heterogeneity in ejecta occurs with respect to depth of excavation of target lithologies: the innermost and uppermost material in the crater is more highly shocked and more distally deposited, while target material from the deeper and outer crater is deposited proximally (Melosh 1989). Second, for larger craters, lateral heterogeneity of the target material would be expected.
2. The original morphology of Tookoonooka's ejecta blanket cannot be precisely determined, as the ejecta were probably deposited and reworked in a marine environment. Thus, a Talundilly contribution would be difficult to resolve on ejecta distribution patterns alone.
3. Mixing of ballistic ejecta with pre-existing surface materials occurs to a greater extent at distance from the rim of a crater, resulting in distal dilution of the primary ejecta (Melosh 1989).
4. Precise impact target lithologies remain unknown. As a target sequence at point of impact is excavated by the cratering process and much of the crater rim (for Tookoonooka, and also likely for Talundilly) was eroded prior to burial (Gostin and Therriault 1997), we can only speculate on the true target sequence by correlation with surrounding rocks at depth.

Subtle differences in clast compositions between the Wyandra CSBC beds in Thargomindah-1 and Eromanga-1 (Table 4) may in part represent the different target sequences of Tookoonooka and Talundilly, respectively, based on crater proximity. Talundilly probably excavated Permo-Triassic Galilee Basin sediments, Devonian-Carboniferous Adavale Basin sediments, and various basement lithologies of the Maneroo Platform (granite, volcanics, and metasediments) in addition to Eromanga Basin sediments (Longley 1989; QPED 2009). The Maneroo Platform basement does not extend south to the Tookoonooka area (Longley 1989), thus differences between it and the Thargomindah Shelf basement may be a key factor in differentiating Talundilly lithic ejecta. For example, a distinct red granule in the basal Wyandra

CSBC bed at Eromanga-1 is similar to red volcanics of the Maneroo Platform at depth in Maneroo-1, whereas prominent metamorphic and vein quartz volumes in the basal Wyandra CSBC bed at Thargomindah-1 may represent a proportionally greater volume of metasedimentary rocks in the basement at Tookoonooka. The much greater volume of coarse sedimentary lithics in the Eromanga-1 bed are unlike the sedimentary lithics in the Thargomindah-1 bed and may originate from Adavale and Galilee Basin sedimentary rocks in Talundilly's target sequence. Adavale and Galilee Basin rocks predate the Eromanga Basin and are not known in the subsurface of the Tookoonooka area. Similarly, the population of coarse chert and volcanic lithics in the Eromanga-1 bed, insignificant in the Thargomindah-1 bed, may also reflect Talundilly's target sequence. Thus, a Talundilly signature is intimated, and may be resolved with future work. As impactoclasts are distributed beyond the location of Talundilly, itself about 10 Rc from Tookoonooka, and some distal Wyandra CSBC beds beyond Talundilly have thicknesses comparable to wells proximal to Tookoonooka, it seems likely that Talundilly could have contributed to this volume of ejecta.

CONCLUSIONS

For an impact crater the size of Tookoonooka, significant volumes of proximal and distal ejecta would be expected. Observations from 31 wells across the Eromanga Basin, covering an area of 400,000 km², imply that the Tookoonooka ejecta are indeed present in the basin, from proximal locations to well beyond 10 crater radii from the impact site. Evidence in the rock record shows:

1. The ambient (preimpact) sediments of the Cadna-owie Formation record a very low-relief, low-energy, low-sediment supply depositional setting with a marine signature and laterally persistent character.
2. Hundreds of meters of fine-grained Cadna-owie deposits are punctuated by an interval of relatively high-energy, high-sedimentation rate, coarse-grained and exotic lithic-rich deposition (the Wyandra Sandstone Member) before returning to quiescent, low-energy marine deposition.
3. Coarse breccia-conglomerate beds in the Wyandra Sandstone Member contain clasts of basement rock, shock metamorphosed grains, and accretionary and melt impactoclasts. An impact clast assemblage can be differentiated based on petrographic results.
4. The upper Cadna-owie contact with the base of the Wyandra is unconformable, and is accompanied by evidence of erosion, water escape, and underlying seismites.

We conclude that the first appearance of Tookoonooka ejecta in the sediment record most likely

occurs at the base of the Wyandra Sandstone Member in the Lower Cretaceous, equivalent to 125 ± 1 Ma. The Cadna-owie contact with the base of the Wyandra represents an event horizon of regional significance. The presence of basement clasts in sediments overlying this horizon is consistent with interpretations of Tookoonooka's transient crater excavation down to basement depths. Tookoonooka was a marine impact; CSBC beds at the base of the Wyandra probably record immediate postimpact sedimentary processes as ejecta were emplaced into a largely shallow, but potentially icy, sea. The low-energy setting in a transgressing epeiric sea presented an ideal opportunity for the preservation of these ejecta by burial.

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Editorial Handling—Dr. Gordon Osinski

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A Tsunamiite Petroleum Reservoir formed from a Binary Meteorite Impact?

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Tookoonooka and Talundilly are two coeval large meteorite impact structures buried within sedimentary rocks of central Australia (Gostin & Therriault 1997; Gorter & Glikson 2012a), and are not only a rare example of an ancient marine impact event (cf. Dypvik & Jansa 2003; Dypvik et al. 2004) but also an even rarer terrestrial example of a probable binary impact event (cf. Bottke & Melosh 1996a; Miljković et al. 2013). A preserved marine impact ejecta horizon spans a vast area of the Australian continent and corresponds to the extent of a Cretaceous epicontinental sea (Bron & Gostin 2012; Bron 2010). Here I present evidence that a sandstone reservoir overlying this horizon is the impact tsunamiite of what may be the largest doublet crater known on Earth.

Analyses of drill core, subsurface drilling data, and outcrops over more than 665,000 km² show that a widespread scour surface exists, which is attributed to impact excavation and tsunami scour mechanisms; removal of at least 30% of the underlying formation from 1-3 crater radii is evident. The stratigraphy of the overlying sandstone reservoir contains elements characteristic of impact tsunami deposition including entrained ejecta, boulder-sized rip-up clasts, highly polymictic clast beds of up to 16m thick, and cyclic sedimentation of tsunami couplets across five depositional realms. These elements contradict the uniformly low-energy nature of the ambient sedimentation, but are consistent with the intense seismicity and high energy seiche action expected following a marine impact in a mostly enclosed basin. A dual impact source is demonstrated, despite the complications of reworking and burial in a marine impact scenario, based on the sediment distribution patterns in combination with the proximity of the craters in age and location.

The Tookoonooka-Talundilly impact event may be an extreme prototype, as very few doublet craters, marine craters, impact tsunamiites, or economic impactites are individually known or preserved on Earth, yet this crater pair may represent all four. This doublet crater provides a model for binary marine impact sedimentation and highlights the significance of ancient impact sediments for petroleum basins. Tookoonooka-Talundilly may be the largest doublet crater on Earth, and presents the first binary impact tsunamiite from large meteorite impacts.

INTRODUCTION AND BACKGROUND

Two buried complex impact structures, Tookoonooka (Gostin & Therriault 1997; Gortler et al. 1989) and Talundilly (Gortler & Glikson 2012a; Longley 1989), are the likely dual source of a marine impact horizon in central Australia of approximately Barremian-Aptian boundary age (Bron & Gostin 2012; Bron 2010). In the early Cretaceous, a vast area of the continent was covered by a shallow, high latitude epeiric sea (Frakes et al. 1987; Veevers 1986) within a volcanically and tectonically inactive basin. The impact horizon is defined by: an erosional surface underlain by seismites; a cessation of bioturbation; the abrupt appearance of accretionary, melt and lithic impactoclasts in breccia-conglomerate beds; sudden high-energy deposition (Bron & Gostin 2012; Bron 2010); and a sudden shift in paleocurrent direction (Root et al. 2005; Musakti 1997). It has been suggested that sediments overlying this impact horizon would record immediately post-impact sedimentary processes such as impact tsunamis (Bron & Gostin 2012; Bron 2010). This paper thus focuses on the Wyandra Sandstone Member (Extended Data 2), a major aquifer and a producing petroleum reservoir (Senior et al. 1975; Root et al. 2005) which directly overlies the impact horizon, hosts the unusual sediments, and is enclosed within quiescent basin deposits. Though highly probable, Talundilly's impact origin is not yet fixed due to lack of drilling (and hence inability to sample in-situ shocked material): shock evidence of Talundilly's impact origin was only recently presented from a non-central drillhole in the buried structure (Gortler & Glikson 2012a), but microscopic analyses were done on allochthonous rather than autochthonous rocks and are not considered conclusive. However, Talundilly's potential contribution to these impact-related sediments cannot be ignored. With crater diameter estimates of 66 km (Gostin & Therriault 1997) and 84 km (Gortler & Glikson 2012a) respectively, Tookoonooka and Talundilly are potentially two of the largest ten impact structures on Earth, yet their contributions to the Cretaceous sedimentary record of Australia are not yet fully appreciated.

Doublet Craters

At least 185 confirmed impact structures are known on Earth (PASSC 2015), of which only 3-5 crater pairs have been identified as doublets, craters formed near-simultaneously from the same impact event, most likely a binary asteroid originating from gravitational aggregates/rubble piles (Bottke & Melosh 1996a; Miljković et al. 2013; Richardson et al. 2002). Well-separated doublet craters would be expected to represent ~2% of all terrestrial impacts based on the population of binary asteroids in the Near Earth Asteroid region. For distinguishable craters in close proximity, shared ejecta blankets would ideally point to a dual impact origin (Bottke & Melosh 1996b), however, for buried craters and marine craters (craters formed in the ocean), such evidence would be concealed or reworked. Tookoonooka and Talundilly's binary origin has thus far been speculated based on their seemingly common impact horizon (Bron & Gostin 2012) and their similar seismic structure and stratigraphy (Longley 1989; Gortler & Glikson 2012a; Gortler 1998). Petrographic work found subtle indications of duality in ejecta deposits which could point to a common impact event but indications could also be explained by unknown or heterogeneous target material or ejecta distribution (Bron & Gostin 2012). Thus, more definitive evidence of their binary impact origin remains to be demonstrated; this paper presents sedimentological evidence and a probability assessment in support of their doublet status.

Marine Impact Cratering

Marine impact structures are statistically under-represented according to expected oceanic cratering rates (Dypvik & Jansa 2003; Dypvik et al. 2004; Ormö & Lindström 2000): only 43 (~23%) of the confirmed impacts on Earth are probable marine (Extended Data 3), compared to an expected 70% (Dypvik & Jansa 2003; Dypvik & Kalleeson 2010). However, questions also remain as to how the terrestrial crater size-frequency distribution is affected by the Earth's ocean cover (Davison & Collins 2007). Of the known marine impact structures, Tookoonooka (Bron & Gostin 2012) and, by extension, Talundilly, are second in size only to Chicxulub. Marine craters vary widely in their features, governed by variables such as impacted water depth, impactor diameter, as well as the strength, porosity, and saturation of the target material, and differ in their morphology from dry target (i.e. subaerial) craters (Dypvik & Jansa 2003; Melosh 1989; Baldwin

et al. 2007; Gault & Sonett 1982). The nominal water depth required to form a marine crater and control cratering processes have been modelled, as has impact tsunami propagation (Glimsdal et al. 2010; Matsui et al. 2002): a large crater radius to water depth ratio (e.g. $d > 2H$, where d =impactor diameter and H =water depth (Shuvalov et al. 2008) applies to large craters formed in a shallow sea such as Chicxulub, Mjølner, Tookoonooka and Talundilly, and results in a well-defined crater and a temporarily dry seabed. Violent resurge into the crater (Simonson et al. 1999) initially precedes a radially propagating tsunami and is associated with rim collapse in unlithified sediments (Dypvik & Jansa 2003; Goto 2008) and ejecta/water curtain collapse (Ormö & Lindström 2000). The resurge and tsunamis of such shallow marine impacts cause strong sediment mixing and transport, significant suspension of seafloor sediments, and extreme alteration of the seabed (Glimsdal et al. 2010); evidence of the latter manifests as a basal unconformity of impact deposits proximal to craters, as observed from the examples of Chicxulub (Albertão et al. 2008; Goto et al. 2008), Kärddla (Suuroja & Suuroja 2006), Manson (Izett et al. 1998), Ames (Mescher & Schultz 1997) and Lockne (von Dalwigk & Ormö 2001; Lindström et al. 2008). In addition, complex stratigraphic architecture and multiple erosion surfaces in sedimentary sequences generated by varied depositional processes have been described from marine impact deposits (Dypvik & Jansa 2003; Goto 2008).

Depositional processes relating to marine impact cratering are not well-understood, being complex and simultaneously influenced by a number of high energy mechanisms such as ballistic sedimentation, base surge and debris flows in addition to crater resurge and tsunamis. Of these mechanisms, the marine depositional processes are sedimentologically alike (Dypvik & Jansa 2003), having in common high energy, sediment-saturated flow, and exceptional erosive potential. Base surges and tsunamis can both produce large-scale couplets (Fisher & Schmincke 1984): one example that these varied mechanisms share characteristics that cannot easily be process-differentiated. Nuclear explosions and explosive volcanism, the nearest known analogues for impact cratering on Earth, produce ejecta deposits emplaced by both ballistic sedimentation and base surge mechanisms (Melosh 1989; Fisher & Schmincke 1984). Fluidized ejecta flows around Martian craters are driven by substrate water content (Barlow 2005; Osinski 2006; Melosh 1989) which may be analogous to the water proportion in ejecta deposits of the shallowest marine craters.

Tsunami Sedimentation

Tsunamis are generated from four different mechanisms: earthquakes, slope failures, volcanism, and meteorite impacts (Dawson & Stewart 2007). Tsunami depositional processes are complex and varied, imitating characteristics of other abrupt, high-energy marine and littoral processes (Dawson & Stewart 2008). Tsunamiites (cf Shiki & Yamazaki 2008; Dawson & Stewart 2007) typically exhibit: unusually coarse sediment with exotic inclusions; erosional basal contacts; seismites; both muddy suspension deposits and organic terrestrial debris; sedimentary structures spanning the flow regime due to rapidly shifting flow velocities and current flow behaviour; a lack of bioturbation; bidirectional flow indications; tsunami couplets; multiple fining-up sequences; and an overall sheet-like morphology (Dawson & Stewart 2007; Shiki et al. 2008a; Morton et al. 2007; Nanayama & Shigeno 2006). Impact tsunamis differ from tsunamis generated from other mechanisms in scale, and thus depositional and erosive potential, and the presence of entrained impact debris (Dypvik & Jansa 2003; Sugawara et al. 2008). This is illustrated in Fig. 1. Reports of ancient tsunamiites from the rock record, particularly *impact* tsunami deposits, are uncommon and impact tsunamiites are the least understood (Dypvik & Jansa 2003; Dawson & Stewart 2007, 2008; Scheffers & Kelletat 2003). The staggering variety of tsunami-related deposits from the Chicxulub impact alone (Goto 2008) gives pause to the enormous task of defining the character of impact tsunami deposition, despite observed sediment thickness, cyclicity and current reversal trends. Only 13 marine impact craters have been associated with tsunami-like deposits (Extended Data 3). Kamensk-Gusev is a recognized marine doublet crater on Earth (Masaitis 1999; Masaitis et al. 1980; Bottke & Melosh 1996a; Miljković et al. 2013; Schmieder et al. 2014), and recent work has paired Lockne with Målingen (Alwmark et al. 2014; Ormö et al. 2014a). Kara-Ust Kara is also a possible marine doublet (Masaitis 1999; Masaitis et al. 1980; Bottke & Melosh 1996a), although Ust Kara's subsea location has limited its study

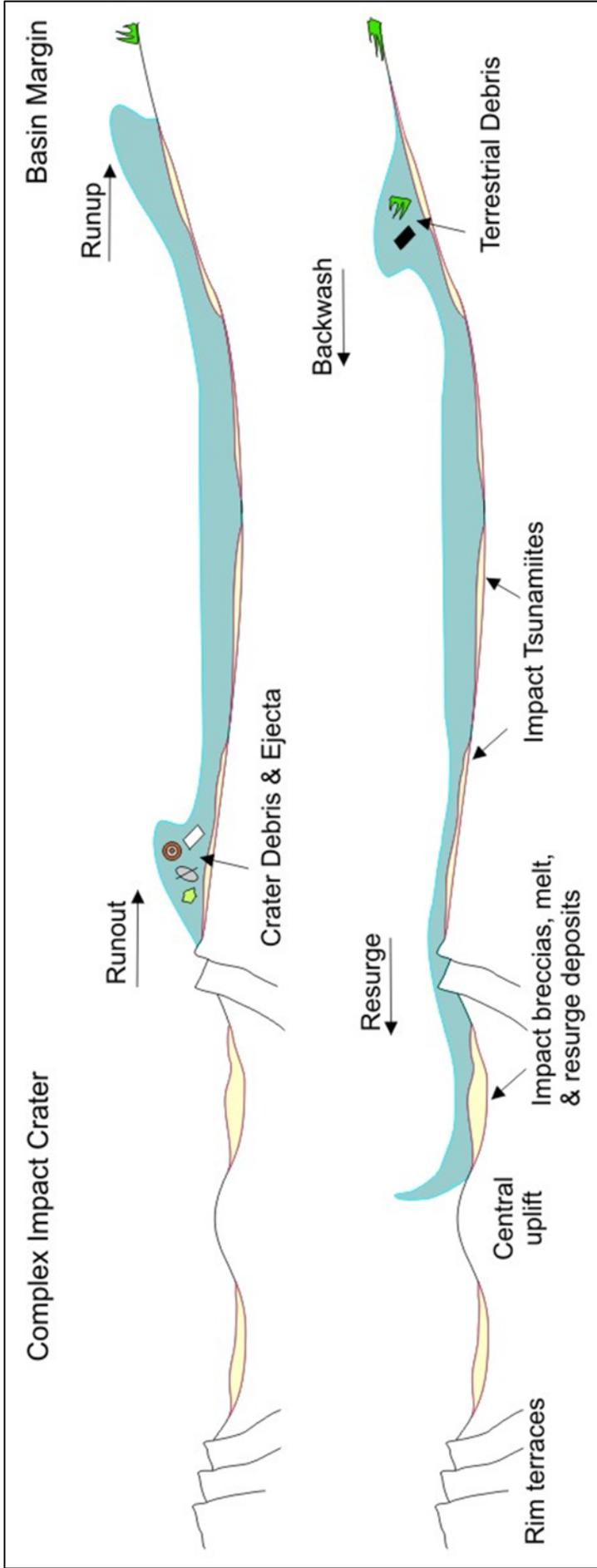


Figure 1: Simplified tsunami flow directions from a shallow marine, complex impact structure. Not to scale. Does not imply order of events (e.g. crater excavation and modification with respect to ocean resurge, ejecta/water curtain collapse, etc). Proximal to crater: runout & resurge. Distal to crater & inundation at basin margins: runup & backwash. See text for details and Figure 3 legend.

(Masaitis 1999). Kamensk-Gusev and Kara-Ust Kara most likely had associated tsunamis, but distal deposits have not been discovered to date (V. Masaitis, pers. comm.).

The Petroleum Prospectivity of Impact Structures

Impact-related features are favourable zones for the localization of hydrocarbons and ore minerals (Masaitis 1989, 2005; Grieve & Masaitis 1994; Reimold et al. 2005). Approximately 25% of proven impact structures are associated with economic deposits. In North America, studies of impact structures in hydrocarbon-producing basins have shown that 42% are associated with commercial oil and gas fields (Donofrio 1997, 1998), and impact breccias have significant reservoir potential (Donofrio 1981). Southeastern Mexican oil fields host a carbonate breccia and overlying ejecta layer (dolomitized seal), stratigraphically correlated to the Chicxulub impact, which are responsible for 1.3 million barrels of daily oil production (Grajales-Nishimura et al. 2000). Donofrio (1998) reported on the commercial success rate of hydrocarbon exploration in confirmed impact structures in American petroleum provinces as 53% (i.e. percentage of producing wells), with up to 86% drilling success rate (i.e. percentage of drilled wells with hydrocarbon shows), which makes impact-related reservoirs an attractive target by commercial standards, and possibly one of the most under-appreciated plays of hydrocarbon-producing regions.

Mazur et al. (2000) consider the breccia infill, the rim uplift, and the central uplift of impact structures as potential areas to collect hydrocarbons, and production has occurred from these trap types in North American craters. A crater may also form its own restricted basin (Castaño et al. 1997; Donofrio 1998), with the potential to create favourable source rock depocentres and hydrocarbon maturation zones. Impact structures have been shown to have lingering, late post-impact hydrothermal systems which are capable of geologically instantaneous hydrocarbon maturation or thermal alteration over thousands of years, and up to a million years in the largest known impact structures (Vlierboom et al. 1986; Arslan et al. 2013; Parnell et al. 2007; Naumov 2002; Ames et al. 1998). Indeed, hydrothermal alteration is most pervasive in shallow marine target craters (Naumov 2002). Other potential hydrocarbon traps include post-impact crater rim reefs (Mazur et al. 2000), as well as impact breccia, ejecta or post-impact sedimentation against crater structure elements (Donofrio 1998). However, little consideration has been given to the unique traps potentially formed at marine impact structures. Tookoonooka and Talundilly, though situated proximally to many producing hydrocarbon fields, are predominantly untested with respect to these trap types.

RESULTS AND DISCUSSION

Doublet Cratering Probability

The probability of the dual origin of terrestrial crater pairs can be assessed based on a combination of crater separation, impactor diameter and age uncertainty (Miljković et al. 2013). To first test the likelihood of Tookoonooka and Talundilly being a doublet crater, documented principles (Collins et al. 2005) and parameters (Miljković et al. 2013) can be applied to calculate this probability. Using a crater centre separation distance (L) of 303km and assumptions such as an asteroid velocity range of 12-20 km/s, impact angle of 45deg, and water depth of 50-200m, the ratio of the secondary to primary impactor diameters D_s/D_p , i.e. $D_{Tookoonooka}/D_{Talundilly}$, is found to be 0.75-0.77 regardless of asteroid type and L/D_p is on the order of 32-50. The crater separation, though large compared to previously considered crater pairs (Bottke & Melosh 1996a; Miljković et al. 2013), is well within the $120D_p$ limit to merit a “possible” doublet designation (Miljković et al. 2013). The average recurrence interval (Miljković et al. 2013) (T_{RL}) for the smaller Tookoonooka asteroid impactor at this separation - in comparison with the uncertainty of the age of the impacts (125 ± 1 Ma from Bron & Gostin 2012; Bron 2010) - gives results on the order of billions of years. Furthermore, Miljković et al. (2014) estimate the occurrence of “false doublets” on Earth as lower than the expected number of doublet craters. Thus statistically, it is highly improbable that Tookoonooka and Talundilly formed from two independent impact events; rather

they are likely to be a doublet crater based on their stratigraphic dating resolution and their proximity. Geological investigations to further substantiate their doublet status follow.

Sedimentology of the Wyandra Sandstone Member

To investigate the depositional processes and stratigraphic architecture of the deposits above the Tookoonooka-Talundilly impact horizon, all known drill cores of the Wyandra Sandstone Member and limited age-equivalent basin margin outcrops over more than 525,000 km² of the basin were examined (Extended Data 1). Sixty-three data locations are shown in Fig. 2a. The Wyandra Sandstone Member (hereafter referred to as the “Wyandra”) occupies the top of the Cadna-owie Formation (Extended Data 2)* and is ≤58m thick outside the impact structures, and is absent only at some distal basin margin locations. The Wyandra can be divided into an upper and lower unit differentiated by distinct sedimentology (Fig. 3b). The lower part has a maximum thickness of 48m, but is more typically 10m thick, bracketed by bioturbation but internally devoid of it, and with internal cyclicity defined by several features. Large polymictic clasts (pebbles, cobbles and rare boulders) in recurring breccia-conglomerate beds are prominent (Extended Data 4a-b), and include altered melt and accretionary impactoclasts. In clast-supported beds, clasts pebble-sized or larger are mostly exotic whereas large clasts in matrix-supported beds are dominantly substrate-derived sedimentary lithic rip-up clasts, often deformed, microfaulted, or syn-depositionally brecciated, as well as wood fragments. Basal scours often accompany the coarsest beds, confirmed in outcrop. Cyclicity is also defined by facies ranging across the flow regime spectrum (Extended Data 5): structureless or graded breccia-conglomerates; massive sandstones with randomly oriented floating pebbles and cobbles; planar-stratified sandstone with bed-parallel-oriented clasts; and low angle bedding and cross-stratification likely equivalent to large-scale cross-bedding observed in outcrop. These structures represent conditions of rapid, high energy deposition and sediment-saturated flow, and pass upward into ripple cross-lamination and thin siltstones indicating waning flow and suspension deposits. Sedimentary fabrics *within beds* such as variable grading (grainsize, density, normal, and reverse were all observed), oscillating clast and matrix-support within breccia-conglomerates, and massive to crudely stratified intervals all represent fluctuating current flow strength. In some locations, beds are >16m thick and indicate near-instantaneous deposition. Cyclicity is also implied from bidirectional flow indicators such as paleocurrent shifts in cross-bedding and bidirectional pebble imbrication. An abrupt shift in flow direction also occurs at the base of the Wyandra, indicating that Wyandra deposition was a departure from the ambient depositional regime. Cyclicity results in large-scale couplets: higher-energy deposits of coarser-grained, poorly-sorted impactoclast-rich sediments capped with siltstone alternate with relatively lower energy deposits of finer-grained, organic-rich, better-sorted sediments capped with carbonaceous sandstone (Fig. 3a). The lower Wyandra Sandstone comprises a stack of fining-upward units and couplets of units that, overall, thin and fine upward and decrease in clast support upward.

Individually, the bedforms and facies observed in the lower Wyandra Sandstone reflect normal marine sedimentary processes, but collectively, the high velocity bedforms, sedimentary fabrics, cyclicity and stacking reflect an unusual event of extraordinary magnitude. Their contrast to the low-energy deposits of the ambient Cadna-owie Formation, in which the most energetic bedform observed in the study area was ripples, is marked. The lower Wyandra interval exhibits features of typical tsunami deposition and, outside the craters, is interpreted to be an impact tsunami sequence. The cyclicity observed within the tsunami sequence is interpreted to be controlled by current reversals, which is confirmed by reservoir-scale studies showing alternating paleoflow directions (Root et al., 2005). Proximal to craters, couplets are interpreted to be runout and resurge deposits. Distal to craters, couplets represent runup and backwash deposits (Figs. 1, 3a). Runout and runup deposits contain more breccia-conglomerate beds with lithic fragments and pebble-boulder-sized ripup clasts than the resurge/backwash deposits which are finer-grained

* Though the Wyandra Sandstone Member occupies the uppermost part of the Cadna-owie Formation as originally defined, for clarity all references to the Cadna-owie Formation in this paper pertain to the Cadna-owie Formation deposits underlying the Wyandra Sandstone Member.

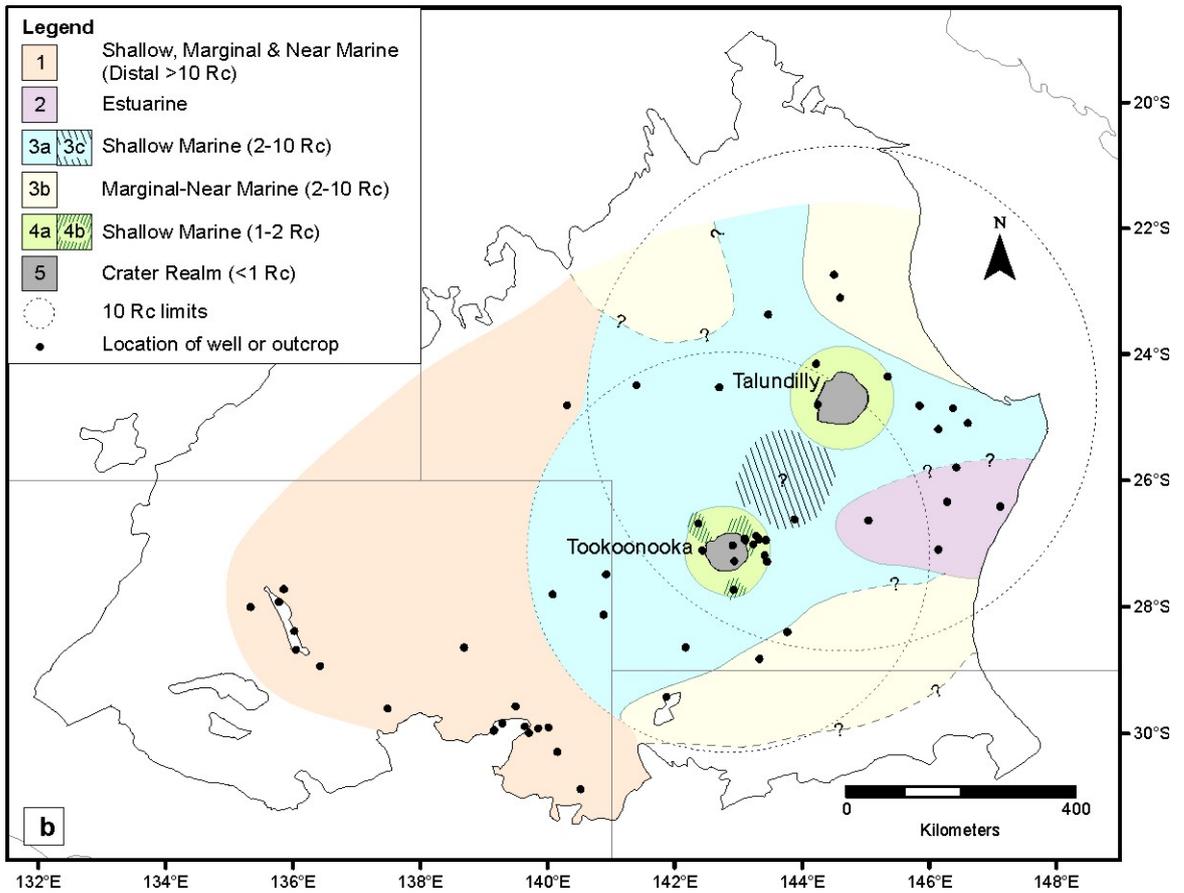
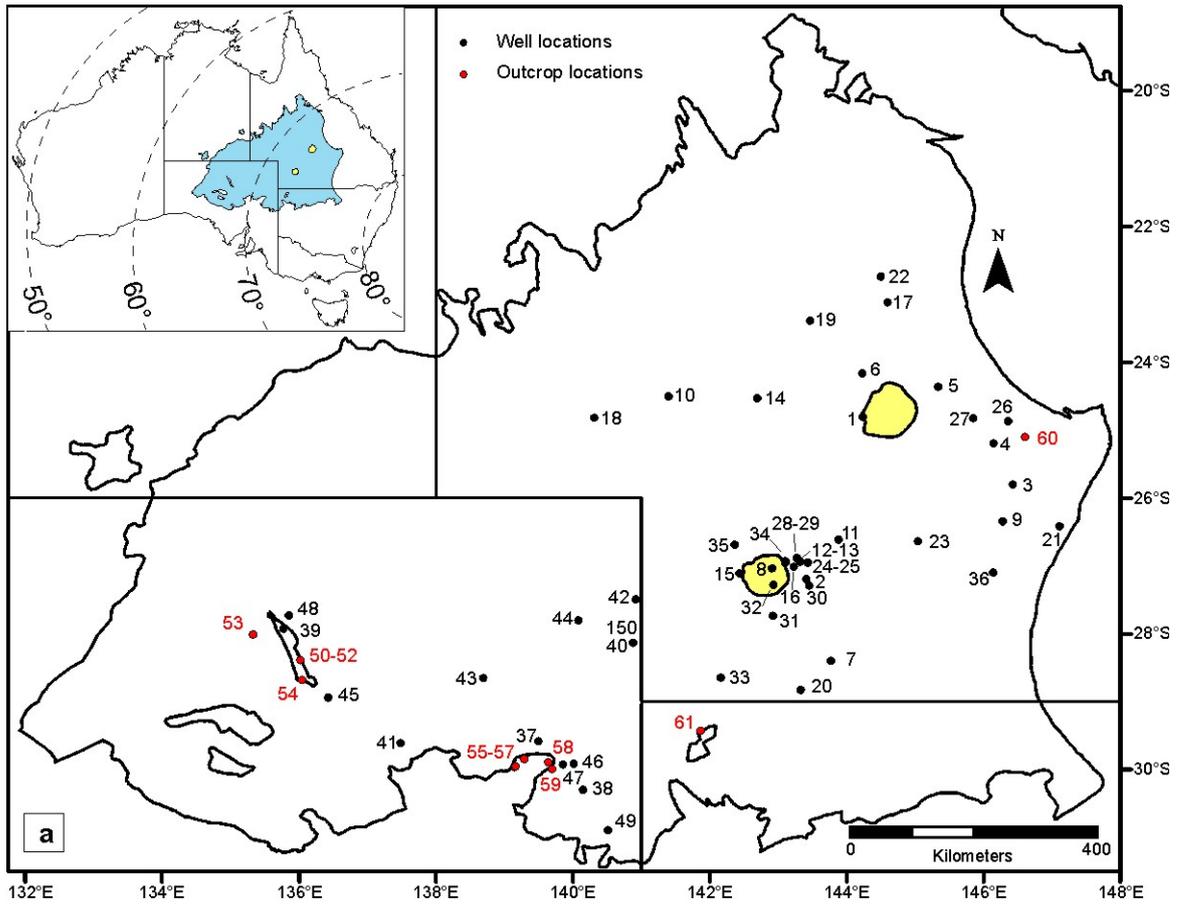
except at distal southwestern basin margins where backwash may have dragged coarser sediment off basement inliers at the paleocoastline. Outcrop observations indicate that runup units are preferentially preserved and lower units are thinner: erosive lower boundaries of breccia-conglomerate units overlie lenses of sandstone, evidencing violent and erosive successive tsunami waves that removed and reworked earlier deposits (Extended Data 4a-b). Deposits from individual waves are not correlative between locations, concurring with studies of modern tsunami deposits which describe varying preservation due to scour from multiple, successive tsunami waves (Morton et al. 2007). Higher in the sequence, differentiation of cyclicity becomes increasingly difficult as sediment becomes mixed to a higher degree and tsunami intensity wanes. The end of tsunami deposition, at the top of the lower Wyandra sequence, can be difficult to identify, likely due to the complexity of waning tsunami seiche deposits, post-impact storm deposits, and slumping from ongoing crater instability creating event beds which conformably merge with tidal processes of the transgressive depositional regime. However, waning depositional flow energy can be recognized, culminating in increased silt content, massive mud beds (suspension deposits), or increased carbonaceous content (rafted organic detritus).

