Journal of Archaeological Science: Reports 26 (2019) 101840

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Synchrotron X-ray tomographic imaging of embedded fossil invertebrates in Aboriginal stone artefacts from Western Australia: Implications for sourcing, distribution and chronostratigraphy

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ARTICLE INFO

Keywords:
Eocene chert
Bryozoans
Stone artefacts
3D visualization
Provenancing

ABSTRACT

Eocene fossiliferous chert is a distinctive rock used in the manufacture of stone artefacts commonly found in archaeological sites in southwestern Western Australia (WA). In this study, we employ non-destructive high-resolution X-ray computer tomographic (CT) imaging at the Australian Synchrotron to map and identify embedded bryozoan (and other) fossils within archival artefact samples and potential source material from offshore drill cores in the Perth Basin and from the Nullarbor Plain to the east. Analysis of synchrotron data confirmed the presence of *Cellaria*, *Porina*, *Quadricellaria*, *Reteporella*, *Siphonicytara*, *Trigonopora*, and *Idmonea* species in chert samples from as far afield as Exmouth Gulf in the north west of WA, Esperance in the south and inland as far as the Goldfields region of WA. This widespread distribution of fossiliferous chert over 1800 km is significantly greater than previously documented and the bryozoan fingerprinting of geological source and artefact material indicates that a potential source within the Eucla Basin located in the SW corner of WA cannot be discounted. In addition, the association of one chert artefact on Doole Island (Exmouth Gulf) with shell midden material dated between 2500 and 770 yr BP also questions the use of fossiliferous chert as a late-Pleistocene-early Holocene chronological marker. The advantages and limitations of synchrotron CT imaging for characterising and sourcing fossiliferous chert are also discussed, with further research warranted on the distribution and probable long-distance trade of this idiosyncratic material.

1. Introduction

1.1. The hypothesis for an inland provenance of Eocene fossiliferous chert

For the past four decades an offshore provenance has been purported for Eocene cryptocrystalline fossiliferous chert material that abounds in Aboriginal artefact assemblages along the western margin of southwestern Australia (Fig. 1). The fossil bryozoans and foraminifera indicated an Eocene age for the chert artefacts and initially an onshore source was postulated (Glover and Cockbain, 1971). Subsequent drilling off the west coast of Australia led Glover (1975a, 1975b) to propose an alternative "offshore hypothesis", which became widely accepted. The "offshore hypothesis" postulated that the lithic source of the fossiliferous artefacts found was submerged and cut off by sea level rise during the early to middle Holocene (Glover, 1975a). Consequently, the presence or absence of Eocene fossiliferous chert in archaeological assemblages in SW Western Australia has been used extensively by researchers and archaeological consultants as a chronological marker to divide sites of Late Pleistocene to Early-Holocene age from those of mid- or Late Holocene age (Hallam, 1987). It has also provided a template for ethnographic investigations of Aboriginal culture in SW Western Australia, i.e. limited trade or movement between Aboriginal groups across southern Australia.

More recent studies of diagnostic fossil bryozoan assemblages within chert artefacts from SW Western Australia found no taxonomic similarities with fossiliferous chert recovered from offshore petroleum wells, noting also that chert units occurred too deep to have ever been accessible to past occupants even at lowest last glacial sea-levels (for

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https://doi.org/10.1016/j.jasrep.2019.05.005
Received 20 November 2018; Received in revised form 20 April 2019; Accepted 2 May 2019

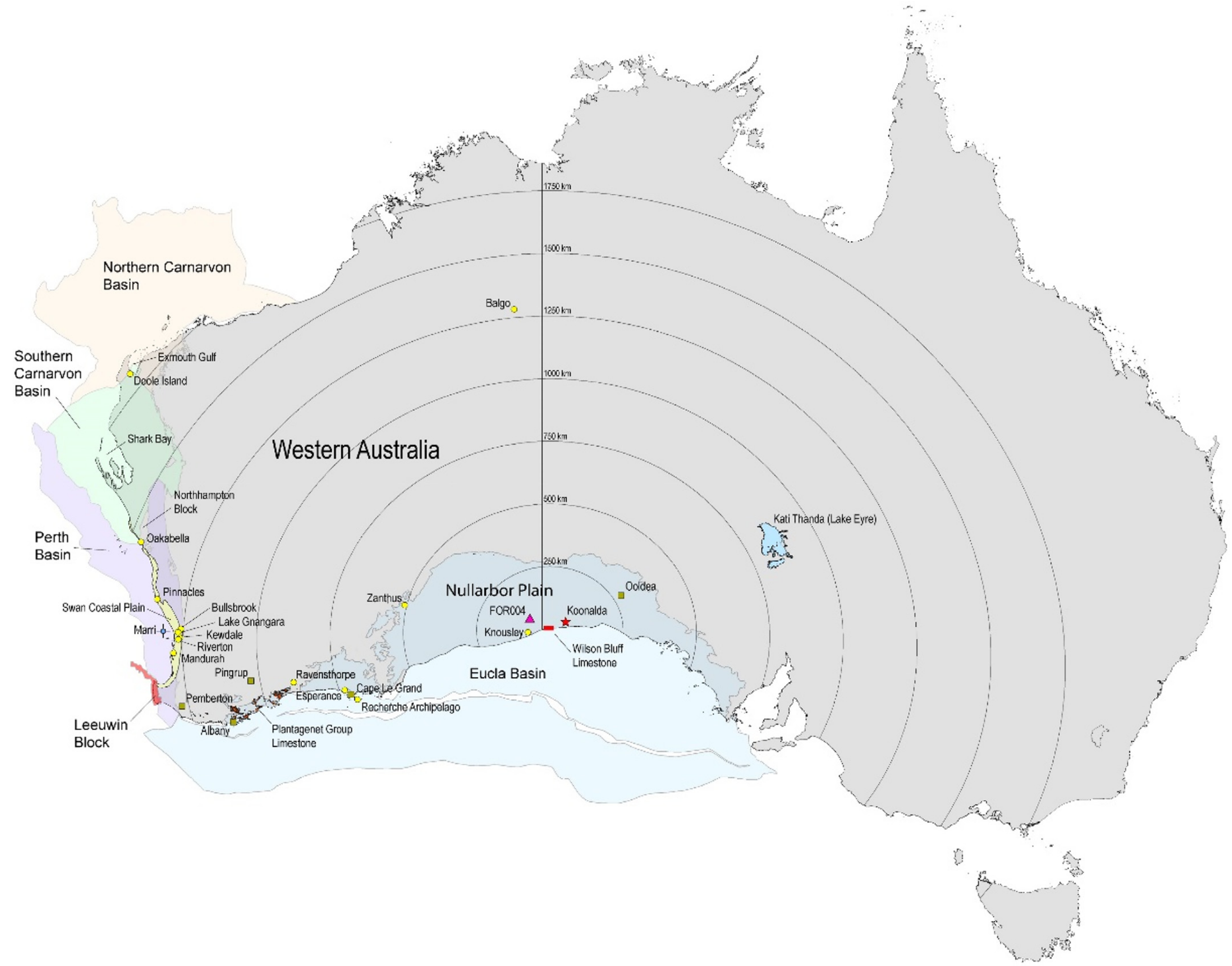

Fig. 1. Location map showing widespread distribution of fossiliferous chert artefacts from the Perth Basin and further afield, including Doole Island, Stanley Island, Ravensthorpe and Balgo. Specific sites and regions mentioned in the text are also included.

full discussion see O'Leary et al., 2017). However, there was an overlap in fossil bryozoan assemblages with chert from Wilson Bluff Limestone located between 900 and 1400 km east of Perth in the Eucla Basin (O'Leary et al., 2017; Key Jr. et al., 2019) (Fig. 1). Although artefacts made from Wilson Bluff Limestone have been found up to 700 km to the east (Nicholson and Cane, 1991) and possibly 900 km north east to Lake Eyre/Coopers Creek (Nicholson, 1994), the possibility of ancient trade routes to the west has largely been dismissed due to the large distances involved – over 1200 km (Glover, 1975a; Dortch and Dortch 2019). Other studies have shown evidence for trade of ochre over distances of > 700 km and of grindstone over distances > 1000 km (McBryde, 1997), hence such distances for trade of other rock types should not be considered extreme. Our initial results indicate that an inland provenance and long-distance trade of fossiliferous chert warrants further investigation. However, this is complicated by the need to identify individual fossil bryozoans within the chert material.

