Sedimentary unknowns constrain the current use of frequency analysis of radiocarbon datasets in forming regional models of demographic change.

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Abstract:

Statistical manipulation of large radiometric datasets ('big data') is increasingly applied to those grand challenges in archaeology that relate to past human-behavioural dynamics, and includes frequency analysis of radiocarbon ages (Summed Probability Distributions, SPD). Australian SPD studies use the radiocarbon database ‘Austarch’ to examine regional- and continental-scale demographic change. We review Australian studies, focussing on sampling bias and taphonomic bias, finding that i) time-averaged radiometric data cannot simply be correlated across regions, and ii) sedimentology imposes genuine constraints upon what can be known. Internationally, flaws in SPD use occur in all main research phases, and most importantly at the initial phase of defining research questions, logic and general approach. Major problems stem from not planning to obtain a sound understanding of the variability of past sedimentary environments, potential occupation sites and site formation processes. Thus, cultural inferences are too often made from archaeological data without due consideration of the natural processes that may explain the data. Highlighting exemplar studies, we present practical approaches to improve SPD use for exploring changes in demography, aimed at reducing uncertainties and reconnecting archaeological, chronological, geological and sedimentary data. Most important is to increase understanding of physical processes and their control on the archaeological record.
1. ARCHAEOLOGY’S GRAND CHALLENGES AND THE ROLE OF “BIG DATA”

“I have scant faith in frequency analysis of $^{14}$C dates as a tool for palaeoclimatic reconstruction.” (Williams, M.A.J., 1976, p. 361).

1.1 The role of “big data”

The contributions of earth sciences, particularly geomorphology and sedimentology, to the interpretation of archaeological phenomena and contexts is called geoarchaeology (Gladfelter, 1977; Karkanas & Goldberg, 2019). A geoarchaeological approach serves to provide the physical basis of archaeological site formation and interpretation at a range of spatial and temporal scales, with the stratigraphic history providing the essential ‘biography’ of a site (Smith, 2012). Extracted from the sedimentary archive, archaeological data is used to frame arguments around the nature of past human societies and is increasingly applied to contemporary issues such as climate change, urbanisation and so on. This contemporary relevance led Kintigh et al. (2014) to try to identify where investments in information technology would best be directed to help answer archaeology’s most important scientific questions. The 25 resulting “grand challenges” were divided into five main themes, of a) Emergence, communities, and complexity, b) Resilience, persistence, transformation, and collapse, c) Movement, mobility, and migration, d) Cognition, behaviour, and identity and e) Human–environment interactions. The challenges focus on dynamic cultural processes and the operation of coupled human and natural systems. Kintigh et al. (2014) argued that the contemporary relevance of archaeology had “led to an increasing focus on the processes underlying cultural transformation and change” (Kintigh et al., 2014, p. 6, their emphasis). In this paper we argue, for Australia at least, that the opposite has been the case, with the focus moving (further) away from the underlying processes and increasingly towards data science, involving use of data mining and algorithms to extract information from increasingly large datasets (see also Longbing, 2017).

This progression towards data science has been driven by an increase in collation of and access to large archaeological–chronological datasets (e.g. Gajewski et al., 2011; Gayo et al., 2015; Loftus et al., 2019; Vermeersch, 2019) and geospatial ‘big data’ (e.g. earth observations, climatic simulations) that can be utilised or transformed. One such transformation is the development of statistical frequency-analysis methods (e.g. Summed Probability Distribution SPD) that attempt to meaningfully summarise (Surovell & Brantingham, 2007; Ballenger & Mabry, 2011; Achino & Capuzzo, 2015; Chaput & Gajewski, 2016; Contreras & Meadows, 2014; Crema et al., 2017; Riris, 2018; Bluhm & Surovell, 2019; Muller & Diachenko, 2019) and apply these large datasets to derive human-behavioural dynamics at regional and continental scales across all parts of the globe including Europe (e.g. Reide, 2009; Shennan et al., 2013; Crombe & Robinson, 2014; French & Collins, 2015; Palmisano et al., 2017; Warden et al., 2017; Pardo-

1 Including a journal dedicated to this: https://openarchaeologydata.metajnl.com/about/
Gordó & Carvalho, 2020; Porčić 2020), the Americas (e.g. Peros et al., 2010; Gayo et al., 2015; Mendez et al., 2015; Goldberg et al., 2016; Muscio and López, 2016; McMichael & Bush, 2019; Riris & Arroyo-Kalin, 2019), Asia and Australasia (Abe et al., 2016; Hosner et al., 2016; Brown & Crema, 2019; Crema & Kobayashi, 2020; Wright et al., 2020). Indeed, the number of published archaeological studies using SPD analysis of large radiocarbon datasets has increased significantly in the last 15 years (Figure 1; see also data in Carlton & Groucutt, 2019). McLaughlin (2018, p. 1) describes this trend as archaeology “re-defining itself as a data-driven discipline at the intersection of science and the humanities”. What we perceive, however, is an increasing separation of the chronological data used in these statistical analyses from the geological and sedimentary contexts from which such data is obtained.

Australia has been at the forefront in the use of large chronological datasets, applying them to several “grand challenges” around key themes of communities and complexity, mobility and migration, and human-environment interactions (refer section 3.3). However, the explicitly exploratory nature of such modelling for setting up hypotheses to understand human-environmental interactions (Smith et al., 2008, p. 399) appears forgotten. Indeed Veth (2014) suggested that “such datasets...are being used as a mainstream proxy to explore archaeological trends and specifically demographic fluctuations” for some regions of Australia. Hence the purpose and some of the key limitations of such modelling have been overlooked, with the end effect that the results may be uncritically treated as fact (e.g. McDonald, 2016; Lancelotti et al., 2016; Brockwell et al., 2017; McDonald et al., 2018; Zeannah et al., 2017; Reynen et al., 2018; Tibby et al., 2018; Kusaka et al., 2018; Cook, 2019; Lopez et al., 2019) and even used as foundational premises of further demographic frequency analysis. We explore some of these radiocarbon-age-based studies and some of their underlying premises below. We do so in the spirit of promoting improvement, noting Vazire’s (2019) wishes for 2020 to be the year in which we value those who help ensure that science is self-correcting.