The upper part of the Wyandra (Fig. 3b) exhibits a return to the pre-impact, low energy sedimentation style indicated by a dominance of fine grain sizes and lower flow regime sedimentary structures with minimal reworking of coarse sediments, a gradual return of trace fossils indicating slower deposition and possibly biogenic recovery, and the appearance of pervasive low-energy marine indicators such as tidal lamination couplets. The upper part of the Wyandra varies in thickness between 0-40m thick outside the impact structures. The Wyandra is capped by a thin unit of intensely bioturbated sediment which marks the final transition to deeper marine deposition of the Walumbilla Formation shales (Extended Data 2). Tsunami deposition is thus interpreted as an interruption of the transgressive basin sedimentation, and the post-tsunami upper Wyandra as a period of “depositional recovery” to the transgressive regime, with coarser grain size fractions apparent only proximal to the crater highs, which would have remained a sediment source in the basin until burial.

Figure 2: Maps of the Eromanga Basin (next page)

a, Locations of Tookoonooka and Talundilly Impact Structures, cores and outcrops. Inset map shows locations of Tookoonooka and Talundilly Impact Structures (yellow dots) within the Eromanga Basin (grey) in Australia. Approximate paleolatitudes after Veevers (1986). See Extended Data 11 for location details.

b, Five Depositional Realms of the Wyandra Sandstone. Regional trends in sedimentation patterns of the impact tsunami sequence (lower Wyandra) are related to paleoenvironment, depositional water depth and crater proximity. See Extended Data 9 and text for detailed descriptions and variations of depositional realms. Edge of coloured realms indicate limit of data. Proximity to impact structures measured in units of crater radii (R_c): 10 R_c extents for both Tookoonooka and Talundilly are shown.



Impact Signature of the Wyandra Sandstone Member

Coarse exotic clasts dominating the Wyandra are thought to be predominantly derived from Tookoonooka and Talundilly. To verify impact provenance, further to previous work which focused on the impact horizon and melt and accretionary impactoclasts (Bron & Gostin 2012; Bron 2010), and to confirm correlations of the tsunami deposits, the impact signature of the tsunami deposit was petrographically assessed. An impact signature in the tsunami sediments in the form of shock-metamorphosed quartz and very rare spherules (cf French 1998) is detectable in the breccia-conglomerate beds of interpreted runout units where there is the greatest apparent concentration of coarse-grained ejecta and less dilution by ambient fine-grained sediments (Extended Data 6). Shocked quartz in grains and lithic fragments was observed at 9 locations. Measurements of planar lamellae (mostly decorated) in shocked quartz grains (mostly toasted) were made: 136 PDF (planar deformation features) sets and 40 PF (planar fractures) sets were measured in 46 quartz crystals from 7 locations with a maximum of 6 PDF sets per grain. Results are consistent with the shock level profiles of marine impacts and establish the impact origin of the tsunami deposits (Extended Data 7-8). Given the presence of shock indices $\{10\bar{1}2\}$ and $\{22\bar{4}1\}$, in addition to others, a shock level of >17.5 GPa is prescribed (Grieve & Robertson 1976). Measurement locations and depths are noted on map and logs (Fig. 2e, Extended Data 10, respectively).

Figure 3: Representative Sections of the Wyandra Sandstone (next page)

See appendices for detailed lithological logs (Extended Data 10), detailed character of each realm (Extended Data 9) and location data (Extended Data 11). Inset: Legend applies to **a**) and **b**).

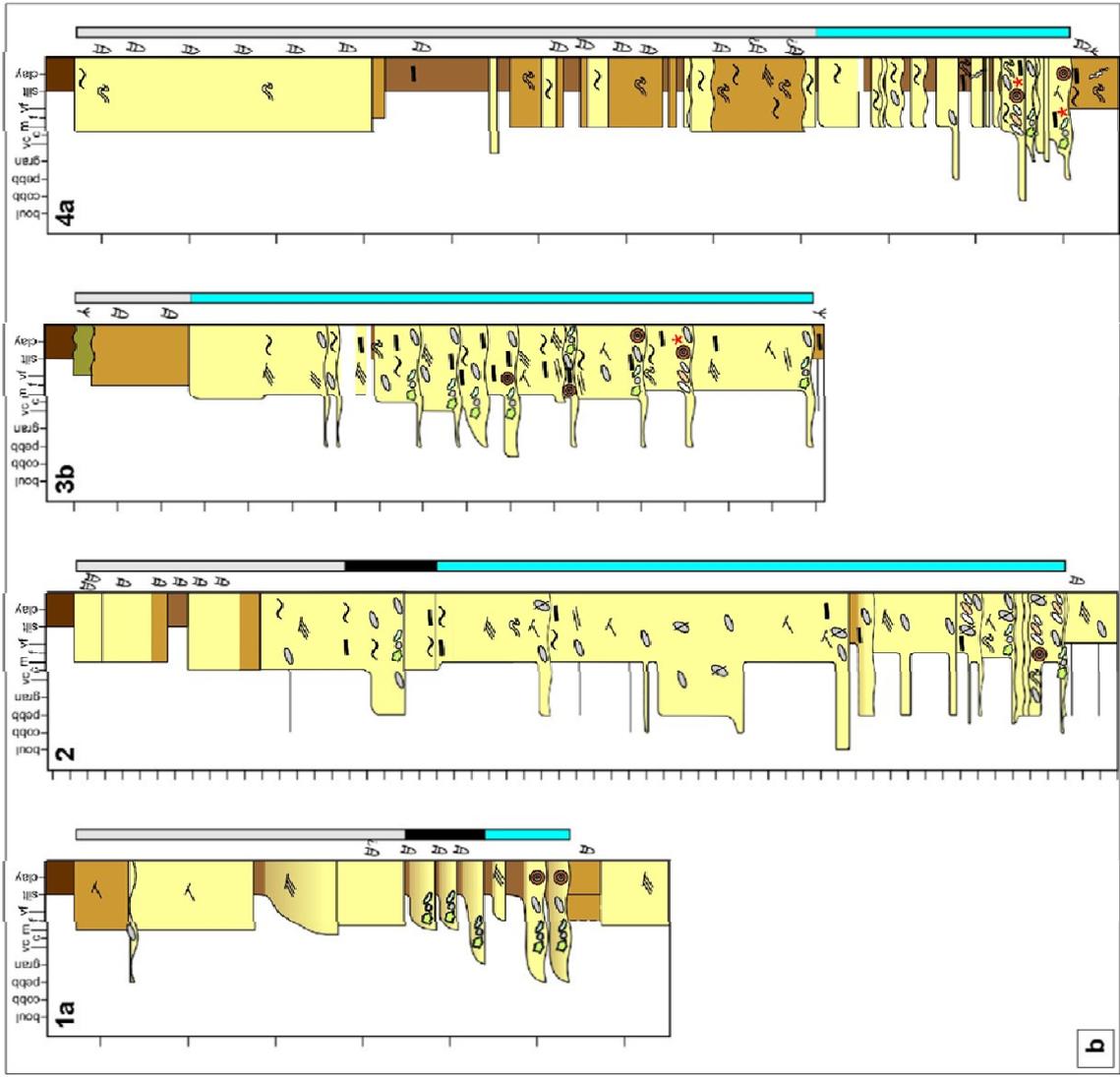
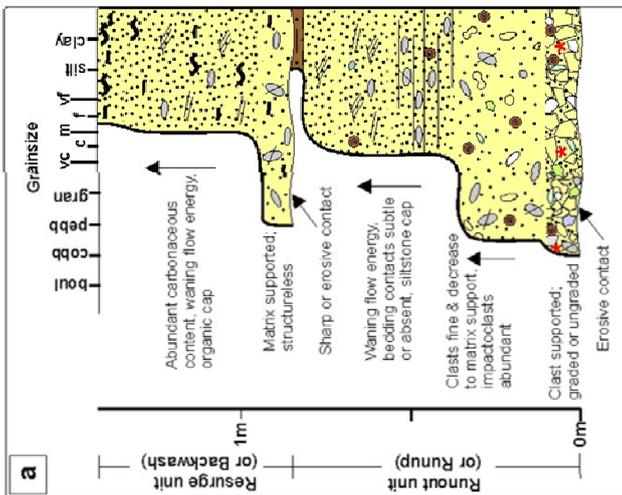
a, Idealized Impact Tsunami Couplet. Total thickness shown ~ 1.5 m. Note: thicknesses of units are widely variable, due to erosion of underlying units by successive waves and proximity to crater. Proximal to crater units are termed Runout and Resurge; distal to crater, units are termed Runup and Backwash (see Figure 1).

b, Simplified Representative Logs of the Wyandra from 4 Depositional Realms with Tsunamiites. See also Figure 2 for corresponding areal extents of depositional realms and data locations. Examples of depositional realms 1a, 2, 3b and 4a are shown. Note: Different vertical scales apply to each depositional realm; vertical scale on each log indicates meter-gradations. Each log shows grain size scale with simplified lithology and sedimentary structures, bioturbation indication and Wyandra sequence interpretation. 1a=Location 18, 2=Location 36, 3b=Location 7, 4a=Location 30.

c, Illustration of Relative Thicknesses of lower and upper Wyandra (Tsunami and Post-Tsunami Sequences) for all Depositional Realms. Note: scale bar applies to this illustration only.

Relative thicknesses shown are for representative logs rather than averages across Depositional Realms. See isopachs in Figures 4b and 4c for areal variation in Wyandra Sandstone and impact tsunamiite (lower Wyandra) thicknesses respectively. 1a=Location 18, 1b=Location 37, 2=Location 36, 3a=Location 60, 3b=Location 7, 4a=Location 30, 5=Location 32. See Figure 2a for data locations.

For Depositional Realm 3a, thickness represents a minimum limited by outcrop exposure, with no upper Wyandra preserved. However, other locations for this realm in this area of the basin indicate average Wyandra thicknesses of ~ 14 m.



Depositional Realms of the Wyandra Sandstone Member

Having established the impact tsunami origin of the Wyandra Sandstone, mapping was undertaken to assess the distribution patterns of the sediments. Geological logs from core and field observations were correlated to show the lateral character of the Wyandra Sandstone, particularly the tsunami sequence. The tsunami deposits were classified based on depositional character, cyclicity, stacking pattern, interpreted processes of deposition and paleoenvironments. The latter was interpreted from a combination of pre-impact facies, water depth indications, basin margin proximity and sparse palynology. Five depositional realms have been identified; most are with respect to crater proximity (R_c is radial range in multiples of crater radii):

1. *Shallow, marginal and near marine (distal >10 R_c)*. Sequences are similar to sequences within $10R_c$ but thinner. Deposits thin and fine toward basin margins and are of two variations: a) northern margin of the basin, with the thinnest tsunami deposits b) southwestern basin margins, with sand-dominant cycles thicker than a) and a thick transitional upper Wyandra interval.
2. *Estuarine*. Thick, clay-rich sequences characterized by very thick beds with fluctuating clast support (beds up to 16m thick). The coarse clast fraction is dominated by sedimentary lithic rip-ups. These are the thickest Wyandra sequences outside the impact structures.
3. *Shallow, marginal and near marine (2-10 R_c)*. Tsunami deposits thin and fine distally. Variations: a) shallow marine; b) marginal to non-marine inundation; and c) a tsunami “interference wave” sequence, with mixed units not exhibiting clear tsunami couplets, was interpreted in one location, the only core data situated between the craters. a) and b) are distinguished by the character of the underlying Cadna-owie, taking into account potential scour intensity proximal to craters. Deposits in this realm are the most “typical” and recognizable tsunami deposits.
4. *Shallow marine (1-2 R_c)*. Couplets are thinner but more numerous than deposits beyond $2R_c$, likely due to a greater degree of wave energy and scour from successive runout and resurge events proximal to impact structures. Deposits are influenced by multiple processes, but to a lesser degree than within the crater. Variations in the character of the underlying Cadna-owie are interpreted to be primarily due to depth of impact/tsunami scour. Sequences near Tookoonooka and Talundilly are similar. Variations are a) undeformed and b) slumped
5. *Crater realm (<1 R_c)*. Thick Wyandra age-equivalent deposits within the impact structures, while correlative to deposits outside the impact structures, are not considered tsunami deposits but instead highly complex resurge and breccia deposits formed by multiple depositional processes. Thus the realm is recognized herein but its detailed sedimentology is beyond the scope of this paper.

Depositional realms are shown in Fig. 2b and described in detail in the appendix (Extended Data 9). A representative log was chosen from each realm for comparison (Fig. 3b).

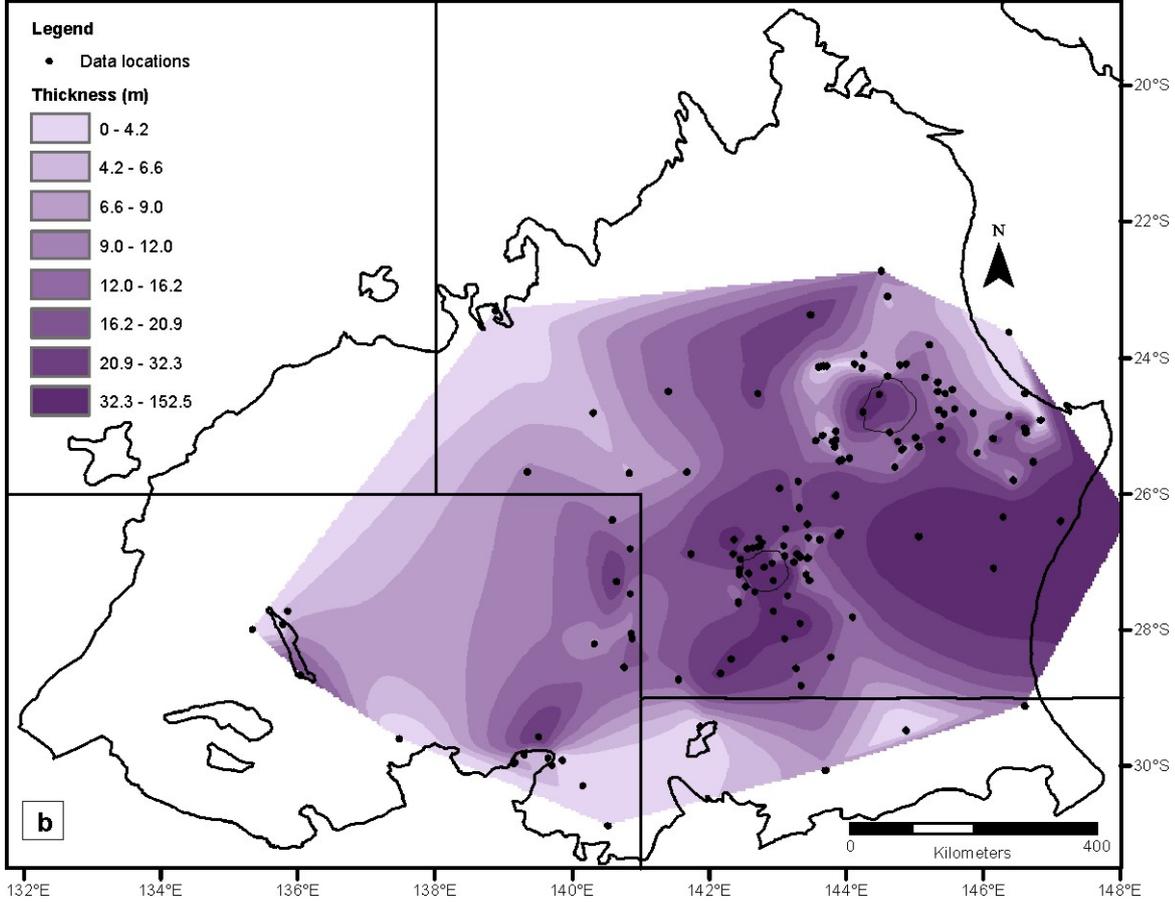
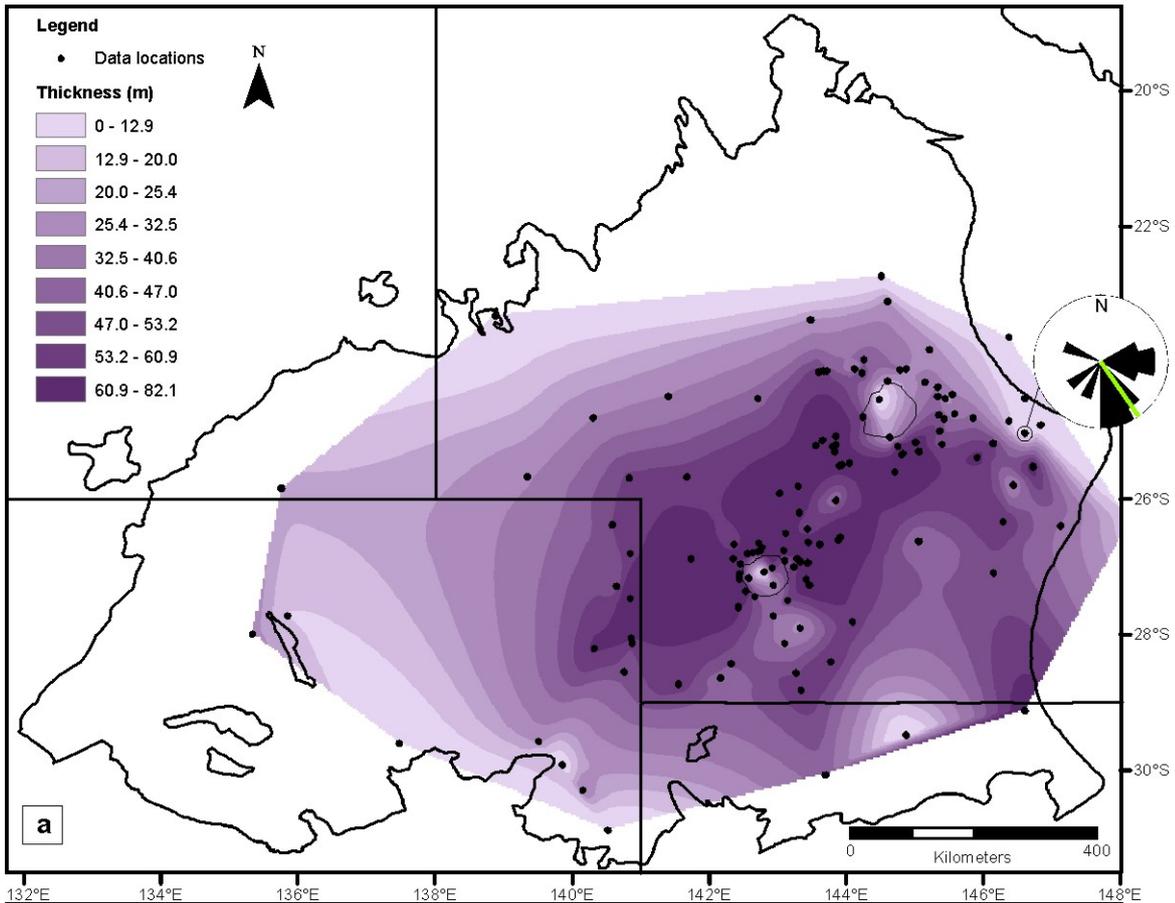
While tsunami sedimentation is interpreted as the primary influence on lower Wyandra deposition basin-wide outside the impact structures, depositional processes - especially proximal to the crater centres as observed in depositional realms 4 and 5 - are interpreted to be highly complex. More chaotic and structureless sedimentary fabrics, slumping, increased intensity of seismites below the impact horizon, and large-scale syn-depositional injectites which intensify with proximity to Tookoonooka crater centre (no drill core from Talundilly crater exists) were observed. Observations are consistent with the influence of other impact-related mechanisms on deposition such as base surge, ballistic sedimentation, seismic waves and resurge. It must be emphasized that sedimentation processes between the crater centres and basin margins occur on a continuum; while the depositional realms interpreted are an attempt to classify the deposits observed across a large area, adjacent elements overlap. The large, shallow marine Chicxulub impact is a good analogue for Tookoonooka-Talundilly: Chicxulub tsunami energy was similarly “trapped” in the relatively enclosed, shallow Gulf of Mexico and proto-Caribbean Sea, where seiching influenced sedimentation in diverse depositional environments across the region and distally (Goto 2008). Super sediment-saturated tsunami flow proximal to shallow marine craters may also be

indistinguishable from fluidized ejecta surge processes described from volatile-rich impacts on Mars and terrestrial craters such as Haughton (Osinski 2006) and Lonar (Maloof et al. 2010). Late post-impact (upper Wyandra), proximal sedimentation was also influenced by increased seafloor rugosity due to the crater structure in the comparatively low-relief basin and crater instability due to the poorly-consolidated sedimentary target.

Mapping the Impact-Related Deposits

To further investigate the sedimentation patterns of the impact-related deposits, isopach maps of the Wyandra Sandstone, the interpreted tsunami sequence, and the underlying Cadna-owie Formation as well as a contour map of maximum grainsize recorded within the Wyandra Sandstone were constructed (Fig. 4). Datasets were extended to an area of >805,000km² with additional data points gathered from subsurface drilling data calibrated from lithological log observations. Since the Wyandra was recognizable and correlative over >665,000km² of the basin, sandwiched between pervasively fine-grained formations of basin-wide extent (shale, siltstone, and fine-medium-grained sandstone with the exception of rare scattered pebbles in basin margin deposits), it was expected that a maximum grainsize distribution could provide a sense of the source of coarse sediment in the Wyandra Sandstone. All isopach maps show distal thinning of deposits toward basin margins. The Cadna-owie isopach map (Fig. 4a) gives a sense of the pre-impact depocentre of the basin: the thickest sedimentation, and likely deepest water, is just north of Tookoonooka, whereas Talundilly is located toward the northeastern basin margin. The Cadna-owie isopach map clearly shows significant thinning of the Cadna-owie at both impact structures. This is interpreted as removal of Cadna-owie by impact excavation (<1 Rc), and scour from ballistic sedimentation (cf Oberbeck 1975) or tsunami erosion (>1 Rc), resulting in a basal Wyandra Sandstone unconformity/impact horizon of regional extent. The Cadna-owie isopach map indicates that most of the Cadna-owie was removed in the impact structures (although some remains as autochthonous breccia, as observed in core from Tookoonooka) and at least 30% of the Cadna-owie thickness was removed within 1-4Rc of Tookoonooka based on a maximum observed Cadna-owie thickness of 82.5m around Tookoonooka. The Wyandra Sandstone and tsunami isopach maps (Fig. 4b-c) similarly show a clear crater influence in their sedimentation patterns; thick Wyandra-equivalent deposits exist at both impact structures, interpreted in the Tookoonooka crater to be tsunami-equivalent resurge deposits in part. Talundilly is not well-represented on the tsunami isopach due to lack of core in the crater. The Wyandra Sandstone and tsunami deposits thin distally from the craters but are thicker to the east in the estuarine area of the depositional realms map, and the tsunami isopach map shows a more sheet-like deposit spanning the basin. Thinner Wyandra Sandstone and tsunami deposits proximal to craters (<3.5Rc) are likely due to greater erosive action (less preservation) around the craters; exposure of the immediate Talundilly crater area before Walumbilla deposition may be indicated.

The grainsize map (Fig. 4d) shows that Tookoonooka is clearly an epicentre of distribution for coarse sediment in the Wyandra. Although data is lacking around the Talundilly crater (e.g. coarse mud-rich lithics such as accretionary impactoclasts are not preserved by the drilling process and thus drill cuttings data – indicated by the white points – can only provide an indicative upper grain size), grain sizes in this part of the basin are significantly larger than the background: Cadna-owie grain size trends show a maximum of medium-grained sand in the central areas of the basin. Fining to the southwest of the basin is confirmed by field observations of less discernible ejecta content distally. A mid-basin source of coarse clasts is atypical in general basin sedimentology, however, distal fining of ejecta from craters is expected, as exemplified by Bunte Breccia primary ejecta of the Ries crater (Hörz et al. 1983), and is evident by the distal fining of shocked quartz from Tookoonooka and Talundilly (Extended Data 8a). Overall, the maps in combination show similar sedimentation patterns at both impact structures, suggesting synchronicity of the Tookoonooka and Talundilly impacts in the same stratigraphic interval.



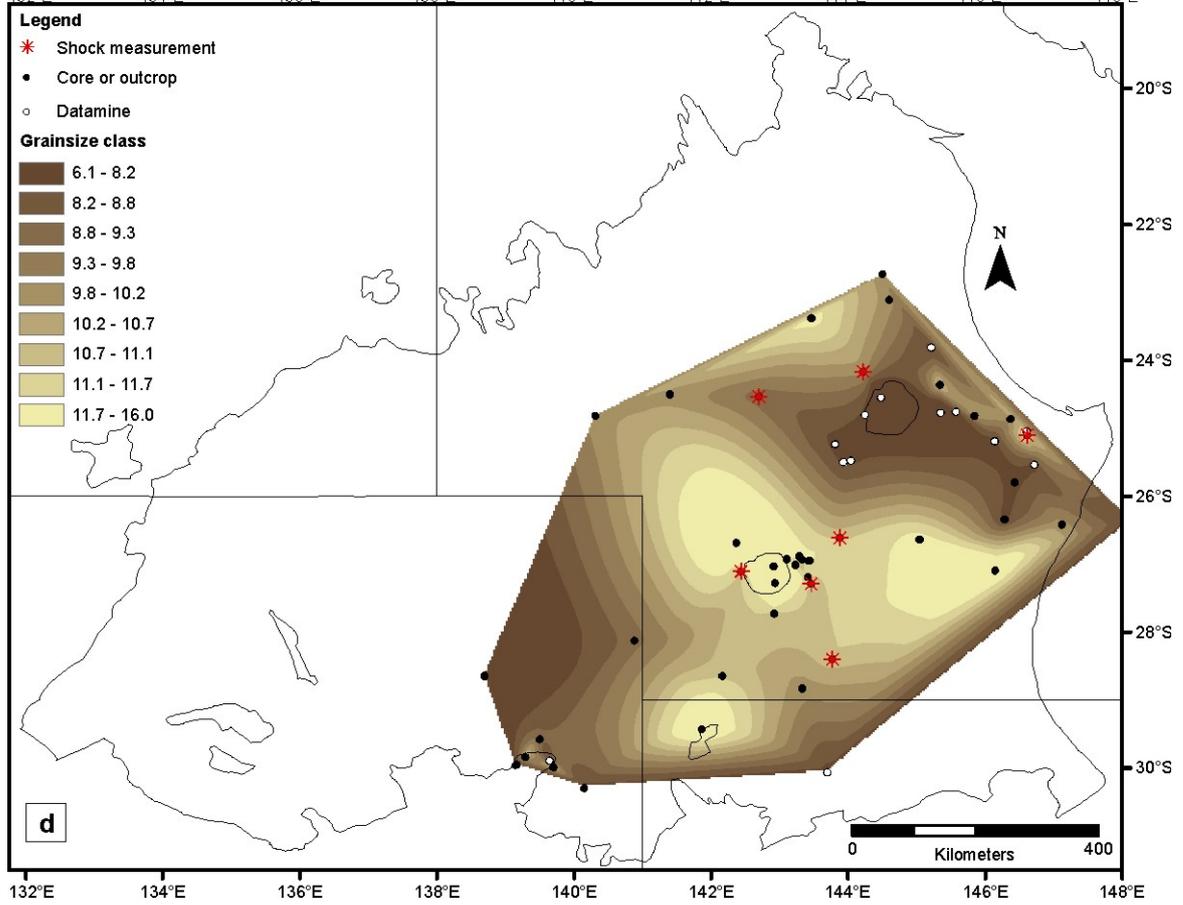
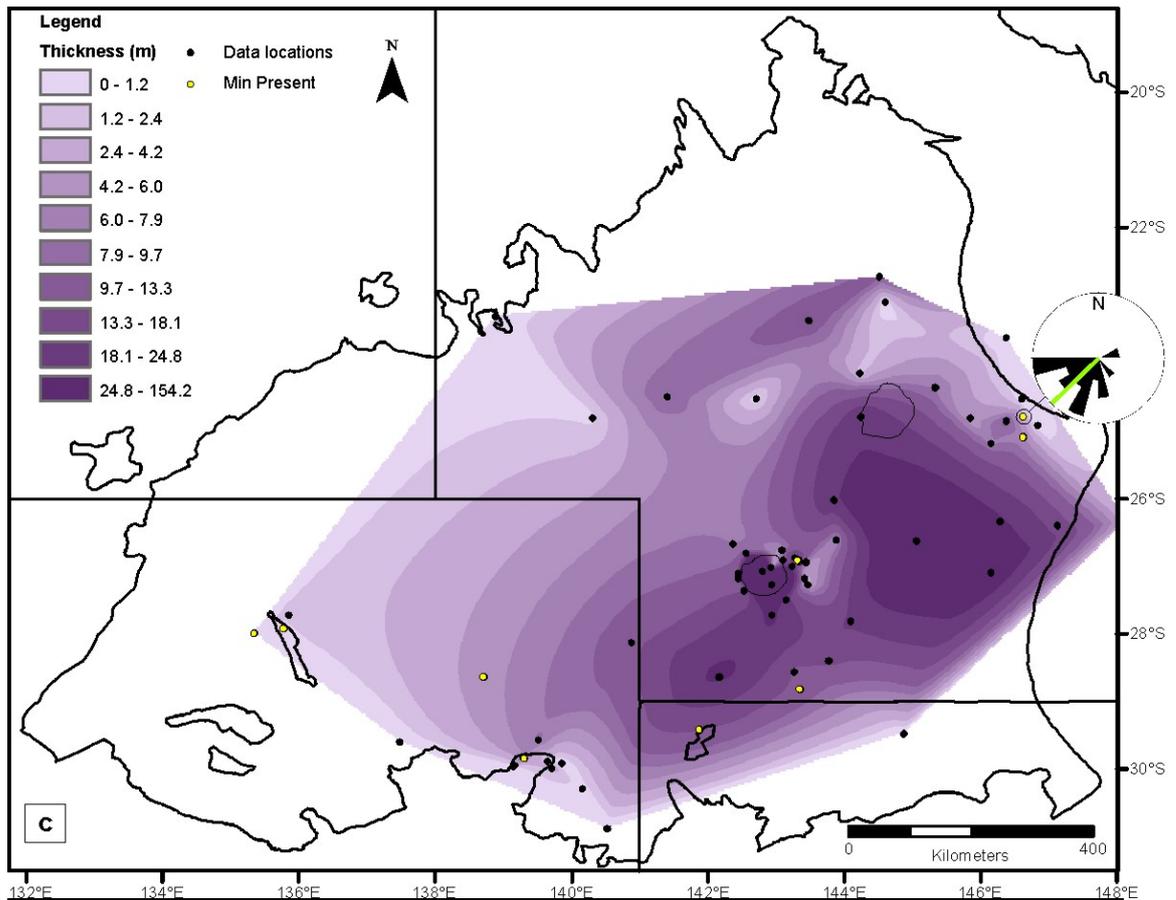


Figure 4: Distribution Pattern Maps of the Tookoonooka-Talundilly Impact-Related Deposits (previous pages).

a, Isopach of the pre-impact Cadna-owie Formation. Notes: In the impact structures, Cadna-owie most likely present only as autochthonous breccia, thus thickness considered a *maximum*. Talundilly has not been full-hole cored, thus coarse grainsizes (\geq pebbles) cannot be confirmed in the crater. Note thickest deposits of Cadna-owie are near Tookoonooka, with absence of section obvious in the crater zones. Inset shows paleocurrent data from an unpublished thesis (Musakti 1997) indicating flow direction in the Cadna-owie just below the Wyandra.

b, Isopach of the Wyandra Sandstone including both lower and upper Wyandra. Note: In the impact structures, the Wyandra Sandstone is considered a time-equivalent deposit to those outside the crater structures for mapping purposes, but crater realm deposits are sedimentologically distinct from the tsunami deposits.

c, Isopach of the interpreted tsunami sequence (the lower Wyandra Sandstone). Notes: In the impact structures, the Wyandra Sandstone is considered a time-equivalent resurge deposit to the tsunami deposits outside the crater structures for mapping purposes, but crater realm deposits are sedimentologically distinct. Green “Min” data points represent locations where deposits are present but incomplete data exists, and are thus not included in the isopach calculation. Inset shows paleocurrent data from an unpublished thesis (Musakti 1997) indicating the flow direction of tsunami backwash units.

d, Maximum grainsize distribution of the Wyandra Sandstone.

Grainsize assumptions: For all locations without whole rock samples available (i.e. “datamine” points from cuttings data vs. drill core or outcrop), grain size data is limited to lithic grain sizes only, and is dependent on sampling resolution while drilling and ability to differentiate clast size in drilling samples. Intraformational clasts, rip-up clasts and other sedimentary lithics as well as altered melt and accretionary impactoclasts (typically the largest grain sizes) are not well-represented in cuttings data due to their low strength. Clasts larger than fine pebbles are not usually represented in cuttings data, and clast sizes larger than fine cobbles are not usually recognized in core. Thus grain sizes shown here are considered an *apparent maximum* grainsize only. Cuttings data may also be affected by lagtime, drilling rate, bed thickness and sampling interval. The colourbar shows coarse grainsizes only: from granules (6) to very coarse boulder (16). The locations of shocked grain measurements are shown.

