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Challenging the 'offshore hypothesis' for fossiliferous chert artefacts in southwestern Australia and consideration of inland trade routes

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ABSTRACT

Surface scatters containing Eocene chert artefacts are a widespread cultural site type along the Swan Coastal Plain; however, no source rock for the chert is known to exist locally. In the absence of chert outcrops onshore, archaeologists have argued for an offshore source that was subsequently flooded during post-glacial sea level rise. Support for this theory has been the decline or absence of Eocene chert artefacts in deposits younger than 6000 years BP, and the apparent decrease in chert assemblage inland from the contemporary coastline, which may call into question a distal eastern source.

This paper presents an alternative theory whereby chert was sourced from the Nullarbor Plain (~1000 km to the east) and traded east as well as west across southern Australia. Evidence to support this theory includes (1) absence of Eocene age sedimentary strata outcropping on the continental shelf, (2) faunal evidence showing bryozoans imbedded in the Swan Coastal Plain chert, with similar environmental affinities to bryozoans embedded in chert outcropping along the Nullarbor Plain sea cliffs, and (3) geochemical evidence showing a similar geochemical fingerprint between artefacts from the Nullarbor Plain and Swan Coastal Plain.

With a peak in fossiliferous chert use around the Last Glacial Maximum, these findings have significant ethnographic implications supporting long distance trade to the east rather than local sourcing of lithic resources by isolated Aboriginal groups. These findings also have chronological implications relating to the use of Eocene fossiliferous chert as a chronological marker for Late Pleistocene to early-Holocene age deposits in southwest Western Australia, albeit with source accessibility following post-glacial sea-level rise still a main factor in the decline in chert use.

1. Introduction

The southwest of Western Australia has a rich record of human occupation extending back to 48,000 years B.P. (Turney et al., 2001), with evidence of resource exploitation documented in the rich faunal remains recovered from limestone rock shelters (Dortch et al., 2012) and mid to late Holocene coastal midden sites (Smith, 1999). Surface artefact scatters comprise the main archaeological site type in the region, and are usually present in the form of concentrated primary- and secondary-flaked and unflaked material in dune depressions created by sand deflation. Raw material types typically include locally-sourced quartzite, mylonite, amygdaloidal basalt and Proterozoic chert (Glover, 1984). Another widespread but more distinctive raw material type is fossiliferous (bryozoan) chert (Hallam, 1972). This cryptocrystalline raw material would have been sought after for tool-making because it breaks with a smooth conchoidal fracture that produces durable, sharp, non-jagged edges.

Faunal analysis of fossiliferous chert artefacts by Glover and Cockbain (1971) was able to identify 15 bryozoan species, as well as the diagnostic foraminifera species (*Maslinella chapmani*) embedded in the chert, indicating a Middle to Late Eocene age for the geological material. Despite the relative abundance of fossiliferous chert artefacts in southwestern Western Australia (Glover,

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1975b) extensive geological surveys within both the Perth and Carnarvon Basins have yet to reveal any Eocene age outcrop or formation that might potentially hosts fossiliferous chert rock (Glover and Cockbain, 1971; Quilty, 1974; Cockbain, 2014). Glover and Cockbain (1971) initially proposed that the chert may have been derived from Eocene sedimentary rock units, either from the Plantagenet Group and Norseman Limestone located over 500 km to the east of Perth, or from the Wilson Bluff Limestone. The latter is exposed in caves of the Nullarbor Plain and along the 60–120 m high Baxter and Bunda sea cliffs that stretch for over 380 km along the Great Australian Bight starting from Point Culver (830 km east of Perth) and ending at Head of the Bight (1500 km east of Perth). However several archaeological peculiarities of the fossiliferous chert artefacts led Glover (1975a) and Quilty (1978) to propose that fossiliferous chert flakes of the Swan Coastal Plain were locally sourced. They argued that chert sediments were exposed along the inner continental shelf during glacial lowstands (i.e. west of the present coastline) but that access was subsequently cut off when the sediments were submerged during post-glacial sea level rise – this was the so-called “offshore hypothesis”.

Several arguments have been put forward in support of the offshore hypothesis. Firstly, Glover (1975a, b) argued that an increase in the abundance of fossiliferous chert westward towards the present coastline would counter Glover and Cockbain's (1971) proposed easterly source, and instead favour a westerly “offshore” source. Secondly the absence of chert artefacts in strata younger than 4500 years BP was attributed to an elimination of source following post-glacial flooding of the continental shelf (see also Quilty, 1978; Glover, 1984). Thirdly, spatial trends in geochemical analysis (primarily Mg/Ca and Na/K ratios) of fossiliferous chert flakes was argued to represent multiple offshore chert sources and highly localised resource-use patterns (Glover and Lee, 1984). Finally, the presence of chert nodules Eocene sediment horizons recovered from a petroleum well drill core from the Rottnest shelf (west of Perth) led Quilty (1978) to suggest the possibility of surface exposures of Eocene chert in Quaternary depressions, now submerged on the continental shelf.

Over the last 40 years the offshore hypothesis has become an accepted central concept within the West Australian archaeological community. It has been used extensively by researchers and archaeological consultants to provide a relative chronology for dating archaeological sites, based on presence of fossiliferous chert to >6500 BP or alternatively its absence to <4500 BP (Hallam, 1972, 1986; Marwick, 2002; Dortch, 1991, 2002). It has also provided a template for ethnographic investigations of Aboriginal culture in southwestern Western Australia, i.e. limited trade or movement between Aboriginal groups across southern Australia. For the first time in 40 years, this study revisits the offshore hypothesis and challenges the notion that chert was sourced from quarries on the continental shelf that were subsequently drowned during post-glacial sea level rise. Instead we use a range of methodologies, including geochemical and faunal fingerprinting, to argue for an eastern source for fossiliferous chert with material being traded over many hundreds to over a thousand kilometers - a theory first proposed by Glover and Cockbain (1971) and subsequently abandoned. This finding has significant implications for our current understanding of Aboriginal ethnographies and may require a revision of the long accepted chronological sequences of archaeological sites in Australia's southwestern regions.

2. The occurrence of fossiliferous chert in the Perth Basin

Fossiliferous chert is a sedimentary rock formed through the deposition and diagenesis of siliceous marine organisms, including (1) diatoms - unicellular phytoplankton, (2) radiolarians - zooplankton, both of which produce a siliceous (opaline) skeleton, and (3) sponges that have an endoskeleton of silica spicules. Once on the sea floor, these siliceous sediments undergo diagenesis from opal-A (siliceous ooze) to opal-CT (porcelanite) through to chalcedony (chert) (Stein and Kirkpatrick, 1976). The maturation process is influenced by solution chemistry and mineralogy of the host sediments but are most strongly affected by temperature (as a function of burial depth) and time, the latter on the order of 25–50 Myr under typical oceanic heat flow conditions (Kastner et al., 1977).