Archaeologists, museum curators and Traditional Owners are generally reluctant to undertake destructive analysis on cultural material, particularly on artefacts with clear evidence of working (e.g. Fig. 2). Thus, the use of X-ray imaging provides a non-destructive means to identify bryozoan fossils embedded within chert artefacts. Bryozoan fossil assemblages within artefactual samples from Western Australia are compared with samples of fossiliferous chert collected from geological deposits both in offshore petroleum wells and inland outcrops as a means to further test the hypothesis of long-distance trade.

1.2. Description and petrology of the Eocene fossiliferous chert artefacts

Fossiliferous chert artefacts include adzes, scrapers, backed pieces, bipolar cores, flaked and unflaked material and most derive from the floor of dune blow-outs, commercial sandpits and other sand formations (Glover, 1975a; Martin, 1982). The chert itself forms large 10 to 30 cm wide nodules within Eocene limestone or calcareous mudstone formations. In thin section, the nodules are shown to contain partly to completely silicified bryozoan fragments, globigerinid foraminifera, sponge spicule fragments, small bivalves and echinoderm fragments (Martin, 1982). Other fossiliferous chert outcrops include the Middle to Upper Eocene Plantagenet Group, which occurs along the south coast from Albany to east of Esperance (Fig. 1). Whilst this has a diverse bryozoan fauna, it is comprised of sponge spicule-dominated opaline and chalcedonic spiculite and has not been definitively linked to Aboriginal artefacts (Dortch and Glover, 1983), which tend to be diatom dominated. These fossiliferous chert types (corresponding to Group 1A of Martin, 1982) differ from 'palaeontologically barren' chert (corresponding to Group 1B of Martin, 1982) that include novaculite, opaline and chalcedonic chert, mottled ferruginous chert and veined epidote-

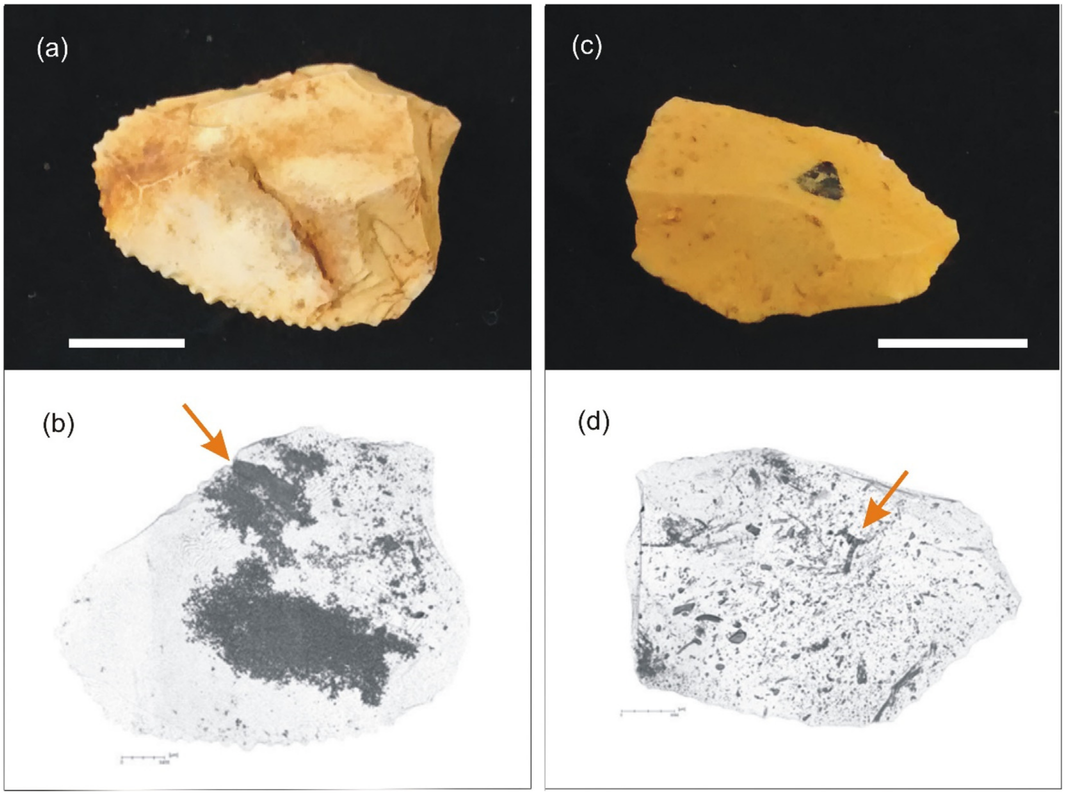

Fig. 2. Example of fossiliferous chert artefacts from the Swan Coastal Plain showing tooth-edge working on the margins, including (a) Bullsbrook South (UWA-74560), (b) associated 'inverted' image showing the dense abundant sponge spicules, and an unidentified bryozoan colony (arrow) visible middle-top, (c) Oakabella (UWA-74462A), and (d) associated 'inverted' image showing a branching *Siphonicytara* bryozoan colony (arrow) and other unknown inclusions. Scale bar is 1 cm.

bearing chert. Indeed Martin (1982) suggests there may be up to five types of chert in SW Western Australia, differentiated by presence/absence, type and abundance of embedded fossil species.

Earlier thin section analysis of fossiliferous chert artefacts from SW Western Australia indicated that ramose cheilostome bryozoans are the most common types of embedded fossils (Cockbain, 1970; Martin, 1982). Unfortunately, these thin sections have been mislaid and hence further petrographic and other analyses are not possible. More recent thin sectioning of three samples of Aboriginal artefacts from SW Western Australia identified three main species: *Adeonellopsis* sp., *Cellaria rigida* and *Idmonea geminata* (Key Jr. et al., 2019). The present study applies non-destructive analysis of these and other archival materials, focusing mainly on the presence or absence of bryozoans, and where possible their identification, within artefacts from across Western Australia.

1.3. Use of synchrotron X-ray tomography for non-destructive analysis of bryozoan taxonomy

As indicated by Key Jr. et al. (2010, 2014, 2014, 2016a), fossils in general and bryozoans in particular are effective tools for discriminating lithic sources and dimension (cut) stones. However, one of the challenges of using fossil bryozoans to source artefacts is the need to image the internal morphology of the colonies to identify the exact species and to characterise growth forms and morphologies which can provide information on the local environment. This is typically done through destructive analysis in two dimensions from thin section or SEM images of the fossil bryozoan (Wyse Jackson and Buttler, 2015). Other methods of analysis include serial sectioning (e.g. Snyder, 1991; Key Jr. et al., 2011) and computer stitching of digitized 2D slices (Sutton et al., 2001), but both are labour intensive and also destructive. X-ray imaging is effective for non-fossilized bryozoans (Key Jr. et al., 2019) but, as the technique relies on X-ray absorption, it can be difficult to generate sufficient contrast between the target fossil material and the surrounding rock matrix when both share similar X-ray attenuation coefficients (Wyse Jackson and Buttler, 2015). X-ray micro-computer tomographic (micro-CT) imaging has been applied on fossil bryozoans with increasing success (Taylor et al., 2008; Viskova and Pakhnevich, 2010; Buttler et al., 2012; Wyse Jackson and McKinney, 2013; Koromyslova and Pakhnevich, 2014, 2016; Koromyslova et al., 2014a, 2014b; Matsuyama et al., 2015; Schwaha et al., 2018).