A Dual Impact Deposit

In addition to the sediment distribution patterns shown by mapping of the impact deposits, synchronicity of the impacts is suggested by contrasting comparably thick deposits at equally distal basin margin locations ($>10R_c$) from Tookoonooka. Tsunamiite run-up units in the southwest contain occasional pebbles in sands slightly coarser than ambient sediments, while deposits in the northeast consist of a thick carpet of polymictic coarse (up to cobble-sized) breccia more typical of a proximal ejecta blanket. Thus Talundilly likely contributed proximal ejecta to tsunamiites in the northeast. This is corroborated by calculating expected thicknesses and mean grainsizes of ejecta for these locations from each crater. Results closely match observations with respect to the grainsizes and volumes of coarse sediment observed, with the caveat that calculations describe theoretical distributions of dry ejecta blankets rather than marine reworked deposits, and as such are indicative only. Arrival time calculations also indicate that outcrop locations in the northeast of the basin would have received Talundilly ballistic ejecta well before tsunami waves arrived. A coarse basal Wyandra carpet shown in Extended Data 4a-b (see also Extended Data 10d) thus may be primarily composed of tsunami-reworked ballistic ejecta from Talundilly, overlain by tsunami deposits with wave-transported and reworked debris from both craters. Paleocurrent data previously recorded at this location (Musakti 1997) indicate lower Wyandra Sandstone flow directions toward Tookoonooka and Talundilly, in contrast to pre-impact (Cadna-owie) flow direction 90-135deg offset from these (Figs. 4a-c), which supports tsunami backwash interpretations.

A review of the entire Cadna-owie to upper Walumbilla Formation interval, representing over 20Ma of marine deposition, in all continuous stratigraphic cores in the study area showed that no other impact horizons of this magnitude are present. The apparent absence of a second large-scale impact event in the stratigraphy indirectly evidences simultaneous origin for Tookoonooka and Talundilly; as there is at least 30Ma of continuous and conformable Lower Cretaceous sedimentation record in the basin (Draper 2002) – excepting the base of the Wyandra Sandstone –

via burial due to marine transgression, the interpretation of a dual impact tsunami sequence is the most logical explanation. Thus, combined sedimentological analyses strongly support contemporaneous impact.

Talundilly, however, appears to have been a shallower marine location than Tookoonooka, and its influence on the tsunami event may have been less significant than Tookoonooka's. This is suggested by a comparison of the Wyandra thickness at Talundilly-1 and Tookoonooka-1 wells (42m and 168m, respectively), which may indicate a lack of resurgence in the Talundilly impact structure. Palynology data (Archer & Armstrong 1986) and the Cadna-owie isopach map also suggest that just northeast of Talundilly, the Cadna-owie was deposited on a non-marine shelf, although impact scour must also be considered within the proximal crater range. The Wyandra isopach map (Fig. 4b) also shows significant thinning in the Wyandra Sandstone around Talundilly, suggesting that the area was exposed before full marine incursion and Walumbilla Formation deposition. These various lines of evidence imply that water depth at impact was too shallow to significantly control Talundilly's crater morphology and that Talundilly crater rim height: water depth ratio was perhaps large enough to prevent resurgence. If Talundilly's water depth was negligible, then Tookoonooka may have been the dominant control on the impact tsunami event.

Reservoir Quality of the Wyandra Sandstone Member

The Wyandra Sandstone is an oil reservoir in the upper part of the Eromanga Basin succession, producing from several fields near Tookoonooka and known as a major aquifer in regional areas of central Australia. It has been known as a "volcaniclastic sandstone" reservoir with substantial permeability heterogeneity (Root et al. 2005). Although a volcanogenic component does exist in the grain provenance of the Wyandra – recently suggested to derive in part from basement lithologies of the Talundilly target sequence (Bron & Gostin 2012) – much of the assumed volcanic content is more likely to be misinterpreted altered impact melt material. Locally, porosity far exceeds that of the underlying Cadna-owie, and it is observed that the best sandstone quality lies in the lower Wyandra, being the interpreted tsunami sequence.

Core studies and microscopic analyses show an abundance of clay content in the Wyandra, which is interpreted to be primarily the alteration product of impactoclasts (Extended Data 5b-g). Altered melt and accretionary impactoclasts (cf Bron 2010) as well as sedimentary lithic fragments and rip-ups are easy to misinterpret as common mud facies in drilling cuttings and formation evaluation logs, and have likely resulted in misinterpretation in petroleum reports as mudstone facies (vs. sandstones and breccia-conglomerates with discrete ripped-up mud-rich cobbles and clay-rich impactoclasts), complicating accurate profiling of the Wyandra sandbody. However, their presence does reduce the reservoir quality of the Wyandra in terms of pore-space-filling clay cementation.

Conversely, compositional maturity and superior primary porosity are conferred on the lower Wyandra by high quartz content derived from the upper part of the impact target sequence (i.e. Cooper and Eromanga Basin successions) (Bron & Gostin 2012) and coarse-grained ejecta, respectively. These features give the Wyandra Sandstone favourable petroleum reservoir quality. However, excellent primary porosity in the breccia-conglomeratic tsunamiite runout beds also accommodated secondary cementation, commonly silicification, calcification and ferruginization (Extended Data 4c, Extended Data 6f-g), leading to highly variable reservoir quality in the Wyandra Sandstone locally. Tsunami reworking/cleaning of the impact deposits also appears to have improved the reservoir quality higher in the tsunami sequence. From core observations, it is clear that reworked, better-sorted resurgence beds correlate to enhanced reservoir quality. This is confirmed by a field-scale reservoir study of the Wyandra (Root et al. 2005) which linked reservoir permeability not only to coarser grain sizes, but also to sediments with paleocurrents trending "west to southwest" (i.e. towards Tookoonooka in that field). Although petroleum studies on the Tookoonooka and Talundilly impact structures remain in their infancy despite initial drilling attempts in the 1980s, this research identifies a new target for petroleum exploration around marine impact structures: impact tsunamiites.

FINAL DISCUSSION

The sedimentary record of impacts on Earth's ever-changing surface is highly variable and ideal subaerial impact ejecta blanket geometries are rarely seen. This study shows that marine impact deposits exhibit a morphology of their own, and sediment distributions give indications of crater source which can be resolved despite burial and marine reworking. Furthermore, observed patterns of grainsize distribution, scour, and sediment thickness in combination with sedimentology may indicate simultaneous marine cratering events. The patterns of Cadna-owie removal and lower Wyandra tsunami deposition appear concurrent around both impact structures, within the Tookoonooka-Talundilly age uncertainty.

Tookoonooka-Talundilly is an important model for research on both binary impacts and paleotsunamis in shallow marine settings. Not only does it appear that a double impact occurred near the centre of an enclosed basin with continuous "layer cake" sedimentation and little tectonic overprint, but impact sedimentation is apparently entirely preserved due to subsequent burial excepting erosion by successive tsunami waves and basin margin exposure. Thus these impact tsunami deposits exhibit both geometrical constraint and measurable regional distribution. Tookoonooka-Talundilly impact tsunamiites agree well with both descriptions of sheet-like modern tsunami deposits and marine impact models which predict thick in-crater resurge deposits. However, the assertion that the regional distribution of ejecta in marine impact scenarios is more restricted than non-marine impact scenarios, by sediment re-mobilization back to the crater cavity by resurge (Dypvik & Jansa 2003), is not supported: instead, ejecta is widely dispersed, though diluted, by impact tsunami processes. Findings in this basin-wide study contrast markedly with the morphology of ejecta deposits of typical subaerial impacts, which exhibit their thickest ejecta blankets continuously out to $2R_c$, and distally thinning, discontinuous ejecta deposits beyond. Tookoonooka-Talundilly tsunamiites show that although a continuum of sedimentation occurs between proximal and distal locations, a critical morphological indicator of marine impact deposits (in addition to the in-crater resurge sequence) is between $1-2R_c$, where both the greatest amount of seafloor scour occurs and thinnest but most complex tsunami deposits lie. Beyond $\sim 2-3R_c$ lie thicker, recognizably cyclical deposits which then thin distally. Impact tsunamiite depositional realms and regional geometry were controlled primarily by paleo water depth and crater proximity. Tsunamiite sediment content was significantly influenced by seafloor scour: observations of abundant rip-up clasts and sedimentary lithic fragments in the Wyandra, in combination with the Cadna-owie Formation isopach results, strongly support impact theory (Oberbeck 1975) and studies of ejecta distribution (Hörz et al. 1983) that around $2/3$ of ejecta deposits actually derive from the substrate (i.e. pre-impact surface) via scour outside the crater rim, which is clearly a commonality of both non-marine and marine impacts. For this size of basin, tsunami deposits would have formed in hours and days from impact, confirmed by impact modelling (cf Collins et al. 2005).

CONCLUSIONS

Tsunamiites were deposited in the wake of a marine impact event in Cretaceous Australia, as evidenced by the coarse debris and impact-shocked grains entrained in high-energy cyclical sedimentation over more than $525,000\text{km}^2$ and correlative over $665,000\text{km}^2$. The morphology of tsunami deposits across the vast epicontinental basin is sheet-like, with grainsize distribution patterns, impact deposit thicknesses, and scour at the impact horizon all pointing to Tookoonooka and Talundilly; these two large marine impacts are the evident source of these ejecta-laden deposits of the Wyandra Sandstone Member. From this one can conclude that in an ancient buried basin defined by continuous quiescent sedimentation, doublet cratering can be demonstrated despite the reworking of ejecta in a marine impact scenario. Although data independently confirming Talundilly's impact status is lacking, its influence in the basin cannot be ignored. Indeed, it is highly probable that, given their biostratigraphic age uncertainty and proximity, Tookoonooka and Talundilly were formed from a binary impact event.

The Wyandra Sandstone is the depositional chronicle of the impact event, from impact through post-impact tsunamis to recovery of the depositional regime. Although depositional processes were undoubtedly complex, tsunamis are interpreted as the dominant depositional process outside the impact structures in the basin. The impact event was responsible for the deposition of the Wyandra Sandstone Member reservoir, and continues to affect its reservoir quality. Tookoonooka and Talundilly provide a unique model for the analysis of binary marine impact dynamics and deposits on Earth.

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EXTENDED DATA

1) Extended Methods

Combined data review represents an area of >805,000 km² out to a maximum extent of 23 Rc from crater centres. The majority are subsurface data (limited to available drilling records), as the Tookoonooka and Talundilly impact structures are both buried structures. Core and outcrop data represent an area >525,000 km².

Core data collection.

Cores were viewed at the South Australian government, Queensland government, and Santos Ltd core libraries. Drill cores were from stratigraphic, mineral, water and petroleum wells. The first three core types are generally 47.6 mm in diameter, while petroleum cores are 65 or 100 mm in diameter.

The presence and character of the Wyandra Sandstone (or equivalent) in the subsurface, both proximal and distal to the Tookoonooka and Talundilly impact structures, were examined in 51 drill cores (Fig. 2a; Extended Data 11) from wells drilled in the Eromanga Basin (Extended Data 2). All known core samples of the Wyandra Sandstone in South Australia and Queensland were examined. The entire Cadna-owie Formation-upper Walumbilla Formation interval was reviewed in all available stratigraphic wells (equivalent of more than 20 Ma in a ≤ 300 m interval of stratigraphic record). The full impact target sequence equivalent (i.e. down to basement lithologies underlying the sedimentary basin, where possible) was also reviewed in the closest stratigraphic wells to the crater structures.

Lithological logs of 25 cores were made across the Wyandra Sandstone outside the impact structures, covering a total of 931m of core (Extended Data 11). Macroscopic descriptions and geological data were recorded: lithology, grain size (cf Tucker 2001; Blair & McPherson 1999), sorting, clast composition, physical and biogenic sedimentary structures, and degree of bioturbation. A modified bioturbation index (cf Taylor & Goldring 1993) was used, ranging from 0 (no bioturbation) and 1 (minimal bioturbation: occasional burrow) to 3 (high degree of bioturbation: biogenically churned bedding with total loss of physical sedimentary structure). Where core was discontinuous, cores were described but not logged. Top and base Wyandra Sandstone and tsunami deposit depths, descriptions of the character of the Wyandra, presence of ejecta, and maximum grain sizes were recorded. Corelogs were constructed in Sedlog (Zervas et al. 2009) and Corel software.

Field data collection.

Outcrops of Cadna-owie Formation and Walumbilla Formation exist at the paleobasin margins in South Australia, New South Wales, and Queensland. Fieldwork at 12 locations was undertaken to determine the presence and character of the Wyandra Sandstone at distal locations and/or basin margin environments, up to 23Rc from the impact structures (Fig. 2a; Extended Data 11). Wyandra-equivalent deposits were interpreted at four locations, and used to confirm interpretations of larger scale sedimentary structures from the cores and assess bedding geometry at outcrop scale.

Lithological logs as above (e.g. Extended Data 10) and/or outcrop descriptions were recorded. Only qualitative data was recorded at basin margin sites where correlations were low confidence due to poor intraformational age constraint, insufficient vertical exposures, thinning due to basement onlap, or deep weathering that affected preservation of original sedimentary textures (e.g. Extended Data 4c). Outcrops are generally of poorer quality on the southern basin margins due to low relief outcrops as well as reduced preservation of microfossils and destruction of original depositional character by regolith processes (Alley & Sheard 1996; Ludbrook 1966), and impact shock signatures are expected to be too dilute at these locations. Thus while fieldwork provided integral insight into the context of the impact environment, it was considered supplemental to the subsurface basin analyses.

Log correlation and Depositional Realms map

Lithological logs from core and field observations were correlated to assess the lateral continuity and character of the Wyandra Sandstone in the basin, particularly the intraformational units

interpreted to comprise the tsunami sequence (Extended Data 9). Sparse palynological data was cross-referenced to confirm interpreted contacts of the Cadna-owie and Wyandra.

Data locations were grouped into depositional realms based on depositional character, interpreted paleoenvironments and processes of deposition with respect to pre-impact facies and crater proximity. Depositional realms were mapped (Fig. 2b). Representative logs were chosen for each interpreted realm (Fig. 3, Extended Data 10).

Datamining and mapping methods

Isopach maps were made to examine the thickness trend of the Wyandra Sandstone, the tsunami sequence, and the underlying Cadna-owie Formation across the basin (Fig. 4). Grainsize data was also used to construct a maximum grainsize distribution map for the Wyandra Sandstone. Maps were constructed using ArcGIS software.

To improve the data resolution for isopach and grainsize mapping over the interpreted distribution of impact-related sedimentation in the basin (n.b. the tsunami sequence is below seismic resolution), lithological logs and palynological data were used as calibrations to extrapolate interpreted stratigraphic contacts to 97 subsurface petroleum and mineral well datasets (Extended Data 11). Supplementary reports of 10 further field locations were also reviewed, and 5 additional occurrences of the Wyandra were interpreted only where strong correlative candidates and age constraint exist (Alley 1987, 1988; Sheard 2009; Alley & Sheard in prep; Musakti 1997; Greenfield et al. 2010; Ludbrook 1966; Morton 1982; Alley & Lemon 1988; Lemon 1988; Wopfner et al. 1970; Forbes 1966). Formation evaluation and drilling data was obtained from the South Australian, New South Wales, Northern Territory and Queensland governments, Santos Ltd. and Magellan Petroleum in the form of well completion reports, mud logs, lithological drill cuttings descriptions, sidewall core descriptions and formation evaluation (FE) logs (Extended Data 11). This data was used to evaluate the top and base depths of the Cadna-owie Formation and Wyandra Sandstone and the maximum grainsize present (where data quality was sufficient). All data used was quality checked for consistency: as the well database spans four states and over a century of drilling, the data required corrections for formation depths, grainsize scale (cf Tucker 2001; Blair & McPherson 1999), metric conversions and formation naming conventions. Additionally, the Wyandra is not always differentiated from the upper Cadna-owie Formation in the basin data/literature.

While FE logs were used as supplementary data, it must be noted that the FE log signature of the impact deposits was not consistent: while the base of the Wyandra *can* be evident by the sudden increase in porous sand content (due to ejecta), it is often masked by the mud content of altered impactoclasts and sedimentary lithic volumes. Cobbles and boulders of Cadna-owie scoured and ejected from the substrate by impact-related processes are evident in the Wyandra in full-hole core, but cannot be differentiated from the underlying Cadna-owie in log signatures. Thus correlations were done using all available well data. Combined data represent 158 locations covering an area of >805,000 km² out to a maximum extent of 23 Rc from crater centres.

Only grain sizes larger than sand-size were recorded to differentiate grains primarily absent from the Cadna-owie and Walumbilla Formations. The following grainsize assumptions were made:

- The upper constraint on grain size data is usually core width in cored wells (maximum: fine cobbles) and maximum cutting size in uncored wells (maximum: pebbles). Thus cobbles and boulders are usually unrecognizable at the stratigraphic core scale, and expected blocks and slabs within the crater realm cannot be resolved in core. Only cored well and outcrop locations register larger grain sizes.
- Maximum grain size data was recorded for the base Cadna-owie Formation to mid-Walumbilla Formation (top Doncaster Member) interval. Occasional coarse-grained beds may be present in the Walumbilla, proximal to the crater locations, correlatable to late post-impact debris flows and turbidites from crater slope slumps.
- Coarse mud-rich clasts, particularly impact-derived sedimentary lithics and altered melt and accretionary impactoclasts, can only be confirmed in full-hole core, as these weaker coarse clasts are pulverized by the drilling process and thus cuttings data are biased toward clay/mud

content in the impact deposits. This potential data skew may have resulted in the misinterpretation in petroleum reports as mudstone facies (vs. sandstone with discrete mud clasts or altered impactoclasts). Coarser grain sizes from cuttings data is assumed to represent other lithic clast types only.

- Uncertainties inherent in the accuracy of drilling data (e.g. cuttings data) include:
 - sampling interval (thin beds can be missed)
 - lagtime (affecting depth accuracy)
 - Rate of Penetration (data resolution is affected by drilling speed)
 - Pulverizing of larger grains by the drilling process (as above).

Binary Impact Probability and Impactor Size Calculations

The probability of Tookoonooka and Talundilly being a doublet crater was calculated using criteria of Miljković et al. (2013) and the program Impact:Earth! (Collins et al. 2005).

Petrography

Petrographic thin sections were made from cores and field samples from 9 locations (Extended Data 11). Polished and double-polished thin sections were professionally produced to 30-40 micron thickness. Petrographic microscopy was used to verify clast compositions and the presence of impact shock features. Shock orientations in quartz grains were measured via universal stage microscopy by previously reported methods (Bron & Gostin 2012). A total of 136 PDF (planar deformation features) sets and 40 PF (planar fractures) sets were measured in 46 quartz crystals of 34 quartz grains from 7 locations. Measurements of PF sets were not included in histograms. Grains with less than 2 sets of PDFs per grain were discarded as they were considered low confidence. Datasets are noted on each histogram (Extended Data 7-8). Due to the paucity of rock sample inherent in core studies, the small area on thin sections accessible for measurement on the universal stage, and the expected dilution of shocked material in reworked deposits, statistical datasets of shock measurements (cf Ferrière et al. 2009) were unfeasible. Depths and locations of measured shock samples are indicated on the grain size map (Fig. 4d) and lithological logs (Extended Data 10), and shock data plotted on histograms (Extended Data 8). Locations where the presence of shock-metamorphosed material could only be determined qualitatively are noted as such (Extended Data 10). Based on ejecta thickness and arrival time calculations, probable crater sources were assumed for all shock measurement locations, as most samples were taken from the base of the Wyandra Sandstone to obtain the least reworked ejecta samples. Maximum shocked grainsize distal fining trends were plotted (cf Izett et al. 1998).

2) **Figure: The Stratigraphic Context of the Tookoonooka-Talundilly Impact.**
 Modified after Bron (2010) and Cohen et al. (2014).

Erathem/ Era	System/ Period	Series/ Epoch	Stage/ Age	Age (Ma)	Biozones	Eromanga Basin Lithostratigraphy SW → NE		
Mesozoic	Cretaceous	Upper	Cenomanian	93.9 100.5	PK7	Winton Fm		
		Lower	Albian		PK6	Mackunda Fm		
					PK5	Oodnadatta Fm Allaru Mudst Toolebuc Fm		
			Aptian		PK4	Coorikiana Ss		
					PK3	Bulldog Shale Walumbilla Fm		
						Wyandra Ss Mbr		
					PK2	Cadna-owie Fm		
			Jurassic	Upper	Barremian	~125.0		
					Hauterivian	~129.4		
		Valanginian			~132.9	PK1	Murta Mbr	
	Berriasian	~139.8				Hooray Ss		
		Tithonian	~145.0	PJ6	Namur Ss	Westbourne Adori Ss		
		Kimmeridgian	152.1 ±0.9					
		Oxfordian	157.3 ±1.0	PJ5	Birkhead Fm			
		163.5 ±1.0						

3) Table: Marine and Possible Marine Impacts. 43 impacts of the current Earth cratering record are categorized as marine, 13 of which are considered possible marine impacts [previous compilations (Dypvik & Jansa 2003; Ormö & Lindström 2000; Abels et al., 2002) identified 20-26 marine impact structures of the confirmed impacts on Earth]. All have confirmed impact origins, though Talundilly and Yallalie are included as highly probable impact structures. Documented tsunami or tsunami-like deposits well beyond the crater rims associated with known marine impacts are noted. "Possible marine" impact structures are included that exhibit typical marine impact features such as lack of melt or unusually thick allogenic breccia sequences (e.g. Mishina Gora), proximity to paleoshorelines, continuous marine sedimentation, or associated marine deposits (e.g. Acraman), but where limited data exist. Lack of data (e.g. due to burial, erosion, lack of paleoenvironmental context) and misinterpretation have likely contributed to the underestimation of marine craters in the Earth impact record, and craters where $d \gg H$ (see text) could have very subdued marine features, although they would have associated impact-related marine realm deposition.

<i>Marine Impact Structures</i>						
Impact Structure [£]	Crater Location	Paleobasin	Age (Ma)*	Crater Diameter (km)*	Tsunami-like deposits documented	References (marine origin)
Alamo ^{#£}	USA	proto-Pacific Ocean	382±4 [†]	N/A (40-60) [†]	Y	1,38,39,40
Ames [#]	USA	Anadarko Basin	450-460 [†]	16	Y	2,11,19,20
Araguainha	Brazil	Paraná-Karoo Basin	254.7±2.5	40	Y	30
Avak [#]	USA	Western Interior Seaway	Mid-late Turonian (±90Ma) [†]	12	Y	1,26
Chesapeake Bay [#]	USA	Atlantic Ocean	35.5±0.3	40	Y	1,2,11
Chicxulub [#]	Mexico	Proto-Caribbean Sea	64.98±0.05	150	Y	1,36
Eltanin [#] (temporary water crater only)	N/A	South Pacific Ocean	2.15	N/A (60)	Y	1,2,9,10,14
Flynn Creek [#]	USA	? very shallow marine	382 [†]	3.6-3.8		2,27,37
Gårdnos [#]	Norway	?	500±10	5		1
Granby [#]	Sweden	Baltoscandian epicontinental sea	~470	3		1,2,3
Gusev [#]	Russia	? shallow marine	49±0.2Ma	3		1,33,(12)
Hummeln [#]	Sweden	? shallow marine	470	1.2		2,3,8,42,43
Kaluga [#]	Russia	epicontinental sea within East European craton	380±5	15	Y	1,2,3,10,12,15
Kamensk [#]	Russia	? shallow marine	49±0.2Ma	25		1,2,11,12,33
Kara [#]	Russia		70.3±2.2	65		1,12,33
Kärdla [#]	Estonia	Baltoscandian epicontinental sea	Upper Ordovician (~455Ma)	4 [†]	Y	1,2,3,8,10,12,16
Karikkoselkä [#]	Finland		~230	1.5		1,3
Lockne [#]	Sweden	Baltoscandian epicontinental sea	~458	7.5	Y	1,2,3,13,(8), (11)
Målingen	Sweden	Baltoscandian	~458	~1		4

Saarijärvi [#]	Finland		214±8 [†]		1.5	possible marine	3
Serra da Cangalha	Brazil	intra-cratonic Parnaíba Basin	>600		13.7 [†]	crater stratigraphy indicates that impact event bounded by marine facies, though post-impact deposits not yet described.	28
Söderfjärden	Finland		~600		6.6	proximity of shoreline & possible tidally-influenced impact setting. Layered sediments in crater fill could indicate resurgence	3
Sudbury	Canada	Animikie Ocean	1850±3		130	Proximity to paleoshore deposits & nearshore sediments as rip-up clasts in breccia. Presence of accretionary impactoclasts are possible substrate water indicators. Debrisites indicate possible tsunami. Possible "surgeback" breccia in crater.	11, 18
Woodleigh	Australia	proximity to paleo-basin	364±8		40-120	Proximity of paleoshoreline: paleoenvironmental maps indicate marginal-very shallow marine. But significant hiatus between undifferentiated Devonian crater fill & overlying Jurassic lacustrine strata.	32

[‡] This list does not include marine-emplaced ejecta without associated craters, except Eltanin and Alamo for which substantial evidence has been found: for Eltanin, an associated crater was non-existent, but much evidence has been found for a deep-sea impact where a temporary water crater was formed (Gersonde et al. 1997); for Alamo, the main crater structure was removed by tectonic burial, although proximal crater realms including a crater rim have been identified (Pinto & Warme 2008).

* Age/diameter from Earth Impact Database (viewed 2015) unless otherwise noted.

Impacts classified as marine prior to this paper in compiled lists (Dypvik & Jansa 2003; Ormö & Lindström 2000; Abels et al. 2002).

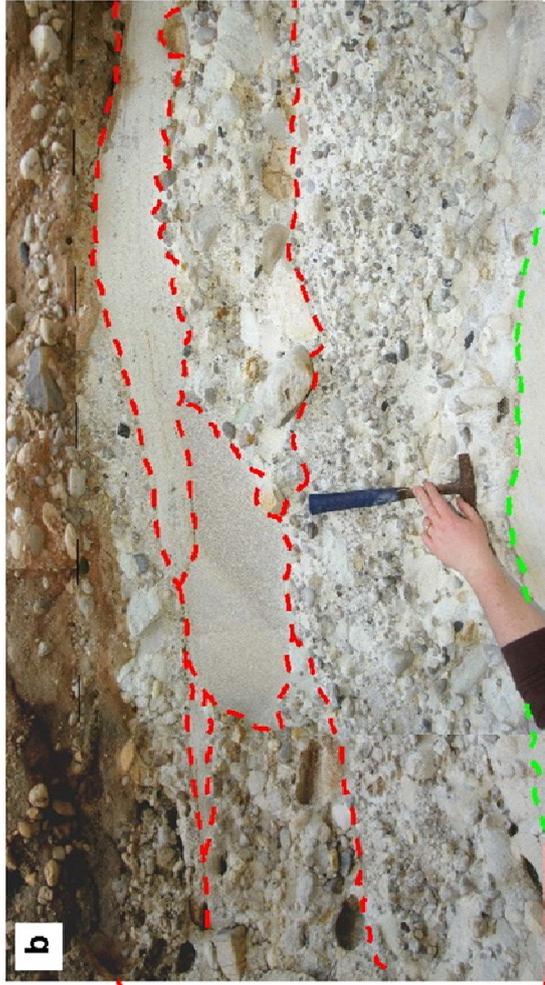
[†] **Alamo** age: Morrow & Sandberg (2005); Alamo size estimate: Morrow et al. (2005); **Ames** age: Repetski (1998); **Banet & Fenton** (2008), Kirschner et al. (1992); **Flynn Creek** age: Schieber & Over (2005); **Kårdla** size: Puura & Suuroja (1992); **Ritland** size: Riis et al. (2011); **Rochechouart** age: Kelley & Spray (1997), Schmieder et al. (2010); **Serra da Cangalha**: Vasconcelos et al. (2013); **Tookoonooka-Talundilly** age: Bron (2010), Bron & Gostin (2012), this paper; Tookoonooka crater size: Gostin & Therriault (1997); Talundilly crater size: Gortler & Glikson (2012a); **Ust Kara**: Masaitis (1999), Masaitis et al. (1980); **Yallalie**: Hawke (2004).

Selected references - marine origin: 1: Dypvik & Jansa (2003); 2: Ormö & Lindström (2000); 3: Abels et al. (2002); 4: Alwmark et al. (2014), Ormö et al. (2014a, 2014b); 5: Bron (2010), Bron & Gostin (2012); 6: Riis et al. (2011), Azad et al. (2012); 7: Schmieder et al. (2010); 8: Frisk & Ormö (2007); 9: Gersonde et al. (1997, 2002); 10: Dypvik et al. (2004); 11: Poag et al. (2004); 12: Masaitis (1999); 13: Lindström et al. (2008), von Dalwigk & Ormö (2001), Sturkell et al. (2000); 14: Ward & Asphaug (2002); 15: Masaitis (2002); 16: Suuroja & Suuroja (2006), Suuroja (2002), Puura & Suuroja (1992); 17: Suuroja & Suuroja (2004), Suuroja et al. (2002); 18: Addison et al. (2010), Pufahl et al. (2007), Ames et al. (2000); 19: Mescher & Schultz (1997); 20: Repetski (1997); 21: Buchanan et al. (1998), Wong et al. (1997), Fischer (1997); 22: Mescher et al. (2012); 23: Wallace et al. (1996), Dyson (2005); 24: Ormö et al. (2007); 25: Izett et al. (1998), Weber & Watkins (2007), Steiner & Shoemaker (1996), Witzke & Anderson (1996); 26: Banet & Fenton (2008), Kirschner et al. (1992); 27: Schieber & Over (2005); 28: Vasconcelos et al. (2013); 29: Forsman et al. (1996); 30: Tohver et al. (2013); 31: Hawke (2004), Bevan et al. (2004), Dentith et al. (1999); 32: Glikson et al. (2005); 33: Masaitis et al. (1980); 34: Dypvik et al. (1996), Glimsdal et al. (2010), Dypvik et al. (2010); 35: Schnyder et al. (2005); 36: Goto (2008), Goto et al. (2008), Albertão et al. (2002), Smit (1999), Matsui et al. (2002), Albertão & Martins (1996), Smit et al. (1996); 37: Roddy (1977); 38: Pinto & Warme (2008); 39: Warme et al. (2008); 40: Morrow et al. (2005); 41: Kelley & Spray (1997); 42: Alwmark et al. (2015); 43: Lindström et al. (1999).

4) Figure: Outcrop photos, lower Wyandra

a-b, Outcrop near northeastern basin margin (Location 60) showing basal contact of Wyandra, underlying Cadna-owie, and lower Wyandra. **a)** outcrop scale: note sheet-like morphology of lowermost coarse-grained unit, ~1m thick, which exhibits an abrupt shift in paleoflow direction from the underlying sandstone across an erosional surface. Coarsest material is thought to be mostly reworked Talundilly proximal ejecta. Measure stick is 5m in height. **b)** Detail of **a)** shows a complex package of multiple units and multiple erosional surfaces that make up the coarse basal carpet. Note pinchouts and lenses of finer-grained backwash units. Coarser breccia-conglomerate beds are interpreted as runup units and appear to be preferentially preserved.

c, Outcrop near southwestern basin margin (Location 53) showing ferruginization common at the *local* top of a Cadna-owie Formation outcrop which is likely to be distal Wyandra Sandstone deposits but unconfirmed due to loss of original bedding fabric.



--- Cadna-owie-Vvyandra contact
--- Runup & Backwash unit contacts

5) Higher depositional energy lithofacies of lower Wyandra tsunami sequences in core and outcrop showing progressive decrease in flow energy.

a, Clast-supported breccia-conglomerate facies of the basal Wyandra in outcrop (Location 60). Note structureless, very poorly sorted fabric, oscillating clast support, very polymictic clast content and the sharp erosive contact with underlying ripple cross-bedded, fine-medium-grained sandstone of the Cadna-owie Formation. Maximum grain size in the Wyandra is coarse cobble.

b-d, Massive sandstone with floating, matrix-supported sedimentary lithic clasts. Facies very common in the estuarine depositional realm. **b-c)** Randomly-oriented clasts are cobble-sized, stratified, apparently brecciating syn-deposition; sedimentary lithic clasts often exhibit soft-sediment deformation or microfaults, and are interpreted as impact-seismite-affected substrate, from crater-proximal areas, ripped-up by either impact or tsunami scour. Location 7. **d)** pebble-sized clasts, location 36. Other lithics are rare in this facies, but melt and accretionary clasts are common.