1.2 Limitations in the use of Summed Probability Distribution (SPD)

In the discipline of archaeology, the major contribution to knowledge of human culture and behaviour derives from data that covers long intervals of time and, increasingly, broad spatial areas. There are specific and emerging issues in the use of big data for spatial mapping (Canning 2005; Burg 2017; McCoy 2017). Regarding SPD analysis, the time component is key, and it is determined using various absolute dating techniques, typically radiocarbon and OSL dating (Aitken, 2009; Holdaway, 2014; Bateman, 2019), although others can also be relevant (Aitken, 2009; Holdaway, 2014). Here it is important to note that the radiocarbon technique indicates the timing of incorporation of atmospheric carbon into a living organism. This contrasts with the output of OSL dating, which indicates the timing of accumulation of material into a sedimentary deposit, beyond the reach of sunlight. These two techniques are particularly powerful when used in tandem - one dating the object and the other the
timing of accumulation. They can thus be used together to help assess in-situ reworking, without which understanding, radiocarbon data alone are weakened.

There are great potential benefits of using new techniques, but also risks, perhaps especially in the early stages of development. Carleton & Groucutt (2019) have presented an excellent historical overview of SPD analysis, particularly focussing on mathematical details and evaluation regarding improving interpretations. When applied to archaeology, SPD analyses begin with the collation of large numbers of radiocarbon ages (calibrated or uncalibrated) from many archaeological sites, and some databases have become of substantial size (e.g. Shennan, 2013; Bevan et al., 2017). These age data are grouped into bins, each a few years to a few centuries wide, so that a graph can be drawn of the different frequencies of the ages through time. This may be a simple indication of frequency (Figure 2, left) or may contain i) indications of uncertainty and ii) the degree of deviation from an assumed model of expected change (Figure 2, right). The fundamental working assumption is that the shape of this graph is a proxy for temporal fluctuations in past population levels in the sampled area (Rick, 1987), which, if correct and applicable, would provide a powerful tool to help answer a wide range of questions regarding long term trends in archaeology. However, there are problems in identifying which fluctuations are significant and which are statistical artefacts, with various attempts to correct or account for these (e.g. Kerr and McCormick, 2014; Brown, 2015; Crema et al., 2017; Crema & Kobayashi, 2020; see also Bronk Ramsey, 2017).

There remain questions regarding i) analytical uncertainties around radiocarbon dating itself (Lowe, 1981; Becerra-Valdivia et al., 2020) ii) in the use of “dates as data” (Attenbrow & Hiscock, 2015; Wood, 2015; Hiscock & Attenbrow, 2016) and iii) what the results of SPD analysis actually represent (Buchanan et al., 2011; Bamforth and Grund, 2012; Phillips, 2013; Mokkonen, 2014; Brown, 2015; Torfing, 2015a, b; Freeman et al., 2018; see also Terrell, 2019a). Carleton & Groucutt’s (2019) mathematical assessment indicates that such frequency analyses provide only an indication of temporal variation in sample frequency and chronological uncertainty and in fact are poor representations of processes changing through time. Added to this mathematical uncertainty are factors which influence the reliability and representative nature of any dated proxy, including problems of differential preservation (Surovell & Brantingham, 2007; Surovell & Pelton, 2016; Surovell et al., 2009; see also Purnell and Donoghue 2005), site disturbance and bioturbation (Williams, 1976; 2019), and site-formation processes more generally (Kroll and Price, 1991; Martinez-Moreno et al., 2016; McLaughlin, 2018). The above represent just some of the limitations of Summed Probability Distribution (SPD) analyses, as outlined by Smith et al. (2008).

Contemporary and post-depositional processes are a critical aspect of any statistical approach used to explore past human-behavioural dynamics (Achino & Capuzzo, 2015; Contreras et al., 2018). Unresolved reworking forms a genuine limitation of all statistical analyses, and it needs to be
understood and acknowledged in any associated interpretation. Of the five biases and uncertainties in SPD analysis identified by Carleton & Groucutt (2019), two are technical and regard the derivation of ages, being i) the quality of the dates themselves (see also Bird, 2013; Becerra-Valdivia, 2020) and ii) artefacts generated from the age-calibration process (Wiener, 2012; Manning et al., 2018). There are also iii) cultural factors, whereby variations in cultural, technological, and economic conditions influence the accumulation of carbon (Rick, 1987), leading to somewhat circular reasoning in SPD analysis.

In this paper, we complement Carleton & Groucutt’s (2019) analysis by focussing on the geoarchaeological context and associated issues. These mainly relate to the final two of the five biases, being iv) sampling bias, in which the data are inherently geographically and geomorphologically biased by a wide range of factors, amongst which are high-density sites, relatively accessible sites, and sites studied associated with potential developments, and v) taphonomic bias, whereby the sedimentary and archaeological record is biased towards periods of greater sediment accumulation, so that periods with less accumulation, stasis or erosion are under-represented. We argue for a considered pause in the use of SPD analysis until these limitations are dealt with, and especially until the physical processes are better understood (see also Cunningham & MacEachern 2016; Carleton & Groucutt, 2019). We revisit, update and repeat many earlier pleas (Williams, 1976; Dean, 1978; Brunsden & Thornes, 1979; Stern, 1993; Holdaway & Wandsnider, 2008; Clarke, 2014; Rehfeld & Kurths, 2014) for archaeologists to return to greater acknowledgement and use of the basic physical driving forces, processes, systems and connections that have created the archaeological record. Understanding physical processes not only contributes to the reconstruction of past human and environmental histories, but it is also essential to decoding what that behaviour was, and then ascribing any significance to it (Robins et al., 2015, p. 203).