Synchrotron X-ray imaging analysis has also been successfully used on non-fossilized bryozoans (David et al., 2009), with studies by Schmidt (2013) indicating synchrotron technologies are best suited to imaging the internal structures of fossilized bryozoans - particularly those that have mineral-filled zooecial cavities, as it can better resolve differences in composition. Indeed this methodology has the potential to add an entirely new suite of 3D morphological characteristics to bryozoan taxonomy. Whilst the use of synchrotron radiation techniques to study cultural heritage and archaeological materials has increased in the last decade, its application to stone artefacts remains limited (Bertrand et al., 2012). Hence this study provides a useful application of synchrotron analysis both to microfossil analysis and artefact provenancing.

2. Methods

2.1. Sampling and analysis procedures

Fossiliferous chert samples were obtained from archive material collected by John Glover (University of Western Australia, UWA) from within or on the margins of the Perth Basin and on the Leeuwin Block in Western Australia (Fig. 1). Samples that have bryozoans visible at or near the surface (e.g. Fig. 3) were deliberately targeted to increase our chances of getting embedded fossils.

Initial studies by O'Leary et al. (2017) and Key Jr. et al. (2019)

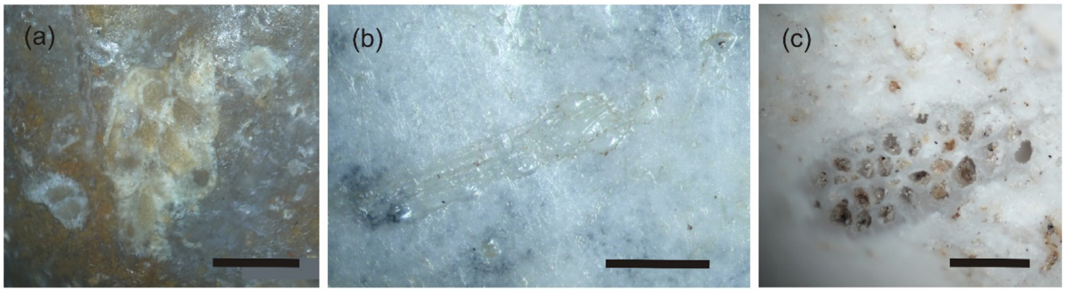

Fig. 3. Examples of bryozoan colonies expressed at surface of chert artefacts, including (a) *Trigonopora* (WAM- B5610, Ravensthorpe), (b) *Idmonea* (WAM-A12769, Balgo) and (c) *Cellaria*, (UWA-74807, Lake Gnangara). Scale bar is 1 cm.

included thirty (30) samples from this collection (although not all had bryozoans), plus an additional three Nullarbor Plain artefacts, and two Wilson Bluff (Eucla Basin) chert nodules, yielding 184 petrographic images of fossil bryozoans. Eleven (11) samples that were used in these initial studies were selected for synchrotron analyses, including eight Swan Coastal Plain (prefix UWA) artefacts, two nodules from the Wilson Bluff Limestone (FOR 004, Knousley South), and carbonate cuttings from offshore drill cores of the Eocene Challenger Formation in the Perth Basin (Mari 1). A further eight samples from the Western Australia Museum (prefix WAM) included three from an island in the Exmouth Gulf region (Doole A, B, #6), one from Stanley Island (Recherche Archipelago) off Cape Arid on the southwest coast, one from Ravensthorpe (B5610) and three potential fossiliferous chert samples from inland sites (A12679 Balgo, A17264 Zanthus A and A17277 Zanthus B) (Fig. 1). The size of the chert artefact samples typically range from ~ 10–50 mm.

2.2. Image processing and analysis

The experiment was conducted in enclosure 3B of the Imaging and Medical Beam Line of the Australian Synchrotron to achieve a viewing area of up to 40 × 30 mm. The detector was a photo-sensitive device coupled by a bright lens to a suitable X-ray sensitive scintillator. Adjustable lens focus and distance between the scintillator and objective allowed variable pixel size, which was tuned to 9.7 µm. A typical bryozoan zooid (i.e. the modular individual animal that makes up a colony which is housed in its skeletal zooecium) is on the scale of 1 mm, and the colonies from the Eocene chert are on the scale of 10–20 mm (Fig. 3). Thus a 9.7 µm voxel will give 50 slices through a typical-sized zooid. In this experiment, each X-ray imaging scan consisted of 1800 projections acquired at a 0.1° step. A standard filtered back-projection algorithm coupled with ring artefact removal was used to reconstruct the X-ray projection images into a stack of 2D slices, creating an isotropic voxel (3D pixels). size of 9.7 µm. Each voxel has a specific grey value (16 bit) representing the linear X-ray attenuation coefficient of the composite material, which is dependent on density and chemical composition. The first steps of image processing, such as flat-field correction, noise suppression, stitching and CT reconstruction were performed using ASCI high performance cluster at the Australian Synchrotron. The subsequent 3D volumes could then be rendered for visualization and undergo subsequent post-processing and analysis. For further details on micro-CT scanning see Ngan-Tillard and Huisman (2017).

The synchrotron images were numerous and data rich. The number of synchrotron image files for each artefact ranged from 340 to 6050 (mean = 3238, standard deviation = 1494). The size of each image file ranged from 0.64 to 20.3 MB (mean = 5.93 MB, standard deviation = 5.41 MB). For the 20 artefacts imaged the total data set was > 800 GB. Hence, the first step involved reducing the data set size by cropping to specific regions of interest (ROIs) using Fiji (ImageJ) software (Schindelin et al., 2012). The ROIs were then analysed using Avizo 9.2.0 (ThermoFisher Scientific) and Drishti 2.6.2 (Limaye, 2012) to assess presence or absence of individual bryozoans. The xyz-position of individual bryozoans were recorded, except where they were too numerous. Examples of different bryozoans were selected from different artefacts to render in 3D, again using Avizo software.

Standard qualitative bryozoan taxonomic characters were analysed from the reconstructed images to narrow down the genus of bryozoan by comparing to those described from the possible source rocks in that part of the world (e.g. MacGillivray, 1895; Brown, 1952, 1958; Cockbain, 1970; Schmidt, 2003; Gordon and Taylor, 2015; Key Jr. et al., 2018). Unfortunately, species level identifications are impossible without detailed taxonomic knowledge of the bryozoan faunas of the Carnarvon, Perth, Bremer, and Eucla Basins, which have not been described. Qualitative characters used in cheilostome bryozoan taxonomy predominantly come from the zooecial surface and include the orifice, frontal shield, and polymorphs (e.g. avicularia and ovicells, Ryland, 2005). Hence virtual sections in three directions were used to characterise internal features and included longitudinal, tangential, and transverse orientations.

3. Results

3.1. Presence and absence of fossil bryozoans within chert samples

Of the 19 samples analysed, 15 were confirmed, either by synchrotron analysis or microscopic examination of the artefact surface (e.g. Fig. 3a–c), to contain bryozoan fossils (Table 1). Of these 15, six samples – namely UWA74619 Kewdale, UWA74781 Mandurah, UWA74807 Lake Gnangara, UWA74827 Riverton, FOR004 and Knousley South – had previously been confirmed from thin-sections to contain bryozoan fossils (O'Leary et al., 2017; Key Jr. et al., 2019). Five of the remaining eight – UWA-4462A Oakabella, UWA-74560 Bullsbrook South, UWA-74610 Pinnacles, UWA-74685 Esperance 3 and UWA-74827 Riverton – had not been thin sectioned but are part of an archival collection (Glover collection) of fossiliferous chert artefacts from the Swan Coastal Plain.