In a global survey of Deep Sea Drilling Project (DSDP) and International Ocean Drilling Program (IODP) sediment cores, Muttoni and Kent (2007) found that cherts are most frequently and geographically widespread in Paleocene to Early Eocene marine sedimentary strata with peak occurrences at 50 Ma. An investigation of 38 DSDP/IODP wells drilled around the Australian continental margin found a peak frequency of biogenic chert beds in the early Eocene, which is also the geological age of the fossiliferious chert artefacts on the Swan Coastal Plain (Glover and Cockbain, 1971). A secondary chert peak is also observed in the Middle Miocene (Muttoni and Kent, 2007). If Glover (1975a; 1984) and Quilty (1978) are correct that the fossiliferous chert was sourced from now submerged outcrops on the continental shelf, then Eocene age sedimentary strata should be observed at or near the present seabed and at a water depth not deeper than ~130 m so as to be accessible during the previous sea level lowstand. However, a detailed geological study of the Perth Basin using onshore hydrological bore holes (Davidson, 1995) and offshore petroleum wells (Marshal et al., 1993), seismic data (Borissova et al., 2015) and seabed surveys (Nicholas et al., 2014) found no evidence of Eocene or Miocene strata outcropping on the continental shelf, or buried onshore by Holocene sediments.

The north-south orientated Swan Coastal Plain (Fig. 1) represents onshore surface expression of the Perth Basin; it is bounded to the east by the Darling Scarp and the Neoproterozoic Yilgarn Craton, and to the west by the present shoreline (Cockbain, 2014). The Kwinana Group sediments cover the coastal plain and include Holocene to Pleistocene marine and coastal sedimentary strata up to 30 m thick. Kwinana Group sediments continue onto the continental shelf with recent geophysical surveys (Nicholas et al., 2014) revealing submerged coastal strandlines, and parabolic dune systems, which would have formed during lower than present sea levels. Underlying the Kwinana Group is the Pliocene mineral-sand-bearing Yoganup Formation representing a former coastal and shallow marine depositional environment. Extensive onshore hydrogeological drilling (Davidson, 1995) reveals these Plio-Pleistocene units to be many tens of metres thick and unconformably overlying Cretaceous age sediments. This indicates there has either been non-deposition or erosion of Paleogene sediments within the onshore Perth Basin. An exception is the Late Paleocene to Early Eocene Kings Park Formation, which was encountered in the Kings Park 2 well. The unit occupies a deep channel incised through the Cretaceous sediments. The top of the section is at a depth of −23 m and is characterized by grey, calcareous, glauconitic siltstone and shale of shallow-marine to estuarine origin. Fossiliferous chert has not been reported from this formation and it is stratigraphically too old to be the source of the chert artefacts. The Kings Park Formation was also encountered in the offshore Quinns Rock 1 well, which reached the Mullaloo Sandstone Member of the Eocene Kings Park Formation at −37 m below the seabed (77 m below sea level) but no chert was found.

Both Miocene and Eocene strata are known from petroleum wells drilled on the continental shelf and shelf slope west of Perth. These are the Miocene Stark Bay Formation, the Late Eocene Challenger and Middle Eocene Porpoise Bay Formations. The Stark

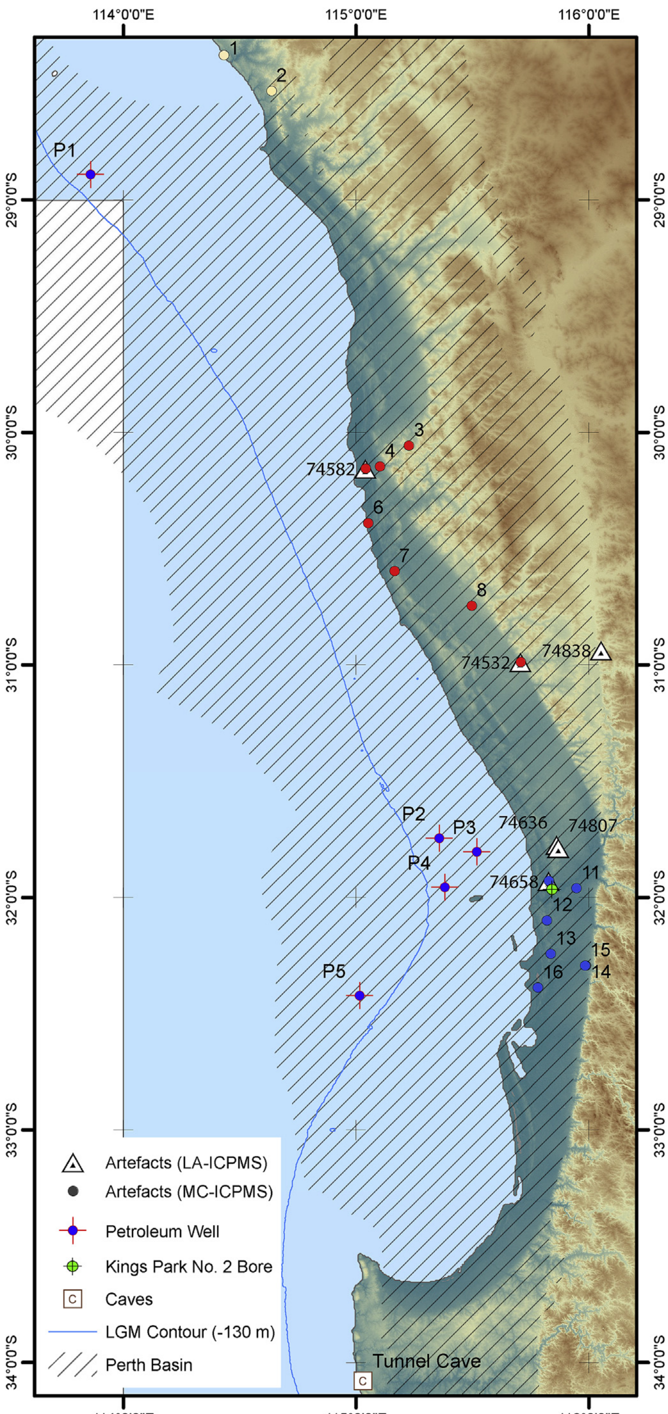

Fig. 1. Location map of Swan Coastal Plain and Perth Basin sample site locations. Chert Artefact MC-ICPMS analysis: **1**-Horrocks; **2**-Howathara; **3**-Kooringa; **4**-Woolmulla; **5**-Cockleshell Gully; **6**-Hill River; **7**-Pinnacle Desert; **8**-Caro Homestead; **9**-Regans Ford; **10**-Lake Monger; **11**-Cloverdale; **12**- Bibra Lake; **13**-Parmelia; **14**,**15**-Mundajong; **16**-Stake Hill – Chert Petroleum Wells with fossiliferous chert horizons: **P1**-Gun Island 1; **P2**-Marri 1; **P3**-Quinns Rock 1; **P4**-Gage Roads 1; **P5**-Challenger 1; Marri and Challenger wells chert sampled for LA-ICPMS analysis – Chert Artefact LA-ICPMS analysis: **74582**-Cockleshell Gully; **74838**-Gillingarra; **74532**-Regans Ford; **74636**-Gnangara; **74807**-Gnangara Lake; **74658**-Lake Monger.