Focusing on the geoarchaeological context, we begin with a consideration of the nature of the sedimentary record in relation to archaeology, including issues of depositional and stratigraphic ‘completeness’ (Tipper, 1987; 2015; Paola et al., 2018; Karkanas & Goldberg, 2019). We then review the Australian usage of age data to address some of archaeology’s grand challenges and describe some common flaws in their use. We conclude this paper by offering some practical considerations for future analysis and interpretation of large radiocarbon datasets.

2. TIME-AVERAGING AND THE NATURE OF THE SEDIMENTARY RECORD

The application of time-series analysis to archaeological radiocarbon datasets is broadly like palaeontological use of the fossil record (Connor, 1986; Hannisdal & Liow, 2018). In both cases, attempts are often made to explore past changes and to explain processes of change through an implicit or explicit correlative approach (see also Coombes & Barber, 2005; Blaauw, 2012; Contreras, 2016). Further, both are complicated by the need to disentangle temporal processes from the stratigraphy or at
least know the degree of complexity within the time-period of interest (Kidwell & Flessa, 1995; Mallol & Hernandez, 2016). This is far from easy, for many reasons, and especially because the stratigraphic record can vary along a spectrum between recording everyday sedimentary processes that involve the opposing processes of vertical accumulation and erosion, and recording episodic sedimentation events. At any point along this spectrum, there can be significant “diastems” – periods of depositional stasis – which may actually be the dominant state (Tipper, 2015; Paola et al., 2018; c.f. Dott, 1996). Where accumulation is interrupted by diastems, the resulting stratigraphic succession – and hence the preserved archaeological record, is as complete as that sedimentary record can ever be (Tipper, 2015) – it is in no way fragmented, incomplete or damaged. This means that the sedimentary record, and any associated archaeological proxy, will tend to document ‘events’ or episodes of sediment accumulation, which may not necessarily be representative of the most common conditions present in the environment and experienced by its occupants.

There are cultural parallels in the suggestion that cultural change ‘comes with a spurt’ in surges between inert phases (Ogburn & Goldenweiser, 1927:74). Building from this, Fernandez-Armesto (2015, p. 217) observes that “we cannot expect to see accelerating [cultural] change and the reasons for it clearly except against the background of normal, long-term stasis”. As the preserved cultural record is highly dependent on the sedimentary archive (Farrand, 2001; Ward & Larcombe, 2003), it makes sense to understand both the short and long-term temporal resolution of that archive. This means more than simply establishing a chronology. It means actually defining the various processes that lead to net sediment accumulation and which delimit the time resolution most appropriate to archaeological interpretation and explanation (Stern, 1993, p. 205; see also Perreault, 2018). This provides the fundamental basis from which to begin to understand the time-averaged distribution of physical materials (e.g. charcoal, shell, stone artefacts) extracted from within strata (Figure 3).

Take the example of a shelf sedimentary unit that is formed from a mixture of shell or artefacts that previously represented a continuous 1000-year record. This record will have the same degree of age-mixing as one that mixes material from two short time-intervals separated by a 1000-year gap but will have a completely different internal completeness (Figure 3; see also Kidwell & Flessa, 1995; Kowalewski & Bambach, 2003), such as for the shell mounds at Weipa, western Cape York (Brockwell et al., 2017). Without more information, such units are not able to be correlated with confidence. Similarly, middens located on a shallow-gradient coastline and continental shelf are generally likely to contain a relatively narrow age range of shells, in contrast to those from steeper parts that were closer to the coast for longer and hence are more likely to have been used for longer (see also Flessa & Kowalewski, 1994).
Whilst archaeological sites are often defined by density characteristics and depositional resolution, SPD analysis based on the spatial distribution of sites inherently incorporates stratigraphic resolution (Figure 3). Stratigraphic resolution is defined using correlative depositional units and their bounding diastems (Kowalewski & Bambach, 2003), and stratigraphic resolution may be improved by overlapping and combining such units (Straub & Foreman, 2018). Where depositional equivalence cannot be demonstrated, it is not justifiable to combine data from separate units. Across a wide range of inland, coastal, estuarine, deltaic, shelf settings, there are many processes which can produce similar degrees of stratigraphic completeness or incompleteness (Kidwell & Flessa, 1995; Sommerfield, 2006; Holdaway & Fanning, 2014; Davies et al. 2016), with stratigraphic incompleteness the norm for the majority of shallow-marine environments, including in strongly tidal estuarine and deltaic systems (Sommerfield, 2006; Larcombe et al., 2018).

Further, any statistical frequency analysis that pools data from multiple sites is unlikely to be able to identify the presence of sedimentary lags or condensed deposits (equivalent to the archaeological palimpsest of Bailey, 2007) (see also Kowalewski et al., 1998). Nor is it possible to simply combine multiple dates from a single cultural feature, layer or phase to try and account for a condensed record, because this may be biased by what dates are included or excluded (Becerra-Valdivia et al., 2019). Although SPD analysis is often used to propose the existence of chronological gaps in the archaeological record (e.g. Williams et al., 2015a; Barberena et al., 2017), it is likely to be exceedingly rare for SPD to adequately define them, even at a local level. Too often, such SPD studies make a cultural inference without full consideration of natural processes that may explain any apparent gaps (Ward & Larcombe, 2003; Larcombe & Ward, 2018).

Ultimately, we can only normalise archaeological (or similar) data and begin to link radiocarbon dates with human populations if we develop a more integrated understanding of stratigraphic resolution and the time–space dynamics of sedimentary deposition and preservation (Paola et al., 2018; see also Torfing, 2015b). Without such an understanding, it is simply inappropriate to correlate or extrapolate within or between different environmental settings or archaeological sites. This remains the case even if dates were representative of demography because sedimentary processes – and intervals between events – may operate at different temporal scales, so that simply using dates as demographic data can lead to circular reasoning (see also Stern et al., 1993; Contreras, 2016). Rather, archaeologists need to return to the basics of linking broad landscape processes to those that operate within individual sites and their associated cultural contexts (Ulm, 2013; Contreras, 2016; Contreras et al., 2018).