A further five WAM samples A12679-Balgo, B5610-Ravensthorpe, Doole A, Doole 6 and B5628-Recherche, the latter three deriving from offshore islands of Western Australia, were also analysed. No fossils were identified in inland samples A17264-Zanthus (A) or A17277-Zanthus (B), or from the Doole Island (Doole B) sample. The final positive sample, Mari, was from carbonate rock cuttings from offshore petroleum wells in the Perth Basin. Previous thin section analysis did not find bryozoans in this sample (O'Leary et al., 2017) hence synchrotron analysis was helpful in confirming this as biogenic chert, albeit not related to the Swan Coastal Plain (Perth Basin) artefacts because of the inaccessible depths at which it occurs offshore.

In addition to the bryozoans, several samples were also found to contain sponge spicules in various relative abundances (Table 1). These samples included Bullsbrook (UWA-74560), Pinnacles (UWA-74610), Mandurah (UWA-74781), Knousley South (UWA, Fig. 2b) and FOR004.

Table 1
List of samples analysed on Synchrotron, with those containing fossil bryozoans identified. Due to the low resolution, it is only possible to identify these samples to the genus and not the species level. UWA = University of Western Australia, WAM = Western Australia Museum.

Sample No.	Bryzoans present	Sponge spicules present	Genus level identification
UWA-74462A Oakabella	yes	no	*Siphonicytara*
UWA-74560 Bullsbrook South	yes	yes	*Porina?*
UWA-74610 Pinnacles	yes	yes	*Quadricellaria*
UWA-74619 Kewdale	yes	no	No fossils were identified
UWA-74685 Esperance 3	yes	no	*Cellaria, Porina*
UWA-74781 Mandurah	yes	yes	*Porina*
UWA-74807 Lake Gnangara	yes	no	*Idmonea, Cellaria, Porina*
UWA-74827 Riverton	yes	no	*Trigonopora*
WAM - A12679 - Balgo	yes	no	*Idmonea* (as identified from the artefact surface photos)
WAM - 17264 - Zanthus A	no	no	No fossils were identified
WAM - 17277 - Zanthus B	no	no	No fossils were identified
WAM - B5628 - Recherche	yes	no	*Porina*
WAM - B5610 - Ravensthorpe	yes	no	*Trigonopora* (as identified from the artefact surface photos)
WAM - Doole A	yes	no	*Trigonopora*
WAM - Doole B	no	no	No fossils were identified
WAM - Doole 6	yes	no	*Porina?*
FOR004 (180 m)	yes	yes	*Trigonopora, Reteporella, Siphonicytara*
Knousley South	yes	yes	*Quadricellaria, Cellaria*
Mari 1	yes	no	*Porina*

Shaded area denotes source rock. All other samples are artefactual.

As found by Martin (1982:17) sponge spicule fragments are commonly whole or broken pieces of elongate single-rayed (monaxon) or, less commonly, triactine (3-sided) spicules ranging in length between 0.06 mm and 0.125 mm. These and other embedded microfossil and shell material may or may not be useful to further differentiate fossiliferous chert types in the future.

3.2. Identification and 3D imaging of fossil bryozoans within chert samples

X-ray absorption is the main mechanism for generating contrast in X-ray CT imaging. As such, the ability to differentiate between features depends on variations in mineral composition and/or porosity, which have a bearing on X-ray attenuation through the sample. Typically, in carbonate sedimentary rocks there is enough mineral variation between the fossils, secondary cements and the supporting sedimentary matrix that sufficient contrast is achieved in X-ray CT imagery. However, in the case of fossiliferous cherts the carbonate fossils can be diagenetically altered or replaced with silica, resulting in little variation in X-ray attenuation (and hence contrast) between the fossil and supporting sedimentary matrix. In these cases, the fossil can be difficult to distinguish from the siliceous matrix even though they may be visible in petrographic thin sections based on colour contrast.

The most distinct and hence identifiable bryozoa occur in sample FOR 004. In this example, one erect branching colony is visible with one of its zooecia in the right-hand branch (just above the bifurcation) shows a secondary(?) orifice and latero-oral avicularium or ascopore that suggests it is the siphonicytarid *Siphonicytara* (Fig. 4, Supplementary Video S1). In another colony it is possible to see the anastomosing branches of a net-like erect rigid fenestrate (reteporiform) colony of *Reteporella* (Fig. 5, Supplementary Video S2). Unfortunately, there is still insufficient fidelity in surface morphology from either of these bryozoans for species level identification. In another part of the sample, it is also possible to 'extract' a colony of a *Trigonopora*, an umbonuloid ascophoran cheilostome bryozoan (Fig. 6, Supplementary Video S3). The individual zooecial cavities that housed the polypides stand out against the un-imaged thick layer of calcified skeleton. It is this missing skeleton that contains the morphology required for more precise taxonomic identification.

Similarly, in the Pinnacles 1 artefact (Fig. 7, Supplementary Video S4), the arrangement of zooecia and the morphology of the zooecial cavities of the bryozoan *Quadricellaria* can be observed. This is made possible by the different composition of the silicified skeletal walls compared to the cements infilling the zooecial cavity. In this particular example, most of the frontal walls of the zooecia have been covered by secondary calcification (coloured green in Fig. 7c). This allows us to infer that the imaged fragment is from a more proximal part of a colony. In some cheilostomes, secondary calcification occurs in the older proximal parts of colonies (Sandberg, 1983). However, silicification can make colonies difficult to differentiate using X-ray CT imaging. For example, in the Ravensthorpe (WAM−B5610, Fig. 3a) and Balgo (WAM-A12679, Fig. 8) samples, the silicified bryozoa could be clearly identified under the microscope but less so in the synchrotron data. The

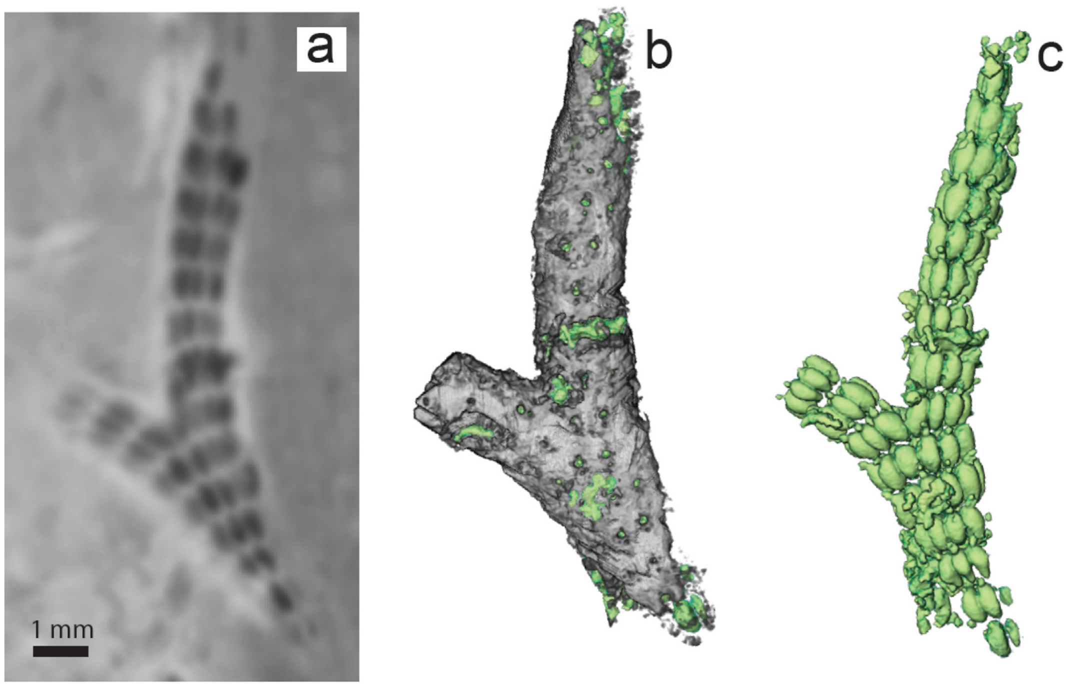

Fig. 4. The bryozoan *Siphonicytara* in FOR 004 sample, showing (a) two-dimensional cross-section, (b) 3D rendering of colony surface, and (c) 3D rendering of zooecial cavities.