Bay Formation as been encountered in the Gage Roads, Roe and Charlotte wells (with the type section in Gage Roads No. 2 well), and it covers the interval between 362 and 577 m below sea level (sea bed 212 m below sea level). The Stark Bay Formation comprises calcarenite, dolomite and very hard, translucent chert, and as it is dated to the Early to Middle Miocene (Quilty, 1974, 1980), it is too young and too deep to be the source of the (Eocene) fossiliferous chert artefacts.

The older Challenger Formation was encountered in the Challenger-1 well with the type section occurring between 362 and 577 m below sea level. The upper subunit (530–567 m) consists of white chalk, changing to coarser friable bryozoan-echinoderm calcarenite towards the base, with abundant chert (Quilty, 1978). The lower subunit (567–597 m) consists of white friable chalk and bryozoan-echinoderm calcarenite with dark grey chert. The shallowest occurring fossiliferous chert unit was encountered in the Gun Island 1 well, which captures a full tertiary sequence, with chert occurring between 173 and 207 m below sea level (Hawkins, 1969). While the Challenger Formation is of the right age range (Middle to Late Eocene) and lithology (chert-bearing calcarenite), it does not outcrop on the Rottnest shelf or onshore (Barr and Bradley, 1975; Quilty, 1978; Cockbain and Hocking, 1989; Shafik, 1992; Devereux, 1993).

In summary, extensive geological analysis of the onshore Perth Basin (Fig. 1) show a distinct absence of chert-bearing Miocene through Paleocene sedimentary strata; and while chert-bearing Miocene and Eocene strata are present in the offshore Perth Basin, it is encountered at depths well below the level of the Last Glacial Maximum (LGM) sea level lowstand (~130 m below present). The only remaining mechanism for Miocene or Eocene strata to be exposed on the continental shelf is through fault inversion (tectonic uplift of hanging wall fault blocks through compressional stress) similar to that which has occurred at Cape Range in the Northern Carnarvon Basin (Cathro and Karner, 2006). However, extensive seismic surveys, petroleum well data, and seabed geomorphic surveys within the Perth Basin have never identified evidence of reverse faulting. In fact the Perth Basin is still undergoing thermal subsidence (Borissova et al., 2015). This being the case, an alternative source for the Eocene chert must be invoked.

3. Alternative sources of Eocene chert

The closest possible onshore source of fossiliferous chert is the Middle to Upper Eocene Pallinup Formation (Glover and Cockbain, 1971; Gammon et al., 2000), which outcrops along the south coast between Albany and Esperance, approximately 400–900 km southeast of Perth (Fig. 2). The Pallinup Formation includes the Fitzgerald and Princess Royal Members, both of which contain spiculite, a silica spicule-dominated sedimentary rock, and also spongolite, which are rocks dominated by rigid-bodied, sponge skeletons. While these rock types can be worked into stone tools (Smith, 1999), basic petrological analysis shows that the Perth Basin artefacts lack the diagnostic spicules and it is therefore unlikely that these formations are the original source (Glover and Cockbain, 1971). The Middle to Late Eocene Norseman Limestone is located 600 km east of Perth and was deposited in brackish estuaries on the western margin of the Eucla Basin. It has a diverse bryozoan fauna and is locally silicified (i.e. silcrete) but lacks true chert and has not been definitively linked to Aboriginal artefacts (Dortch and Glover, 1983; Clarke et al., 1996). In addition, Glover and Cockbain (1971) could not find a source for this chert within the bryozoan-rich Eocene Giralia Calcarenite which is located > 600 km north of Perth in the Carnarvon Basin (Condon, 1968; Cockbain, 2014).

Further east is the Wilson Bluff Limestone, which is exposed near the base of the 50–90 m high sea cliffs, extending essentially unbroken for almost 900 km along the Great Australian Bight (Lowry, 1970), and in caves in the semi-arid Nullarbor Plain (Webb and James, 2006; Miller et al., 2012). The formation was deposited during the Mid to Late Eocene (Li et al., 2003) as part of the broad