3. THE AUSTRALIAN RADIOCARBON DATASET

3.1 Paleoenvironmental change in Australia
At present, the oldest record of human presence upon the Australian continent is dated at around 65 ky BP (Clarkson et al., 2017; Malaspinas et al., 2016; Veth et al., 2017), though more recently occupation back to 120,000 ky BP has been touted (Bowler et al., 2018). Through this full glacial cycle there have been a wide variety of physical and biogeographic changes (e.g. Figure 4) on the Australian continent and its coastal regions, associated with changing climate, sea-level and solar insolation (Johnson et al., 1999; Kuhnert et al., 2000; Hesse et al., 2004; Fitzsimmons et al., 2013; Reeves et al., 2013; Wyrtwoll & Miller, 2001; see also Whitley et al., 2018 for a visualisation of some of these changes in NW Australia). Combined, these changes mean that at any particular time, there are a great number of complex spatial gradients of erosion, sediment transport and sediment accumulation across the continent; and also that for any single location through time, there have been a variety of changes to sedimentary processes and geoarchaeological context (e.g. Larcombe et al., 2018). Further, archaeological data derived from these sedimentary contexts are inherently complicated, often representing poly-temporal, palimpsest deposits, formed by a suite of natural and cultural processes operating at a variety of scales (Dunnell & Dancey, 1983; Bailey, 2007; Holdaway & Wandsnider, 2008). This means that, because of the often-weak understanding of the physical processes that produced and preserved these records (Ward & Larcombe, 2003; Holdaway & Fanning, 2014), it is generally only defensible to make interpretations that are site-specific and may be limited in scope, rather than able to be generalised across a region or time period (see also Arponen et al., 2019).

3.2 The AustArch database

The AustArch database (Williams, 2012 and references therein; Williams et al., 2014a) was the first comprehensive synthesis of archaeological ages for Australia, building upon an earlier collection of data by Smith et al. (2008). It contains over 5,000 radiocarbon age determinations (modern to >51,000 yrs uncalibrated) and over 470 non-radiocarbon age determinations (modern to >450,000 yrs) from nearly 2,000 archaeological sites across Australia, with most dates concentrated along the periphery of the continent (Figure 5). The data in the AustArch database derive from publications dating back to the late 1950’s and early 1960’s (Williams et al., 2014a) for which methods of recovery, recording and pre-treatment may be poor relative to those of today, hence the data should be treated with extreme caution (Pettitt & Zilhão, 2015; Becerra-Valdivia et al., 2020). Most sites in the database have low-medium temporal resolution (75% of sites have <15 samples/ka) and most (73% of sites) also derive from deposits younger than 14 ky BP.

The AustArch depositional contexts are mostly rockshelters (44%), coastal middens (22%) and open sites (18%), with the remainder being contextually-undefined rock-art, hearth/oven mounds, fish-traps or burial sites (Williams et al., 2014a). The dataset is particularly useful in highlighting several areas across Australia where archaeological knowledge – and hence also depositional resolution – is minimal, with almost three-quarters of the continent’s bioregions (i.e. ~5.9 million km²) each containing fewer
than 50 ages (Figure 5). In other words, there is an extremely poor understanding of the regional variability of what the archaeological record is or might be. Smith et al. (2008, p. 392) had argued that the broad scale of the early version of the dataset made it possible for comparisons to be made between areas of different geomorphology, and to examine trends derived from a range of different site types, and later, Williams et al., (2014a: 3) stated that “the complete dataset has special value in allowing trends across an entire continent to be tracked.” Unfortunately, even if questions of biases and reliability in the dataset itself are ignored (see Blaauw et al., 2018; Bocerra-Valdivia et al., 2019; Carleton and Croucutt, 2019), the views of Smith et al. (2008) and Williams et al. (2014a) are both incorrect because they implicitly assume that the processes that create and preserve the archaeological record are the same, or at least largely similar, across the continent and through time - this is not the case.

The issues of how much of the archaeological record is preserved and can be seen or detected are of international concern (e.g. Frederick & Krahtopoulou, 2000; Ayala & Fitzjohn, 2002; Gouma et al., 2011; Holdaway & Fanning, 2014) and differences in physical processes and associated stratigraphic resolution between sites and between regions are enormous. Such differences cannot be treated simply as low-level noise and averaged away (Lowe, 1981; Silva & Steele, 2014, p. 610; Larcombe et al., 2018). The conclusion is inescapable – namely that it is impossible to make meaningful correlations and trends between sites, especially at a continental scale, without acknowledging and understanding preservation bias and stratigraphic resolution. Whilst there remain assertions or assumptions that biases in the radiometric records are insignificant and that SPD analysis is effective (e.g. Chaput & Gajewski, 2016; Bluhm & Surovell, 2018) these are spurious.

### 3.3 Application of SPD analysis to grand challenges in Australian Archaeology

As in other parts of the world, SPD analysis of the Australian radiocarbon database has been applied to key aspects of archaeology’s “grand challenges”. Specifically the applications include: i) Late Holocene population growth, expansion and increased cultural complexity, ii) the human control of fire and land management by past occupants, iii) human settlement patterns and climate change, iv) human use of refugia, particularly during the Last Glacial Maximum (LGM), and v) demography and sea-level change during the most recent transgression (Table 1, columns 1 and 2). Below we note each application in turn, identifying the issue, what has been done and the main pros and cons. Table 1 (column 2), summarises some of the common sources of uncertainty in the Australian SPD work.

i) **Late Holocene population growth, expansion and increased cultural complexity** (Key papers: Williams et al., 2015c; see also Johnson & Brook, 2011)

The issue. On the basis of continental-scale studies of radiocarbon age determinations, the Late Holocene in Australia has been viewed as a period of demographic expansion and growth, greater
sedentism and increased social and technological complexity (Johnson & Brook, 2011; Williams, 2013). Such views have not gone unquestioned (Attenbrow, 2006; Morgan, 2015; Vaesen et al., 2016; Davies & Holdaway, 2017). Critics argue that consideration needs to be given to the succession of processes that occurred in the past, including the time-averaging effect of near-surface reworking (Bateman et al., 2007; Davies et al., 2016), and time-dependent degradation of inorganic and organic deposits (Marwick 2009; see also Behrensmeyer, 1988; Jablonksi et al., 2003). Studies elsewhere also point to understanding sites within the context of changing local geography, ecology and history over time, rather than through the lens of sociocultural complexity (Stewart et al., 2020).