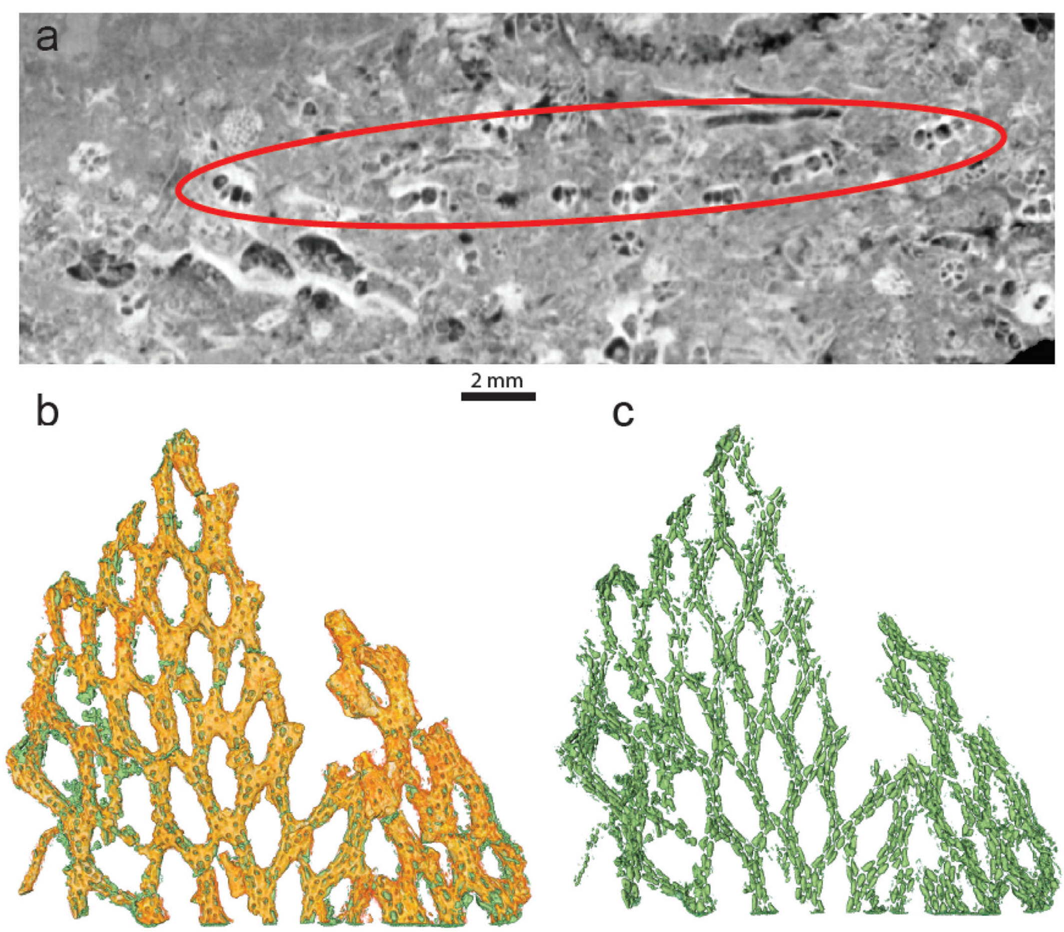

Fig. 5. The bryozoan *Reteporella* in FOR 004 sample, showing (a) two-dimensional cross-section, (b) 3D rendering of colony surface, and (c) 3D rendering of zooecial cavities.

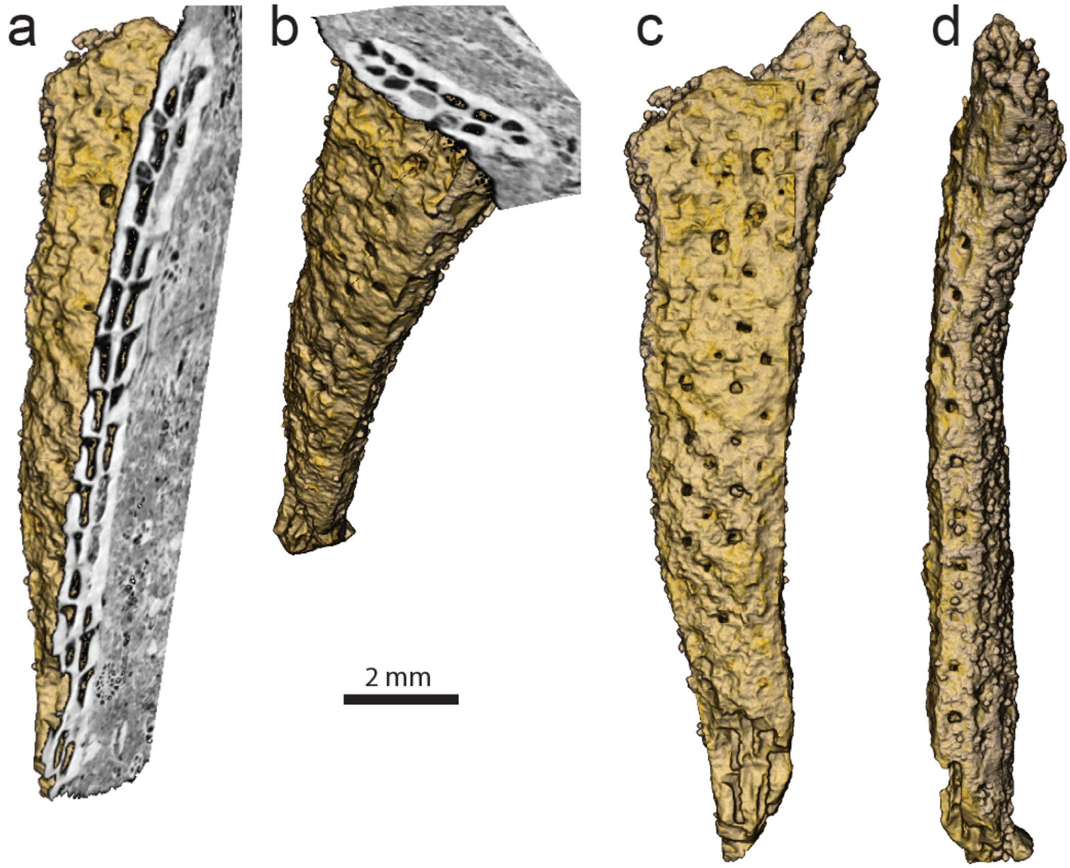

Fig. 6. The bryozoan *Trigonopora* from the FOR 004 artefact, showing (a) two-dimensional longitudinal cross-section and partial 3D rendering, (b) two-dimensional transverse cross-section and partial 3D rendering, (c) 3D rendering of frontal colony surface, and (d) 3D rendering of side colony surface.

latter is the cyclostome bryozoan *Idmonea* that has previously been identified in chert from the Nullarbor (O'Leary et al., 2017).

One other bryozoan genus to be identified was *Porina* in the Mandurah sample (UWA-74781, Fig. 9, Supplementary Video S5), Esperance 3 (UWA-74685), Lake Gnangara (UWA-74807), possibly Bullsbrook South (UWA-74560), Recherche (WAM−B5628), Doole Island (WAM-Doole 6) and also in one fragment from the Mari 1 sample (Table 1). Previous thin sections had confirmed that no bryozoans were present in the Mari 1 drillcore chert, and demonstrates the advantage of X-ray CT imaging in being able to provide a more comprehensive digital exploration of any particular sample.