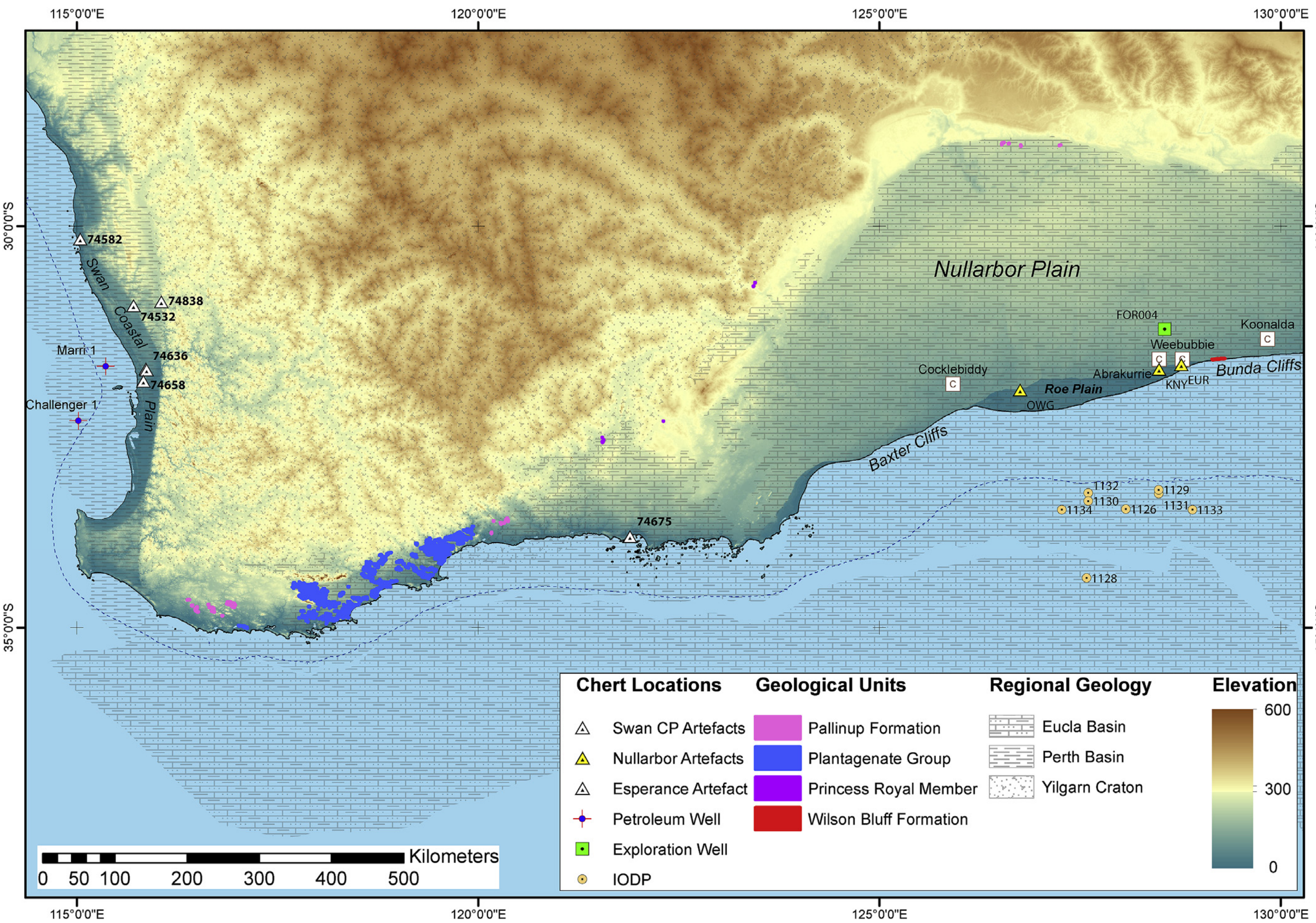

Fig. 2. Location of chert artefact samples, offshore wells, and geological outcrops of Eocene chert and location of caves mentioned in the text.

shallow epicontinental Eucla Basin and its offshore Bight Basin (McGowran et al., 1997; Feary and James, 1998). It is characterized by a fine-grained, medium-to thick-bedded, chalky, bryozoan-rich limestone with abundant chert nodules in a matrix of micrite and silt-sized skeletal fragments (Lowry, 1970; James and Bone, 1991; James et al., 1994; Li et al., 1996; Gammon et al., 2000). The formation grades upwards from a whiter, harder, denser, more crystalline brachiopod-rich limestone to a yellower, softer, friable, and more poorly lithified, bryozoan-rich limestone (Lowry, 1968; Lindsay and Harris, 1975). It was deposited in a low energy, cool-water, normal marine salinity open shelf, with carbonate muds and little terrigenous input (Lowry, 1970; Lindsay and Harris, 1975; O'Connell et al., 2012). The chert nodules from the Wilson Bluff Limestone range in colour from opaque white to translucent pale grey, contain traces of bryozoans, and lithologically are very similar to the Swan Coastal Plain artefacts.

4. Using bryozoan faunal assemblages to source eocene fossiliferous chert

Fossil bryozoans contained within fossiliferous chert artefacts are excellent tools for discriminating potential source rocks (Key and Wyse Jackson, 2014; Key et al., 2014). Firstly, fossils tend to be relatively unaltered during the manufacturing of the tool and secondly, environmental and evolutionary processes create species with distinct temporal and geographic distributions, so the fossils can be easily related back to their source rock (i.e. used for provenance studies) (Rapp and Hill, 2006; Key et al., 2010, 2016). For instance, Cockbain (1970) examined the distribution of cheilostomatous bryozoans, identifying 40 species within the Eocene Wilson Bluff Limestone. Similarly Glover and Cockbain (1971) identified 15 species of fossil cheilostome bryozoan embedded in fossiliferous chert artefacts from the Swan Coastal Plain, and all 15 species can be found in the Wilson Bluff Limestone (Table 1). Most recently, Key et al. (2017) described two cheilostomes and one cyclostome species from the Wilson Bluff Limestone from the Eucla area. Despite this clear association between the faunas, no one has previously used fossil bryozoan faunal assemblages to constrain the source of the lithic artefacts found on the Swan Coastal Plain. This study is the first to do so by analysing bryozoan assemblages from fossiliferous chert artefacts from the Swan Coastal and Nullarbor Plains and geological chert samples from drill cores in the Perth and Eucla Basins.

A total of thirty Swan Coastal Plain artefacts, three Nullarbor Plain artefacts, and two Wilson Bluff (Eucla Basin) chert nodules were thin-sectioned, yielding 184 petrographic images of fossil bryozoans. From these, five bryozoan species were distinguished. Two species were the cyclostome bryozoans *Idmonea geminata* and *Idmonea incurve*, which were not included in Glover and Cockbain's (1971) study. The remaining three are the cheilostome bryozoans *Adeonellopsis* sp., *Cellaria rigida*, and *Cellaria australis*. Both genera were listed in Glover and Cockbain's (1971) chert artefacts of the Swan Coastal Plain study. While all five species are present in the larger sample of Swan Coastal Plain artefacts, only three of these

Table 1
Fossil Bryozoan species list. The asterix in the Cockbain 1970 list of Wilson Bluff Limestone fossil Bryozoan indicate that that same species was also identified in fossiliferous chert artefacts from the Swan Coastal Plain (SCP).

Glover and Cockbain 1971 *SCP Artefacts*	Cockbain 1970 *Wilson Bluff Limestone*	This Study *SCP Artefacts*	This Study *Nullarbor Artefacts*	This Study *Nullabor Chert*
Acerinucleus sp.	**Acerinuceus incudiferus*	*Adeonellopsis* sp	*Adeonellopsis* sp	*Cellaria rigida*
Ascophoran spp.	*Adeonellopsis yorroensis*	*Cellaria rigida*	*Cellaria rigida*	*Idmonea geminate*
Aspidostoma clarkei	*Amphiblestrum sexspinosum*	*Cellaria australis*		
Arachnopusia ferrea	**Arachnopusia ferrea*	*Idmonea geminate*		
Cellaria spp.	**Ascophoran* spp.	*Idmonea incurva*		
Celleporaria tridenticulata	**Aspidostcma clarkei*			
Crateropora sp.	*Cellano bicornis*			
Cribrilaria sp.	*Cellano contigua*			
Foveoaria savartii	*Cellano rigida*			
Membranipora cf. *cyclostoma*	*Cellano robusta*			
Ogiva sp.	*Cellano tumida*			
Porina gracilis	**Cellaria rigida*			
Schizophoria vigilans	**Celleporaria tridenticulata*			
Sertella mucronata	*Celleporina* spp.			
Tubitrabecularia elevata	*Corbulipora ornate*			
	Crassimarginateila cf. *sculpta*			
	**Crateropora inconspicua*			
	**Cribrilaria cornuta*			
	Cribrimorph sp.			
	Ellisino profunda			
	**Foveolaria savartii*			
	Gigantopara sp.			
	Hipposparino burlingtoniensis			
	**Membranipora cyclostoma*			
	Membranipora cf. *elliptica*			
	Membranipora fossa			
	Micrapora coriacea			
	Micrapora cf. *lunipuncta*			
	**Ogiva concamerata*			
	**Ogiva elliptica*			
	Pachystomaria parvipuncta			
	Phidolopora rimata			
	**Porina gracilis*			
	Retepora complanata			
	**Schizoporella vigifans*			
	Selenaria cupola			
	**Sertella mucronata*			
	Smittoidea n. sp.			
	**Tubitrabecularia elevota*			
	Vittoticella spp.			

species (*Adeonellopsis* sp., *Cellaria rigida*, and *Idmonea geminata*) were found in the Nullarbor artefacts and Wilson Bluff Chert samples (Fig. 3). This still allows for the premise that Wilson Bluff Limestone could be a source for Swan Coastal Plain artefacts.