**What was done.** Combining SPD of archaeological radiocarbon data with geospatial techniques, Williams et al. (2015c) aligned measures of continental-scale demographic change and late Holocene intensification with major climatic events including the Holocene climatic optimum, El Niño Southern Oscillation (ENSO), Medieval Climatic Anomaly (MCA), and Little Ice Age (LIA).

**Pros.** Williams et al. (2015c, p 18) explicitly acknowledge a number of limitations in the analysis, including the use of radiocarbon data as a proxy, limited data in some time slices, automated processes, and disregard for local environmental situations [our emphasis].

**Cons.** In the SPD analysis, those archaeological sites with two or more radiocarbon ages in each 500 yr time-slice were considered to reflect longer residence times and/or more permanent occupation, particularly in the late Holocene. Long-term sediment accumulation rates in rockshelters – the main type site used in this statistical analysis - may range between 3 and 15 mm/1000 years (Farrand, 2001; Ward et al., 2006). Hence a 500 year time-slice might equate to a deposit 1.5 – 7.5 mm thick, which is less than the typical excavation spit depth (2 – 5 cm) and smaller than most depths of reworking (Grave & Kealhoefer, 1999; Ward et al., 2017). Thus, although testing is laudable, given age data of such limited resolution, it appears highly optimistic to even claim to “produce a first-order framework for researchers to test” (Williams et al. 2015c, p. 12). No caveats were provided in Williams et al.’s (2015c) conclusions.

**ii) Human control of fire and land management by past occupants over the last 20,000 years**

(Key paper: Williams et al. 2015a).

**The issue.** The nature of humans’ past interactions with fire remains topical in various parts of the world (e.g. Bowman et al., 2011; Codding & Bird, 2013; Matlack, 2013; Iglesias & Whitlock, 2014) including Australia (e.g. Portenga et al., 2016; Bliege Bird et al., 2008; 2016 and references therein). Sedimentary charcoal is widely used to indicate fire history, but specific links with Aboriginal burning on the landscape remain tenuous (Mooney et al., 2011).

**What was done.** Sedimentary charcoal “influx” (with units of particles/cm²/yr) was used to explore human-fire interactions over the last 20,000 years. The study was based on “statistically robust cross-correlation of archaeological [uncorrected] radiocarbon data (n = 4102 ages from 1616 sites)” with a
“synthesis of charcoal records [from a wide variety of lakes and lagoons situated across the continent] (n= 155 sites)”. Data were compared to some climatic changes associated with ENSO and the Antarctic Cold Reversal (ACR).

Pros. If some level of coherence can be found between charcoal proxy records and available independent archaeological evidence (Mooney et al. 2011, p. 41), it might be possible to develop hypotheses about these relationships and the response to fire, including the critical factor of human behaviour (Benton et al., 2006). As a proxy of past fire events, Williams et al. (2015a, p. 50) acknowledged that charcoal data are confounded by several inter-connected issues including fuel load and type, proximity of the fire to the site of deposition, and disturbance and differential preservation (see also Bird, 2013; Whitlock & Larsen, 2001).

Cons. Williams et al. (2015a, p 50) indicated that consideration would be given for “any change in charcoal (not just an increase or decrease) in the statistical examination of the relationship between fire and people”. However, such consideration is not apparent in their results or discussion sections. Further, Williams et al. (2015a) found a positive cross-correlation of the radiocarbon and charcoal datasets with some climatic changes associated with ENSO and the Antarctic Cold Reversal (ACR), whereas previously, Mooney et al. (2011) used the same AustArch dataset and charcoal data but had associated charcoal peaks to different climate factors. Given such uncertainties and selective correlations, we agree with Williams et al. (2015a, p. 56) that the archaeological and charcoal data have no relationship to each other at a regional or continental scale. Indeed, based on a study in Australia’s Western Desert but with wider applicability, Bliege Bird et al. (2016) demonstrated that links between radiocarbon and charcoal datasets are questionable because of the impossibility of decoupling human from climatic drivers of fire-regime change.

iii) Human settlement patterns and climate change over the last 35,000 years (Key papers: Williams et al., 2014b; 2015b) and in the last two millennia (Key paper: Williams et al., 2010)

The issue. The interpreted distribution of humans and/or their apparent settlement patterns is often derived from archaeological assessments of site distribution and artefact density, and is used to provide a regional perspective on behavioural change in response to the natural environment. However, the precise ways in which climatic and environmental thresholds impinge upon human life remain debated (Coombes & Barber, 2005; Faulseit, 2015; Arponen et al., 2019). Furthermore, to study human-environment interactions, there is a critical need for proximal palaeoclimatic data, which is lacking in many regions (Williams et al., 2015b, p. 91).

What was done. In a particular region or environmental ‘zone’, a change in the number of documented sites in a particular area, the amount of material at individual sites and/or number of radiocarbon dates
in specific time periods have been used to interpret the redistribution of humans in response to climatic variation. In one study, 5044 radiocarbon dates from ~1750 archaeological sites were used to develop regional time-series curves of human demographics for temperate, tropical, interior and Southern Ocean sectors of Australia to compare against regional and continental-scale palaeoclimatic data compiled by Reeves et al. (2013). In a more focused study, Williams et al. (2010) performed SPD analysis of 1275 radiometric ages from 608 archaeological sites across northern and central Australia and used results to correlate with climate variability over the last 2 ka, and in particular with the transitions of the El Niño–Southern Oscillation (ENSO), as determined from a range of palaeoclimatic data.