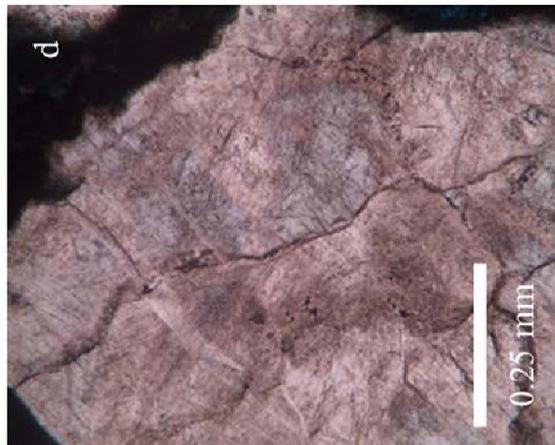
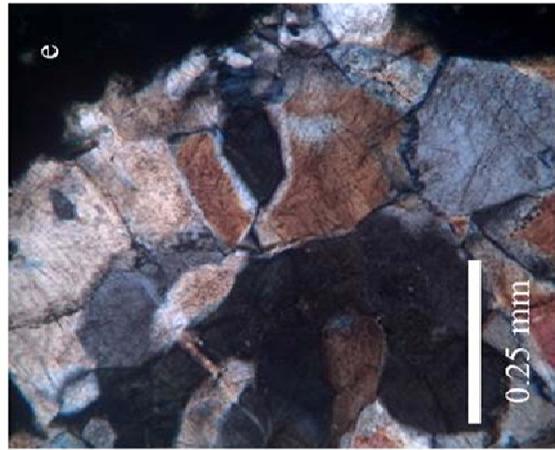
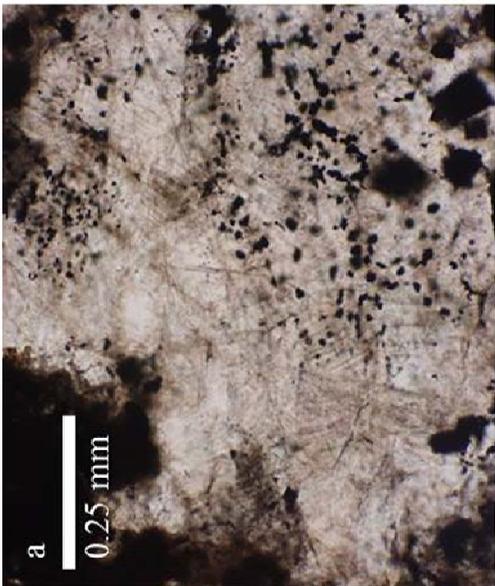
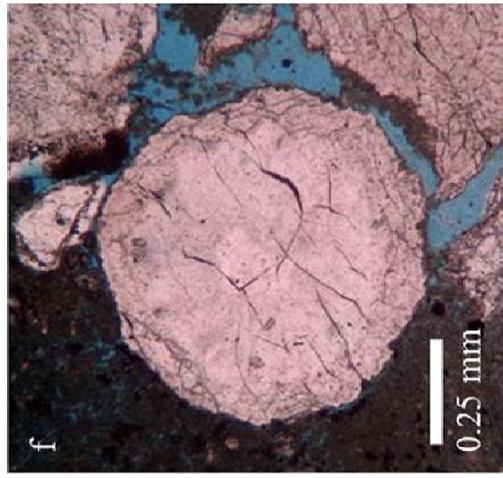
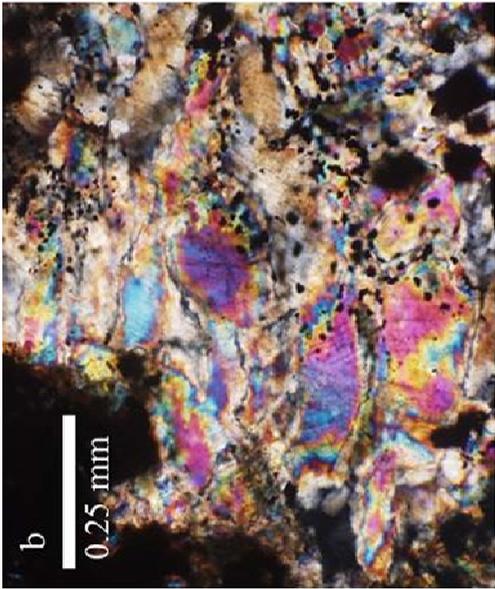
e-g, Upper flow regime planar-stratified to low angle cross-stratified sandstone with plane-parallel clasts. Clasts are usually pebble-sized sedimentary lithic clasts and melt and accretionary impactoclasts. **e)** More carbonaceous-rich laminations at bottom of photo more typical of resurge, whereas stratification at top more typical of runout. Location 28. **f)** planar stratification to low angle cross-stratification, with elongate sedimentary lithic pebbles and melt and accretionary impactoclasts from location 23. **g)** Location 33: finer-grained and more clast-poor than **e)**. Probably related to pebble-entrained trough cross-bedding observed in outcrop **h)**.

h, Trough cross-bedded sandstone with entrained pebbles. Outcrop face is roughly perpendicular to the flow direction. Troughs are several meters across, defined by pebble horizons.



6) Petrographic Impact Evidence in the Wyandra Sandstone

a-e, Shocked quartz within the Wyandra Sandstone. **a-b**) A toasted, polycrystalline, irregularly-shaped metamorphic lithic grain from location 6, exhibiting 2-3 sets of shock lamellae in most quartz subgrains. Photos show grain under **a**) plane-polarized light and **b**) crossed polarizers. Note: black speckles are pyrite crystals in intragranular cement. **c**) A very coarse sand-sized monocrystalline grain of igneous quartz from location 20, slightly toasted, shown in plane-polarized light. Dominant set of planar lamellae is oriented WNW-ESE. **d-e**) A toasted, polycrystalline, angular metamorphic quartz grain from location 30, with multiple sets of shock lamellae in each sub-grain. Photos show grain under **d**) plane-polarized light and **e**) crossed polarizers. **f-g**) Devitrified and altered spherule from the lower Wyandra in location 30 in **f**) plane-polarized light and **g**) crossed polarizers. Spherule is a rare example of four spherules discovered in microscopic analyses of the lower Wyandra Sandstone. Spherule is 0.9 mm in diameter. Radially-textured core with dissolution edge is 0.6 mm in diameter. Rim is 0.15 mm thick, likely replaced silicate glass rim or a diagenetic quartz overgrowth.



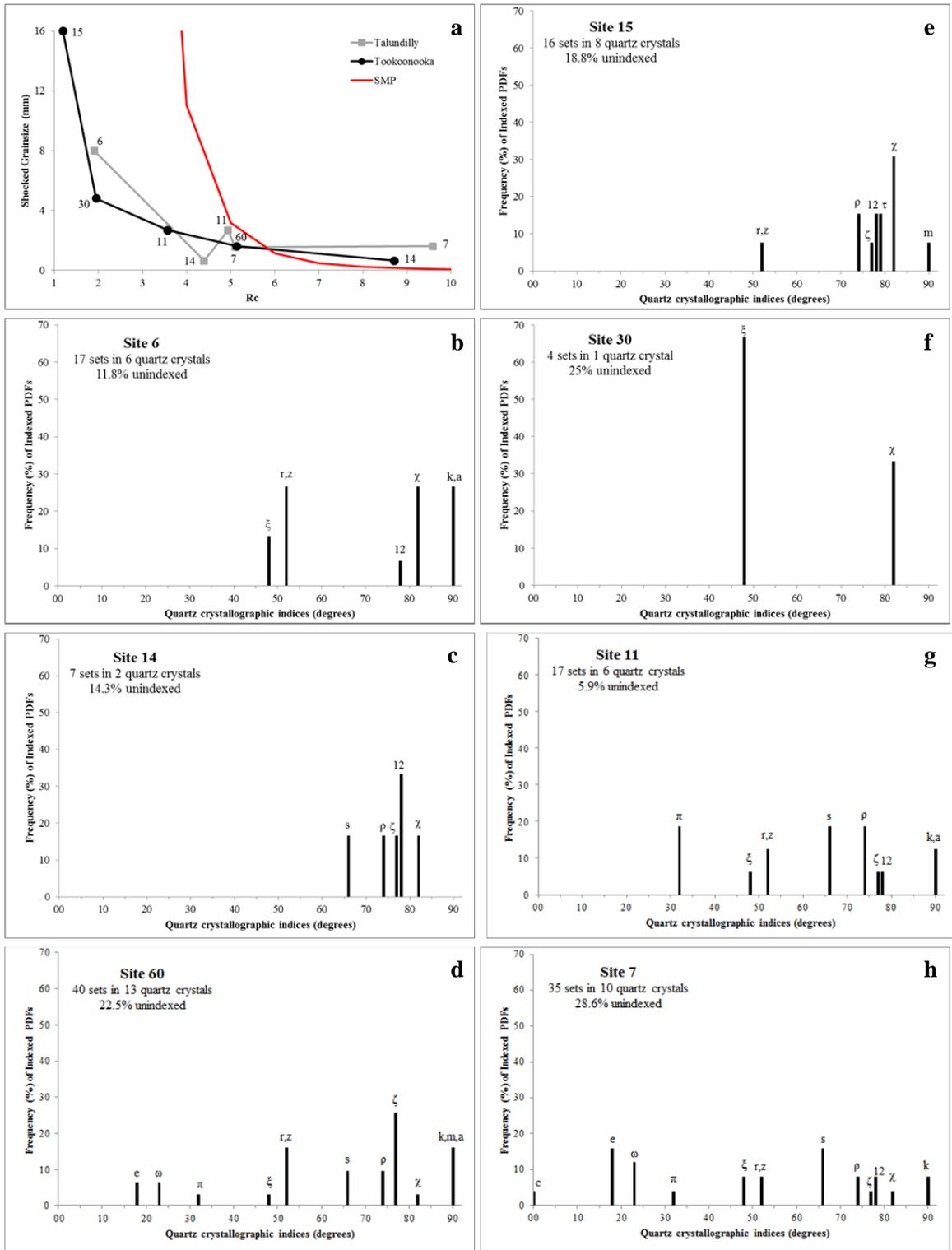
7) Table: Summary of crystallographic orientations of Planar Deformation Features (PDFs) in shocked quartz for 7 samples of interpreted Tookoonooka-Talundilly ejecta within the lower Wyandra Sandstone. A total of 136 PDF sets were measured in 46 quartz crystals of 34 quartz grains and lithic fragments. Due to the paucity of rock sample inherent in core studies, the small area on thin sections accessible for measurement on the universal stage, and the expected dilution of shocked material in reworked deposits, statistical datasets of shock measurements were unfeasible.

Plane #	Symbol	Miller-Bravais index	Polar angle with c-axis (deg)	# PDF sets	Frequency (%)
1	c	(0001)	0.00	1	0.74
e	-	$\{10\bar{1}4\}$	17.62	6	4.41
2	ω	$\{10\bar{1}3\}$	22.95	5	3.68
3	π	$\{10\bar{1}2\}$	32.42	5	3.68
6	ξ	$\{11\bar{2}2\}$	47.73	8	5.88
4	r, z	$\{10\bar{1}1\}, \{01\bar{1}1\}$	51.79	14	10.29
7	s	$\{11\bar{2}1\}$	65.56	11	8.09
8	ρ	$\{21\bar{3}1\}$	73.71	11	8.09
11	ζ	$\{22\bar{4}1\}$	77.20	12	8.82
12	-	$\{31\bar{4}1\}$	77.91	8	5.88
13	τ	$\{40\bar{4}1\}$	78.87	2	1.47
9	χ	$\{51\bar{6}1\}$	82.07	12	8.82
5,10,14	m, a, k	$\{10\bar{1}0\}, \{11\bar{2}0\}, \{51\bar{6}0\}$	90.00	14	10.29
Total Indexed PDF sets				109	80.15
Unindexed PDF sets				27	19.85
Total PDF sets				136	100.00

8) Figure: Shocked Quartz Grain Measurements for seven samples of interpreted Tookoonooka-Talundilly ejecta within the lower Wyandra Sandstone.

a, Shocked grainsize vs Rc graph (maximum shocked grainsize per sample from 7 sample locations). Rc are units of crater radii. Assumptions: As most samples were taken from basal Wyandra breccia-conglomerate beds, ejecta arrival time and ejecta layer thickness calculations were performed using reasonable estimates of 40-50 km transient crater diameter. The distance at which ejecta thicknesses for Tookoonooka & Talundilly are equal is 129.3 km (3.9 Rc) from Tookoonooka and 174.1km (4.2 Rc) from Talundilly. Thus indicative crater source was assigned to each shocked grain sample location, i.e. probability that ejecta derived from Tookoonooka or Talundilly. These calculations are indicative only and do not take into account the complexity of tsunami redistribution and reworking in the marine environment. Distal fining of shocked grains is indicated, and can be compared to distal fining trends at Manson impact site (Izett et al. 1998) and Ries (Hörz et al. 1983); the S_{MP} curve shows the mean grain size of primary ejecta from a subaerial impact, and does not account for marine reworking.

b-h, Histograms of shocked quartz grain measurements from seven sample sites. A total of 136 PDF sets were measured in 46 quartz crystals, with a maximum of 6 PDF sets per grain. Due to the paucity of rock sample inherent in core studies, the small area on thin sections accessible for measurement on the universal stage, and the expected dilution of shocked material in reworked deposits, statistical datasets of shock measurements were unfeasible. Results are consistent with the shock level profiles of marine impacts and establish the impact origin of the tsunami deposits. Dataset in histogram **g** (Location 11) includes two grains shown in Bron & Gostin (2012). **b)** Location 6; **c)** Location 14; **d)** Location 60; **e)** Location 15; **f)** Location 30; **g)** Location 11; **h)** Location 7.



9) Table: Characteristics of Depositional Realms.

Depositional Realm	1. Shallow Marine, Marginal Marine, Near Marine: Distal >10Rc		2. Estuarine		3. Shallow Marine, Marginal Marine, Near Marine: 2-10Rc			4. Shallow Marine: 1-2Rc		5. Crater Realm: <1Rc
	a) Northern basin margin (QLD)	b) South-western basin margin (SA)	Locations 23, 36, 21, 9, 3#, 115, 31#	Locations 37, 38, 59, 58, 57, 55, 56, 53, 39, 48.	a) Shallow Marine	b) Marginal-Near Marine	c) Interference/Mixed	a) General	b) Slumped zone	
Locations assigned	Locations 18, 10, 14*#, 19	Locations 37, 38, 59, 58, 57, 55, 56, 53, 39, 48.	Locations 23, 36, 21, 9, 3#, 115, 31#	Locations 37, 38, 59, 58, 57, 55, 56, 53, 39, 48.	Locations 26, 27, 60*, 4, 10, 19, 3#, 33, 40, 14*#	Locations 7*, 22, 20*, 17?	Location 11*, 31?#	Locations 25, 30*, 2, 15*, 5*, 28, 29, 12, 13, 24, 31#, 6?*	Locations 34, 35	Location 32*
	Location 18 endmember	Location 37 endmember	Location 36	Location 37 endmember	Location 60* endmember	Location 7* endmember	Location 11*	Location 30* (Tookoonooka) & Location 5* (Talundilly)	Location 34	Location 32*
Locations assigned	Location 18 endmember	Location 37 endmember	Location 36	Location 37 endmember	Location 60* endmember	Location 7* endmember	Location 11*	Location 30* (Tookoonooka) & Location 5* (Talundilly)	Location 34	Location 32*
Uppermost Wyandra: Transition unit to Walumbilla	None at location 18, but locations 10, 14, 19 consistent average 1.6m thick, muddy f-mgr Bioturbation Index=3.	Commonly extremely gradational: 18.1m thick transition at location 37, fining from mgr up to sst. Other locations more like rest of basin: 0-1.5m in thickness.	Vfgr-mgr, Bioturbation Index= 2-3. Average thickness: 2.1m (locations 23&36)	Commonly extremely gradational: 18.1m thick transition at location 37, fining from mgr up to sst. Other locations more like rest of basin: 0-1.5m in thickness.	NE basin margin: m-cgr. Bioturbation Index =1-3. S of Tookoonooka: fgr, Bioturbation Index =3. N basin margin: f-mgr, Bioturbation Index =3. Average thickness 2.13m, but slightly thinner in NE margin (average 0.5m). Thickness 2.3-2.6m in north & south respectively.	NE basin margin: m-cgr. Bioturbation Index =1-3. S of Tookoonooka: fgr, Bioturbation Index =3. N basin margin: f-mgr, Bioturbation Index =3. Average thickness 2.13m, but slightly thinner in NE margin (average 0.5m). Thickness 2.3-2.6m in north & south respectively.	Average thickness 2.7m. Average Bioturbation Index =3. Average grain-size mgr. Blocky (rarely coarsening or fining up).	Location 34: thick 2.44m. Bioturbation Index =3.		

Upper Wyandra (Post-tsunami Sequence)		4.8m thick at location 18. Highly variable thicknesses across north. Locations 10 & 18: generally mgr with a few sst interbeds until transition. Location 18 has a couple gran-pebb beds between. Bioturbation Index= 0-1.	Mgr: if any. Obvious transgressive fining pkg is in transition above at location 37. Most field locations missing section. Existing data range: 0-5.2m	Interbedded ss with lesser sst, rhythmic-tidal indications, subtle, gradual fining/silting up (1-2 grainizes up to transition), disappearance of coarse clasts, bioturbation returns halfway up this section, Bioturbation Index increasing from 1-2 up to 3. Average thick: 24m.	Variable grainsize profile. Generally maximum mgr ss, common interbedded sst, occasional reworked pebble. Increasing bioturbation upward (maximum at transition). Average thickness: 7.9m	Average thickness 3.37m. Generally fining up, m/cgr up to fgr, rarely coarsening up. Bioturbation Index =1 (occasionally up to 3).	Variable but minimal, proximal to crater (depending on crater slope?) (none at location 34, 1.5m at location 35).	Wyandra age-equivalent deposits within the crater are correlative to deposits outside the crater but are highly complex resurge and crater-fill breccia deposits formed by multiple processes. Details are beyond the scope of this paper and different terminology applies to these deposits.
Lower Wyandra (Impact Tsunami Sequence)	General Description	Variation due to basin margin topography and lithology, proximity (>10Rc from both craters up to >20Rc), and terrestrial inundation. Similar to more proximal sequences but thinner.	Massive-bedded, clay-rich, sand-dominant and thick-bedded. Abundant floating clasts dominated by rip-ups (various sedimentary lithics such as stratified mud clasts, siltstone clasts, red mudclasts), lithic clasts much less common.	Variation due to crater proximity and paleo water depth. Most variability and largest of all realms.	Similar to deposits >2Rc but thinner. Mixed processes as per crater realm but less intense.	Similar to (a) but deformed by slumping (syn- & post-depositional; post-tsunami slumping likely dominant).		

Maximum grain size in core ⁺	≤Pebble	Location 18 thickness 0.9m. All northern wells highly variable	Highly variable thickness (due to basin margin topography/ water depth). Thickness range: 0.4-8.1m (not counting MINs), average 2.1-2.8m. Location 37: 8.1m.	Boulder (intraformational/ sedimentary lithic)	Average 33m thick: Thickest deposits of all realms outside crater.	Occasional cobbles or boulder, but predominantly maximum pebble	Occasional boulder but predominantly maximum cobble
	Thickness tsunami sequence					Average 8.8m thick	Average thick: 6.26m (average of locations around both craters). Average thick: 7.9m (locations 34 & 35 only) – section thickened due to slumping?
Geometry, Lateral trend		Deposits fine & thin distally.	Deposits thin distally, drastically where close to ranges (where preserved). Deposits fine distally: mostly sandstone (location 37) until near the ranges, where backwash is coarsest. Fewer couplets distally.	Distal thinning of succession. Variation due to proximity (and possibly paleo-water depth).		Outcrops evidence the nature of the basal deposits: sheet-like overall, but inconsistent thickness of individual beds due to variable scour. Lower part of section thinner beds, more scour, upper are thicker.	Variation due to proximity (highest energy outside crater), presence of crater slopes, resurge channels & slump blocks.

Preservation		Variable	Runout better preserved. Relative volume of Runout: Resurge: Mixed unit=45:30:25%	First preserved unit is generally Runout/runup	First preserved unit is predominantly runout/runup	
Cadna-owie	Average no. wave packages	4-5 average	Up to 7	5 average (where mixed harder to estimate)	±10. Many wave cycles preserved.	
	Dominant Depositional Processes	Tsunami	Tsunami Runout units: coarser; erosive bases. Resurge units: less energy; more organics; finer. Mixed units: late-stage seiching; lower energy.	Tsunami	Hybrid processes: Tsunami & Debris flow	Hybrid processes: Tsunami & slumping
		Bioturbation Index =0-2, intermittent. Only location 10 regular bioturbation (more open marine?). sst-mgr irregular, all wells have occasional granule-pebble lenses	Location 37: Bioturbation Index=2, vf-gr. Locations 59 & 58: mgr, organics, bioturbation is deeper. Further west: gets coarser off the ranges, thins and overlies vcgr Algebuckina.	NE basin margin: Bioturbation Index=1-3, f-mgr, occasional pebble. Northern basin: Bioturbation Index=1-2, fgr w occasional pebble. S of Tookoonooka: Bioturbation Index=1, fgr. Marginal-non-marine deposits underlie tsunami sequence in 4 cores, but dominantly Cadna-owie deposits underlying tsunami sequence are shallow marine, bioturbated. Tsunami sequence overlying does not vary with paleo-environment of Cadna-owie.	Lower Cadna-owie facies most common around Tookoonooka, due to significant proximal impact scour (see above). Amount of Cadna-owie removed by impact scour around Talundilly more difficult to assess due to coarser Cadna-owie in northeast of basin. Average: f-vfgr, Bioturbation Index=1-2. Talundilly: more variable, occasional pebble, occasional sst, vf-cgr beds.	Present as autochthonous breccia only. Only lower Cadna-owie observed due to impact removal of upper sections.

Notes: *Locations with shock evidence confirmed. #Locations exhibiting attributes of more than 1 depositional realm. †Grainsize assumptions: For all locations without whole rock samples available (i.e. cuttings data vs. drill core or outcrop), grain size data is limited to lithic grain sizes only, dependent on sampling resolution while drilling and ability to differentiate clast size in drilling samples. Intraformational clasts, rip-up clasts and other sedimentary lithics as well as altered melt and accretionary impactoclasts (typically the largest grain sizes) will typically not be well-represented in cuttings data, and may result in misinterpretation in petroleum reports as mudstone facies (vs sandstone with discrete mud clasts or altered impactoclasts), complicating accurate profiling of Wyandra sandbody. Clasts larger than pebbles are not usually represented in cuttings data. Clast sizes larger than fine cobbles are not usually recognized in core. Cuttings data may also be affected by lagtime, drilling rate, bed thickness and sampling interval. See [Supplementary Information for core logs](#).

10) Detailed lithological logs – representative logs of depositional realms.

- a,** Location 18 corelog
- b,** Location 37 corelog
- c,** Location 36 corelog
- d,** Location 60 outcrop log
- e,** Location 7 corelog
- f,** Location 11 corelog
- g,** Location 30 corelog
- h,** Location 5 corelog
- i,** Legend

Location 18 Core Interpretation

Well Name: GSQ Machattie-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.8152°S / 140.3095°E
Distance from Tookoonooka / Talundilly (crater centre): 10.8 Rc / 10.3 Rc
Depositional Realm: Shallow, Marginal & Near Marine (distal >10 Rc)
Corelogged Interval: 770-790 m
Depth Units: meters MD
Author: Katherine Bron

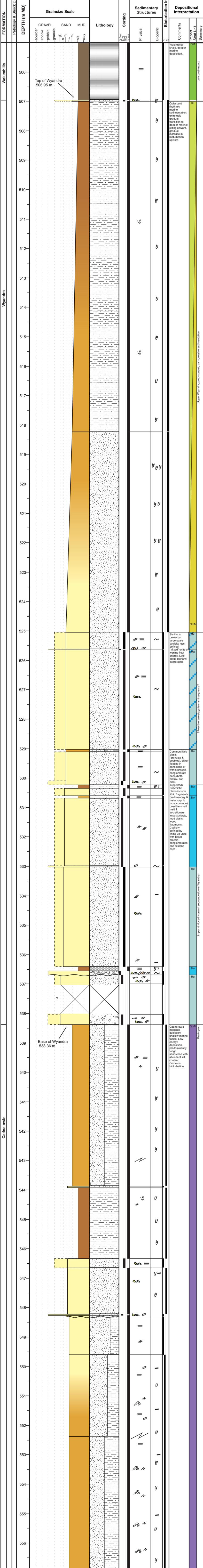
FORMATION	Petrology & Shock Data	DEPTH (m MD)	Grainsize Scale							Lithology	Sorting	Sedimentary Structures		Bioturbation Index	Depositional Interpretation		
			GRAVEL			SAND			MUD			Physical	Biogenic		Comments	Impact Strat Unit	Summary
			boulder	cobble	pebble	granule	vc	m	vf								
Walumbilla		774											0123	Walumbilla lithologically more similar to lower Cadna-owie (or South Australian Bulldog Formation) than typical Walumbilla shale here. Inundation of marginal marine (?) environment.	Qm	Late post-impact	
		775															
		776															
Wyandra		777									>		0123	Sedimentation style returns to pre-impact, ambient character but with slightly coarser grainsize. Quiescent rhythmic marginal marine (?) sedimentation.	QmM	Transgressive sedimentation, post-tsunami (upper Wyandra).	
		778									>						
		779															
		780															
		781															
		782															
		783															
		784															
		785															
		786															
Cadna-owie		787											0123	Possible late-stage tsunami, waning flow energy with longer wave transits (bioturbation capping units).	Ru	?Possible late-stage tsunami?	
		788															
		789															
		790															
		791															
	783											0123	3 fining upward cycles w/ erosional bases & silt caps. Breccia-cong w/ lithic frags, impactoclasts & mudclasts	Bw	Impact induced tsunami sequence		
	784																
	785																
	786																
	787																
	788											0123	Cadna-owie facies: predominantly low-energy sedimentation, silt-rich, bioturbation.	QmM	Pre-impact.		
	789																
	790																
	781											0123	Possible late-stage tsunami, waning flow energy with longer wave transits (bioturbation capping units).	Ru	?Possible late-stage tsunami?		
	782																
	783																
	784											0123	Structureless. (due to soft-sed deformation or intense bioturbation)	QmM	Pre-impact.		
	785																
	786																
	787											0123	Intensely fluidized, calcareous. Possible seismites?	QmM	Pre-impact.		
	788																
	789																
	790											0123	Lower Cadna-owie facies.	QmM	Pre-impact.		
	791																
	792																

Location 18 Core Interpretation

Well Name: GSQ Machattie-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.8152°S / 140.3095°E
Distance from Tookoonooka / Talundilly (crater centre): 10.8 Rc / 10.3 Rc
Depositional Realm: Shallow, Marginal & Near Marine (distal >10 Rc)
Corelogged Interval: 770-790 m
Depth Units: meters MD
Author: Katherine Bron

Location 37 Core Interpretation

Well Name: CBH-2
 Well Type (core width): Stratigraphic (WC gauge ~4.5cm)
 Location: South Australia, Australia
 Basin: Eromanga
 Latitude / Longitude: 29.5791°S / 139.5013°E
 Distance from Tookoonooka / Talundilly (crater centre): 12.7 Rc / 17.4 Rc
 Depositional Realm: Shallow, Marginal & Near Marine (distal >10 Rc)
 Corelogged Interval: 506-557 m
 Depth Units: meters MD
 Author: Katherine Bron



Location 37 Core Interpretation

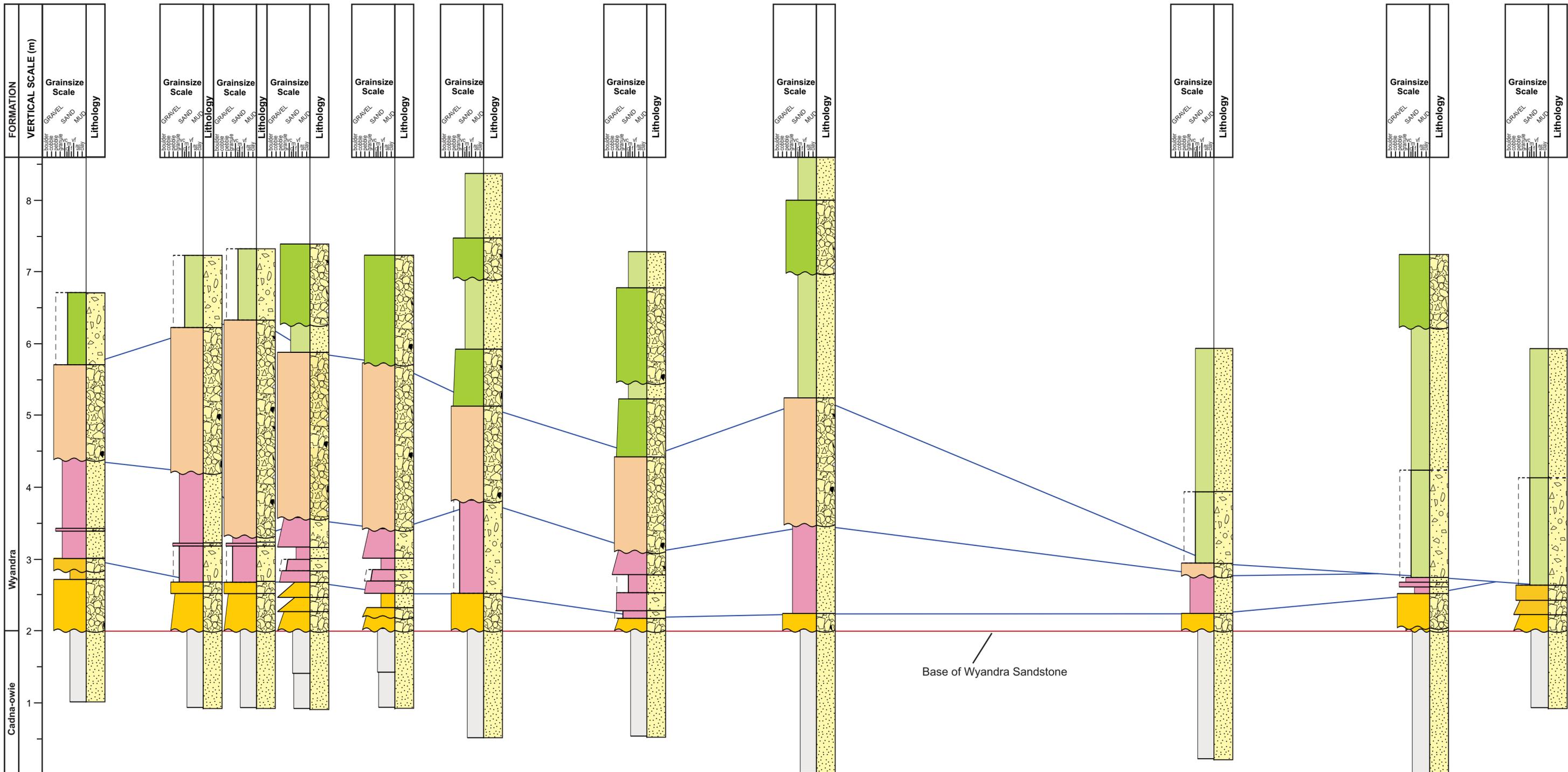
Well Name: CBH-2
 Well Type (core width): Stratigraphic (WC gauge ~4.5cm)
 Location: South Australia, Australia
 Basin: Eromanga
 Latitude / Longitude: 29.5791°S / 139.5013°E
 Distance from Tookoonooka/Talundilly (crater centre): 12.7 Rc / 17.4 Rc
 Depositional Realm: Shallow, Marginal & Near Marine (distal >10 Rc)
 Corelogged Interval: 506-557 m
 Depth Units: meters MD
 Author: Katherine Bron

Location 60 Outcrop Log Correlation

Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 25.1°S / 146.6°E
Distance from Tookoonooka / Talundilly (crater centre): 13.3 Rc / 5.1 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Outcrop height: Maximum 8.6m (maximum 6.6m of Wyandra)
Outcrop length: 180m
Depth Units: meters
Author: Katherine Bron

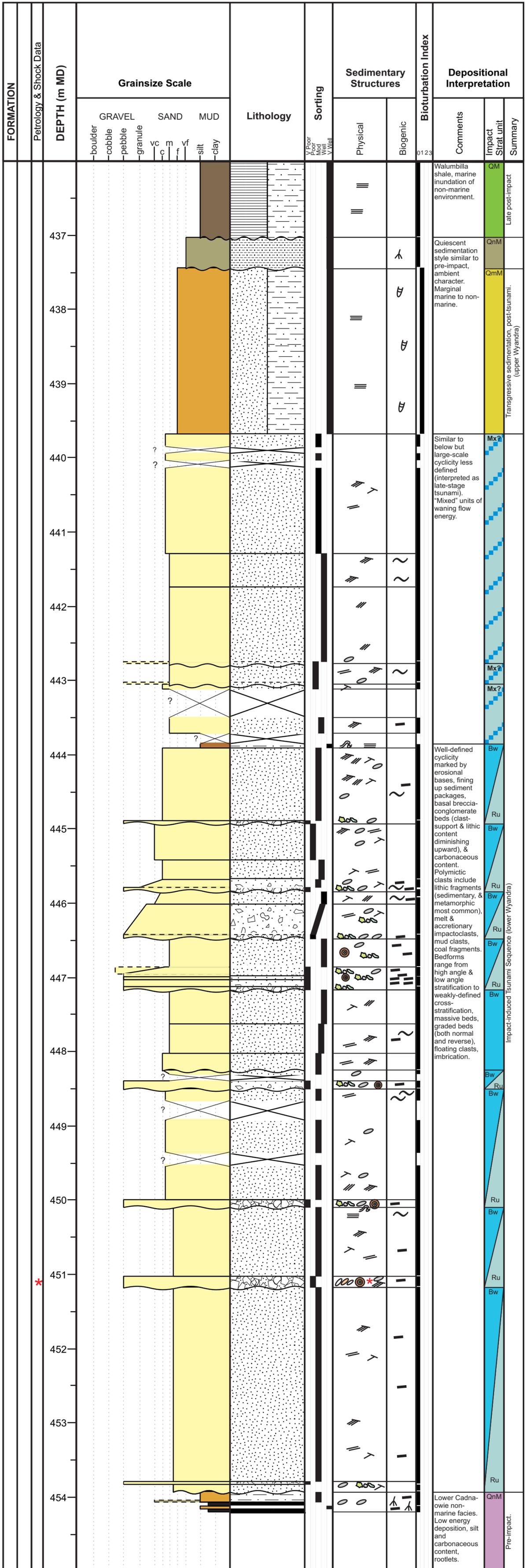
Legend/Summary

Outcrop Unit	Lithology	Typical Sedimentary Structures	Interpretation	Description
VII			Ru	CSBC. Lateral character not clear due to outcrop preservation. Max pebble-sized clasts (?). Base contact sharp and often erosive.
VI			Bw	Varying clast content vertically and laterally (sandstone to MSBC). Clasts generally fine up and decrease in clast support up. Commonly trough cross-bedded with floating pebbles. Base contact sharp.
V			Ru	Thickly-bedded CSBC. Highly erosive base. Mostly structureless, very poorly-sorted. Occasional suggestion of crude but complex internal structure. Highly polymictic, angular to rounded clasts, max cobble-sized. Laterally variable thickness.
IV			Bw	Generally fining up and decreasing clast content and clast support up. Variable bedding structure, varying both vertically and laterally, from planar stratification with plane-parallel oriented floating elongate clasts to low-angle-bedding and trough cross-bedding with pebble lags. Sandstone to MSBC. Max pebble-cobble-sized clasts. Base contacts sharp.
III			Ru	Lower Wyandra Sandstone: Thinly-bedded, multiple clast-supported breccia-conglomerate beds with common erosive bases, structureless, very poorly-sorted. Occasionally crudely graded. Highly polymictic, angular to rounded clasts, max cobble-sized. Overall laterally consistent character.
I			QmM	Cadna-owie Formation: f-mgr sandstone, rare well-rounded quartzose fine pebbles, planar-tabular cross-bedded, ripple cross-lamination.