Comparison of the bryozoan morphometric data from the Nullarbor Plain artefacts and the Eucla Basin nodules with the Swan Coastal Plain artefacts shows they are almost indistinguishable. The mean branch widths between the two bryozoan sources were not significantly different for *Cellaria rigida* and *Idmonea geminata* but they were for *Adeonellopsis* sp. (t-Test, $P = 0.022$). Comparison of the zooecial diameters of each of the three-shared species (Fig. 4) showed that the two sources did not have significantly different means (t-Tests, $P > 0.050$). This morphometric data indicates that bryozoan communities preserved within the Swan Coastal Plain, Eucla Basin and Nullarbor Plain all inhabited a similar depositional environment (i.e. low energy, deep water).

It should be noted that this study did not find bryozoans in either the chert or associated carbonate sediment cuttings from Eocene Challenger Formation in either the Marri 1 or Challenger 1 Petroleum wells. This was a surprising finding as Quilty (1978) defines the Challenger type section as a white friable chalk and bryozoan-echinoderm calcarenite with dark grey chert. Barr and Bradley (1975) similarly reported bryozoans in the Eocene cuttings from the Challenger 1 well at 545–599 m depth, with Cockbain and Hocking (1989) assigning this chert-rich calcarenite to the Late Eocene Challenger Formation. However bryozoans were observed in the Miocene Stark Bay formation of both wells, although they account for less than 5% of the total fraction and are too young in age to be considered as potential source material. The absence of bryozoans embedded the late Eocene chert of the Challenger formation effectively rules out the Perth Basin as a probable source of chert artefacts, and even if Barr and Bradley (1975) are correct about there being Eocene bryozoans at 545–599 m depth below the rotary drilling table, this is well below the peak sea-level lowstand during the LGM.

The bryozoan analyses show that the Swan Coastal Plain artefacts, Nullarbor Plain artefacts and Eucla Basin cherts are similar, not only in their gross qualitative morphology (i.e. species assemblage data) but also in their subtle quantitative morphology (i.e. morphometric data). This would indicate that bryozoan assemblages embedded in the Swan Coastal Plain artefacts were sourced from a marine chert whose habitat and environment of deposition closely matches that of the Wilson Bluff Limestone cherts.

5. Geochemical fingerprinting of Eocene chert artefacts

Geochemical fingerprinting utilizes the distinct chemical and isotopic patterns preserved in the rock record to determine the

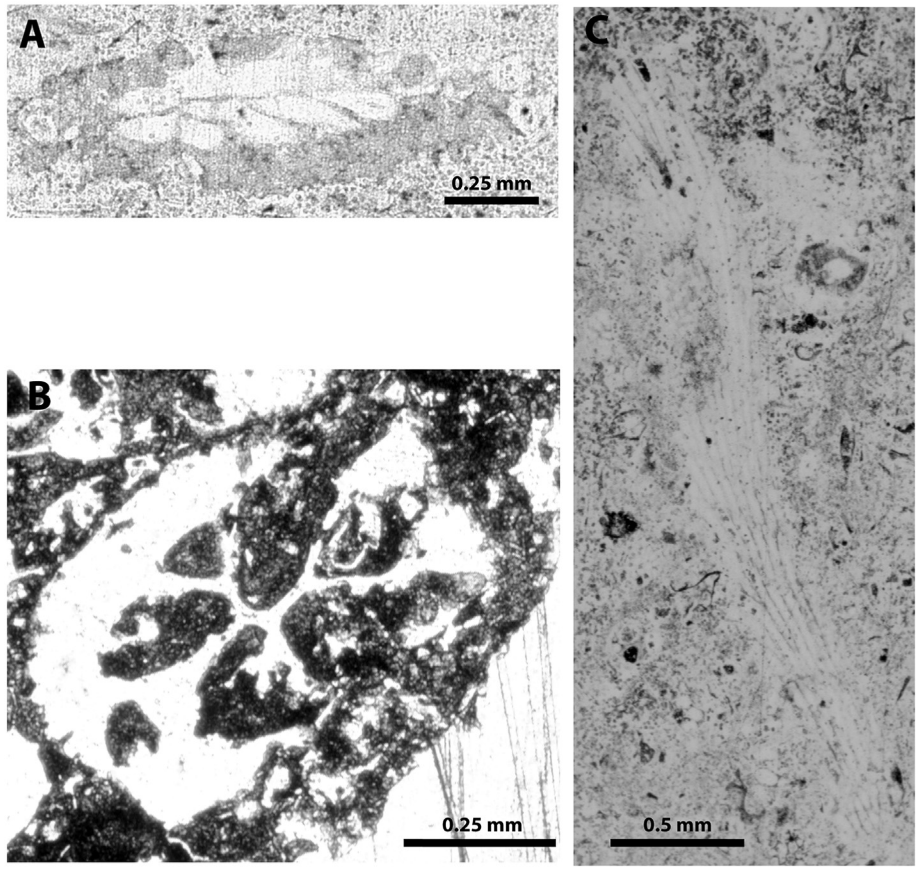

Fig. 3. Fig. 2. Silicified fossil bryozoan species identified in chert samples from the Eocene Wilson Bluff Limestone from the vicinity of Eucla, Western Australia. A) *Adeonellopsis* sp. from Knousley, KNY, B) *Cellaria rigida* from Well FOR004-2, C) *Idmonea geminata* from Knousley South 2, KNX-52.