Pros. The work identified some geographic areas and temporal periods where chronological data is sparse and warrants attention. The studies acknowledge that ‘taphonomic loss of sites’ remains an issue, with Williams et al. (2015b) attempting to apply statistical correction procedures to address these.

Cons. Whilst Williams et al. (2010, p. 833) correctly acknowledged that “differential archaeological survivability and preservation” may impact the distribution of age data, they then implicitly used the variability of such features across Australia to validate the available dataset. Such false logic was also used by Riris and Arroya-Kalin (2019). The corrections do not account for punctuated environmental change – and by inference episodic sedimentation – nor for loss of coastal sites through inundation (Williams et al. 2015b, p. 107).

It was acknowledged that humans do not mechanistically respond to environmental (and by inference palaeoclimatic) change, but the results and interpretations are nonetheless “spatially and temporally correlated with the archaeological changes and causally linked through their impact on subsistence and settlement systems” (Williams et al., 2010, p. 835). Williams et al. (2010) also applied the results of a local study of cyclone effects on a single spit in a north Queensland embayment (Bird, 1992) to the wider part of Australia – this is inappropriate on sedimentological grounds, because different parts of a coastline might be altered by cyclones in completely different ways depending on a variety of physical factors (Woodroffe & Grime, 1999; Nott, 2006; Larcombe & Carter, 2004; Larcombe et al., 2018). Flooding and storms are viewed by Williams et al. (2010) as having disrupted past human subsistence patterns but the critical underlying impacts on sedimentation and archaeological site formation are overlooked.

iv) Human use of refugia – well-watered ranges and major riverine systems – particularly during the Last Glacial Maximum (Key papers: Williams et al., 2013; 2014b; 2015b)

The issue. It is proposed that at times of climatic or resource stress, people tended to migrate to isolated locations, termed refugia, where water and other resources were more reliable (Veth, 1993; Smith, 2013; Langley, 2014; see also Reynen et al., 2018 and references therein). Upland ranges, lowland riverine
and gorge systems, separated from sand-ridge deserts, are argued to have been particularly important refugia for human survival during the LGM.

What was done. Williams et al. (2013) explored the refugial claim for the Late Pleistocene, using 477 radiocarbon dates aged between 25 and 12 ky BP from the AustArch database. The low number of dates meant that the demographic study was considered preliminary. A later study explored the refugia concept at a local level, with Williams et al. (2014b) comparing absolute age dates from excavations across a ridgeline near the Hawkesbury River (near Sydney, New South Wales) with the demographic model of Williams (2013). The local age data filled a gap in the continental-scale radiocarbon age record and was argued to partially support the idea of the Sydney Basin region as a refuge area.

Pros. Like the palaeoclimatic study (Williams et al., 2015b), the continental-scale refugial study identified geographic areas for future research including possible distinctive refugia or microhabitats. The analysis is consistent with previous ideas (e.g. Veth, 1993) but still requires appropriate field testing to “confirm/refute their assignment as refugia” (Williams et al., 2013, p. 4623). The Hawkesbury River study (Williams et al., 2014b) forms a partial test of this for the Sydney Basin.

Cons. In the local Hawkesbury River excavation, a ‘pulse of occupation’ between ~12 and 8 ka in the excavation was suggested to have occurred, and interpreted as the result of population pressure following sea-level rise, which rise also supposedly cut access to gravel deposits use for stone tool manufacture, leading to abandonment of the site around 8 ky BP (Williams et al., 2014b, p. 745–746). The data does not support such interpretations, indeed it indicates a relatively condensed deposit in the older, deeper part of the sequence and more dispersed in the younger part of the sequence where the sediment accumulation rate is higher (Figure 6). Therefore, natural processes appear able to explain the cultural record without the need to invoke any cultural explanation.

More broadly, across many arid regions of Australia, terrestrial (palaeoclimatic) data that span the LGM and deglaciation are sparse and are limited to discontinuous sedimentological and geomorphological records with relatively large chronological uncertainties (Treble et al., 2017). It follows that palaeoclimatic and chronological data are also likely to be discontinuous and of uncertain age, so cannot be assumed to form a valid proxy for demographic trends. Whilst it may seem logical for regional occupation records to follow long-term trends in water availability, testing this hypothesis requires that both archaeological and non-archaeological data are able to reflect i) the scale of human decision-making and behaviour and ii) the nature of the local environment (Phillips, 2013; see also Haynes, 2001, p. 129; Contreras et al., 2018). There are also large biogeographic zones less than optimal for ongoing human occupation that might hold vital data on human dispersal across them (Leppard & Runnels, 2017), between or towards refugia. Due to the aggregated nature of the age data, frequency analysis of radiocarbon ages does not contain enough information to ultimately resolve those mechanisms that
might link environmental variation with human behavioural dynamics (see also Knape & Vlapine, 2011, p. 991). We conclude that whether and how Pleistocene populations across Australia might have been influenced by climatic and environmental change (Williams et al., 2013; 2015b) remains largely untested.

v) **Demography and sea-level change during the most recent transgression** (Key paper: Williams et al., 2018).

**The issue.** Routes of human migration to Australia and the developmental changes of Aboriginal populations through time necessarily involves the recognition of past sea-level changes and their influences upon environments and human activities (Groucutt et al., 2015; Bird et al., 2016; Westaway, 2019). Radiocarbon-date proxies have been used to explore climate-driven fluctuations in sea-level (Geyh, 1971; 1980) and associated human demographic change (e.g. Abe et al., 2016).

**What was done.** Williams et al. (2018) examined possible links between past sea-level changes and inferred human demographics across continental Australia associated with the Post-Glacial transgression.

**Pros.** The work generated archaeological hypotheses that could be tested with appropriate field sampling and analysis.