3.3. Chronological results from Doole Island

Radiocarbon dating of 11 shell samples from sites across Doole Island returned ages of between 770 and 2500 yr BP, indicating that the island was utilised well into the late Holocene. The chert artefact WAM Doole 6 was found in association with a small but dense concentration of cockle shells (*Tegillarca granosa*) with dates of 1068 ± 18 yr BP (WK-47018) and 1330 ± 30 yr BP (WK-47017).

4. Discussion

4.1. Advantages and limitations of X-ray computer tomographic imaging of embedded microfossils

Imaging zooecial surface morphology is required for species level identification in some bryozoans, especially the cheilostomes (Ryland, 2005), and is essentially impossible with 2D thin sections made of fossil bryozoans in limestone or chert artefacts. Fortunately, the use of synchrotron X-ray imaging provides access to the zooecial surface morphology, for example in the *Siphonicytara* within the FOR004 sample, and the bryozoan *Quadricellaria* in the Pinnacles 1 artefact. This detail would be almost impossible to see in a 2D thin section. Unfortunately, there is still insufficient surface morphology accessible from these cemented and silicified bryozoans for species level identification (*c.f.* uncemented *S. occidentalis* colony by Schmidt (2013, his fig. 21.1-21.5)).

As demonstrated by the colony of *Reteporella* in the FOR004 sample (Fig. 5), the hard matrix does allow for the preservation of the original morphology of erect fenestrate fossil colonies, that otherwise might be compacted and fragmented following burial, to be preserved (see also Key Jr. et al., 2016b; Suárez Andrés and Wyse Jackson, 2015, their Fig. 3b). The counter side to this is that silicification can make colonies difficult to differentiate using X-ray CT imaging (e.g. WAM−B5610, and WAM-A12679). In an examination of some SW Western Australian fossiliferous chert artefacts, Glover (1975b: 82) also identified partly to completely silicified bryozoans, foraminifera, sponge remains, small bivalves and echinoderm fragments in an essentially cryptocrystalline matrix. In addition, many fossils were partly replaced by very finely divided opal or have a drusy opaline fringe that is chemically indistinct and makes them opaque under magnifications below ×100. Hence, the use of X-ray analysis alone may not be sufficient to identify fossils embedded within cherts.

Another key advantage of X-ray CT imaging is the ability to explore and visualise the digital volume in any direction or orientation, which greatly increases the sampling volume compared to, for example, petrographic thin sections. As an illustration of this, the initial thin section analysis of the offshore drill samples (Mari 1) from the Perth Basin were not able to confirm the presence of bryozoan fossils (O'Leary et al., 2017), whilst X-ray CT analysis confirmed the presence of at least one *Porina* colony in one small sample from this drill core. Despite this, the

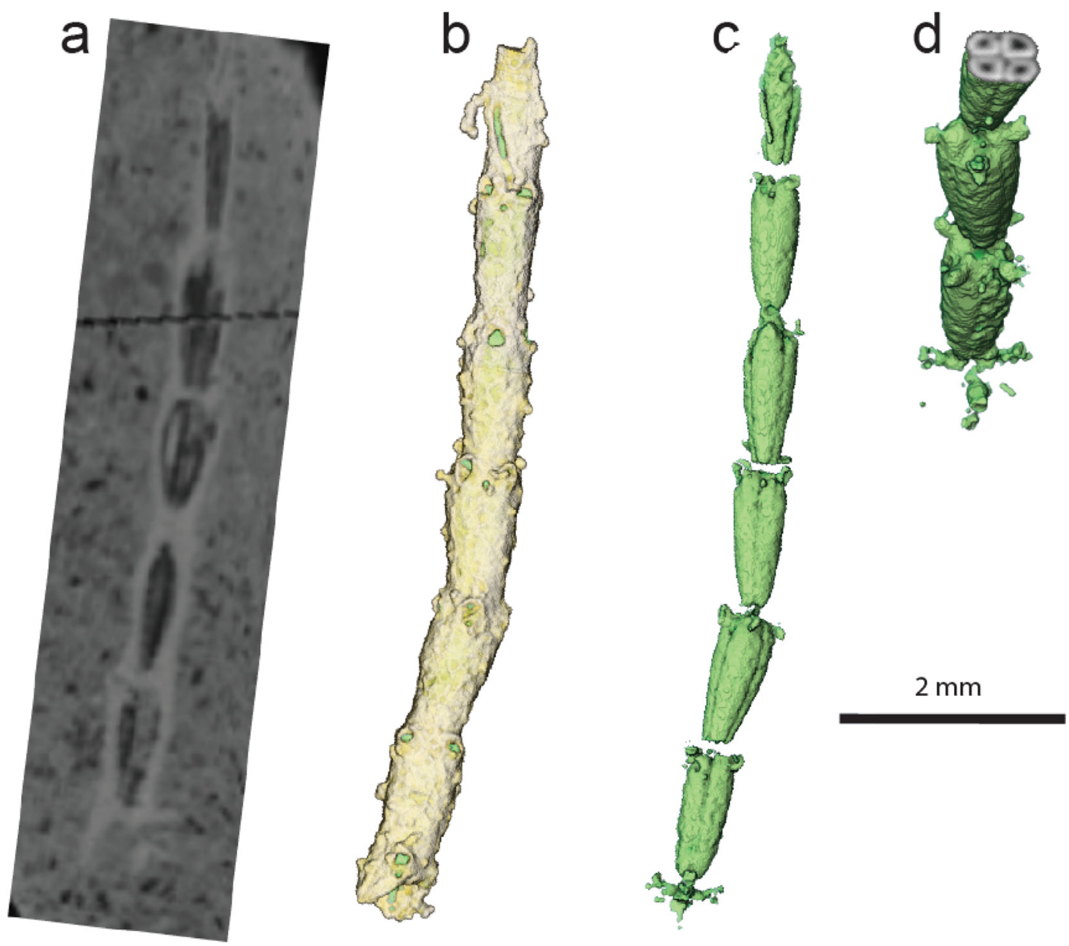

Fig. 7. The bryozoan *Quadricellaria* from the Pinnacles artefact, showing (a) two-dimensional longitudinal cross-section, (b) 3D rendering of colony surface, (c) 3D rendering of zooecial cavities, and (d) two-dimensional transverse cross-section and partial 3D rendering of zooecial cavities.

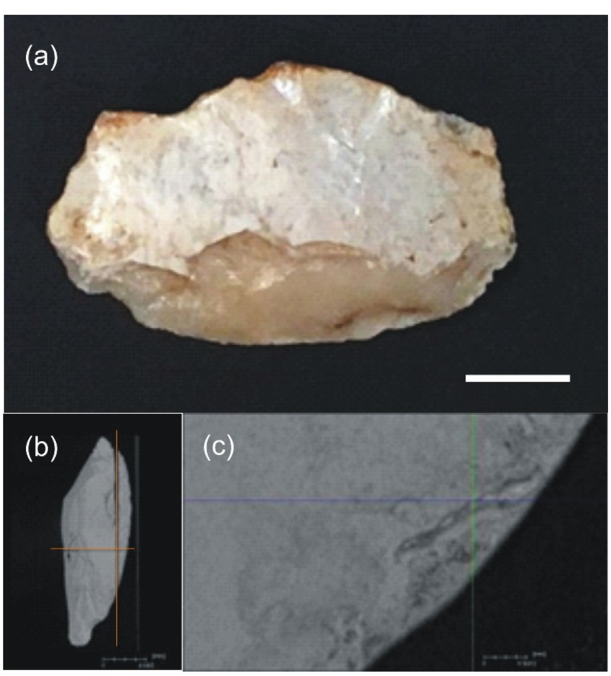

Fig. 8. Balgo sample (WAM-A12679) showing (a) photo of chalcedonic chert artefact, (b) position of cross section shown in (c) with silicified *Idmonea bryozoan* colony exposed on artefact surface.

fact remains that this offshore Eocene fossiliferous chert source is sparse and occurs at ocean depths far too deep to be a potential source for the Swan Coastal Plain artefacts (O'Leary et al., 2017).