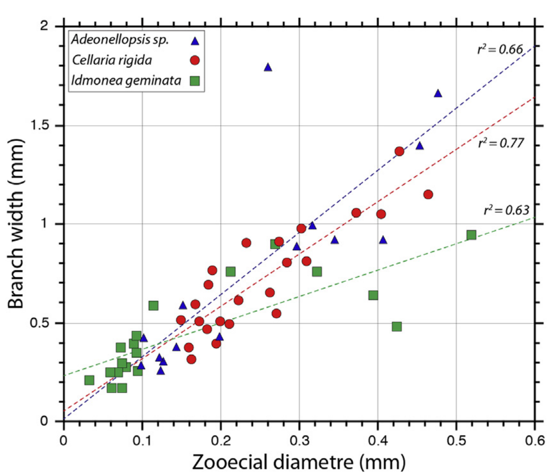

Fig. 4. Plot of branch width versus zooecial diameter for the three species of Eocene bryozoans found both in Aboriginal artefacts from the Perth Basin as well as in the Wilson Bluff Limestone from the Eucla Basin. Error bars represent 3% measurement error. When comparing the bryozoan morphometric data between the Wilson Bluff Limestone and the Perth Basin artefacts, they are almost indistinguishable. The mean zooecial diameters between the two source were not significantly different for *Cellaria rigida* and *Idmonea geminata*, but they were for *Adeonellopsis* sp. (t-Test, $P = 0.022$). We compared the branch widths of each of the three species and found they did not have significantly different means between the two sources (t-Tests, $P > 0.050$).

provenance of material that has been transported away from its source through either natural or cultural processes. Typically geochemical fingerprinting will involve the characterisation of geochemical concentrations of the transported material and of a similar material from potential source regions or locations. Here we utilised Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS), which has been successfully used in a number or archaeological fingerprint applications including classification and use patterns of ochres in the Mid West region of Western Australia (Scadding et al., 2015) and identifying the geological source of Clovis period projectile points in central Texas, America (Speer, 2014).

Analysis of carbonate in thin section was determined utilizing a RESOlution M-50A-LR incorporating a Compex 102 excimer laser, coupled to an Agilent 7700s quadrupole ICP-MS at the GeoHistory Facility, John de Laeter Centre, Curtin University. Following 4 cleaning pulses and a 30s period of background analysis, samples were spot ablated for 40 s at a 10 Hz repetition rate, using a 90 μm beam and laser energy of 10 J cm^{-2}. International glass standard NIST 612 was used as the primary reference material, to calculate elemental concentrations (using stoichiometric ^{43}Ca as the internal standard element) and to correct for instrument drift on all elements. Secondary standards (NIST 610 and BCR-2G) yielded an accuracy of between 0.5 and 5% on most elements. Standard blocks were run every 20 unknowns. The mass spectra were reduced using Iolite (Paton et al., 2011 and references therein).

Data were collected on a total of 50 isotopes (^{7}Li, ^{9}Be, ^{24}Mg, ^{27}Al, ^{28}Si, ^{39}K, ^{43}Ca, ^{44}Ca, ^{45}Sc, ^{46}Ca, ^{47}Ti, ^{49}Ti, ^{51}V, ^{52}Cr, ^{56}Fe, ^{57}Fe, ^{59}Co, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{85}Rb, ^{88}Sr, ^{89}Y, ^{90}Zr, ^{93}Nb, ^{95}Mo, ^{107}Ag, ^{115}In, ^{118}Sn, ^{121}Sb, ^{133}Cs, ^{139}La, ^{140}Ce, ^{141}Pr, ^{146}Nd, ^{147}Sm, ^{151}Eu, ^{157}Gd, ^{159}Tb, ^{163}Dy, ^{165}Ho, ^{166}Er, ^{169}Tm, ^{172}Yb, ^{175}Lu, ^{178}Hf, ^{181}Ta, ^{182}W, ^{208}Pb, ^{232}Th) on seven Swan Coastal Plain Eocene chert artefacts, three Eoene chert artefacts collected from the Nullarbor Plain, as well as biogenic chert collected from Marri and Challenger petroleum wells in the Perth Basin, and biogenic chert collected from the Forrest core (FOR04) drilled into the Eucla Basin. The Perth Basin Eocene chert samples were collected at drill depths of 370, 475 and 530 m below the seabed and, therefore, are not related to the Swan Coastal Plain artefacts. They were analysed to provide a test of the geochemical variation in Eocene chert across two distinct sedimentary basins. A total of 40 individual laser ablation analyses were made on each sample for a total of 680 spots.

Based on analysis results, geological and artefact samples were classified using linear discriminant functions. Element data were mean centred and scaled to unit variance prior to analysis. Initial screening of the data reduced multi-collinear variables to single variables and removed outlying ablation points based on the Mahanalobis distance. Data screening retained 28 elements for inclusion in the linear discriminant function for classification. Two linear discriminant functions were determined using a training dataset consisting of half the ablation points from each sample from the Perth Basin (PB), Eucla Basin (EB) and Nullarbor Artefacts (NA) and a test dataset consisting of the other half of these samples. The functions were then used to classify ablation data from the Swan Coastal Plain artefact samples as having a geochemical composition more similar to the PB, EB or NA samples.

The linear discriminant functions separated the Nullarbor artefacts and Eucla Basin cherts into two distinct geochemical populations (Fig. 5). This was surprising considering the likelihood of the Nullarbor artefact being sourced locally from the Eucla Basin chert, either outcropping in caves or along the sea cliffs. The fact that already these two groups have distinct geochemical fingerprints indicates that there is a reasonable degree of heterogeneity in the elemental composition of chert across the Eucla Basin. When

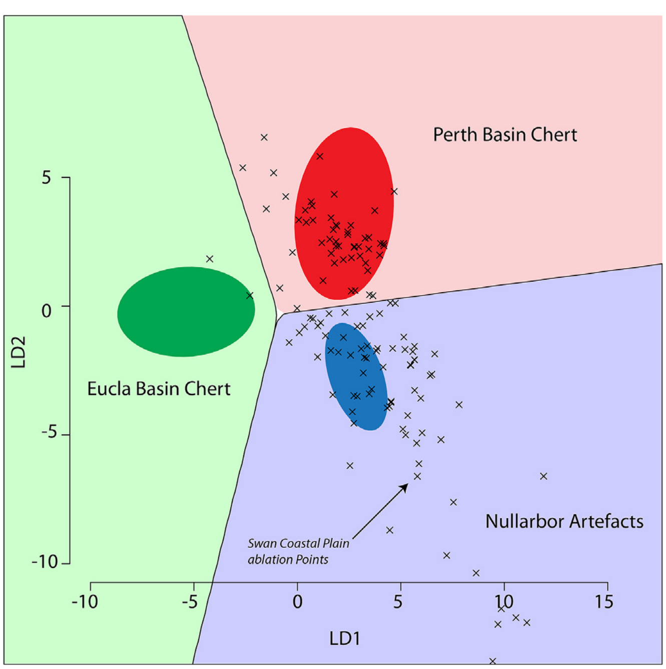

Fig. 5. Geochemical classification of LA-IPCMS spot data for Perth Basin geological chert, Eucla Basin geological chert and Nullarbor artefact samples. Ellipses represent the 95% confidence interval of ablation points for each sample group with the coloured areas representing classification regions. The black crosses represent the Swan Coastal Plain artefact ablation data and plot within a classification region in which they are geochemically most similar. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

individual chert ablation points from the Swan Coastal Plain artefacts are included into the discriminant analysis, the results show a wide spread of data that falls across the Perth Basin and Nullarbor artefacts regions (Fig. 5). The wide scatter of data compared to the 95 percentile ellipses of the Nullarbor artefact, Perth and Eucla Basin samples indicates that either the Swan Coastal Plain artefacts have been affected by post-deposition geochemical alteration, or more likely, each of the samples have been sourced from multiple chert outcrops along the Baxter and Bunda cliffs or within caves. While there is a significant geochemical similarity to between the Nullarbor chert and Swan Coastal Plain chert artefacts, the fact that they are also similar to the Perth Basin chert samples (when it is clear they cannot be original source due to the depth of burial) would indicate that the elemental composition of the biogenic chert can be highly varied at both the basin and local scales.