Location 7 Core Interpretation

Well Name: GSQ Bulloo-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 28.3999°S / 143.7693°E
Distance from Tookoonooka / Talundilly (crater centre): 5 Rc / 9.8 Rc
Depositional Realm: Marginal-Near Marine (2-10 Rc)
Corelogged Interval: 437-454.2 m
Depth Units: meters MD
Author: Katherine Bron

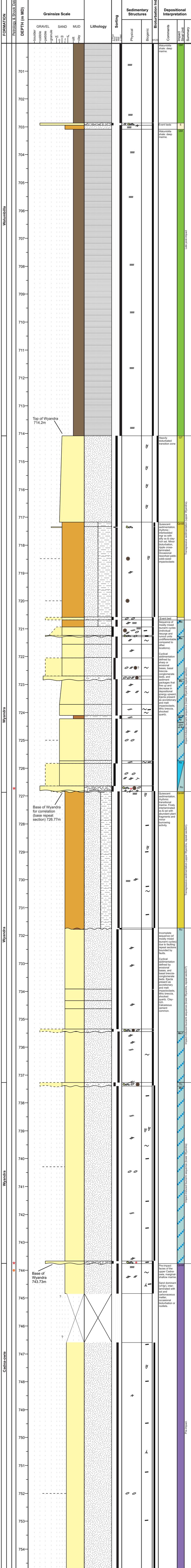


Location 7 Core Interpretation

Well Name: GSQ Bulloo-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 28.3999°S / 143.7693°E
Distance from Tookoonooka / Talundilly (crater centre): 5 Rc / 9.8 Rc
Depositional Realm: Marginal-Near Marine (2-10 Rc)
Corelogged Interval: 437-454.2 m
Depth Units: meters MD
Author: Katherine Bron

Location 11 Core Interpretation

Well Name: GSQ Eromanga-1
 Well Type (core width): Stratigraphic (48 mm)
 Location: Queensland, Australia
 Basin: Eromanga
 Latitude / Longitude: 26.6146°S / 143.8801°E
 Distance from Toookoonooka / Talundilly (crater centre): 3.6 Rc / 5.2 Rc
 Positional Realm: Shallow Marine - Interference (2-10 Rc)
 Corelogged Interval: 700-755 m
 Depth Units: meters MD
 Author: Katherine Bron

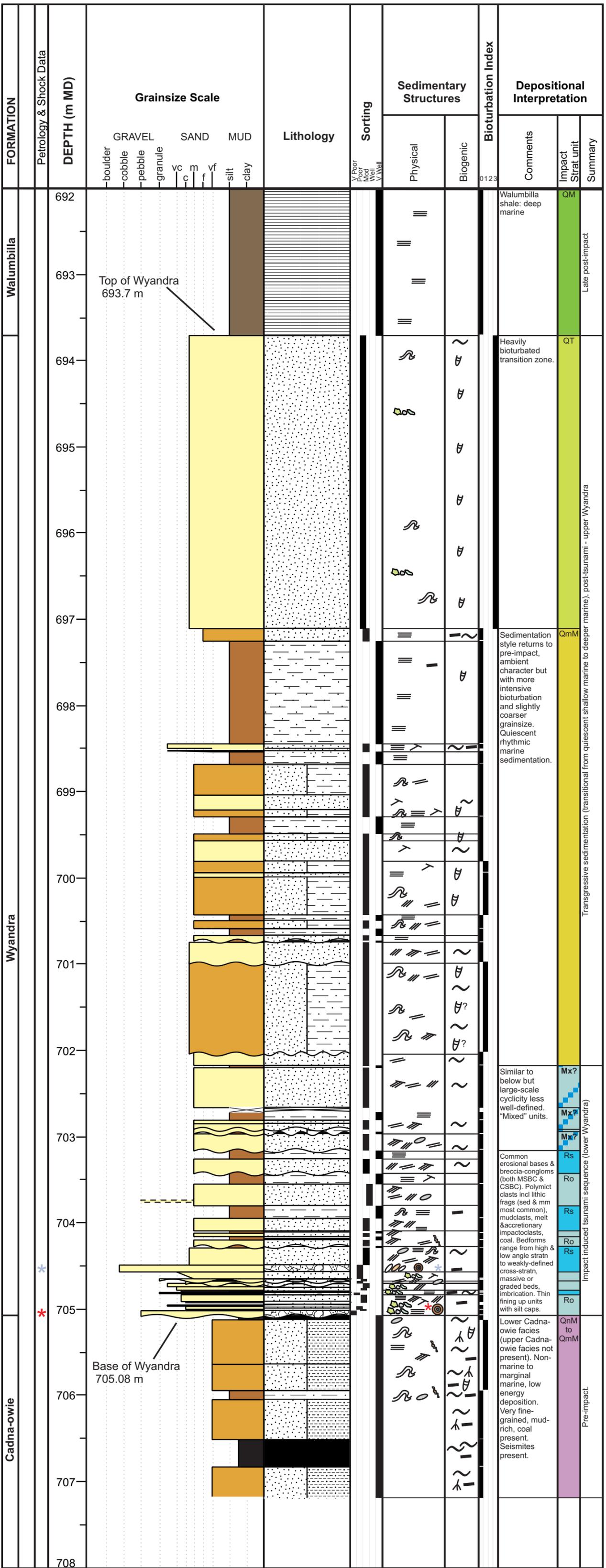


Location 11 Core Interpretation

Well Name: GSQ Eromanga-1
 Well Type (core width): Stratigraphic (48 mm)
 Location: Queensland, Australia
 Basin: Eromanga
 Latitude / Longitude: 26.6146°S / 143.8801°E
 Distance from Toookoonooka / Talundilly (crater centre): 3.6 Rc / 5.2 Rc
 Positional Realm: Shallow Marine - Interference (2-10 Rc)
 Corelogged Interval: 700-755 m
 Depth Units: meters MD
 Author: Katherine Bron

Location 30 Core Interpretation

Well Name: GSQ Thargomindah-1
 Well Type (core width): Stratigraphic (48 mm)
 Location: Queensland, Australia
 Basin: Eromanga
 Latitude / Longitude: 27.2874°S / 143.4554°E
 Distance from Tookoonooka / Talundilly (crater centre): 1.9 Rc / 7.2 Rc
 Depositional Realm: Shallow Marine (1-2 Rc)
 Corelogged Interval: 691.2-707.2 m
 Depth Units: meters MD
 Author: Katherine Bron

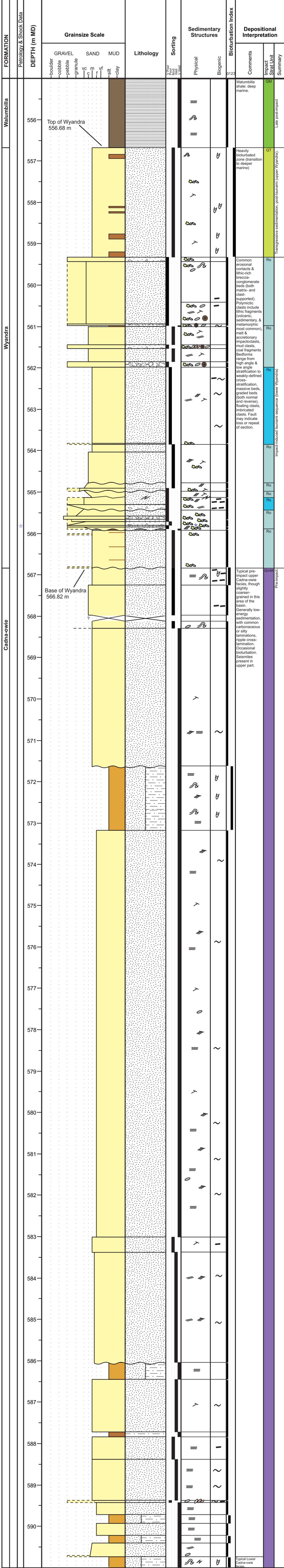


Location 30 Core Interpretation

Well Name: GSQ Thargomindah-1
 Well Type (core width): Stratigraphic (48 mm)
 Location: Queensland, Australia
 Basin: Eromanga
 Latitude / Longitude: 27.2874°S / 143.4554°E
 Distance from Tookoonooka / Talundilly (crater centre): 1.9 Rc / 7.2 Rc
 Depositional Realm: Shallow Marine (1-2 Rc)
 Corelogged Interval: 691.2-707.2 m
 Depth Units: meters MD
 Author: Katherine Bron

Location 5 Core Interpretation

Well Name: GSQ Blackall-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.3601°S / 145.3414°E
Distance from Tookoonooka / Talundilly (crater centre): 11.9 Rc / 2 Rc
Depositional Realm: Shallow Marine (1-2 Rc)
Corelogged Interval: 555-591 m
Depth Units: meters MD
Author: Katherine Bron

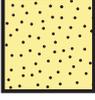


Location 5 Core Interpretation

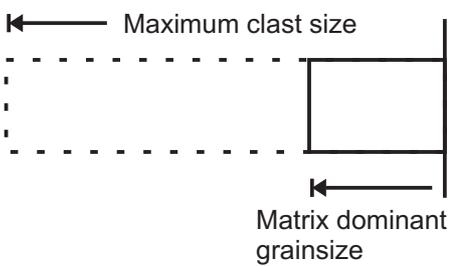
Well Name: GSQ Blackall-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.3601°S / 145.3414°E
Distance from Tookoonooka / Talundilly (crater centre): 11.9 Rc / 2 Rc
Depositional Realm: Shallow Marine (1-2 Rc)
Corelogged Interval: 555-591 m
Depth Units: meters MD
Author: Katherine Bron

Corelog Legend

Lithology

-  Matrix-supported breccia-conglomerate (MSBC)
-  Clast-supported breccia-conglomerate (CSBC)
-  Sandstone (ss)
-  Shale (sh)
-  Siltstone (sst)
-  Mudstone (mst)
-  Interlaminated/thinly interbedded Siltstone (sst) & Sandstone (ss)
-  Coal
-  Missing Core

Grainsize



- | | |
|-------------|------|
| Boulder | bldr |
| Cobble | cobb |
| Pebble | pebb |
| Granule | gran |
| Very coarse | vcgr |
| Coarse | cgr |
| Medium | mgr |
| Fine | fgr |
| Very fine | vfgr |

Sedimentary Structures

Physical

-  Soft sediment deformation (SSD)
-  Microfaults & fractures (μF)
-  Injectite (Inj)
-  Low angle beds/lamination
-  High angle beds/lamination
-  Cross-stratification
-  Weak/vague bedding structure
-  Planar stratification or horizontal lamination
-  Lithic clasts (granular or larger grainsizes)
-  Mudclasts, rip-up clasts, sedimentary lithic clasts
-  Accretionary or Melt Impactoclasts (AI/MI)
-  Brecciated or μF sedimentary lithic clasts (pebble or larger; angular)
-  Imbricated clasts
-  Shocked quartz grains: **measured** or **qualitative only**
-  Cone-in-cone

Biogenic

-  Burrows/Bioturbation
-  Coal clasts, woody material or plant fragments
-  Carbonaceous Laminations (organic detritus)
-  Rootlets

Impact Stratigraphy (outside crater)

Pre-impact

-  Quiescent Marginal to Shallow Marine (Cadna-owie Formation)
-  Non-marine (Cadna-owie Formation)

Post-impact

-  Runout or Runup
 -  Resurge or Backwash
 -  Mixed
- } Impact-generated Tsunami Sequence (lower Wyandra)
-  Non-Marine
 -  Quiescent Marginal to Shallow Marine
- } Post-tsunami Sequence (upper Wyandra)

Late Post-impact

-  Quiescent Transitional Marine (late Wyandra, transition to deeper marine)
-  Quiescent Marine (open marine; Walumbilla shelfal environments)
-  Event bed (crater high source?)

Contacts/Boundaries

- (none) Gradational
-  Erosive/Scour
-  Sharp
-  Fault

Bioturbation Index

- | | | | |
|-----------------|--------------------|-----------------------|--------------------|
| 0 | 1 | 2 | 3 |
| | | | |
| No bioturbation | Minor bioturbation | Moderate bioturbation | Heavy bioturbation |

11) TABLE: Database used in this paper

Location #	Site type	State	Top Wyandra (m)	Base Wyandra (m)	Well Completion Report	Other Reports	Logs	Mudlogs +/- or Cuttings Report	Core	SW core	Outcrop	Petrography	Palyology	Latitude (deg)	Longitude (deg)
Location 1	Well	QLD	1085-1090	1129 MIN										-24.8057	144.2439
Location 2	Well	QLD	666.88	673.67										-27.1934	143.4153
Location 3	Well	QLD	400.7	424-426.7										-25.8037	146.4295
Location 4	Well	QLD	277.8	286.77										-25.1934	146.1450
Location 5	Well	QLD	556.68	566.82										-24.3601	145.3414
Location 6	Well	QLD	819.4	821.34										-24.1607	144.2237
Location 7	Well	QLD	437.05	488.08 lower, 453.9 upper (repeat)										-28.3999	143.7693
Location 8	Well	QLD												-27.0322	142.9145
Location 9	Well	QLD	408.7	456.3										-26.3426	146.2809
Location 10	Well	QLD	783.2	796.99										-24.4985	141.3970
Location 11	Well	QLD	714.2	726.77 (faulted/repeat), 743.73										-26.6146	143.8801
Location 12	Well	QLD	812.5	827.14										-26.9368	143.3268
Location 13	Well	QLD	807	816.17										-26.9196	143.3140
Location 14	Well	QLD	749.85	772.45										-24.5304	142.7015
Location 15	Well	QLD	945.75	965										-27.1077	142.4346
Location 16	Well	QLD	692.2	713.35										-27.0113	143.2351
Location 17	Well	QLD	618.05	623.81										-23.1118	144.5995
Location 18	Well	QLD	776.75	782.4										-24.8152	140.3095
Location 19	Well	QLD	872.85	900.13			N							-23.3818	143.4678
Location 20	Well	QLD	645.4	664.285										-28.8257	143.3309
Location 21	Well	QLD	19	74.61										-26.4151	147.1178
Location 22	Well	QLD	598.38	609.85										-22.7318	144.5011
Location 23	Well	QLD	612.1	669.87										-26.6335	145.0420
Location 24	Well	QLD	839.7	856.74										-26.9496	143.4384
Location 25	Well	QLD	840.6	851.77										-26.9485	143.4298
Location 26	Well	QLD	36	47.2			N							-24.8651	146.3678
Location 27	Well	QLD	343	353.56										-24.8193	145.8478
Location 28	Well	QLD	815.5	844.5 MAX										-26.8840	143.2826
Location 29	Well	QLD	810	844.5 MAX										-26.8874	143.2826
Location 30	Well	QLD	693.7	705.08										-27.2874	143.4554
Location 31	Well	QLD	931.99	971.21										-27.7304	142.9240
Location 32	Well	QLD	975.81 (equiv)	1082.4 (equiv)										-27.2769	142.9314
Location 33	Well	QLD	809.6	847.6										-28.6435	142.1635
Location 34	Well	QLD	732.7	744.6										-26.9268	143.1034
Location 35	Well	QLD	1096.67	1132.5 MIN, 1136.5 prob										-26.6849	142.3679
Location 36	Well	QLD	392.35	448.99										-27.0948	146.1437
Location 37	Well	SA	506.95	538.36										-29.5791	139.5013
Location 38	Well	SA	413.31	414.85										-30.2983	140.1490
Location 39	Well	SA	112.78	113.4 MIN										-28.0064	135.3332
Location 40	Well	SA	1369.4	1387.1										-28.1318	140.8776
Location 41	Well	SA	0	0										-29.6112	137.4835
Location 42	Well	SA	-	-										-27.4879	140.9200
Location 43	Well	SA	?	?										-28.6499	138.6888
Location 44	Well	SA	-	-										-27.8020	140.0804
Location 45	Well	SA	-	-										-28.9383	136.4269
Location 46	Well	SA	521	-										-29.9073	140.0144
Location 47	Well	SA	0	0										-29.9257	139.8542
Location 48	Well	SA	266.18	271.5 MIN										-27.7283	135.8499
Location 49	Well	SA	0	0										-30.8900	140.5157
Location 50	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A				-28.3864	136.0237
Location 51	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A				-28.3860	136.0217
Location 52	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A				-28.3861	136.0202
Location 53	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A				-27.9228	135.7742
Location 54	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A				-28.6818	136.0424
Location 55	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A				-29.9635	139.1491
Location 56	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A				-29.9505	139.1608

Location #	Site type	State	Top Wyandra (m)	Base Wyandra (m)	Well Completion Report	Other Reports	Logs	Mudlogs +/-or Cuttings Report	Core	SW core	Outcrop	Petrography	Palynology	Latitude (deg)	Longitude (deg)
Location 57	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A				-29.8427	139.2907
Location 58	Outcrop	SA	20.2 MIN	17.2	N/A		N/A	N/A	N/A	N/A				-29.8900	139.6400
Location 59	Outcrop	SA	22	16.8	N/A		N/A	N/A	N/A	N/A				-29.9943	139.7042
Location 60	Outcrop	QLD	6.6 MIN	0	N/A		N/A	N/A	N/A	N/A				-25.0990	146.6072
Location 61	Outcrop	NSW	-	-	N/A		N/A	N/A	N/A	N/A				-29.4265	141.8643
Location 62	Well	QLD	-	-										-24.9151	146.8345
Location 63	Well	QLD	945.1	954.6										-25.6935	139.3437
Location 64	Well	QLD	823.6	860.4										-25.2071	145.3884
Location 65	Well	QLD	1203	1235-1244										-26.8035	142.6343
Location 66	Well	QLD	666.5	673.4										-27.1938	143.4151
Location 67	Well	QLD	178.3	198.1										-25.5354	146.7122
Location 68	Well	QLD	760.74	763.18										-24.1307	143.7051
Location 69	Well	QLD	1291	1303										-25.4810	144.0439
Location 70	Well	QLD	578.2	592.8										-24.2843	145.1395
Location 71	Well	QLD	1425.8	1448.3										-26.8865	141.7343
Location 72	Well	QLD	530.7	539.5										-25.4046	145.9084
Location 73	Well	QLD	968.5	982.5										-26.7735	143.0765
Location 74	Well	QLD	990.2	MIN 996.6										-25.7068	140.8307
Location 75	Well	QLD	1066	1092										-26.4479	143.4237
Location 76	Well	QLD	991.5	1013.1 MIN, 1022.2 MAX										-26.8218	142.5601
Location 77	Well	QLD	696.2	711										-25.0121	145.3670
Location 78	Well	QLD	441.3	459.3										-24.7573	145.5778
Location 79	Well	QLD	1129	1135										-25.1457	143.6481
Location 80	Well	QLD	403.7	414										-24.4676	145.5439
Location 81	Well	QLD	943.61	984.46										-26.9713	142.4573
Location 82	Well	QLD	890.5	899.77										-25.2371	143.8089
Location 83	Well	QLD	1167.5	1197										-27.4527	142.6551
Location 84	Well	QLD	1207.5	1227.5										-27.3629	142.5293
Location 85	Well	QLD	624.8	637										-24.8393	145.4311
Location 86	Well	QLD	634	675										-27.9054	143.3229
Location 87	Well	QLD	1243.5	1269.1										-25.2382	144.7512
Location 88	Well	QLD	1519.05	1528.2										-25.6949	141.6720
Location 89	Well	QLD	775	783										-23.9646	144.2553
Location 90	Well	QLD	829.3	843										-24.7715	145.3500
Location 91	Well	QLD	1072	1080										-26.6729	143.6081
Location 92	Well	QLD	643.1	652.2										-24.4954	145.3314
Location 93	Well	QLD	839.2	842.2										-24.0929	144.1192
Location 94	Well	QLD	996.7	1011.2										-28.7371	141.5515
Location 95	Well	QLD	994.8	1010										-25.3140	145.0503
Location 96	Well	QLD	1118.6	1127.7										-25.3576	144.8117
Location 97	Well	QLD	1094	1099.5										-25.3457	144.8298
Location 98	Well	QLD	690	723										-28.1426	143.0951
Location 99	Well	QLD	1365	1376										-25.1076	144.6239
Location 100	Well	QLD	966.2	1007.3										-27.1724	142.5776
Location 101	Well	QLD	1668.7	1692.8										-25.9332	143.0284
Location 102	Well	QLD	861.8	868										-24.2796	144.5925
Location 103	Well	QLD	1021.3	1039.3										-27.6074	142.4190
Location 105	Well	QLD	1063.7	1075.6										-27.5929	142.4154
Location 106	Well	QLD	869	871.5										-25.3115	143.8367
Location 107	Well	QLD	1269.49	1281.38										-25.2163	143.5417
Location 108	Well	QLD	0	0										-23.6318	146.3678
Location 109	Well	QLD	1035.1	1046.5										-25.6171	144.6962
Location 110	Well	QLD	1001.5	1014.5										-26.6510	143.4406
Location 111	Well	QLD	1404	1423										-25.8218	143.2890
Location 112	Well	QLD	1024.7	1046										-25.1729	145.0045
Location 113	Well	QLD	1451	1471										-26.6649	142.7162
Location 114	Well	QLD	744	752										-24.1040	144.7847
Location 115	Well	QLD	21.4	97.01										-26.3437	148.1331
Location 116	Well	QLD	0	0										-23.3085	138.8779
Location 117	Well	QLD	1177	1201.5										-26.5201	143.1176
Location 118	Well	QLD	1139	1174										-26.0360	143.8412

Location #	Site type	State	Top Wyandra (m)	Base Wyandra (m)	Well Completion Report	Other Reports	Logs	Mudlogs +/- or Cuttings Report	Core	SW core	Outcrop	Petrography	Palynology	Latitude (deg)	Longitude (deg)
Location 119	Well	QLD	832.5	846.5										-25.2015	143.8537
Location 120	Well	QLD	1364	1383										-26.2118	143.3079
Location 121	Well	QLD	937.5	942										-25.0921	143.8451
Location 122	Well	QLD	1330.5	1361.5 MIN, 1380.5 MAX										-26.7290	142.7687
Location 123	Well	QLD	511.5	522.3										-23.8143	145.2142
Location 124	Well	QLD	999.74	1002.79										-24.1443	143.5862
Location 125	Well	QLD	720	736										-24.0974	144.8684
Location 126	Well	QLD	584	594										-24.5293	145.4364
Location 127	Well	QLD	1044-1053	1090-1095										-24.5479	144.4787
Location 128	Well	QLD	0	0										-24.5318	146.6011
Location 129	Well	QLD												-26.9304	143.1034
Location 130	Well	QLD	552	572.5										-28.5713	143.2543
Location 131	Well	QLD												-26.9499	143.1065
Location 132	Well	QLD	1094.8	1114.9										-27.1877	142.4354
Location 133	Well	QLD	882	1050										-27.0893	142.7907
Location 134	Well	QLD	692.2	715										-27.5024	143.1440
Location 135	Well	QLD	741	758										-26.5804	143.9095
Location 136	Well	QLD	0	39.6										-25.0457	146.6011
Location 137	Well	QLD	1309	1330										-26.7682	142.7407
Location 138	Well	QLD	1332	1353.5										-26.7821	142.7012
Location 139	Well	QLD	885.7	918										-26.8954	142.3459
Location 140	Well	QLD	274.3	286.59										-25.1893	146.1350
Location 141	Well	QLD	644	655.5										-24.1224	143.6656
Location 142	Well	QLD	592	605										-27.8182	144.0848
Location 144	Well	QLD	847.3	883.9										-28.4343	142.3126
Location 145	Well	QLD	1302.11	1313										-25.5038	143.9312
Location 146	Well	QLD	1187.2	1203.05										-25.5263	143.8940
Location 147	Well	SA	1947	1976.8										-27.2878	140.6430
Location 148	Well	SA	1605.6	1613.5										-28.2120	140.3111
Location 149	Well	SA	1231.3	1247.8										-28.5551	140.7530
Location 150	Well	SA	1428.8	1439.5										-28.0542	140.8583
Location 151	Well	SA	1228.9	1233.5-1244.7										-26.3970	140.5923
Location 152	Well	SA	1192.6	1205.4										-27.4759	140.8414
Location 153	Well	SA	1546.5	1562										-26.8139	140.8478
Location 154	Well	NSW	?	?										-29.6111	146.0236
Location 155	Well	NSW	307.8	316.1										-30.0667	143.7000
Location 156	Well	NSW	338.3	350.5										-29.1306	146.6028
Location 157	Well	NSW	?	?										-29.4833	144.8750
Location 158	Well	NT	?	?										-25.8574	135.7527

5. Thesis Conclusions

Tookoonooka and Talundilly, discovered in the 1980s, are two impact structures buried in the Cretaceous strata of central Australia in a basin of active petroleum exploration. They have not been studied extensively since their discovery, prior to this research, although they were proposed to be the result of a simultaneous impact event based on their similar seismic stratigraphy. The foundation of this research was the hypothesis that remnant impact deposits exist from this event, preserved in the stratigraphy. Furthermore, it was believed that investigation of the sedimentology of the Tookoonooka and Talundilly impacts could provide evidence of the environmental context of the impacts as well as elucidate a potential connection between the impact events and petroleum systems in the basin. It was also thought that our current understanding of the relationship between Tookoonooka and Talundilly themselves could be furthered via this investigation. This thesis has addressed these theories, making scientific contributions in four key areas, as summarized below.

Preservation of Ejecta. The discovery of coarse-grained, polymictic breccia-conglomerate overlying a regionally correlative erosional surface is interpreted to define the impact horizon. Altered melt, accretionary and lithic impactoclasts in addition to shock-metamorphosed quartz and basement fragments were identified as reworked impact ejecta. This significant discovery led to the following conclusions:

- a Tookoonooka-Talundilly impact signature exists in the stratigraphy, correlative from the crater fill to the basin strata well beyond the impact structures;
- the base of the Wyandra Sandstone Member is the impact horizon;
- the impacts occurred in a cold, shallow marine environment;
- accretionary impactoclasts are indicators of vapour plume conditions and may be indicators of wet impact targets;
- uniquely marine impact ejecta highlighted the need for a reclassification of impact terminology; and
- identification of the impact horizon leads to the biostratigraphic constraint of impact timing at the base of the Wyandra Sandstone Member, at the Barremian-Aptian boundary in the Lower Cretaceous, equivalent to 125 ± 1 Ma.

Marine Impact Environment. Detailed analyses of the sedimentology of the impact horizon and enveloping deposits describe the high energy, high sedimentation rate and cyclicity of impact-related deposits over a vast regional area of $>665,000 \text{ km}^2$; hundreds of metres of fine-grained Cadna-owie Formation deposits are punctuated by an interval of relatively high-energy, coarse-grained and exotic lithic-rich deposition before returning to quiescent, low energy marine deposition. Five main depositional realms were interpreted. These findings led to the following conclusions:

- the Wyandra Sandstone Member contains the sedimentary record of the Tookoonooka and Talundilly impacts;

- marine impact deposition from the Tookoonooka and Talundilly impacts are dominated by tsunami depositional processes outside the impact structures, although ballistic sedimentation, resurge, base surge and vapour plume fallout have also contributed to deposition;
- impact and tsunami scour as well as impact seismites, reworked impact ejecta and bioturbation trends delineate the impact deposition throughout the basin;
- the impact tsunamiites are sheet-like in morphology and share similarities with modern tsunami deposits from known tsunami-generation mechanisms of terrestrial origin;
- impact deposits were well-preserved by the near-continuous sedimentation in the basin afforded by the burial of a transgressive depositional regime in the Australian Cretaceous; and
- the Tookoonooka-Talundilly case study has given substantial insight to the understanding of marine impact depositional processes and their effect on the sedimentary record.

Simultaneous Impact. Calculations of doublet cratering probability based on a combination of crater separation, impactor diameter and age uncertainty show that statistically, it is highly improbable that Tookoonooka and Talundilly formed from two independent impact events. Extensive sedimentological observations also show that only one major impact event is apparent in the stratigraphy over a depositional interval much larger than the known age uncertainty of the impacts. Sediment distribution patterns from isopach and grainsize maps show similar trends related to both impact structures, implying synchronicity of the Tookoonooka and Talundilly impacts in the short-lived Wyandra Sandstone Member depositional interval. Petrographic analyses also show distinct grain populations within the ejecta, interpreted as differentiable basement contributions from the two impact target sequences. These results and interpretations led to the following conclusions:

- Tookoonooka and Talundilly are a probable doublet crater based on their stratigraphic dating resolution, their proximity, distributions of impact deposits, and petrographic indicators in the ejecta; and
- in a basin exhibiting continuous quiescent sedimentation, doublet cratering can be demonstrated by sediment distributions despite burial or the reworking of ejecta in a marine impact scenario.

Relevance to Petroleum Systems. Impact cratering in sedimentary basins has the potential to create significant petroleum traps, although petroleum traps unique to marine impact structures have not been fully realized. Results of this research have shown that the Wyandra Sandstone Member, a petroleum reservoir and aquifer in Australia's Eromanga Basin, is in part a marine impact tsunamiite from a probable double meteorite impact. This research shows that the character of the Wyandra Sandstone Member was influenced in its entirety by impact mechanisms, impact recovery, and the impact crater-forms as a sediment source in the post-impact basin. Impact ejecta have both improved and degraded the reservoir quality of the Wyandra Sandstone Member due to high

primary porosity and impactoclast alteration, respectively. These results and interpretations led to the following conclusions:

- the first known impact-related reservoir has been identified in Australia;
- the understanding of impact-related deposits as they relate to hydrocarbon potential has been advanced; and
- this research has identified a new target for petroleum exploration around marine impact structures: impact tsunamiites.

This research has made significant advances in the knowledge of the Lower Cretaceous stratigraphic record of Australia, starting with the discovery of an ancient marine impact horizon. Lower Wyandra Sandstone Member deposits described and classified in this thesis represent the marine impact tsunamiite of a probable large doublet crater. Although data independently confirming Talundilly's impact status through drilling is lacking, Talundilly's influence in the basin and contribution to these impact deposits cannot be ignored. The Wyandra Sandstone Member is the depositional chronicle of the impact event, from impact through post-impact tsunamis to recovery of the depositional regime.

Insight into the geochemistry and microscopic character of the Tookoonooka-Talundilly impact ejecta, the character of shallow marine impact deposition and paleotsunamis, Tookoonooka-Talundilly's probable doublet crater status and an appreciation of the petroleum prospectivity of marine impacts have been gained. This research has also resulted in a newly proposed classification for impactoclasts. Parallels with volcanic sedimentation processes and high-energy marine depositional processes have been recognized. The Wyandra Sandstone Member is a superb example of a hydrocarbon reservoir originating from a marine impact. Tookoonooka and Talundilly provide a unique model for the analysis of binary marine impact dynamics and deposits on Earth.

6. Future Work

Key outstanding questions relating to Tookoonooka and Talundilly remain, which were emphasized by this research. This study has also raised many new issues around marine impacts and binary impacts into sedimentary basins. As petroleum exploration continues in central Australia, it is hoped that more data will become available to enable further study of Tookoonooka and Talundilly, and advance Talundilly's impact status.

The Cadna-owie Formation, the setting for the impact event, remains one of the most poorly understood units of the Cooper- Eromanga Basin succession. As it is neither an efficient reservoir nor adequate source rock, it has attracted little attention from the petroleum industry. Little is known of its provenance beyond speculation, nor has the astounding vastness of its paleoenvironment and its recording of the opening of the epeiric sea attracted the study that it duly deserves. Can we establish better constraint on paleo water depths? How much was the basin and deposition affected by the low latitudes? Was ice cover seasonal or more pervasive?

Additionally, more study is needed on basin margin sites where age constraint within the Cadna-owie Formation is poor and correlation of the Wyandra Sandstone Member is less certain. More work remains to trace the extent of preserved tsunami deposits in these areas. This would ideally be done with the addition of detailed palynology (particularly on the southern margins) to better delineate the strata in the upper Cadna-owie Formation to base Walumbilla Formation interval. Basin margins closest to the impact structures in New South Wales and Queensland are ideal candidates for field studies based on crater proximity, as evidence of tsunami is more equivocal in more distal outcrops at the southwestern basin margin in South Australia. Gaining knowledge of the character and extent of run-up and backwash phases of impact tsunamiites at these margins would add important knowledge to the field of tsunami research and allow better constraints on marine impact modelling.

No full-hole cores exist within the Talundilly structure, thwarting efforts to better understand and constrain the circumstances of the Talundilly impact. Additionally, no full-hole cores through the Cadna-owie Formation-Walumbilla Formation interval exist for assumedly deeper water deposits of the Eromanga paleosea north and west of Tookoonooka, and data is sparse in the potential "interference" zone between the two impact structures. Thus the character of ejecta and tsunamiites in these environments remains largely unknown, although the former are likely similar to the debris flow-influenced deposits of the proximal slump zone realm and the mudclast-rich estuarine realm (Depositional Realms interpretation is detailed in Paper 3). Deeper water realms proximal to Tookoonooka may also contain post-impact sandy turbidites originating from crater rim terraces, as have been observed within the Tookoonooka crater structure.