The disadvantages of using a synchrotron X-ray source for imaging relative to thin sections include expense (although access grants are available), geographical restrictions (< 50 synchrotrons available globally, and not all with beamlines suitable for imaging relatively large and dense objects) and the generation of very large image datasets (> 150 GB per sample). The post-processing of 3D tomographic data is also time consuming. In addition, the spatial resolution is typically less than thin sections (Fig. 10). Higher resolution sub-micron X-ray CT scanning facilities exist as both synchrotron and laboratory based X-ray sources and could provide greater spatial resolution, thereby providing more detailed taxonomic identification of embedded bryozoan fossils (Huisman et al., 2014). However, most laboratory X-ray sources have limited flux, making the imaging and analysis of large/dense samples impractical, but could be useful for imaging artefacts smaller than those described here. A sub-micrometer scale X-ray CT beamline is now under construction at the Australian Synchrotron and is planned to be available from 2022.

4.2. Implications of results on known distribution of fossiliferous chert artefacts

As indicated by Glover (1975a), fossiliferous cryptocrystalline chert artefacts are found throughout the Swan Coastal Plain, and on the Northampton Block to the north and the Leeuwin Block to the south-west, a north south distance of 700 km. With the identification of

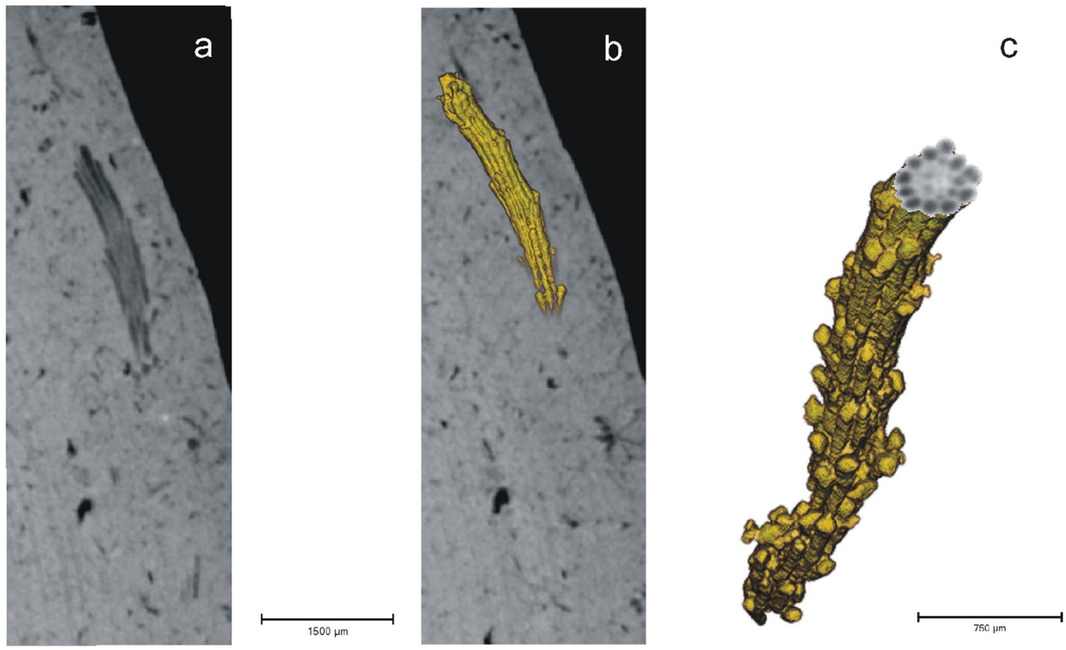

Fig. 9. Mandurah sample (UWA-74781) showing (a) photo of chert artefact, (b) 'inverted' image showing 3D rendering of *Porina* (highlighted in blue), (c) XY(?) cross-section through *Porina*, and (d) XZ(?) cross-section through *Porina*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

bryozoan fossils within chert from Doole Island and also Recherche Archipelago, our findings extend this distance to 1200 km to the north and 770 km to the SE of Perth, respectively – a north south distance of 1860 km. This distance is considerably further than the 1200 km from the Eneabba-Mandurah belt to Koonalda Cave, highlighted by Glover (1975a, 1975b) as being too distant to be a source of artefacts in SW Western Australia. Of further interest is a note added to Glover's (1975b) paper that bryozoan chert artefacts, including one large core (7 × 9 × 5 cm) was found 20 km south of Shark Bay, 800 km north of Perth. Martin (1982) also mapped fossiliferous chert (Type 1A) adzes, scrapers, backed pieces and bipolar cores at Pemberton; adzes at Ravensthorpe; and smallish flakes and chips as far east as Cape Le Grand – distances of 380 km, 500 km and 730 km to the SE of Perth, respectively. Hence the widespread distribution of fossiliferous chert cannot be disputed.

Previous thin section analyses indicated overlap in the bryozoan fossils within chert artefacts from SW Western Australia and those from inland Nullarbor (O'Leary et al., 2017). X-ray CT imaging provides further support for this – and for the onshore source of fossiliferous chert as initially proposed by Glover and Cockbain (1971) – with *Trigonopora*, *Siphonicytara*, *Quadricellaria* and *Cellaria* found in both sets of samples. According to Clarke et al. (2003), outcrops of chert are widely scattered along the margin of the Eucla Basin and are often deeply weathered, or are otherwise largely inaccessible except in cliffs and caves along the basin's southern margin. Hence, it is possible that there are outcrops of fossiliferous crystalline chert on the westerly margins of the Eucla Basin but this would still be over 1000 km from Perth.

Nevertheless, the similar lithology of fossiliferous chert artefacts from SW Western Australia and the Wilson Bluff Limestone (Glover, 1975b:84), as well as the similar assemblage of bryozoan fossils means that this distant onshore source cannot be ruled out. Indeed, flint from a quarry at Wilson Bluff was described by Bates (1918, 1920) as being traded considerable distances, possibly as far as the Lake Eyre/Coopers Basin a distance of over 900 km. We argue that a (re)consideration of the existence of wider exchange networks of stone materials as proposed by Bates (1920:74) and Tindale (1974) is warranted (although see Benbow and Nicholson, 1982 and Cundy, 1990).

A further curiosity is the WAM sample (A12679) from Balgo, a small town on the western edge of the Tanami Desert (Fig. 1) approximately 1800 km from Perth. This artefact is more typical of the chalcedonic or opaline chert described by Glover but nevertheless does contain at least one bryozoa (Fig. 8). Balgo (*Wirrumanu*) was established as a Catholic mission station in the early 1900s for Aboriginal people[1] and later became famous for its artists' cooperative (Moyle, 2001). The adze is one of about 20 stone artefacts of chalcedony and silcrete collected in the 1950s from a surface site a few kilometres south of the mission. The presence of contact material at the site (an iron adze) may indicate that the chert was brought to Balgo in recent times, adding to the complexity regarding the timing and provenance of isolated surface samples.