One of the original arguments used by Glover and Lee (1984) in support of the offshore hypothesis, was an apparent regional geochemical relationship between Na/K and Ca/Mg ratios for chert artefacts that they postulated corresponded with a series of discrete Eocene chert deposits outcropping in a north/south band along the continental shelf, and that these deposits were exploited locally. This study re-analysed 15 Eocene chert artefacts collected by John Glover from Geraldton (−28.7°S), Jurien Bay (−30.3°S) and Perth (−32.0°S) region. Using MC-ICPMS, the following elements were measured: Mn, Co, Ni, Cu, Rb, Sr, Zr, Nb, Cs, Ba, La, Ce, Nd, Sm, Eu, Dy, Er, Tm, Lu, Pb, Th and U. Unlike the earlier interpretation by Glover and Lee (1984), multivariate cluster analysis (Fig. 6) found no geochemical similarities between samples collected from the same region. Again this goes to the question of geochemical heterogeneity of fossiliferous with more work needing to be done to determine the full range of variability in the elemental compositions of known chert outcrops and how this can then be more tightly correlated with fossiliferous chert artefacts.

6. Chronological implications

In southwest Australia, fossiliferous chert has remained an archaeological enigma based on its supposed offshore source. As outlined above, archaeologists working in the Perth Basin have accepted the offshore theory and used it as a chronological marker to divide sites of Late Pleistocene to early-Holocene age from those of mid or Late Holocene age (Dortch and McArthur, 1985; Dortch, 1986a; Hallam, 1987; Glover et al., 1993; Smith, 1993; Marwick, 2002). However chronological studies have shown chert artefacts persist through the middle to late Holocene archaeological record, which post-dates the timing of sea-level rise and stabilisation and subsequent submergence of offshore sources. For example radiocarbon dating of deposits containing Eocene chert provide age estimates ranging from ~12 ky BP at Devil's Lair (Dortch and Merrilees, 1973) to between 6135 ± 100 yr BP and 3220 ± 100 yr BP at Walyunga (Glover et al., 1978). A more ambiguous record comes from Arumvale, near Devil's Lair, where Eocene bryozoan chert artefacts were found together with geometric quartz microliths in a unit dated to 9220 ± 135 BP (SUA-455) (Dortch, 1986b). This is unusual because microliths are generally considered to be of mid-to late Holocene age and hence, following the “offshore source hypothesis”, are chronologically inconsistent with a mid-Holocene or older age for the Eocene chert.

A more simple explanation put forward for this temporal inconsistency was the recycling of chert (Ferguson, 1980a) with denticulated flakes often found in bryozoans chert tool assemblages in the region (Dortch, 1979, 1984; Ferguson, 1980b: 61), including Devil's Lair (Dortch, 1996: 68). However a more recent analysis of material from Dunsborough, Tunnel Cave and Devil's Lair shows neither any significant increase in the level of reduction

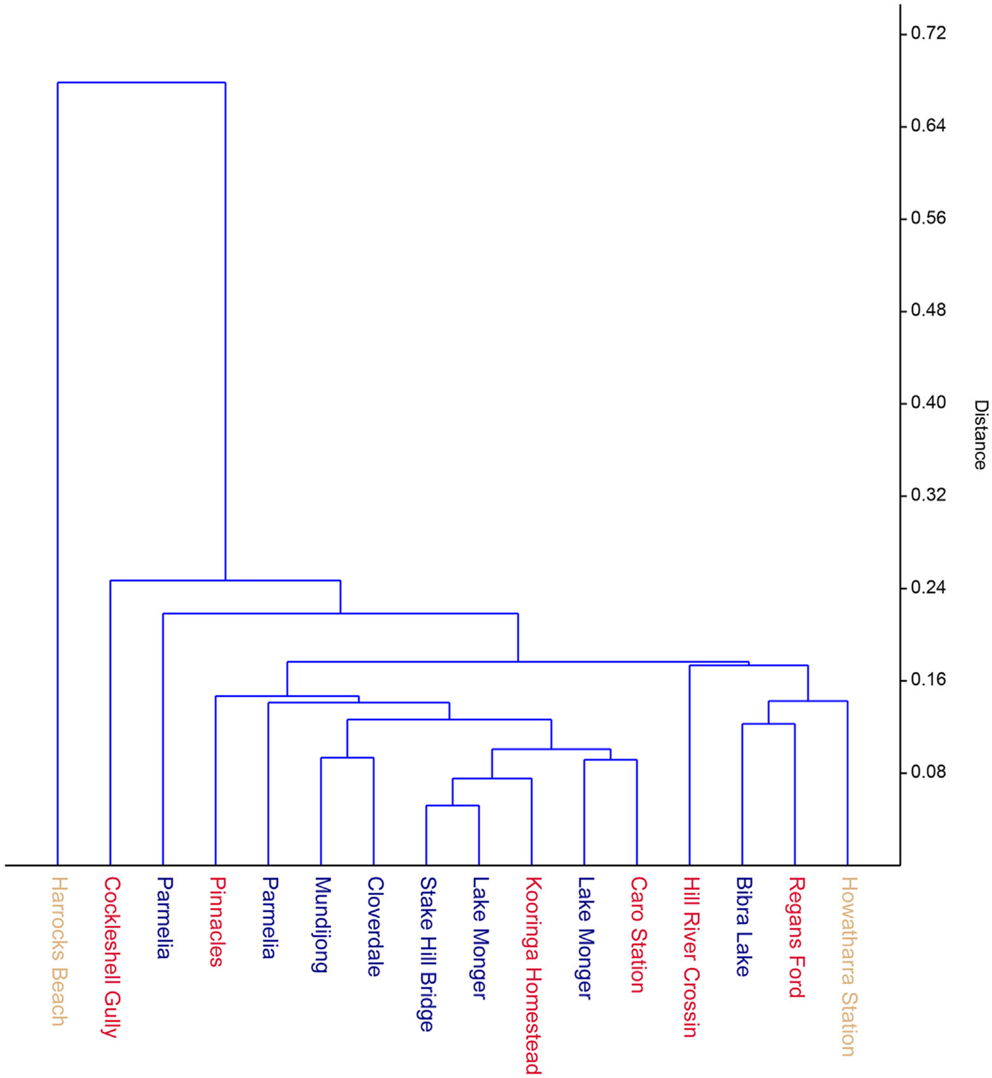

Fig. 6. Hierarchical Cluster Analysis (Gower Method) of SCP artefact MC-ICPMS geochemical data. the closer the connection between two samples, the more geochemically similar they are. Brown samples from Geraldton region, Red samples from Jurien Bay region, Blue samples from Perth region. The lack of geochemical similarity in samples collected from the same region contradicts Glovers and Lee's (1984) study, which states that SCP chert must be locally sourced because there is a observed latitudinal trend in the geochemical composition of chert artefacts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of chert artefacts, nor an increase in the numbers of utilised, retouched artefacts through time (Worrell, 2008: 60). Rather Worrell's evidence shows a fairly smooth transition from the use of fossiliferous chert to the use of quartz at these sites, albeit with an increase in knapping frequency as a result of the difference in raw material properties. Thus, although the evidence is limited, it indicates that chert recycling was not a major strategy and instead there must be some other explanation for the continued availability of chert into the middle late Holocene.