This study has been confined to the Eromanga Basin. Indications in core suggest that the Eromanga Basin was in communication with neighbouring, age-equivalent basins such as the Surat and Carpentaria, and it is most probable that the impact horizon and/or tsunamiites are distally recorded there too. Thus exciting future work would include the search for distal ejecta at the Barremian-Aptian boundary in Australia and beyond, as the Eromanga Basin was part of the Great Australian Superbasin extending as far north as Indonesia (Jell et al. 2013). Since the Eromanga Basin straddles four states and territories of Australia, correlation of the Wyandra Sandstone Member and the discovery of age-equivalent core samples have been hampered by inconsistent naming conventions of formations (Table 6.1). It is believed that with improved correlation of formation names in existing databases, the extension of the known distribution of Tookoonooka-Talundilly impactites should be possible in all neighbouring age-equivalent basins; the designation of the impact horizon as an absolute time marker can aid with both correlation and the standardization of naming conventions. Of specific interest are:

- the Mt Anna Sandstone in South Australia as a candidate for backwash deposits;
- the Minmi Member of the Bungil Formation in the Surat Basin: as there is good correlation between Mitchell-1 and Mitchell-2 wells, on either side of the Nebine Ridge between the Eromanga and Surat Basins, contemporaneous communication between the two basins is implied. Thus the presence of tsunami deposits in the Surat is likely;
- the Coffin Hill Member of the Gilbert River Formation in the Carpentaria Basin most likely contains distal tsunamiites based on lithological descriptions which contain elements similar to the Wyandra Sandstone Member;
- the Mokely Creek Sandstone Member in the Tibooburra region of New South Wales appears to be a tsunami deposit in its entirety but needs more work to better define its internal character. It has been recently recognized as an age-equivalent deposit of the Wyandra Sandstone Member (Greenfield et al. 2010).

Continuing work will serve to elevate the stratigraphic status of the Wyandra Sandstone Member; as the base of the Wyandra Sandstone Member is the Tookoonooka-Talundilly impact horizon and thus an absolute time marker across the basin, the Wyandra Sandstone Member is stratigraphically distinct from its bounding formations (the Cadna-owie Formation and the Walumbilla Formation) and thus needs to be elevated to Formation status in its own right (cf. King & Petruny 2003).

Ongoing work will also investigate the scope of the environmental and biological impact in the Eromanga Basin. Since the Eromanga was a mostly enclosed basin, further research should be able to identify regional effects of the impact on the shallow sea. Recovery of bioturbation intensity in the upper part of the Wyandra Sandstone Member implies that impact effects were not particularly devastating in duration. Interestingly, speculation on the possible binary impact Kara and Ust-Kara, of comparable diameters to Tookoonooka and Talundilly, led to the supposition that they “must have been an important geological event with at least regional, if not global, significance” (Koeberl et al. 1990). However, impacts of this magnitude would not be expected to cause devastation on a global scale, which can be indicatively confirmed by generic modelling via Collins et al. (2005). A

Table 6.1 Stratigraphic nomenclature across the age-equivalent Eromanga, Surat and Carpentaria Basins that is common in the basin literature and databases of South Australia, Queensland, and New South Wales.

Region	South Australia			Queensland			New South Wales										
	Eromanga Basin (SW – NE)			Carpentaria Basin			Surat			Eromanga /Surat Basin			Eromanga (Bulloo Embayment)			Eromanga (Tibooburra)	
Age	Late Jurassic-Albian	Nales River Group	Bulldog Shale	Wulpoorinna Breccia	Walumbilla Fm	Coreena Mbr	Doncaster Mbr	Walumbilla Fm	Coreena Mbr	Doncaster Mbr	Walumbilla Fm	Coreena Mbr	Doncaster Mbr	Walumbilla Fm	Coreena Mbr	Doncaster Mbr	Oornoo Beds
			Cadna-owie Fm (locally Pelican Well Fm, Parabarana Sandstone)	Mt Anna Sandstone & Trinity Well Sandstone	Cadna-owie Fm	Wyandra Sandstone	Coffin Hill Mbr	Minmi Mbr ('Transition Beds')	Bungil Fm	Nullawurt Sandstone	Kingull Mbr	Mooga Sandstone	Transition Beds	Cadna-owie Fm (also "Upper Hooray Sandstone")	Gum Vale Beds/ Gum Vale Fm	Wittabrenna Beds/Wittabrenna Shale	Mokely Creek Sandstone Mbr
		Alge-buckina Sandstone	Mooga Fm	Murta Mbr	Namur Mbr	Hooray Sandstone	Namur Sandstone	Murta Fm	Hooray Sandstone	Mooga Sandstone	Mooga Sandstone	Mooga Sandstone	Mooga Sandstone	Mooga Sandstone	Mooga Sandstone	Mooga Sandstone	Mooga Sandstone

Cross-section covers late Jurassic (Tithonian) to early Cretaceous (Aptian) timespan. Compiled from: Hawke & Cramsie (1984); Draper (2002); Wopfner et al. (1970); Alley (1988); Senior et al. (1978); Morton (1982); Drexel & Preiss (1995), from Alexander & Krieg, and Krieg & Rogers therein; and Jell (2013), from Cook, McKellar, & Draper therein. See also Fig. 2.6 for chronostratigraphic detail.

quick look using their program indicates that for impacts the size of Tookoonooka *or* Talundilly, a fireball causing thermal radiation may or may not have occurred and seismicity could have been only proximally damaging, although the airblast was capable of stripping vegetation from coastal forests and was thus likely responsible for the organic content of the resurge/backwash deposits. However, the devastation resulting from two contemporaneous large impacts is an unknown that merits further detailed investigation and comprehensive modeling.

Future work should also investigate the question of impact angle. Further studies on impact deposit distribution or detailed crater geometry may be able to resolve this, which has large implications for crater scaling and tsunami modeling. Binary impact tsunami modeling has not been investigated to date, as few marine impacts have revealed associated tsunami deposits. The Tookoonooka-Talundilly impact, with its well-preserved tsunami deposit geometry within the mostly enclosed, epicontinental Eromanga Basin, would be an excellent case study for such an investigation.

Many questions remain regarding the depositional processes of marine impacts. Complex dynamics of vapour plume collapse, ballistic sedimentation, base surge, crater resurge, rim collapse, debris flows, and tsunamis all appear to contribute to the impact deposits, though their relative contributions are far from well-understood. This research on Tookoonooka-Talundilly contributes to this growing field of research, and these two impact structures are an excellent model of the complex processes at work immediately following marine impacts in a shallow marine basin. Further detailed sedimentological research and marine impact modelling is necessary to elucidate the contributions of these varied processes, particularly within 2Rc of the impact structures.

Interesting future work would also be to investigate the effect of the tsunami on the connections between the contemporaneous basins. For example, the relationship between the Eromanga and Surat Basins during the early stages of the marine incursion (~time of impact) is currently unknown. Petrographic work on the Cadna-owie Formation (Paper 2) points to provenance areas toward the east. Geometries of the Wyandra Sandstone Member and tsunami deposits seen in Paper 3 maps show thick tsunamiites deposited east of the impacts in estuarine environments toward the Surat Basin. If, as suggested above, impact deposits can be traced into the Surat Basin, a pre-Wyandra-age link between the Eromanga & Surat Basins was likely in place. It is also possible that the energy of the impact tsunami waves could have significantly altered the seaway between the Eromanga and Surat Basins. Evidence from other large marine impacts such as Chicxulub shows intense alteration of the seabed, mass-wasting of shorelines, and speculation of deeply eroded submarine channels and continental slope scouring: “a mega-tsunami may have played an important role in the Blake Plateau shelf scouring, opening a deep-water passage from the Yucatan toward the Blake Nose” (Dypvik & Jansa 2003). Which begs the question: did the marine inlet to the Surat Basin exist already at time of impact, and was it affected by the tsunami event?

As discussed in Paper 2, more work is needed to investigate a possible dual impact signature in the petrography of the ejecta. This should be possible via a more widespread petrographic study to analyse, in particular, the contribution of the deeper target sequences to the ejecta volumes, as Tookoonooka and Talundilly have slightly different target strata underlying their Eromanga Basin sequences. Emphasis, again, should be on the lowermost breccia-conglomerate units in the sequence to minimize the complications of later post-impact reworking of ejecta in the basin. The Tookoonooka target sequence contains quartz-rich sediments of the Permian-Triassic Cooper Basin in addition to Thargomindah Shelf metasediments of the Thomson Orogen, while Talundilly's target sequence contains Carboniferous-Triassic Galilee Basin sediments, Devonian Adavale Basin sediments (including carbonates and evaporites), and underlying volcanics, intrusives, and metasediments of the Maneroo Platform of the Thomson Orogen (Figure 2.5). Further geochemical analyses on the ejecta are also warranted, though the usefulness of, for example, trace element geochemistry on ejecta deposits diluted by marine reworking is debateable.

Petroleum studies on the Tookoonooka and Talundilly impact structures are in their infancy, despite initial drilling attempts in the 1980s. This research has identified a new target for petroleum exploration around marine impact structures: impact tsunamiites. Impact deposits at Tookoonooka and Talundilly are dominantly mud-rich due to the nature of the ambient sedimentation and paleoenvironment, and altered melt products imply substantial diagenetic and hydrothermal influences on the post-impact basin sediments and craters. However, this research shows the potential benefits of an ejecta contribution to the sediments: namely, improved porosity and permeability due to the coarse-grained influx and cleaning of the sediment due to tsunami reworking. Many potential stratigraphic and structural traps around the impact structures still remain untested, and will be the subject of future work.

Many of the remaining questions outlined above could be explored via analyses of existing geological data, however data leading to further insight for the impact structures themselves will rely on further drilling exploration programs and geophysical studies. But as the grainsize study in this thesis demonstrates, there is also abundant historical data available for compilation from petroleum exploration databases to give unique solutions and insights to impact studies.

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Note: References listed below pertain to all Thesis Sections and Appendices with the exception of Section 4: references specific to individual paper contributions (Section 4) are included therein.

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Appendices

Appendix 1

Marine and possible marine impacts: 43 impacts of the current Earth cratering record are categorized as marine, 13 of which are considered possible marine impacts [previous compilations (Dypvik & Jansa 2003; Ormö & Lindström 2000; Abels et al., 2002) identified 20-26 marine impact structures of the confirmed impacts on Earth]. All have confirmed impact origins, though Talundilly and Yallalie are included as highly probable impact structures. Documented tsunami or tsunami-like deposits well beyond the crater rims associated with known marine impacts are noted. "Possible marine" impact structures are included that exhibit typical marine impact features such as lack of melt or unusually thick allogenic breccia sequences (e.g. Mishina Gora), proximity to paleoshorelines, continuous marine sedimentation, or associated marine deposits (e.g. Acraman), but where limited data exist. Lack of data (e.g. due to burial, erosion, lack of paleoenvironmental context) and misinterpretation have likely contributed to the underestimation of marine craters in the Earth impact record, and craters where $d \gg H$ (see text) could have very subdued marine features, although they would have associated impact-related marine realm deposition.

<i>Marine Impact Structures</i>						
Impact Structure [£]	Crater Location	Paleobasin	Age (Ma)*	Crater Diameter (km)*	Tsunami-like deposits documented	References (marine origin)
Alamo ^{#£}	USA	proto-Pacific Ocean	382±4 [†]	N/A (40-60) [†]	Y	1,38,39,40
Ames [#]	USA	Anadarko Basin	450-460 [†]	16	Y	2,11,19,20
Araguainha	Brazil	Paraná-Karoo Basin	254.7±2.5	40	Y	30
Avak [#]	USA	Western Interior Seaway	Mid-late Turonian (±90Ma) [†]	12	Y	1,26
Chesapeake Bay [#]	USA	Atlantic Ocean	35.5±0.3	40	Y	1,2,11
Chicxulub [#]	Mexico	Proto-Caribbean Sea	64.98±0.05	150	Y	1,36
Eltanin ^{##} (temporary water crater only)	N/A	South Pacific Ocean	2.15	N/A (60)	Y	1,2,9,10,14
Flynn Creek [#]	USA	? very shallow marine	382 [†]	3.6-3.8		2,27,37
Gårdnos [#]	Norway	?	500±10	5		1
Granby [#]	Sweden	Baltoscandian epicontinental sea	~470	3		1,2,3
Gusev [#]	Russia	? shallow marine	49±0.2Ma	3		1,33,(12)
Hummeln [#]	Sweden	? shallow marine	470	1.2		2,3,8,42,43
Kaluga [#]	Russia	epicontinental sea within East European craton	380±5	15	Y	1,2,3,10,12,15
Kamensk [#]	Russia	? shallow marine	49±0.2Ma	25		1,2,11,12,33
Kara [#]	Russia		70.3±2.2	65		1,12,33
Kärdla [#]	Estonia	Baltoscandian epicontinental sea	Upper Ordovician (~455Ma)	4 [†]	Y	1,2,3,8,10,12,16
Karikkoselkä [#]	Finland		~230	1.5		1,3
Lockne [#]	Sweden	Baltoscandian epicontinental sea	~458	7.5	Y	1,2,3,13,(8), (11)
Målingen	Sweden	Baltoscandian	~458	~1		4

Saarijärvi [#]	Finland		214±8 [†]		1.5	possible marine	3
Serra da Cangalha	Brazil	intra-cratonic Parnaíba Basin	>600		13.7 [†]	crater stratigraphy indicates that impact event bounded by marine facies, though post-impact deposits not yet described.	28
Söderfjärden	Finland		~600		6.6	proximity of shoreline & possible tidally-influenced impact setting. Layered sediments in crater fill could indicate resurgence	3
Sudbury	Canada	Animikie Ocean	1850±3		130	Proximity to paleoshore deposits & nearshore sediments as rip-up clasts in breccia. Presence of accretionary impactoclasts are possible substrate water indicators. Debrisites indicate possible tsunami. Possible "surgeback" breccia in crater.	11, 18
Woodleigh	Australia	proximity to paleo-basin	364±8		40-120	Proximity of paleoshoreline: paleoenvironmental maps indicate marginal-very shallow marine. But significant hiatus between undifferentiated Devonian crater fill & overlying Jurassic lacustrine strata.	32

[‡] This list does not include marine-emplaced ejecta without associated craters, except Eltanin and Alamo for which substantial evidence has been found: for Eltanin, an associated crater was non-existent, but much evidence has been found for a deep-sea impact where a temporary water crater was formed (Gersonde et al. 1997); for Alamo, the main crater structure was removed by tectonic burial, although proximal crater realms including a crater rim have been identified (Pinto & Warme 2008).

* Age/diameter from Earth Impact Database (viewed 2015) unless otherwise noted.

Impacts classified as marine prior to this paper in compiled lists (Dypvik & Jansa 2003; Ormö & Lindström 2000; Abels et al. 2002).

[†] **Alamo** age: Morrow & Sandberg (2005); Alamo size estimate: Morrow et al. (2005); **Ames** age: Repetski (1998); **Banet & Fenton** (2008), Kirschner et al. (1992); **Flynn Creek** age: Schieber & Over (2005); **Kårdla** size: Puura & Suuroja (1992); **Ritland** size: Riis et al. (2011); **Rochechouart** age: Kelley & Spray (1997), Schmieder et al. (2010); **Serra da Cangalha**: Vasconcelos et al. (2013); **Tookoonooka-Talundilly** age: Bron (2010), Bron & Gostin (2012), this paper; Tookoonooka crater size: Gostin & Therriault (1997); Talundilly crater size: Gortler & Glikson (2012a); **Ust Kara**: Masaitis (1999), Masaitis et al. (1980); **Yallalie**: Hawke (2004).

Selected references - **marine origin**: **1**: Dypvik & Jansa (2003); **2**: Ormö & Lindström (2000); **3**: Abels et al. (2002); **4**: Alwmark et al. (2014), Ormö et al. (2014a, 2014b); **5**: Bron (2010), Bron & Gostin (2012); **6**: Riis et al. (2011), Azad et al. (2012); **7**: Schmieder et al. (2010); **8**: Frisk & Ormö (2007); **9**: Gersonde et al. (1997, 2002); **10**: Dypvik et al. (2004); **11**: Poag et al. (2004); **12**: Masaitis (1999); **13**: Lindström et al. (2008), von Dalwigk & Ormö (2001), Sturkell et al. (2000); **14**: Ward & Asphaug (2002); **15**: Masaitis (2002); **16**: Suuroja & Suuroja (2006), Suuroja (2002), Puura & Suuroja (1992); **17**: Suuroja & Suuroja (2004), Suuroja et al. (2002); **18**: Addison et al. (2010), Pufahl et al. (2007), Ames et al. (2000); **19**: Mescher & Schultz (1997); **20**: Repetski (1997); **21**: Buchanan et al. (1998), Wong et al. (1997), Fischer (1997); **22**: Mescher et al. (2012); **23**: Wallace et al. (1996), Dyson (2005); **24**: Ormö et al. (2007); **25**: Izett et al. (1998), Weber & Watkins (2007), Steiner & Shoemaker (1996), Witzke & Anderson (1996); **26**: Banet & Fenton (2008), Kirschner et al. (1992); **27**: Schieber & Over (2005); **28**: Vasconcelos et al. (2005); **29**: Forsman et al. (1996); **30**: Tohver et al. (2013); **31**: Hawke (2004), Bevan et al. (2004), Dentith et al. (1999); **32**: Glikson et al. (2005); **33**: Masaitis et al. (1980); **34**: Dypvik et al. (1996), Glimsdal et al. (2010), Dypvik et al. (2010); **35**: Schnyder et al. (2005); **36**: Goto (2008), Goto et al. (2008), Albertão et al. (2002), Smit (1999), Matsui et al. (2002), Albertão & Martins (1996), Smit et al. (1996); **37**: Roddy (1977); **38**: Pinto & Warme (2008); **39**: Warme et al. (2008); **40**: Morrow et al. (2005); **41**: Kelley & Spray (1997); **42**: Alwmark et al. (2015); **43**: Lindström et al. (1999).

Appendix 2

Ejecta thickness calculations. Supplementary to Methodology (Section 3).

Theoretical Ejecta Thicknesses

McGeehin et al. (1973) Collins et al. (2005), McKimmon & Schenk (1985)

R (km)	r (m)	t (m)	R _c
Tookoonooka	20275	121534.32	1,000
Tahndilly	25100	158589.83	1,000
			3.68
			3.78

0 1
1 R_c

insignificant t range
within final crater rim

$$t = 0.14Rt^{0.74}(r/Rt)^{-3.0}$$

$$D_t^{1.13} \approx 0.9942 D_f$$

R _t (km)	r (km)	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	110	120	130	140	150	160	170	180	190	200	
10	37.8	16.0	8.2	4.7	3.0	2.0	1.4	1.0	0.8	0.6	0.5	0.4	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	54.0	22.8	11.7	6.8	4.3	2.8	2.0	1.5	1.1	0.8	0.7	0.5	0.4	0.4	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
12	74.8	31.6	16.2	9.4	5.9	3.9	2.8	2.0	1.5	1.2	0.9	0.7	0.6	0.5	0.4	0.3	0.3	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
13	100.9	42.6	21.8	12.6	7.9	5.3	3.7	2.7	2.0	1.6	1.2	1.0	0.8	0.7	0.6	0.5	0.4	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
14	133.2	56.2	28.8	16.6	10.5	7.0	4.9	3.6	2.7	2.1	1.6	1.3	1.1	0.9	0.7	0.6	0.5	0.4	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.0
15	172.4	72.7	37.2	21.5	13.6	9.1	6.4	4.7	3.5	2.7	2.1	1.7	1.4	1.1	0.9	0.8	0.7	0.6	0.4	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
16	219.4	92.6	47.4	27.4	17.3	11.6	8.1	5.9	4.5	3.4	2.7	2.2	1.8	1.4	1.1	1.0	0.9	0.7	0.6	0.4	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1
17	275.3	116.1	59.5	34.4	21.7	14.5	10.2	7.4	5.6	4.3	3.4	2.7	2.2	1.8	1.5	1.3	1.1	0.9	0.7	0.5	0.4	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1
18	340.9	143.8	73.6	42.6	26.8	18.0	12.6	9.2	6.9	5.3	4.2	3.4	2.7	2.2	1.9	1.6	1.3	1.2	0.9	0.7	0.5	0.4	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1
19	417.2	176.0	90.1	52.2	32.8	22.0	15.5	11.3	8.5	6.5	5.1	4.1	3.3	2.8	2.3	1.9	1.6	1.4	1.1	0.8	0.6	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.1	0.1
20	505.5	213.3	109.2	63.2	39.8	26.7	18.7	13.6	10.3	7.9	6.2	5.0	4.0	3.3	2.8	2.3	2.0	1.7	1.3	1.0	0.8	0.6	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.1
21	606.7	255.9	131.0	75.8	47.8	32.0	22.5	16.4	12.3	9.5	7.5	6.0	4.9	4.0	3.3	2.8	2.4	2.0	1.5	1.2	1.0	0.9	0.7	0.6	0.5	0.4	0.4	0.3	0.3	0.3
22	722.0	304.6	155.9	90.2	56.8	38.1	26.7	19.5	14.6	11.3	8.9	7.1	5.8	4.8	4.0	3.3	2.8	2.4	1.8	1.4	1.1	0.9	0.7	0.6	0.5	0.4	0.4	0.4	0.4	0.3
23	852.5	359.7	184.1	106.6	67.1	45.0	31.6	23.0	17.3	13.3	10.5	8.4	6.8	5.6	4.7	3.9	3.4	2.9	2.2	1.7	1.3	1.0	0.9	0.7	0.6	0.5	0.4	0.4	0.4	0.4
24	999.6	421.7	215.9	125.0	78.7	52.7	37.0	27.0	20.3	15.6	12.3	9.8	8.0	6.6	5.5	4.6	3.9	3.4	2.5	2.0	1.5	1.2	1.0	0.8	0.7	0.6	0.5	0.4	0.4	0.4
25	1164.5	491.3	251.5	145.6	91.7	61.4	43.1	31.4	23.6	18.2	14.3	11.5	9.3	7.7	6.4	5.4	4.6	3.9	3.0	2.3	1.8	1.4	1.1	0.9	0.7	0.6	0.5	0.4	0.4	0.4
26	1348.5	568.9	291.3	168.6	106.2	71.1	49.9	36.4	27.4	21.1	16.6	13.3	10.8	8.9	7.4	6.2	5.3	4.6	3.4	2.6	2.1	1.7	1.3	1.1	0.9	0.7	0.6	0.5	0.4	0.4
27	1552.9	653.1	333.4	194.1	122.2	81.9	57.5	41.9	31.5	24.3	19.1	15.3	12.4	10.2	8.5	7.2	6.1	5.2	3.9	3.0	2.4	1.9	1.5	1.1	0.9	0.8	0.7	0.6	0.5	0.4
28	1779.2	750.6	384.3	222.4	140.1	93.8	65.9	48.0	36.1	27.8	21.9	17.5	14.2	11.7	9.8	8.2	7.0	6.0	4.5	3.5	2.7	2.2	1.8	1.5	1.1	0.9	0.8	0.7	0.6	0.5
29	2028.7	855.9	438.2	253.6	159.7	107.0	75.1	54.8	41.2	31.7	24.9	20.0	16.2	13.4	11.1	9.4	8.0	6.8	5.1	4.0	3.0	2.5	2.0	1.7	1.4	1.1	0.9	0.8	0.7	0.6
30	2303.0	971.6	497.4	181.3	121.4	85.3	62.2	46.7	36.0	28.3	22.7	18.4	15.2	12.7	10.7	9.1	7.8	6.5	5.8	4.5	3.5	2.8	2.3	1.9	1.6	1.3	1.1	1.0	0.9	0.8

Appendix 3

Database: Well and Outcrop data collected for this thesis.

Location #	Well Name	Site type	State	Top Wyandra (m)	Base Wyandra (m)	Well Completion Report	Other Reports	Logs	Mudlogs +/- or Cuttings Report	Core	SW core	Outcrop	Petrography	Geochemistry	Palyonology	Latitude (deg)	Longitude (deg)
1	Albilbah 1	Well	QLD	1085-1090	1129 MIN											-24.8057	144.2439
2	Aros 2	Well	QLD	666.88	673.67											-27.1934	143.4153
3	Augathella 1	Well	QLD	400.7	424-426.7											-25.8037	146.4295
4	Augathella 2-3R	Well	QLD	277.8	286.77											-25.1934	146.1450
5	Blackall 1	Well	QLD	556.68	566.82											-24.3601	145.3414
6	Blackall 2	Well	QLD	819.4	821.34											-24.1607	144.2237
7	Bulloo 1	Well	QLD	437.05	488.08 lower, 453.9 upper (repeat)											-28.3999	143.7693
8	Caracal 1	Well	QLD													-27.0322	142.9145
9	Charleville 1	Well	QLD	408.7	456.3											-26.3426	146.2809
10	Connemara 1	Well	QLD	783.2	796.99											-24.4985	141.3970
11	Eromanga 1 GSQ	Well	QLD	714.2	726.77 (faulted/repeat), 743.73											-26.6146	143.8801
12	Ipundu 6	Well	QLD	812.5	827.14											-26.9368	143.3268
13	Ipundu North 1	Well	QLD	807	816.17											-26.9196	143.3140
14	Jundah 1	Well	QLD	749.85	772.45											-24.5304	142.7015
15	Kercummurra 1	Well	QLD	945.75	965											-27.1077	142.4346
16	Koorooopa 1	Well	QLD	692.2	713.35											-27.0113	143.2351
17	Longreach 1-1B	Well	QLD	618.05	623.81											-23.1118	144.5995
18	Machattie 1	Well	QLD	776.75	782.4											-24.8152	140.3095
19	Maneroo 1	Well	QLD	872.85	900.13			N								-23.3818	143.4678
20	Mirintu 1	Well	QLD	645.4	664.285											-28.8257	143.3309
21	Mitchell 1	Well	QLD	19	74.61											-26.4151	147.1178
22	Muttaborra 1 GSQ	Well	QLD	598.38	609.85											-22.7318	144.5011
23	Quilpie 1	Well	QLD	612.1	669.87											-26.6335	145.0420
24	Talgeberry 1	Well	QLD	839.7	856.74											-26.9496	143.4384
25	Talgeberry 2	Well	QLD	840.6	851.77											-26.9485	143.4298
26	Tambo 2	Well	QLD	36	47.2			N								-24.8651	146.3678
27	Tambo 4	Well	QLD	343	353.56											-24.8193	145.8478
28	Tarbat 6	Well	QLD	815.5	844.5 MAX											-26.8840	143.2826
29	Tarbat 8	Well	QLD	810	844.5 MAX											-26.8874	143.2826
30	Thargomindah 1-1A	Well	QLD	693.7	705.08											-27.2874	143.4554
31	Thargomindah 2	Well	QLD	931.99	971.21											-27.7304	142.9240
32	Thargomindah 3	Well	QLD	975.81 (equiv)	1082.4 (equiv)											-27.2769	142.9314
33	Tickalara 1 GSQ	Well	QLD	809.6	847.6											-28.6435	142.1635
34	Tintaburra 2	Well	QLD	732.7	744.6											-26.9268	143.1034
35	Toby 1	Well	QLD	1096.67	1132.5 MIN, 1136.5 prob											-26.6849	142.3679
36	Wyandra 1	Well	QLD	392.35	448.99											-27.0948	146.1437
37	CBH 2	Well	SA	506.95	538.36											-29.5791	139.5013
38	Cootabarlow 2	Well	SA	413.31	414.85											-30.2983	140.1490
39	Cootanoorina 1	Well	SA	112.78	113.4 MIN											-28.0064	135.3332
40	Dullingari 1	Well	SA	1369.4	1387.1											-28.1318	140.8776
41	Finniss 2	Well	SA	0	0											-29.6112	137.4835
42	Innamincka 1	Well	SA	-	-											-27.4879	140.9200
43	Kopperamanna Bore 1	Well	SA	?	?											-28.6499	138.6888
44	Pelican 2	Well	SA	-	-											-27.8020	140.0804
45	Ruby Hill 1	Well	SA	-	-											-28.9383	136.4269
46	Skeleton 2	Well	SA	521	-											-29.9073	140.0144
47	SPH 1	Well	SA	0	0											-29.9257	139.8542
48	Toodla 1	Well	SA	266.18	271.5 MIN											-27.7283	135.8499
49	Yalkalpo 1	Well	SA	0	0											-30.8900	140.5157
50	P&D East (WP163)	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A					-28.3864	136.0237
51	P&D East (WP165)	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A					-28.3860	136.0217
52	P&D East (WP167)	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A					-28.3861	136.0202
53	CO Algebuckina Hill	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A					-27.9228	135.7742
54	Mt Anna ss	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A					-28.6818	136.0424
55	Pelican Well 1	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A					-29.9635	139.1491
56	Pelican Well 2	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A					-29.9505	139.1608
57	Trinity Well	Outcrop	SA	-	-	N/A		N/A	N/A	N/A	N/A					-29.8427	139.2907
58	Mt Babbage	Outcrop	SA	20.2 MIN	17.2	N/A		N/A	N/A	N/A	N/A					-29.8900	139.6400
59	Parabarana Hill	Outcrop	SA	22	16.8	N/A		N/A	N/A	N/A	N/A					-29.9943	139.7042
60	Field	Outcrop	QLD	6.6 MIN	0	N/A		N/A	N/A	N/A	N/A					-25.0990	146.6072
61	Black Stump Dam	Outcrop	NSW	-	-	N/A		N/A	N/A	N/A	N/A					-29.4265	141.8643
62	(Nive River) 1	Well	QLD	-	-											-24.9151	146.8345
63	Adria Downs 1	Well	QLD	945.1	954.6											-25.6935	139.3437
64	Alva 1	Well	QLD	823.6	860.4											-25.2071	145.3884
65	Arima 1	Well	QLD	1203	1235-1244											-26.8035	142.6343
66	Aros 1	Well	QLD	666.5	673.4											-27.1938	143.4151

Location #	Well Name	Site type	State	Top Wyandra (m)	Base Wyandra (m)	Well Completion Report	Other Reports	Logs	Mudlogs +/- or Cuttings Report	Core	SW core	Outcrop	Petrography	Geochemistry	Palynology	Latitude (deg)	Longitude (deg)
67	Balfour 1	Well	QLD	178.3	198.1											-25.5354	146.7122
68	Ban Ban 1	Well	QLD	760.74	763.18											-24.1307	143.7051
69	Banmirra 1	Well	QLD	1291	1303											-25.4810	144.0439
70	Barcoo 1	Well	QLD	578.2	592.8											-24.2843	145.1395
71	Barrolka 3	Well	QLD	1425.8	1448.3											-26.8865	141.7343
72	Barwinock 1	Well	QLD	530.7	539.5											-25.4046	145.9084
73	Berellem 1	Well	QLD	968.5	982.5											-26.7735	143.0765
74	Betoota 1	Well	QLD	990.2	MIN 996.6											-25.7068	140.8307
75	Bodalla South 1	Well	QLD	1066	1092											-26.4479	143.4237
76	Boldrewood 1	Well	QLD	991.5	1013.1 MIN, 1022.2 MAX											-26.8218	142.5601
77	Bonnie 1	Well	QLD	696.2	711											-25.0121	145.3670
78	Boree 1	Well	QLD	441.3	459.3											-24.7573	145.5778
79	Brightspot 1	Well	QLD	1129	1135											-25.1457	143.6481
80	Brynderwin 1	Well	QLD	403.7	414											-24.4676	145.5439
81	Buckaroola 1	Well	QLD	943.61	984.46											-26.9713	142.4573
82	Budgerygar 1	Well	QLD	890.5	899.77											-25.2371	143.8089
83	Bundeena 1	Well	QLD	1167.5	1197											-27.4527	142.6551
84	Callisto 1	Well	QLD	1207.5	1227.5											-27.3629	142.5293
85	Carlow 1	Well	QLD	624.8	637											-24.8393	145.4311
86	Chesson 1	Well	QLD	634	675											-27.9054	143.3229
87	Collabara 1	Well	QLD	1243.5	1269.1											-25.2382	144.7512
88	Cuddapan 1	Well	QLD	1519.05	1528.2											-25.6949	141.6720
89	Doherty 1	Well	QLD	775	783											-23.9646	144.2553
90	Eastwood 1	Well	QLD	829.3	843											-24.7715	145.3500
91	Eromanga 1 HOA	Well	QLD	1072	1080											-26.6729	143.6081
92	Fairlea 1	Well	QLD	643.1	652.2											-24.4954	145.3314
93	Gaza 1	Well	QLD	839.2	842.2											-24.0929	144.1192
94	GIBBA 1	Well	QLD	996.7	1011.2											-28.7371	141.5515
95	Gifford 1	Well	QLD	994.8	1010											-25.3140	145.0503
96	Gilmore 1	Well	QLD	1118.6	1127.7											-25.3576	144.8117
97	Gilmore 5	Well	QLD	1094	1099.5											-25.3457	144.8298
98	Goallah 1	Well	QLD	690	723											-28.1426	143.0951
99	Grey Range 1	Well	QLD	1365	1376											-25.1076	144.6239
100	Hooley 1	Well	QLD	966.2	1007.3											-27.1724	142.5776
101	Horse Creek 1	Well	QLD	1668.7	1692.8											-25.9332	143.0284
102	Isis Downs 1	Well	QLD	861.8	868											-24.2796	144.5925
103	Jackson 1	Well	QLD	1021.3	1039.3											-27.6074	142.4190
105	Jackson 6	Well	QLD	1063.7	1075.6											-27.5929	142.4154
106	Jampot 1	Well	QLD	869	871.5											-25.3115	143.8367
107	Jedburgh 1	Well	QLD	1269.49	1281.38											-25.2163	143.5417
108	Jericho 1 GSQ	Well	QLD	0	0											-23.6318	146.3678
109	Kaloola 1	Well	QLD	1035.1	1046.5											-25.6171	144.6962
110	Kenmore 1	Well	QLD	1001.5	1014.5											-26.6510	143.4406
111	Kyabra 1	Well	QLD	1404	1423											-25.8218	143.2890
112	Lisburne 1	Well	QLD	1024.7	1046											-25.1729	145.0045
113	Majestic 1	Well	QLD	1451	1471											-26.6649	142.7162
114	McVerry 1	Well	QLD	744	752											-24.1040	144.7847
115	Mitchell 2	Well	QLD	21.4	97.01											-26.3437	148.1331
116	Mount Whelan 1	Well	QLD	0	0											-23.3085	138.8779
117	Mount Bellalie 1	Well	QLD	1177	1201.5											-26.5201	143.1176
118	Opal 1	Well	QLD	1139	1174											-26.0360	143.8412
119	Petworth 1	Well	QLD	832.5	846.5											-25.2015	143.8537
120	Raymore 1	Well	QLD	1364	1383											-26.2118	143.3079
121	Sands 1	Well	QLD	937.5	942											-25.0921	143.8451
122	Sheoak 1	Well	QLD	1330.5	1361.5 MIN, 1380.5 MAX											-26.7290	142.7687
123	Speltz 1	Well	QLD	511.5	522.3											-23.8143	145.2142
124	Stormhill 1	Well	QLD	999.74	1002.79											-24.1443	143.5862
125	Stratavon 1	Well	QLD	720	736											-24.0974	144.8684
126	Swaylands 1	Well	QLD	584	594											-24.5293	145.4364
127	Talundilly 1	Well	QLD	1044-1053	1090-1095											-24.5479	144.4787
128	Tambo 1-1A	Well	QLD	0	0											-24.5318	146.6011
129	Tintaburra 1	Well	QLD													-26.9304	143.1034
130	Titheroo 1	Well	QLD	552	572.5											-28.5713	143.2543
131	Toobunyah 1	Well	QLD													-26.9499	143.1065
132	Tookoonooka 1	Well	QLD	1094.8	1114.9											-27.1877	142.4354
133	Tookoonooka 1	Well	QLD	882	1050											-27.0893	142.7907
134	Toorpa 1	Well	QLD	692.2	715											-27.5024	143.1440
135	Ueleven 1	Well	QLD	741	758											-26.5804	143.9095
136	Valetta 1	Well	QLD	0	39.6											-25.0457	146.6011
137	Vernon 1	Well	QLD	1309	1330											-26.7682	142.7407