**Cons.** There are no archaeological data for the c. 30% or more of Australia’s landmass lost by sea-level transgression (Larcombe & Ward, 2018). The age data used were only radiocarbon in nature, divorced from their sedimentary contexts, and the method of their combination with bathymetric and sea-level reconstructions took no account of the then sedimentary environment or potential site formation processes. The relevant sedimentary deposits are either no longer present or have not yet been sampled and understood, so all these key factors remain absent from the chronological dataset or the inferred demographic one. Finally, Benton et al. (2006) explain that for understanding population dynamics of any given system, the devil is in the detail, yet for coastal Australia during the transgression, there are no demographic data whatsoever.

**4. FLAWS IN THE USE OF SPD AND ‘BIG DATA’ FOR EXPLORING CULTURAL CHANGE**

As noted above, whilst offering a range of hypotheses to be tested, some of the Australian SPD papers suffer significant flaws, a situation largely married elsewhere. Focussing on sampling and taphonomic bias, below we consider some of the key issues in the use of large radiocarbon datasets for exploring cultural change in Australia and elsewhere around the world. As our framework, we use generic main phases of research projects:

a. defining the research questions, the logic and then the general approach;
b. choosing sampling and other investigative techniques;

c. clarifying the study assumptions, biases, uncertainties, and associated limitations;

d. designing appropriate data analysis;

e. undertaking data interpretation in the clear light of the uncertainties and limitations, and;

f. forming conclusions and commenting on the broader significance of the work.

In this framework, use of “big data” is mostly an investigative technique, used as part of addressing a specific question or set of questions. We have analysed a wide variety of radiocarbon-age-based papers and their underlying premises, using our focus on sampling and taphonomic bias to identify flaws, clarify problems and note some of the consequences. Below use the above research phases to consider these issues. Whilst there is clearly considerable overlap between these phases, the first is by far the most important.

4.1 Defining the research questions, the logic and then the general approach

These aspects control most other project phases. There are many examples of studies that set out to i) examine demographic patterns as implied from SPD analyses for a particular period and region or set of regions (e.g. Crombe & Robinson, 2014; Goldberg et al., 2016; Zahid et al., 2016; Barberena et al., 2017; Brown & Crema, 2019; Riris & Arroya-Kalin, 2019), or ii) to undertake a correlative study with other archaeological parameters to support the use of SPD analyses (e.g. French & Collins, 2015; Palmisano et al., 2017). What can be missing are the questions that set out to understand and explain the human or natural drivers for change in the archaeological record. For the most part, cultural inferences have been made from archaeological data without full consideration of the natural processes that may actually explain the data by themselves. Hence some major problems in use of SPD and inferred demography stem from not setting out to obtain a sound understanding of the temporal and spatial variability of sedimentary environments, potential occupation sites, site formation and preservation processes (e.g. Phillips, 2013; Robins et al., 2015; Davies et al., 2016; Toffolo et al., 2016; Larcombe & Ward, 2018). In many cases, issues of ‘differential archaeological survivability and preservation’ (Williams et al., 2010; 2013; 2018) and effects of ‘local environmental and resource factors’ on the preserved archaeological record (Williams et al., 2013, p. 4623) are generally poorly identified and explained.

For those coastal regions of Australia where there is an apparent absence of archaeological sites older than mid or late-Holocene and other older periods of relatively low sea levels, there is a need to define tests to determine whether this result is a result of differential preservation or might genuinely reflect absence of occupation. In Williams et al’s (2018) study, the interpreted movement of people inland in response to sea-level rise is based on the simple binary opposites of presence or absence of sites. Yet as Phillips (2013, p. 212) noted, if human presence or absence alone is employed as the proxy for
climatic change, any hypothesis that climate drove processes of human occupation, mobility or abandonment is actually untestable. Aside from the vast areas of Australia’s landmass drowned by the Post-Glacial transgression (Williams et al., 2018), modern Australia has over 8000 islands (depending precisely on how they are counted (Low, 2011) and many more drowned bathymetric highs. At present, there is little knowledge about what proportion of the changing transgressive coasts and islands were both suitable for site use or occupation and were of high preservation potential. Small-scale but possibly significant and/or short-term events of maritime dispersal and island occupation may also be overlooked (Leppard & Runnels, 2017). We can conclude that the potential significant role of islands in post-glacial and transgressive life and occupation is not well understood at present (Erlandson & Fitzpatrick, 2006; Rowland et al., 2015; Ward & Veth, 2017).

Many published SPD analyses omit discussion of episodic sedimentation events that might have influenced the preservation of artefacts or associated environmental data. Williams’ et al. (2015a) charcoal data, for example, was normalised by a ‘sample deposition period’ calculated using a depth-age model at each site. Such depth-age models are themselves problematic because they assume, amongst other things, that the overall sediment accumulation and erosion patterns are well approximated by the net rate (Trachsel & Telford, 2017). Further, and critically, SPD analyses rarely account for diastems, yet the significance of gaps in the records and of changes in accumulation rates remain fundamental to almost all branches of archaeology (see also Ward & Larcombe, 2003; Wallach, 2019). Thus, a variety of interpretative issues can be an inevitable result of not considering context, logical tests, and forming a clear approach.

4.2 Choosing sampling and other investigative techniques

Whereas archaeology has learned that ‘pots do not directly equal people’, the discipline remains unsure what the distribution of similar elements of material culture across a landscape does equal (Parkinson, 2006, p. 33). Ecological, ethnographic, and archaeological data have all been used to estimate past population density (see Müller & Dichenko 2019) but should be viewed cautiously when inferring any temporal change. Chronological and numerical datasets no more reflect population, ancient migrations or dispersals than do genetic data - they are all simply samples (see Terrell, 2019a).

In Australia, stone tools make up most of the archaeological record in Australia, but tool numbers alone cannot reflect population (or ‘intensity of site use’) or mobility. More informative is the use of combined measures, such as selection and discard, tool retouch and use, core reduction and artefact transport (Ditchfield, 2018). The lithic record, however, is not the only indicator of occupation. At Gledswood Shelter 1, magnetic susceptibility studies reveal initial signs of human occupation (heated sediments) earlier than the first appearance of stone artefacts or even charcoal (Lowe & Wallis, 2020). When combined with the archaeology and analysis of sedimentary characteristics, geophysical survey
results can assist in understanding stratigraphic associations, site formation processes and roof fall events – including those in which stone artefacts may be concentrated (Lowe & Wallis, 2020).