Essentially there remains a temporal conundrum if the “offshore hypothesis” is assumed. However, if this sea-level constraint is removed, it opens up the possibility of other explanations for the presence and general decline of fossiliferous chert from the Late Pleistocene to the mid to late Holocene, not least the possibility of long-distance trade from an eastern source. Here the study of Worrell (2008) is again useful. Both Tunnel Cave and Devil's Lair show a peak in fossiliferous chert artefacts around the LGM (~22,000 yr BP) when ‘chert use became increasingly unrestricted’ (Worrell, 2008: 58). In the subsequent period, there was a higher proportion of longitudinal flakes and decrease in complete flakes until occupation ceased around 12,000 yr BP. This broadly corresponds with the timing of flint mining in Koonalda Cave between 24,000 and 14,000 years ago (Wright, 1971a). It is only in the final phase from 12,000 yr BP to 6200 yr BP that chert artefact numbers decline (Worrell, 2008). The reason for this decline is likely to be a combination of both source accessibility and human behavioral processes, perhaps linked with intensification (Lourandos and Ross, 1994; Williams et al., 2015a,b).

A possibility is that Nullarbor caves and cliffs, both with access challenges, were worked for chert at various times during the late Pleistocene through to the Holocene. Cave mining was clearly happening at Koondala Cave (Wright, 1971a), hence it is highly probable that chert was also being worked from the coastal cliffs. While the observed height (several 10's of metres) of outcropping chert nodules above the base of the cliffs would have made access extremely challenging, eolian dunes that had been blown against the base of the cliff would, over time, have accreted vertically becoming “climbing dunes”, eventually reaching a horizon where chert was outcropping. These climbing dunes would have provided a convenient ramp for accessing the outcropping chert nodules.

Remnant climbing dunes are observed along the cliffs near Eucla today, however most dunes were eroded away during the late Holocene sea-level highstand.

7. Ethnographic implications

There is no doubt that the fossiliferous cherts in the Wilson Bluff Limestone were quarried by Aborigines in caves around Eucla (Gallus, 1971; Wright, 1971a, b). Furthermore chert artefacts of similar lithology to Wilson Bluff's chert nodules have been recorded at Ooldea, 350 km to the east of Eucla (Bates, 1921; Johnston, 1941) and in archaeological sites 600–700 km along the coast in Elliston to the southeast (Nicholson and Cane, 1991). Whilst the implication of long-distance trade with the east has never been questioned, the idea of long-distance trade with Aboriginal groups in the west has largely been dismissed due to the apparently large distances involved (Glover, 1975a).

Other evidence of long-distance trade include the presence of seed-grinding implements of non-local granite at James Range in Central Australia (sourced from at least 160 km away), along with fragments of diorite from a ground-edge axe that may have originated in the Flinders Range, about 800 km to the southeast (Gould and Saggers, 1985). On the limestone-dominated Barrow Is. and Montebello Is. artefacts made of volcanic and non-local sedimentary rocks imply long-distance procurement from the Pilbara ranges, at least 200 km or so distant (Veth et al., 2007, 2014). Similarly, ochre was recovered from Mandu Mandu Creek rockshelter in northwestern Australia, but the nearest known sources are on the Hammersley Plateau some 300 km to the northeast or 850 km to the southeast at Wilgie Mia (Morse, 1993). There is also a posited trade of ochre from Wilgie Mia in mid-West Western Australia as far as Queensland (Woodward 1914), although the latter is largely anecdotal. In addition, there is now detailed geochemical fingerprinting of the Wilgie Mia ochres that can be used to investigate the antiquity and nature of long distance ochre trade networks from rock-art and excavated ochre fragments (Scadding et al., 2015).

In the Western Desert, the presence of non-local or “exotic” stones were interpreted as evidence for long-distance social networks that operated to overcome or mitigate stresses imposed by drought (Gould and Saggers, 1985: 118). Central to the “exotic stone hypothesis” is the existence of long-distance social relationships or, as Gould and Saggers (1985:122) describe, a kind of “envelope” of social space that expands or contracts according to the degree of stress imposed by drought or other conditions.

In other words, long-distance trips were of adaptive significance. There may be other functional or social purposes to maintaining long distance networks, as, for example, indicated from overlapping styles of rock art stretching 1000s of kilometres ‘from the coastal to inland Pilbara, and beyond to the Western Desert’ (McDonald and Veth, 2008; Brady and Carson, 2012: 101). Interestingly McDonald and Veth (2013) present a five-phase model for rock art in the Pilbara and Western Desert region that shows the LGM (Phase 3) as being a period when broad-scale social cohesion was needed to maintain connections. This contrasts with Williams et al. (2015b) who suggest people had a smaller range territory during the LGM. These broad scale networks later broke down (Phase 4) with increased territoriality (Phase 5). Hence it follows that perhaps the peak in fossiliferous chert use in the LGM in southwestern Western Australia, as shown by Worrell (2008), may somehow be related to an adaptive need for strong broad scale networks; with the subsequent decline related to a reduction in stress in the mid-Holocene and/or a breakdown of such networks. Regardless, as with the Wilgie Mia ochres, research is now needed to explore the nature and antiquity of any long-distance trade in fossiliferous chert and their subsequent decline in Western Australia and South Australia.

8. Conclusions

Despite an early consideration of an (easterly) inland source for fossiliferous chert artefacts in southwest Western Australia, the putative idea of an (westerly) offshore source has never been questioned. A review of the regional geology, along with microfossil (bryozoan) and geochemical fingerprinting of John Glover's fossiliferous chert artefact archives has revealed that an offshore source is no longer a viable consideration. It is acknowledged that there is considerable geochemical heterogeneity of fossiliferous chert sources and more work is needed to maximise the potential of geochemical provenancing of fossiliferous chert artefacts. However, the evidence from the bryozoans themselves is more conclusive and further consideration should be given in using microfossil evidence for artefact provenancing work. At the same time, studies are now needed to characterize both fossiliferous and non-fossiliferous chert artefacts (both of which exist in the original archives of John Glover) in terms of their attributes and what this might tell us about possible changes in lithic practices through time.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2016.11.016.

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