Location #	Well Name	Site type	State	Top Wyandra (m)	Base Wyandra (m)	Well Completion Report	Other Reports	Logs	Mudlogs +/- or Cuttings Report	Core	SW core	Outcrop	Petrography	Geochemistry	Palynology	Latitude (deg)	Longitude (deg)
138	Vernon West 1	Well	QLD	1332	1353.5											-26.7821	142.7012
139	Wareena 1	Well	QLD	885.7	918											-26.8954	142.3459
140	Westbourne 1	Well	QLD	274.3	286.59											-25.1893	146.1350
141	Widnerpool 1	Well	QLD	644	655.5											-24.1224	143.6656
142	Wiralla 1	Well	QLD	592	605											-27.8182	144.0848
144	Wompah 1	Well	QLD	847.3	883.9											-28.4343	142.3126
145	Yongala 1	Well	QLD	1302.11	1313											-25.5038	143.9312
146	Yongala 2	Well	QLD	1187.2	1203.05											-25.5263	143.8940
147	Beanbush 1	Well	SA	1947	1976.8											-27.2878	140.6430
148	Big Lake 28	Well	SA	1605.6	1613.5											-28.2120	140.3111
149	Burrinna 1	Well	SA	1231.3	1247.8											-28.5551	140.7530
150	Dullingari 11	Well	SA	1428.8	1439.5											-28.0542	140.8583
151	Haddon Downs 1	Well	SA	1228.9	1233.5-1244.7											-26.3970	140.5923
152	Innamincka 4	Well	SA	1192.6	1205.4											-27.4759	140.8414
153	James 1	Well	SA	1546.5	1562											-26.8139	140.8478
154	DM Bellfield 1	Well	NSW	?	?											-29.6111	146.0236
155	DM Wanaaring 1	Well	NSW	307.8	316.1											-30.0667	143.7000
156	DM Weilmoringle 1	Well	NSW	338.3	350.5											-29.1306	146.6028
157	DM Yantabulla 1	Well	NSW	?	?											-29.4833	144.8750
158	Etingimbra 1	Well	NT	?	?											-25.8574	135.7527

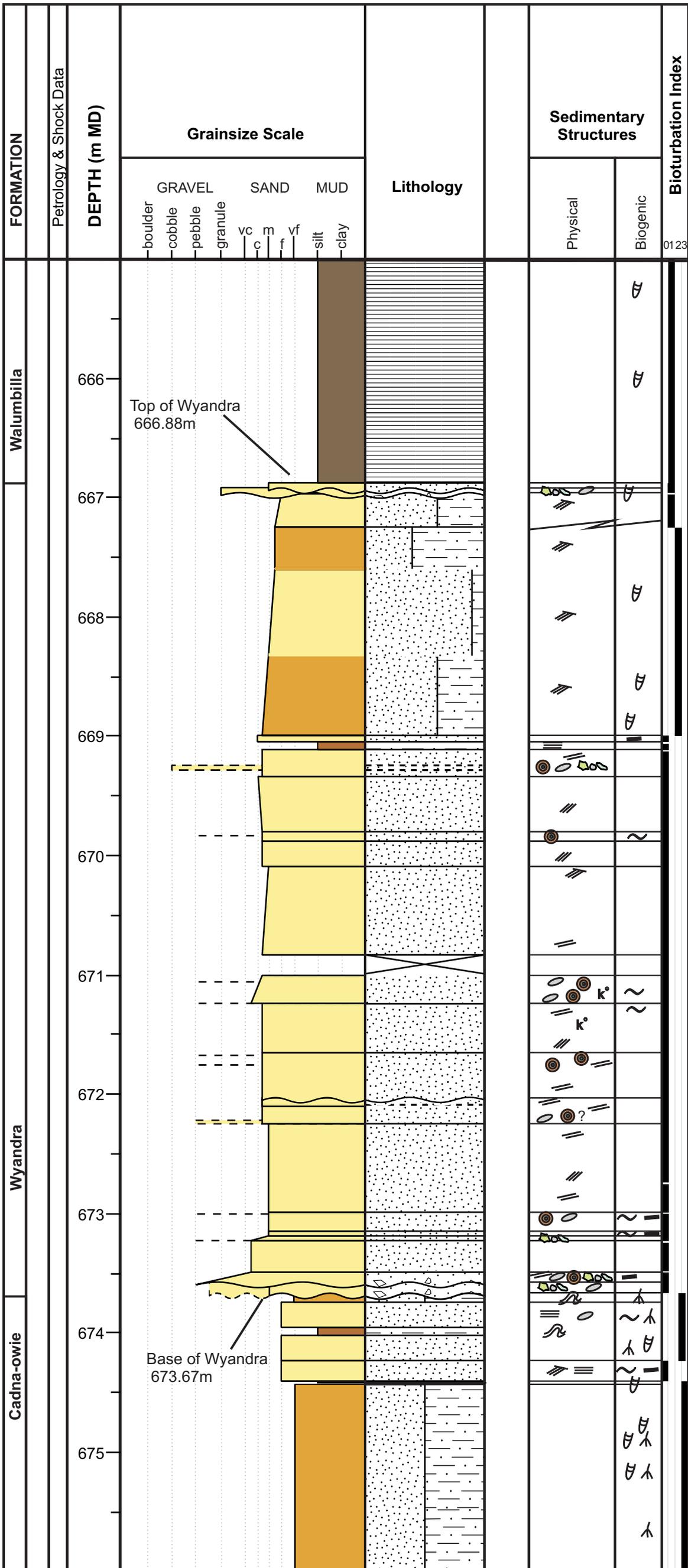
Appendix 4

Detailed lithological logs of cores for the Cadna-owie Formation -Walumbilla Formation interval for 13 locations (unpublished core logs, supplementary to Paper 3). Included are:

Location 2 corelog
Location 6 corelog
Location 10 corelog
Location 14 corelog
Location 15 corelog
Location 19 corelog
Location 23 corelog
Location 25 corelog
Location 26 corelog
Location 27 corelog
Location 31 corelog
Location 33 corelog
Location 34 corelog
Legend

Location 2 Core Interpretation

Well Name: Aros-2
Well Type (core width): Petroleum (100 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 27.1934°S / 143.4153°E
Distance from Tookoonooka / Talundilly (crater centre): 1.76 Rc / 7.02 Rc
Depositional Realm: Shallow Marine (1-2 Rc)
Corelogged Interval: 665-676 m
Depth Units: meters MD
Author: Katherine Bron

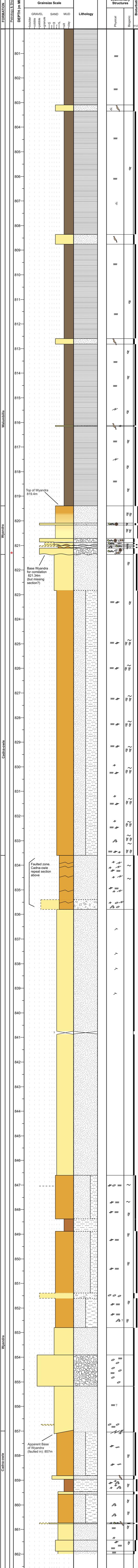


Location 2 Core Interpretation

Well Name: Aros-2
Well Type (core width): Petroleum (100 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 27.1934°S / 143.4153°E
Distance from Tookoonooka / Talundilly (crater centre): 1.76 Rc / 7.02 Rc
Depositional Realm: Shallow Marine (1-2 Rc)
Corelogged Interval: 665-676 m
Depth Units: meters MD
Author: Katherine Bron

Location 6 Core Interpretation

Well Name: GSQ Blackall-2
 Well Type (core width): Stratigraphic (48 mm)
 Location: Queensland, Australia
 Basin: Eromanga
 Latitude / Longitude: 24.1607°S / 144.2237°E
 Distance from Toookoonooka / Talundilly (crater centre): 10.7 Rc / 1.7 Rc
 Depositional Realm: Shallow Marine (1-2 Rc)
 Corelogged Interval: 800-862 m
 Depth Units: meters MD
 Author: Katherine Bron

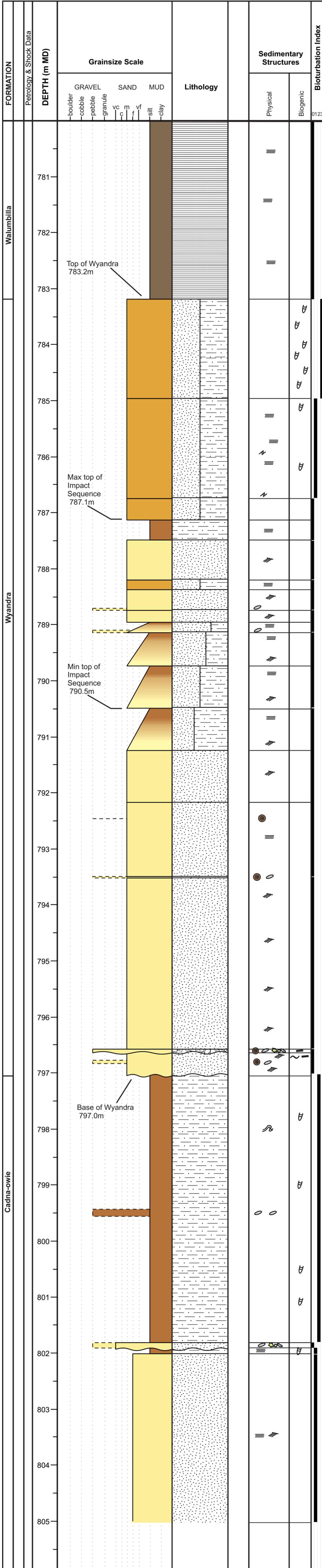


Location 6 Core Interpretation

Well Name: GSQ Blackall-2
 Well Type (core width): Stratigraphic (48 mm)
 Location: Queensland, Australia
 Basin: Eromanga
 Latitude / Longitude: 24.1607°S / 144.2237°E
 Distance from Toookoonooka / Talundilly (crater centre): 10.7 Rc / 1.7 Rc
 Depositional Realm: Shallow Marine (1-2 Rc)
 Corelogged Interval: 800-862 m
 Depth Units: meters MD
 Author: Katherine Bron

Location 10 Core Interpretation

Well Name: GSQ Connemara-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.4985°S / 141.3970°E
Distance from Tookoonooka / Talundilly (crater centre): 9.8 Rc / 7.7 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 780-805 m
Depth Units: meters MD
Author: Katherine Bron

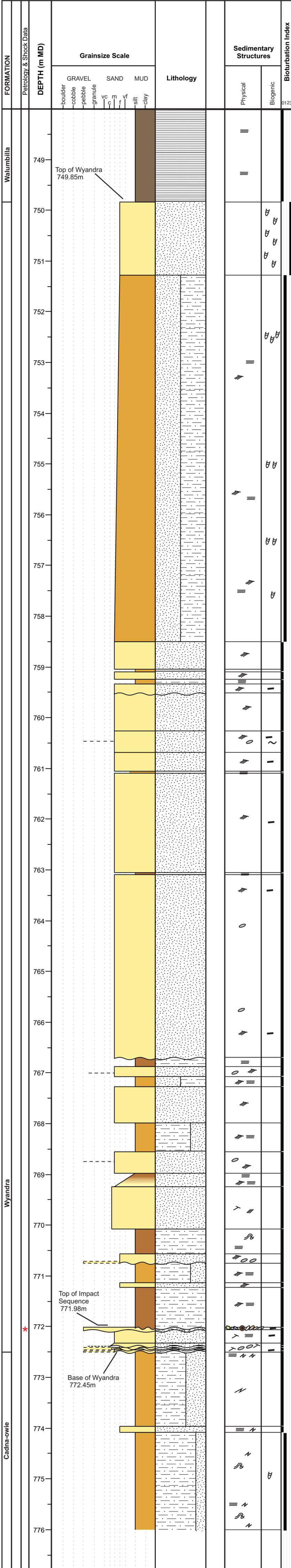


Location 10 Core Interpretation

Well Name: GSQ Connemara-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.4985°S / 141.3970°E
Distance from Tookoonooka / Talundilly (crater centre): 9.8 Rc / 7.7 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 780-805 m
Depth Units: meters MD
Author: Katherine Bron

Location 14 Core Interpretation

Well Name: GSQ Jundah-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.5304°S / 142.7015°E
Distance from Tookoonooka / Talundilly (crater centre): 8.7 Rc / 4.5 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 748-776 m
Depth Units: meters MD
Author: Katherine Bron

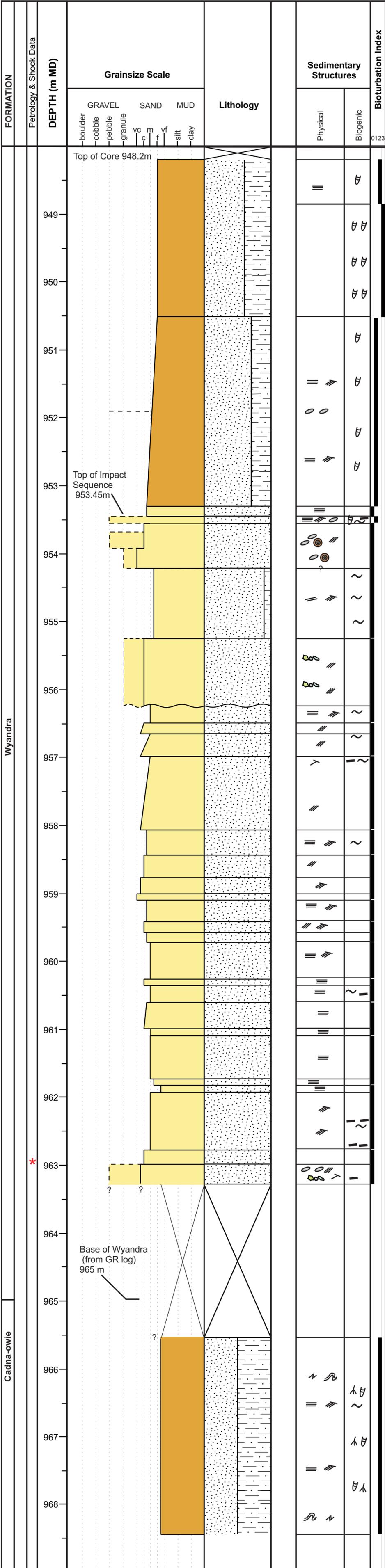


Location 14 Core Interpretation

Well Name: GSQ Jundah-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.5304°S / 142.7015°E
Distance from Tookoonooka / Talundilly (crater centre): 8.7 Rc / 4.5 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 748-776 m
Depth Units: meters MD
Author: Katherine Bron

Location 15 Core Interpretation

Well Name: Kercummurra-1
Well Type (core width): Petroleum (100 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 27.1077°S / 142.4346°E
Distance from Tookoonooka / Talundilly (crater centre): 1.15 Rc / 8.07 Rc
Depositional Realm: Shallow Marine (1-2 Rc)
Corelogged Interval: 948.2-968.4 m
Depth Units: meters MD
Author: Katherine Bron

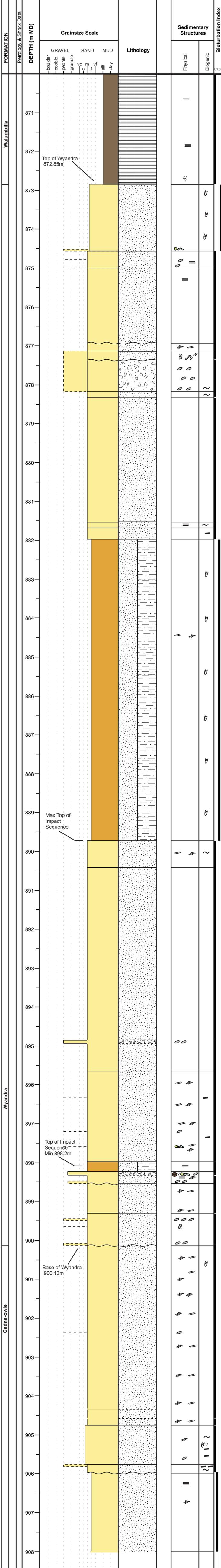


Location 15 Core Interpretation

Well Name: Kercummurra-1
Well Type (core width): Petroleum (100 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 27.1077°S / 142.4346°E
Distance from Tookoonooka / Talundilly (crater centre): 1.15 Rc / 8.07 Rc
Depositional Realm: Shallow Marine (1-2 Rc)
Corelogged Interval: 948.2-968.4 m
Depth Units: meters MD
Author: Katherine Bron

Location 19 Core Interpretation

Well Name: GSQ Maneroo-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 23.3818°S / 143.4678°E
Distance from Tookoonooka / Talundilly (crater centre): 12.6 Rc / 4.5 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 870-908 m
Depth Units: meters MD
Author: Katherine Bron

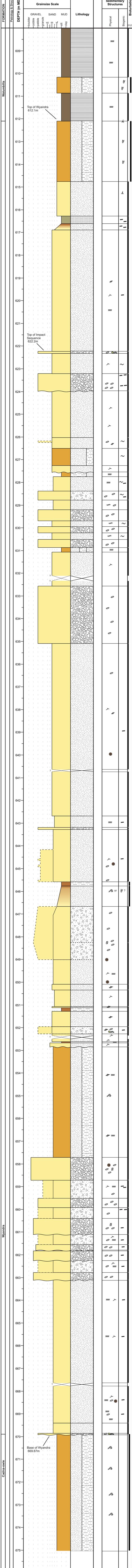


Location 19 Core Interpretation

Well Name: GSQ Maneroo-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 23.3818°S / 143.4678°E
Distance from Tookoonooka / Talundilly (crater centre): 12.6 Rc / 4.5 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 870-908 m
Depth Units: meters MD
Author: Katherine Bron

Location 23 Core Interpretation

Well Name: GSQ Quilpie-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 26.6335°S / 145.0420°E
Distance from Tookoonooka / Talundilly (crater centre): 6.8 Rc / 5.1 Rc
Depositional Realm: Estuarine
Corelogged Interval: 608-675 m
Depth Units: meters MD
Author: Katherine Bron

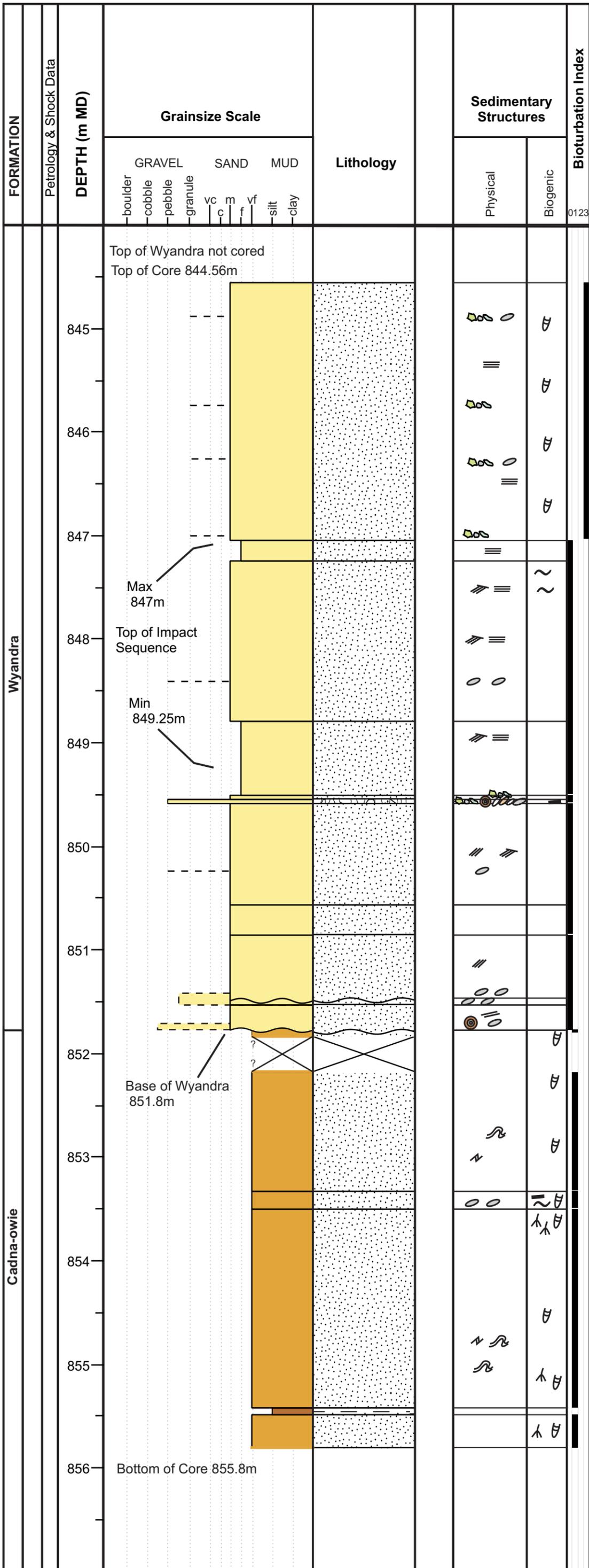


Location 23 Core Interpretation

Well Name: GSQ Quilpie-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 26.6335°S / 145.0420°E
Distance from Tookoonooka / Talundilly (crater centre): 6.8 Rc / 5.1 Rc
Depositional Realm: Estuarine
Corelogged Interval: 608-675 m
Depth Units: meters MD
Author: Katherine Bron

Location 25 Core Interpretation

Well Name: Talgeberry-2
Well Type (core width): Petroleum (100 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 26.9485°S / 143.4298°E
Distance from Tookoonooka / Talundilly (crater centre): 1.9 Rc / 6.4 Rc
Depositional Realm: Shallow Marine (1-2 Rc)
Corelogged Interval: 844.5-855.8 m
Depth Units: meters MD
Author: Katherine Bron

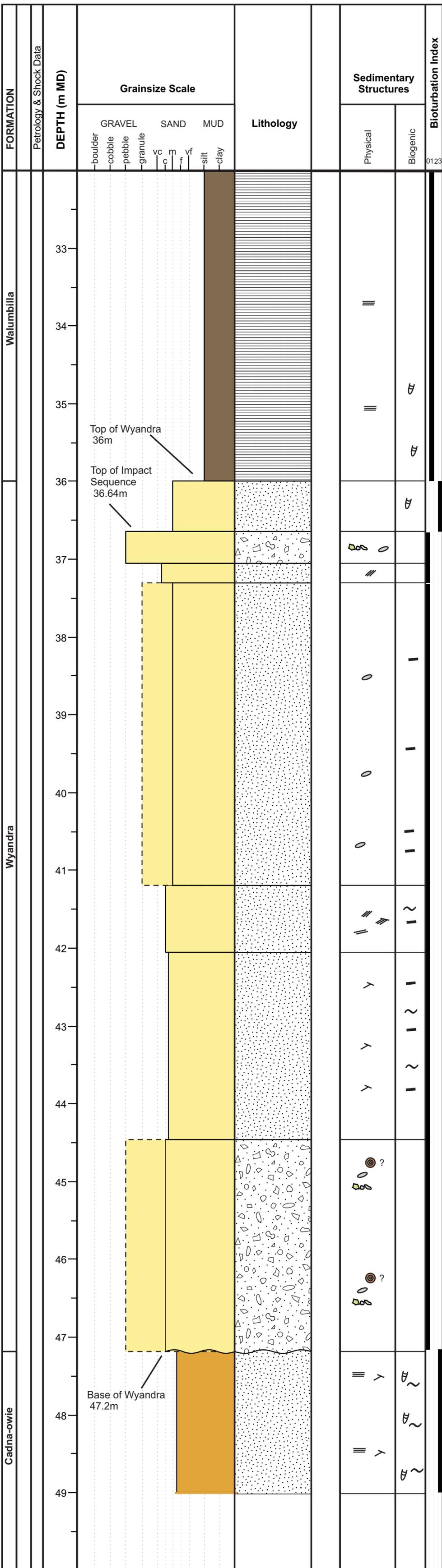


Location 25 Core Interpretation

Well Name: Talgeberry-2
Well Type (core width): Petroleum (100 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 26.9485°S / 143.4298°E
Distance from Tookoonooka / Talundilly (crater centre): 1.9 Rc / 6.4 Rc
Depositional Realm: Shallow Marine (1-2 Rc)
Corelogged Interval: 844.5-855.8 m
Depth Units: meters MD
Author: Katherine Bron

Location 26 Core Interpretation

Well Name: GSQ Tambo-2
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.8651°S / 146.3678°E
Distance from Tookoonooka / Talundilly (crater centre): 13.0 Rc / 4.2 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 32-49 m
Depth Units: meters MD
Author: Katherine Bron

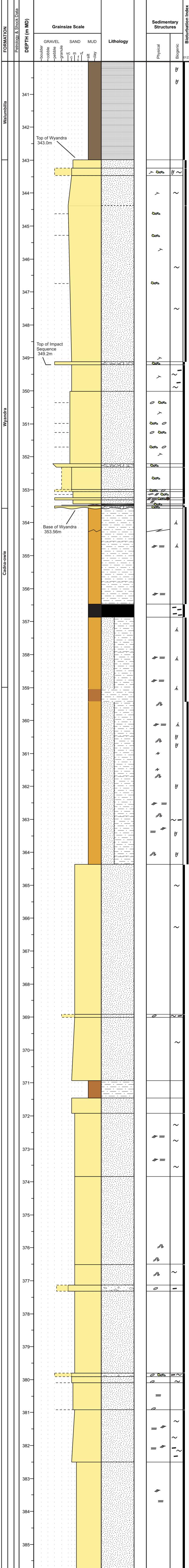


Location 26 Core Interpretation

Well Name: GSQ Tambo-2
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.8651°S / 146.3678°E
Distance from Tookoonooka / Talundilly (crater centre): 13.0 Rc / 4.2 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 32-49 m
Depth Units: meters MD
Author: Katherine Bron

Location 27 Core Interpretation

Well Name: GSQ Tambo-4
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.8193°S / 145.8478°E
Distance from Tookoonooka / Talundilly (crater centre): 11.9 Rc / 3.0 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 340-386 m
Depth Units: meters MD
Author: Katherine Bron

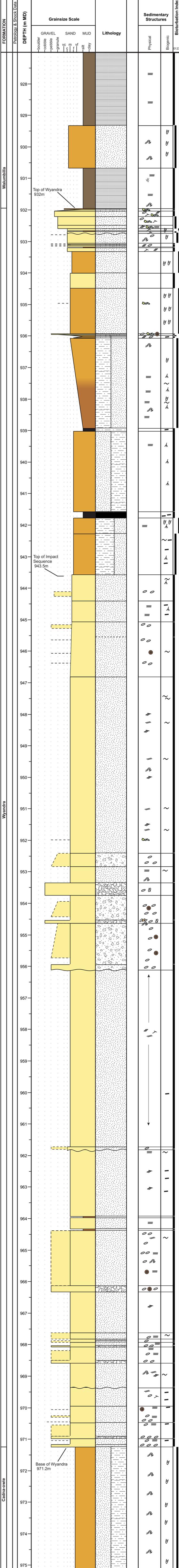


Location 27 Core Interpretation

Well Name: GSQ Tambo-4
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 24.8193°S / 145.8478°E
Distance from Tookoonooka / Talundilly (crater centre): 11.9 Rc / 3.0 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 340-386 m
Depth Units: meters MD
Author: Katherine Bron

Location 31 Core Interpretation

Well Name: GSQ Thargomindah-2
 Well Type (core width): Stratigraphic (48 mm)
 Location: Queensland, Australia
 Basin: Eromanga
 Latitude / Longitude: 27.7304°S / 142.9240°E
 Distance from Tookoonooka / Talundilly (crater centre): 2.0 Rc / 8.8 Rc
 Depositional Realm: Shallow Marine (1-2 Rc)
 Corelogged Interval: 927-976 m
 Depth Units: meters MD
 Author: Katherine Bron

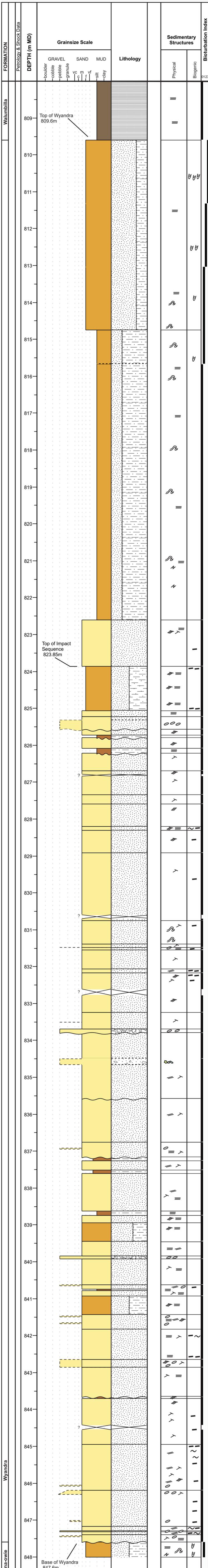


Location 31 Core Interpretation

Well Name: GSQ Thargomindah-2
 Well Type (core width): Stratigraphic (48 mm)
 Location: Queensland, Australia
 Basin: Eromanga
 Latitude / Longitude: 27.7304°S / 142.9240°E
 Distance from Tookoonooka / Talundilly (crater centre): 2.0 Rc / 8.8 Rc
 Depositional Realm: Shallow Marine (1-2 Rc)
 Corelogged Interval: 927-976 m
 Depth Units: meters MD
 Author: Katherine Bron

Location 33 Core Interpretation

Well Name: GSQ Tickalara-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 28.6435°S / 142.1635°E
Distance from Tookoonooka / Talundilly (crater centre): 3.9 Rc / 10.6 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 808-848 m
Depth Units: meters MD
Author: Katherine Bron

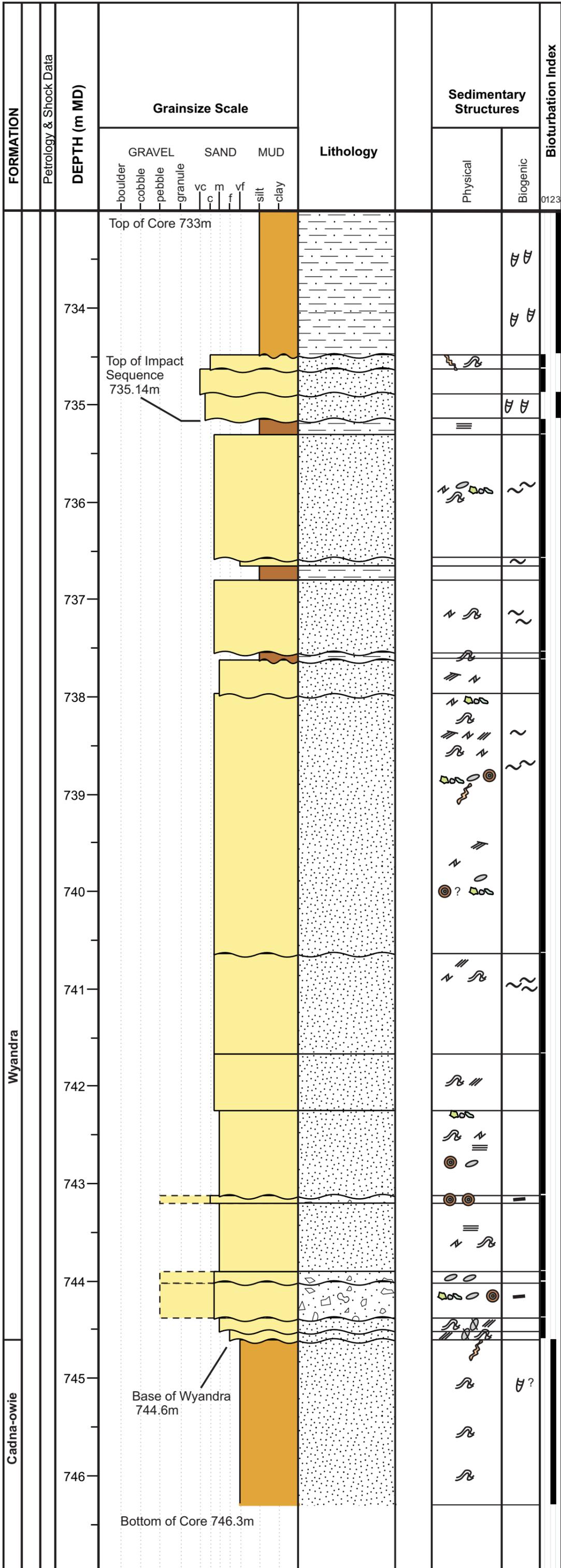


Location 33 Core Interpretation

Well Name: GSQ Tickalara-1
Well Type (core width): Stratigraphic (48 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 28.6435°S / 142.1635°E
Distance from Tookoonooka / Talundilly (crater centre): 3.9 Rc / 10.6 Rc
Depositional Realm: Shallow Marine (2-10 Rc)
Corelogged Interval: 808-848 m
Depth Units: meters MD
Author: Katherine Bron

Location 34 Core Interpretation

Well Name: Tintaburra-2
Well Type (core width): Petroleum (100 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 26.9268°S / 143.1034°E
Distance from Tookoonooka / Talundilly (crater centre): 1.1 Rc / 6.8 Rc
Depositional Realm: Shallow Marine 1-2 Rc (Slumped zone)
Corelogged Interval: 733-746.3 m
Depth Units: meters MD
Author: Katherine Bron



Location 34 Core Interpretation

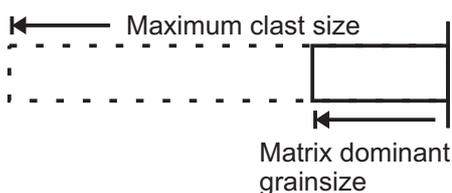
Well Name: Tintaburra-2
Well Type (core width): Petroleum (100 mm)
Location: Queensland, Australia
Basin: Eromanga
Latitude / Longitude: 26.9268°S / 143.1034°E
Distance from Tookoonooka / Talundilly (crater centre): 1.1 Rc / 6.8 Rc
Depositional Realm: Shallow Marine 1-2 Rc (Slumped zone)
Corelogged Interval: 733-746.3 m
Depth Units: meters MD
Author: Katherine Bron

Corelog Legend

Lithology

	Matrix-supported breccia-conglomerate (MSBC)
	Clast-supported breccia-conglomerate (CSBC)
	Sandstone (ss)
	Shale (sh)
	Siltstone (sst)
	Mudstone (mst)
	Interlaminated/thinly interbedded Siltstone (sst) & Sandstone (ss)
	Coal
	Missing Core

Grainsize



Boulder	bldr
Cobble	cobb
Pebble	pebb
Granule	gran
Very coarse sand	vcgr
Coarse sand	cgr
Medium sand	mgr
Fine sand	fgr
Very fine sand	vfgr

Bioturbation Index

0	1	2	3
No bioturbation	Minor bioturbation	Moderate bioturbation	Heavy bioturbation

Sedimentary Structures

Physical

	Soft sediment deformation
	Microfaults & fractures
	Injectite
	Low angle beds/lamination
	High angle beds/lamination
	Cross-stratification
	Weak/vague bedding structure
	Planar stratification or horizontal lamination
	Lithic clasts (granular or larger grainsizes)
	Mudclasts, rip-up clasts, sedimentary lithic clasts
	Accretionary or Melt Impactoclasts (AI/MI)
	Brecciated or μF sedimentary lithic clasts (pebble or larger; angular)
	Imbricated clasts
	Shocked quartz grains: measured or qualitative only
	Cone-in-cone

Biogenic

	Burrows/Bioturbation
	Coal clasts, woody material or plant fragments
	Carbonaceous Laminations (organic detritus)
	Rootlets

Contacts/Boundaries

(none)	Gradational
	Erosive/Scour
	Sharp
	Fault

Appendix 5

Abstracts and posters completed in the course of PhD research.