4.3. Implications of the Doole Island artefact on use of chert as a chronological indicator

This study has also identified several fossiliferous chert artefacts from island contexts, namely Recherche and Doole Islands (Fig. 1). These islands were cut off from the mainland during the post-glacial transgression between 7000 and 3000 years ago, with the Recherche Islands now lying 60 km south of the mainland (Dortch and Morse, 1984).[2] The Doole Island artefact was found in association with a shell scatter located atop a 10 m high ridge. The island is located 1.5 km from the mainland and separated by a shallow tidal flat that becomes exposed during low water spring tides making the islands relatively accessible. Several small concentrated shell scatters and mixed shell and artefact scatter sites reflect past use of the island by Aboriginal people. The association of the chert artefact with a late Holocene shell scatter suggests that this material was still actively traded after the island was cut off from the mainland. This again questions using fossiliferous chert as a chronological marker to divide sites of Late Pleistocene to Early Holocene age from those of mid or Late Holocene age (Hallam, 1987).

Whilst the majority of fossiliferous chert samples that have been

[1] https://www.findandconnect.gov.au/guide/wa/WE00246.

[2] See also http://www.abc.net.au/news/2016-06-14/underwater-archeological-site-reveals-ancient-artefacts/7506486.

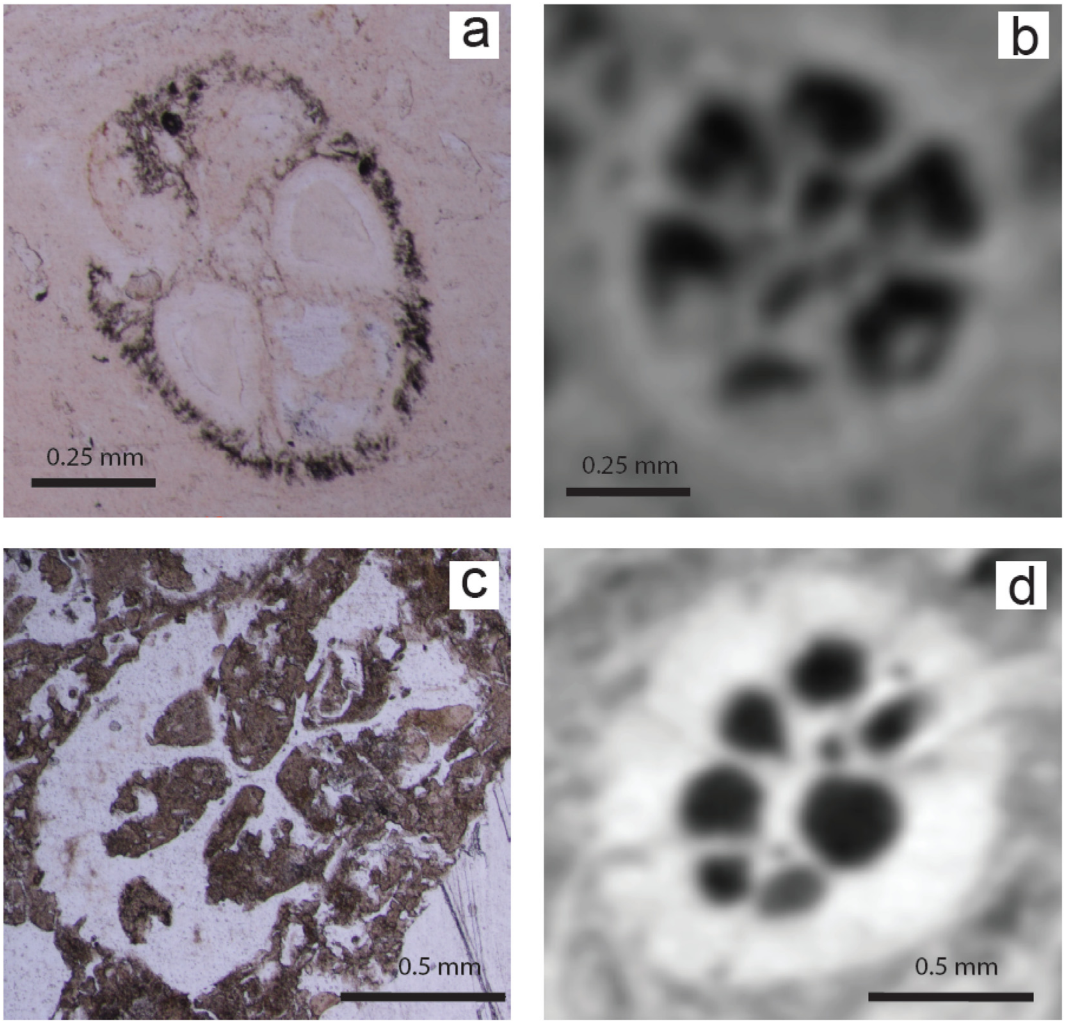

Fig. 10. Comparison of bryozoan image resolution in thin section photomicrographs of artefacts (a and c) versus 2D synchrotron scans of artefacts (b and d). *Cellaria* from UWA-74807 - Lake Gnangara (a and b). *Trigonopora* from FOR 004 (c and d).

collected and archived are from coastal settings, this may reflect a sampling and/or preservation bias. Aside from the Balgo sample, no bryozoan fossils could be identified in either of the other two inland artefacts from Zanthus (although, the samples may be so heavily silicified that the fossils are indistinguishable from the matrix). However, scrapers from fossiliferous chert were documented by Martin (1982) at Pingrup, approximately 150 km inland from the southern coastline. It is possible that there was a coastal focus for the sourcing and trading of Eocene fossiliferous chert, although Martin (1982: 42) suggested that Aborigines moved not only along the coast but also inland along riverine routes to obtain lithologies suitable for working. Hence, inland, coastal and offshore sites all warrant further investigation.

5. Conclusion

Biogenic chert has the potential to preserve diagnostic bryozoan communities that provide a unique means of sourcing stone tools in southern and southwestern Australia, but this is complicated by the need to avoid any destructive analysis of the artefacts in question. X-ray-CT imaging is non-destructive and thereby mitigates the issue of culturally sensitivity surrounding destructive sampling methods. Although time-consuming, data processing does allow for the whole sample (actual and digital) to be archived for future analyses. The high-resolution imaging allows for a comprehensive overview and orientation of embedded fossils and also a three-dimensional rendering of the whole bryozoan colony structure, including the arrangement of zooecia and 3D morphology of zooecial cavities, for better taxonomic characterisation.

Whilst somewhat limited by the scanning resolution of the available beamline at the Australian Synchrotron, CT imaging confirms the presence of bryozoans in chert artefacts distributed over a thousand kilometres north and east of Perth, including some offshore islands. Several of the identified bryozoans are morphologically and taxonomically similar to chert source rocks from the inland Nullarbor, again providing support for the possibility of long-distance trade and widespread distribution of this material across Australia. In addition, an Early Holocene age of the archaeological site from one of these island contexts puts doubt on the validity of using fossiliferous chert as a chronological marker in archaeological sites in Western Australia.

Few other artefactual rock types have such diagnostic fossiliferous signatures that can not only provide potential provenance markers but also serve as critical evidence in understanding and reconstruction of human behaviour, including mobility, trade and exchange, stone technology and stone artefact assemblage formation. Further work will continue to explore this possibility through investigation and characterisation of potential source rocks within the Eucla Basin and through additional analysis of fossiliferous chert artefacts from both South Australian and West Australian archives.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2019.05.005.

Acknowledgements

This project was funded by Australian Synchrotron grant no. (AS171/IM/11589). Kane Ditchfield (Uni. Western Australia) helped with an initial Synchrotron experiment. We thank John Reeve, Curator, Clarke Earth Science Museum, University of Western Australia, for access to the John Glover's artefact collections. The following colleagues helped us identify the bryozoan species: D. Gordon (National Institute of Water & Atmospheric Research, New Zealand), R. Schmidt (Museum Victoria, Australia), Y. Bone (University of Adelaide, Australia), N. James (Queen's University, Canada), and P. Taylor (Natural History Museum, London). We thank Gnulli Traditional Owners for permission to collect chert and shell samples from Doole Island. Finally we thank the reviewer for helpful comments on the manuscript.

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