Abstract 1: Bron, K., and Gostin, V., 2008. Sedimentary and petrologic evidence of a Tookoonooka Impact Event ejecta layer, Australia: Geological Society of Australia and the Australian Institute of Geoscientists, Australian Earth Sciences Convention (AESC) 2008, Abstracts no. 89 of the 19th Australian Geological Convention, Perth WA, Australia, p. 60.

Abstract 2 & Poster: Bron, K., 2008. Accretionary Lapilli from the Tookoonooka Impact Event, Australia: Lunar and Planetary Institute, Proceedings of Large Meteorite Impacts IV 2008, LPI Contribution no. 1423, Abstract no. 3072, Vredefort, South Africa.

Abstract 3: Bron, K., 2009. The Tookoonooka Tsunami Sequence: Evidence for Marine Impact in Australia's Lower Cretaceous: Lunar and Planetary Institute, 40th Lunar and Planetary Science Conference, Abstract no. 2560, Houston, Texas.

Abstract 4: Bron, K.A., 2010. Tookoonooka Impact Sedimentation: Evidence for Resurge Cyclicity within the Crater Fill: Lunar and Planetary Institute, 41st Lunar and Planetary Science Conference, Abstract no. 2034, Houston, Texas.

Abstract 5: Bron, K.A., 2012. Sedimentological aspects of the Tookoonooka impact event, Eromanga Basin, Queensland: Australian School of Petroleum, University of Adelaide, Australian School of Petroleum Post-graduate Conference 2012, Abstract no. 5, Adelaide SA, Australia.

Abstract 6: Bron, K.A., 2012. Marine Impact Sedimentation of the Tookoonooka-Talundilly Event, Lower Cretaceous, Australia: Australian Geosciences Council, Proceedings of the 34th International Geological Congress 2012, Abstract no. 3532, Brisbane QLD, Australia, p. 3958.

Abstract 7: Bron, K., 2015. The Tookoonooka-Talundilly Tsunami Sequence: Constraining Marine Impact Stratigraphy: Lunar and Planetary Institute, Proceedings of Bridging the Gap III: Impact Cratering in Nature, Experiment, and Modeling 2015, LPI Contribution no. 1423, Abstract no. 1089, Freiburg, Germany.

Abstract Listing:

Abstract #	Event	Year	Contribution
1	Australian Earth Sciences Convention, Perth, Australia	2008	Abstract, Speaker
2	Large Meteorite Impacts IV, Vredefort, South Africa	2008	Extended Abstract, Speaker, Poster
3	Lunar and Planetary Sciences Conference, Houston, USA	2009	Extended Abstract - print only (in absentia)
4	Lunar and Planetary Sciences Conference, Houston, USA	2010	Extended Abstract, Speaker
5	Australian School of Petroleum Conference	2012	Abstract, Speaker
6	International Geological Congress, Brisbane, Australia	2012	Abstract, Invited Speaker
7	Bridging the Gap III, Freiburg, Germany		Abstract, Speaker

Sedimentary and Petrologic Evidence of a Tookoonooka Impact Event Ejecta Layer, Australia

Katherine Bron¹, Victor A. Gostin²

¹*Australian School of Petroleum, University of Adelaide, Adelaide, SA 5005, Australia
(tbron@asp.adelaide.edu.au)*

²*Department of Geology and Geophysics, University of Adelaide, Adelaide, SA 5005, Australia (victor.gostin@adelaide.edu.au)*

A search for an impact ejecta layer for the confirmed subsurface Tookoonooka impact structure (27°07'S, 142°50'E) was undertaken in the lower Cretaceous (Aptian-Barremian) strata of the Eromanga basin of southwestern Queensland.

An unusual 5-cm thick layer, observed in core, is believed to represent the impact horizon. This crudely graded, very poorly sorted layer is composed of pebble to fine sand and silt-size, highly angular to rounded clasts. The layer overlies an erosional surface. Clasts are of various lithologies including metamorphic and vein quartz, volcanic and sedimentary rock fragments, feldspars variously altered to carbonate, and iron oxides. Petrologic evidence also includes shocked grains, including probable planar deformation features (PDFs) in quartz. This unit has experienced significant diagenetic alteration, particularly the feldspar component.

An investigation of diagnostic shock metamorphic and geochemical signatures is underway. Confirmation of this layer as the impact horizon holds implications for the constraint of impact timing and understanding the paleo-environment at the time of impact.

ACCRETIONARY LAPILLI FROM THE TOOKOONOOKA IMPACT EVENT, AUSTRALIA.

K. Bron, Australian School of Petroleum, University of Adelaide, Adelaide, SA 5005, Australia –
tbron@asp.adelaide.edu.au

Introduction: The lower Cretaceous Tookoonooka proven impact structure (27°07'S, 142°50'E) is a subsurface structure of the Eromanga Basin in Queensland, Australia. A Tookoonooka ejecta layer has now been identified in drillcore in the extensive sedimentary basin succession, [1]. The investigation of probable accretionary lapilli associated with the ejecta layer is discussed here.

Background - Accretionary Lapilli: Accretionary lapilli have been recognized in association with a number of impact events worldwide, including the Ries [2], Alamo [3], Popigai [4], Azuara [5], and Chicxulub [6,7,8] among others. Typical characteristics of impact-produced accretionary lapilli include internal concentric zonation, rims and nuclei, inclusions of rock fragments or grains (which may exhibit shock features), a fining outward texture, elemental anomalies suggesting a meteoritic input, and an original spherical to sub-spherical shape.

For clarification, this discussion will use the same terminology as [3], i.e. “crust” for the outer rim or shell, “mantle” for the main body of the lapilli comprising accreted particles, and “nucleus” where an inner core is present.

Observations and Discussion: Within the ejecta layer are unusual, light brown-tan clay-rich clasts. The apparent diameters of these clasts in core sample are commonly less than 1.5 cm, but may be up to 6 cm. Clast shapes are ellipsoidal, spherical, elongate, and irregular, and are consistently rounded (no angular or broken examples of these clasts have been observed). Clasts exhibit concentric zonation, a very fine-grained outer crust (possibly altered from a devitrified texture), and a relatively coarser-grained mantle with inclusions of quartz and partially-altered feldspar. Rare lithic nuclei are present. The clasts have been observed in a number of stratigraphic drillcores in the basin. Within 4 crater radii (proximal to the impact site), they may occur in clast-supported breccia layers which are interpreted to contain primary ejecta. More distal occurrences are reworked within tsunami deposits, often ‘floating’ within planar-bedded sandstone or in matrix-supported conglomerates.

Petrographic observations reveal that inclusions within the mantle of the clasts are complex. Minor feldspar (predominantly plagioclase, with some K-feldspar; both heavily altered) and quartz (some of which have a euhedral crystal shape) are enveloped in colourless, crystalline carbonate overgrowths. In some cases, pyritic overgrowths are also present. These complex mantle grains are set in a largely

massive, brownish sideritic matrix exhibiting poikilotopic fabric under cross-polars. The carbonate and pyrite phases (and likely the euhedral quartz) are interpreted to be the result of post-depositional diagenesis; it is clear that these clasts have experienced extensive alteration although the primary zonation is still subtly apparent below the diagenetic overprint in many.

Conclusion: The clasts described are unusual within the context of the predominantly siliciclastic sedimentary basin. They exhibit many of the characteristics of previously described impact lapilli, [e.g. 2-8], even though they are pervasively altered and much of their original texture has been lost. These clasts are interpreted to be accretionary lapilli derived from the Tookoonooka impact event. Their presence provides evidence of impact provenance for the ejecta layer.

Ongoing work which will be presented includes geochemical studies and microscopic investigation of the primary crystal inclusions within the mantle of the lapilli for shock metamorphic features.

References: [1] Bron K., in prep. [2] Graup G. (1981) *EPSL*, 55, 407–418. [3] Warne J. et al. (2002) *GSA SP 356*, 489-504. [4] Masaitis V. (2003) *Impact Mark. in the Strat. Rec.*, Springer, 137-162. [5] <http://www.impact-structures.com/Archiv/archiv.html> [6] Ocampo A. et al. (1996) *GSA SP 307*, 75-88. [7] Pope K.O. et al. (1999) *EPSL*, 170, 351–364. [8] Montanari A. (1990) *J. Sed. Petrol.*, 61, 315–339.

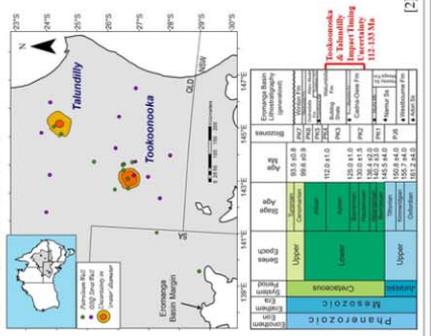
Accretionary Lapilli from the Tookoonooka Impact Event, Australia

Katherine (Treena) Bron

Australian School of Petroleum, University of Adelaide, SA 5005 Australia. contact: bron@asp.adelaide.edu.au

Introduction: The lower Cretaceous Tookoonooka proven impact structure is a subsurface structure of the Eromanga Basin in Queensland, Australia. A Tookoonooka ejecta layer has now been identified in drifone in the extensive sedimentary basin succession [1], with multiple lines of evidence. The investigation of probable accretionary lapilli associated with the ejecta layer is underway.

Location & Stratigraphic Context:



Tookoonooka Background [3,4,5,6]



- Confirmed subsurface impact structure
 - Dc=55-66 km
 - Possible binary impact with Talundilly (possible subsurface structure, Dc=50-55km)
- Focus of Current Work:**
- Constrain time of impact within stratigraphy
 - Improve understanding of paleosommatism
 - Investigate marine impact evidence
 - Assess impact influence on proximal petroleum systems
 - Mapping distribution across the basin, relationship to Talundilly
 - Geochemical analyses

Sedimentary Character of Ejecta Layer:

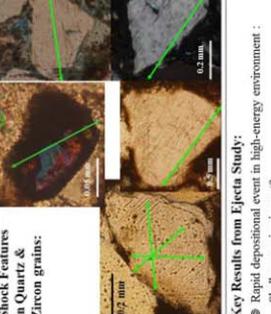
- 5-6 cm thick (layers at these locations, within 3 Rc)
- Clast-supported pebble layers, imbrication
- Very poorly sorted, may be crudely graded & cross-bedded
- Litic & breccia content
- Sedimentary context: Bedded sandstones & coal



Petrographic Observations:

Mineralogy of Ejecta Layer

- 2% lithic content, including 9% glass
- 2% lapilli



- Shock Features in Quartz & Zircon grains:**
- Rapid depositional event in high-energy environment: Shallow marine impact?
 - Distribution across the basin
 - Grain variety & lithic content of clast layer indicate new source material including basement source
 - Shock deformation: impact provenance
 - Time of impact has been stratigraphically constrained to base of the Wyandra Sandstone Member: base of PK3 biozone (approx 125 Ma)

Background - Accretionary Lapilli: Accretionary lapilli have been recognized in association with a number of impact events worldwide, including the Ries [7], Alamo [8], Popigai [9], Azusa [10], and Chicxulub [11,12,13] among others. Typical characteristics of impact-produced accretionary lapilli include internal concentric zonation, rims and nuclei, inclusions of rock fragments or grains (which may exhibit shock features), a fine outward texture, elemental anomalies suggesting a meteoritic input, and sub-spherical to angular shapes. Definitions: "crust" = outer rim/shell, "mantle" = main body of lapilli (comprising accreted particles), "nucleus" = inner core (if present).

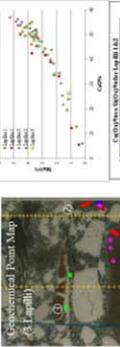
Tookoonooka Accretionary Lapilli?:



Macroscopic Observations/Features:

- Observed both in crater structure (A,B) & ejecta (C-E)
- Apparent diameters commonly <1.5 cm, but up to 6 cm
- Clast shapes: ellipsoidal, spherical, elongate, irregular
- Concentric zonation
- Very fine-grained outer crust (possibly altered from a devitrified texture) & relatively coarser-grained mantle
- Inclusions of quartz & feldspar, rare lithic nuclei

Geochemical Results:



Conclusions:

The lapilli-like clasts described are unusual within the context of the predominantly siliciclastic sedimentary basin. They exhibit many of the characteristics of previously described impact lapilli, [e.g. 7-13], even though they are pervasively altered and much of their original character has been lost. These clasts are interpreted to be accretionary lapilli derived from the Tookoonooka impact event. Their presence provides further evidence of impact provenance for the ejecta layer. Geochemical trends across the concentric zones, and the presence of Ir and other anomalies require further investigation.

- References** [1] Bron K. (2008) *JESC*, 19th *Int. Geol. Cong.*, Abstract V4888, 60. [2] Bron K., Gaudin, O. & Smith (2004), *Space Pollution*, Phase 1977, Wood, G. [3] Bron K., Gaudin, O., & Smith (2004), *Space Pollution*, Phase 1977, Wood, G. [4] Bron K., Gaudin, O., & Smith (2004), *Space Pollution*, Phase 1977, Wood, G. [5] Bron K., Gaudin, O., & Smith (2004), *Space Pollution*, Phase 1977, Wood, G. [6] Loope, L. (1989), [7] Gault, G. (1982) *LEPS*, 15, 407-418. [8] Weimer, J. et al., (2002) *GSA*, SP 258, 489-504. [9] Masaitis, V. (2003) *Impact Mark. in the Strat. Rec.*, Springer, 137-162. [10] <http://www.impactearth.org/Archiv/worksheets.html> [11] Masaitis, V. (2003) *Impact Mark. in the Strat. Rec.*, Springer, 137-162. [12] Masaitis, V. (2003) *Impact Mark. in the Strat. Rec.*, Springer, 137-162. [13] Masaitis, V. (2003) *Impact Mark. in the Strat. Rec.*, Springer, 137-162.

Thank you to Sponsors: ASP, Queensland Government

THE TOOKOONOOKA TSUNAMI SEQUENCE: EVIDENCE FOR MARINE IMPACT IN AUSTRALIA'S LOWER CRETACEOUS. Katherine (Treena) Bron, Australian School of Petroleum, The University of Adelaide, Adelaide, SA 5005, Australia (tbron@asp.adelaide.edu.au).

Introduction: The Tookoonooka Impact Structure is located in the subsurface of central Australia. It was initially discovered by seismic exploration and was confirmed to be of impact origin with the detection and measurement of PDFs (Planar Deformation Features) in shock metamorphosed quartz [1, 2]. Tookoonooka ejecta have recently been discovered in drill core in the extensive Eromanga Basin sedimentary succession within the Wyandra Sandstone Member [3-5]. The discovery has stratigraphically constrained the time of impact to approximately 125 Ma, in the Lower Cretaceous. The Wyandra Sandstone overlies the fine-grained sandstones and siltstones of the largely paralic Cadna-Owie Formation and precedes deposition of the marine shale of the Walumbilla Formation. Sedimentary evidence within ejecta beds has pointed to the probability of Tookoonooka being a marine impact event. The investigation of the broader sedimentary & stratigraphic context of the ejecta is the subject of this paper.

Background – Tsunami Sedimentation:

Tsunami sedimentation is not well known from the ancient rock record [6]. Tsunami or resurge sedimentation known to originate from ancient marine impact events is even rarer. However, tsunami deposits have been associated with a few marine impact events, Chicxulub [e.g. 7], Alamo [8], Chesapeake [9], and Lockne [10] among them. Evidence cited as proof of impact provenance of tsunami deposits usually includes stratigraphic proximity to the timing of impact and entrainment of impact ejecta.

Methodology: Subsurface datasets are required to analyze the largely buried sediments of the Eromanga Basin. Whole rock samples are sparse and often discontinuous, but can be supplemented with digital data gained from petroleum exploration. Examination and detailed core-logging of 22 drill cores (including 13 continuously cored stratigraphic bores) and correlations with petroleum logs were used to provide a robust indication of the distribution of impact-related sedimentation across the basin and the stratigraphy of the Wyandra Sandstone.

Observations and Discussion: In the cores logged, the thickness of the Wyandra Sandstone varies from few meters to about 60 m. Ejecta is confined to the Wyandra Sandstone, except for a brief return to background Cadna-Owie sedimentation styles in a few locations. Only rarely do ejecta appear to be reworked into the overlying Walumbilla Formation. Plant debris is common in the

Wyandra compared to the underlying Cadna-Owie, and may be an important indication of tsunami sedimentation. In none of the wells observed has ejecta been found to be deposited in a non-aqueous depositional context.

Detailed core-logging confirmed that coarse impact ejecta (up to cobble and boulder-sized) is present throughout the Wyandra Sandstone. It occurs as floating clasts within fine- to coarse-grained (usually planar-bedded or massive) matrix-supported sandstones and concentrated in clast-supported breccia-conglomerate layers. The latter are often repeated throughout the Wyandra, and occur as the basal lags of sediment packages. Thus sedimentation cycles can be resolved. Core-logging revealed that regionally the Wyandra Sandstone is comprised of a sequence of fining-upward sediment packages of decreasing energy that are thinning upward overall. Sediment packages are often capped with thin siltstones. Where fining upward trends are subtle or coarse basal layers are absent, patterns of sedimentary structures as they represent gradual waning flow energies were found to be reliable correlation tools. Individual packages, where interpreted to represent continuous deposition of a complete cycle, show a neat trend of sedimentary structures that grade from high-energy at the base (e.g. massive and planar-bedded sandstones often with floating clasts entrained) to low-energy at the top (e.g. rippled sandstones and thin laminated siltstones).

Based on the occurrence and depositional setting of the ejecta and the sedimentation style of the Wyandra, the Wyandra Sandstone appears to be intimately linked with the impact event. It is proposed that the Tookoonooka Impact was a paralic to shallow marine target impact and that the Wyandra represents an impact tsunami sequence. It is interpreted that each fining-upward package of the Wyandra represents a single tsunami wave cycle. Based on the incompleteness of many packages, it is inferred that significant erosion would have occurred prior to the deposition of many of the sediment packages. Thus multiple tsunami cycles are represented by the thickness of the Wyandra. It is inferred that the Wyandra Sandstone was deposited very rapidly in geological terms, likely within days. Time between waves (possibly hours) is implied by the siltstone layers that would have required periodic quiescence for suspension-settling. While it is believed that individual wave cycles are not correlatable across the breadth of the basin due to localized scouring, the overall sedimentation

style is consistent across most of the basin where data exists.

Conclusions: Detailed core-logging and correlation of the Wyandra Sandstone in 22 wells across the Eromanga Basin has been accomplished, and results correlated against multiple digital logs of the same section. Results show that, in concert with previous sedimentological and petrographic evidence, the Tookoonooka Impact was a paralic to shallow marine impact and the Wyandra Sandstone is an ejecta-bearing tsunami sequence originating from the impact.

This tsunami sequence is one of the few recognized impact tsunami sequences in the world. These findings have important implications for the consideration of impacts into extremely shallow marine epicontinental basins, the extent of the Tookoonooka Impact's effect on the paleo-basin, the recognition of tsunami sedimentation (and particularly *impact* tsunami sedimentation) in the ancient rock record, and the stratigraphic status of the Wyandra Sandstone Member.

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TOOKOONOOKA IMPACT SEDIMENTATION: EVIDENCE FOR RESURGE CYCLICITY WITHIN THE CRATER FILL. K. A. Bron¹,

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Introduction: The buried Tookoonooka 66-km diameter complex impact structure [1, 2] in central Australia has recently been interpreted as being the product of a marine impact event [3-5]. Thargomindah-3, a well drilled into the outer zone of the structure in 1987 to assess seismically-defined channel features, was originally interpreted to intersect a diamictite-filled 'canyon' [6, 7]. This work was done prior to a full knowledge of the impact origin of the structure. Recent studies have prompted the re-interpretation of the intersected 'canyon-fill' as a marine impact resurge sequence capped with debris flow deposits and finally the normal basin marine transgressive sequence.

Depositional processes that accompany marine impacts are not well understood, in part relating to the variability of known marine impact structures. Recent work on a handful [e.g. 8-10] has helped to better characterize the mechanisms and sedimentation styles related to these events.

Results: Detailed core logging of Thargomindah-3 has been done for the purpose of re-interpreting the 'diamictite' sequence intersected in the context of Tookoonooka's impact origin.

Almost 200 meters (thicker than originally defined) of stratified deposits overlie the autochthonous sedimentary basin rocks, and can be divided into three types. The lowermost unit is comprised of very poorly sorted polymict breccia within a sandstone matrix. The proportions of the larger clasts cannot be well-ascertained in core, though lithic clasts of up to several meters in height can be differentiated. Melt clasts are also present (clasts exhibiting flow structures or contact-metamorphosed rims). Overall, the matrix of this unit fines upward from coarse- to fine-grained. Cyclicity can be distinguished on the basis of varying matrix type: the matrix switches between primarily light-beige-grey coloured sandstone and chiefly fine-grained, dark grey sandstone. At least three cycles can be differentiated within this unit. Cycles thin upward.

A middle unit is made up of poorly-sorted, dark grey, matrix-supported sandstone interbedded with siltstone. The siltstone to sandstone ratio is about 1:3. The sandstone includes common pebble-sized, polymict, lithic clasts of varied shapes. The matrix is fine-grained.

An upper unit resembles the middle unit, but does not contain siltstone interbeds. Within this unit, the fraction of lithic clasts fines upward.

Both the upper and lower contacts of the whole deposit appear sharp. Various types of deformation such as soft-sediment deformation structures, fractures, and injectites are pervasive throughout the underlying in-situ rock types as well as within the sequence.

Discussion & Conclusions: It is interpreted that marine impact resurge sedimentation and post-impact debris flow deposits are preserved in this location. The three types of deposits observed are likely formed by different processes. The lowermost unit is interpreted to be a resurge deposit incorporating megabreccia-scale clasts. At least three cycles of resurge-runout sedimentation are suggested by the periodic shifts in matrix. The lighter-coloured matrix is thought to represent the resurge into the crater, whereas the dark-grey sandstone matrix is thought to signal the runout phase of deposition. The upward-thinning character of the unit corresponds to waning flow energies. This depositional phase would have occurred immediately post-impact.

The middle and upper units within the sequence suggest that at least two phases of slumping or slope failure likely occurred in this part of the crater. These units are interpreted as post-impact debris flow deposits. Palynological analyses [11] concur with this interpretation.

Rather than a 'canyon' as proposed in the original descriptions of this well, the stratified deposits presumably occupy a concentric slump scar caused by listric faulting of the peak ring. Likely resurge processes and peak ring slumping were contemporaneous. This re-interpretation of the stratigraphy at Thargomindah-3 furthers the understanding of Tookoonooka post-impact mechanisms and marine impact processes.

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Sedimentological aspects of the Tookoonooka impact event, Eromanga Basin, Queensland

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Abstract

The Tookoonooka impact structure is a large subsurface feature of the Eromanga Basin in Queensland. An impact ejecta horizon of regional extent has recently been discovered in drill core in the Lower Cretaceous strata of central Australia.

Drill core was examined from over 35 wells within and beyond the crater to establish the sedimentary context and character of the impact event. The base of the Wyandra Sandstone Member of the Cadna-owie Formation is an unconformity overlain by very poorly sorted, bimodal sediments with imbricated pebbles and occasional boulders. Exotic clasts include accretionary and melt impactoclasts, basement lithologies, and shock metamorphosed quartz and lithic grains. Accretionary impactoclasts resemble hydroclastic volcanic accretionary lapilli. Petrographic analyses confirm the existence of an impact signature in basal Wyandra breccia-conglomerate beds in the form of planar deformation features (PDFs), a diagnostic impact indicator. The Wyandra sediments differ markedly from laterally persistent, unimodal, fine-grained underlying (Cadna-owie Formation) and overlying (Walumbilla/Bulldog Formation) sediments deposited in a cold epeiric sea. Observations from these well locations indicate a minimum distribution of impact debris over 400,000 km² of the Eromanga Basin.

The base of the Wyandra Sandstone Member is interpreted to be the Tookoonooka impact horizon, thus the timing of the impact event is stratigraphically constrained to 125± 1 Ma. Tookoonooka was likely a shallow marine impact event. The Wyandra Sandstone Member preserves both impact ejecta and post-impact marine sediments. Further analyses are underway to determine the extent of the influence of the impact sedimentation and impact-induced structures on petroleum systems in the basin.

Marine impact sedimentation of the Tookoonooka-Talundilly event, Lower Cretaceous, Australia

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The Tookoonooka and Talundilly complex impact structures are buried within the Lower Cretaceous strata of Queensland, Australia. A marine impact horizon has recently been discovered spanning the extensive Eromanga Basin. This horizon is thought to originate from the likely dual impact event, and constrains the time of impact to approximately 125 Ma. Sediments overlying this horizon are believed to record the sedimentary processes immediately subsequent to impact.

Analyses of formation evaluation datasets and over 35 drill cores from within and beyond the crater structures provide a reasonable indication of the variety and distribution of impact-related sedimentation across the basin. Various types of sedimentation are recognized, including tsunami deposits, marine resurge and runout units, and post-impact debris flow deposits. Evidence of impact provenance of these sediments includes entrained accretionary and melt impactoclasts, shock metamorphosed grains, and exotic lithic clasts. The sediments host unusually large clast sizes compared to ambient (pre-impact) deposition. Trends in stratification throughout the study area can be resolved from flow regime indications, grain size, matrix style, grading, and other indicators.

Depositional processes that accompany marine impacts are not well understood, in part relating to the variability of known marine impact craters. This study on impact stratigraphy helps to better characterize the mechanisms and sedimentation styles related to marine impact events. The influence of impact sedimentation and impact-induced structures on petroleum systems in the basin is also discussed.

THE TOOKOONOOKA-TALUNDILLY TSUNAMI SEQUENCE: CONSTRAINING MARINE IMPACT STRATIGRAPHY. K. Bron, Australian School of Petroleum, The University of Adelaide, Adelaide, SA 5005, Australia (tbron@asp.adelaide.edu.au).

Introduction: The Tookoonooka and Talundilly Impact Structures, 66km and 84km diameter respectively, are among the largest impact structures on Earth. They are located in the subsurface of central Australia. A biostratigraphically-dated impact horizon in their host sedimentary basin constrained them as an ancient marine impact event of approximately Barremian-Aptian boundary age [1-3]. The impact horizon spans a vast area of the Australian continent and is overlain by complex strata representing a geologically brief timeframe within near-continuous basin sedimentation.

Marine Impact Cratering: Marine cratering processes are less understood and more variable than their subaerial counterparts within Earth's cratering record, with water cover and target material saturation adding to the complexity of impact-related deposition and crater formation [4-7]. The nominal water depth required to form a marine crater and control cratering processes and crater morphology have been modelled, as has impact tsunami propagation [e.g. 8-9]. A large crater radius to water depth ratio [10] applies to large craters formed in a shallow sea. In these scenarios, violent resurge and tsunamis are associated with crater rim collapse, strong sediment mixing and significant seabed erosion [4,8].

Tsunamiites in the Geological Record: Tsunami deposits in the ancient rock record are rare. Tsunami or resurge sedimentation known to originate from ancient marine impact events is even less common [4,11,12]. However, tsunami deposits have been associated with a subset of marine impacts, with Chicxulub's being well-documented and recognized in a variety of depositional environments [e.g. 13,14].

Methodology: Interpretation of Tookoonooka's and Talundilly's post-impact sedimentation was accomplished with the analyses of 51 drill cores, 12 geological outcrops and 158 additional subsurface petroleum exploration well datasets. Data represent >805,000 km² of the depositional basin and 931m of logged section. Analyses of core and outcrop were supplemented with formation evaluation data to aid in stratigraphic interpretation, isopach mapping and evaluating the distribution of the impact-related sedimentation.

Tookoonooka-Talundilly Tsunamiite Sedimentology: Detailed logging confirmed that the ambient low-energy basin sedimentation was interrupted by an unusual geological event of short duration. The impact horizon is a widespread scour surface overlain by a sedimentary sequence

with entrained impactoclasts, breccia-conglomerates, rip-up clasts of unusual size, large-scale couplets, highly polymictic clasts in high flow regime bedforms, as well as widely varying bed thicknesses correlative to crater proximity. Trends in stratification throughout the study area can be resolved from flow regime indications, grain size, matrix style, grading and bioturbation. Individually, the bedforms and facies observed reflect normal marine sedimentary processes, but collectively, the high velocity bedforms, coarse sedimentary fabrics, cyclicity and stacking reflect an unusual event of extraordinary magnitude. This sedimentary sequence, beyond the crater rims, is interpreted to be a Tookoonooka-Talundilly tsunami sequence.

Depositional Realms Interpretation and Mapping: Distribution patterns of the sediments were assessed by correlation and mapping. Geological logs from core and field observations were correlated to show the lateral character of the tsunami sequence. The tsunami deposits were classified based on depositional character, cyclicity, stacking pattern, interpreted processes of deposition and paleoenvironments. Five depositional realms with respect to crater proximity have been identified.

Isopach maps were constructed, utilizing extensive subsurface drilling data calibrated from lithological log observations. A sheet-like tsunami deposit is interpreted to span the paleo-basin. The widespread scour surface at the base of the impact sequence is attributed to impact-related excavation and tsunami scour mechanisms proximal to the crater structures. Removal of at least 30% of pre-impact strata beyond the crater rims is indicated. The tsunamiite exhibits complex stratigraphic architecture that is interpreted to vary with crater proximity, paleoenvironment, and paleo-water depth.

Conclusions: Detailed core-logging, correlation and mapping, over an area of >805,000 km², of an interpreted impact tsunamiite has been accomplished. Impact tsunami deposits are well-preserved due to burial, excepting erosion by successive tsunami waves and distal basin margin exposure. This study improves the current understanding of the depositional processes and impact sediment distribution following marine impacts. Tookoonooka-Talundilly provides an important model for marine impact sedimentation in shallow marine settings.

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