Consideration also needs to be given to the surrounding regional variation in available resources, such as whether they are homogenous or heterogenous (see also Boone, 2002; Whallon, 2006; Clarke, 2014). Important parts of the archaeological record are “off-site”, i.e. at locations with little or no cultural or chronological trace, including those i) locations of a small-scale and short-term nature (e.g. Leppard & Runnels, 2017), ii) areas outside resource-rich zones (e.g. Marsh et al., 2018), and/or iii) areas that are culturally undisturbed, such as areas of hunting or seed collecting (Dunnell & Dancey, 1983; Rhoads, 1992; Wobst, 2004; Caraher et al., 2007). Any regional-scale analysis that only uses data from known sites (or visible records) systematically excludes all other evidence of the off-site articulation between people and their environment, so that all studies would benefit from considering areas beyond the local site and its artefacts.

Changes in human activity are not usually contemporaneous with those of the environment (e.g. Mendez, 2019; see also Ferguson et al., 2017), so that attempts to align environmental and demographic proxies should be performed with caution (Blaauw, 2012). Furthermore, studies over longer timescales have established that humans adapt and respond to local variation rather than regional change (Grove, 2011; Donges et al., 2011; Stewart et al., 2019), so it is important to choose reliable proxies sensitive enough to reveal these local variations. For example, regarding fire, investigative techniques might include analysis of charcoal fragment sizes to help account for fire proximity, disturbance and differential preservation (Leys et al., 2013; Vachula et al., 2018), and assessment of off-site dated charcoal records and other variables influenced by fire, such as molecular signatures (Schüpbach et al., 2015) and post-depositional processes (Whitlock & Larsen, 2001; Purnell & Donoghue, 2005). Time-series analysis of charcoal abundance may require consideration of at least two different components, such as a ‘peaks’ component superimposed on a slowly varying ‘background’ component, to be interpreted separately (Whitlock & Larson, 2001), not done by Williams et al. (2015a).

The concept of understanding relatively spiky local changes set against a more slowly varying regional signal applies to charcoal but also to other environmental data, and is relevant for all the datasets on which SPD has been applied. At the same time, use of multi-proxy data (Grave & Kealhofer, 1999) and complementary microanalytical techniques (e.g. Goldberg & Berna, 2010; Mentzer, 2014; Karkanas et al., 2015; Karkanas & Goldberg, 2019), can also significantly improve understanding of local site formation processes versus regional change.

4.3 **Clarifying the study assumptions, biases, uncertainties and associated limitations**
In addition to dedicated research projects, archaeology includes many opportunistic studies from compliance work associated with development activities, with limited opportunity for background research and design beyond asking ‘what’s there?’ In such cases, it is especially important to acknowledge and explain the resulting limitations upon the work’s conclusions. Similarly, the historic tendency, notably in Australia, to define the distribution of cultural material from arbitrary depth ‘spits’ implicitly or explicitly assumes, incorrectly, that records within these necessarily constitute a cultural or functional unit, and such an assumption tends to mask the natural formational context of excavated assemblages (Ward et al., 2016). Rather than a default tendency to interpret observed trends as cultural (Ward & Larcombe, 2003; see also Otte et al., 2003; Arponen et al., 2019), a more pragmatic and rewarding approach is to rationalise the archaeological record in the context of natural formation processes and not dismiss these as unwanted noise (Karkanas et al., 2015, p. 2). There are many good international examples of excavation methods that follow the stratigraphy and take into account time-averaged patterns produced through both natural and cultural processes (e.g. Marean et al., 2010; McPherron et al., 2005; Perreault, 2018; Graf et al., 2019; Reeves et al., 2019).

In some Australian work, there remains weak appreciation of depositional processes, leading to highly doubtful archaeological interpretations, as noted above for Williams et al. (2010). The site of Serpents Glen (Karnatukul) in Australia’s Western Desert, for example, is described as being located in a valley at the head of which there are “no geomorphic processes…to provide significant accumulations of sediment”. At the same time, the site itself is described as subject to alluvial, colluvial and in situ weathering processes, with the medium to coarse sands described as predominantly aeolian in origin (McDonald et al. 2018, p. 2). Given this confusion about physical driving processes and significant time-averaging in the deposit, it is difficult to see how the sequence here “recalibrates important features of the arid zone time-series data (Williams et al. 2015b) and confirms aspects of the relationships between site occupational intensity and phases of climatic amelioration” (McDonald et al., 2018, p. 30).

At cave sites in the Kimberley and Southeast Asia, archaeological work has arrived at notions whereby human occupation has the capacity to increase in situ weathering and natural sedimentation processes for multiple millennia (e.g. O’Connor et al., 2017; Louys et al., 2017) or alternatively to limit or even pause them (e.g. Reynen et al., 2018). Again, it is difficult to see how these assumptions are tenable without sedimentary justification. Whilst in arid settings, occupation can sometimes be correlated with phases of dune stabilisation and reduced net sediment transport (Karkanas & Goldberg, 2019), occupation per se does not limit natural sedimentary processes. In caves and rockshelters, human activity can certainly favour the addition of cultural material within mineral sediments that have been accumulating slowly for centuries or millennia. In some cases, this leads to
condensed deposits of low net sediment accumulation rate, with important implications for interpretations of cultural complexity (e.g. Butzer, 1981).

Some biases are implicit, such as the apparent confidence in demographic indices derived from positive correlations of age data with other archaeological indices, such as artefact discard rates (Williams et al., 2013; 2015b, c) although these are not mutually exclusive. Such apparent correlations may simply reflect a depositional or post-depositional association, rather than demonstrate a direct or ‘functional (cultural) association’ (Taylor, 1987; Parkinson, 2006). These aspects require acknowledgement, so that study uncertainties and associated limitations become clear.

4.4 Designing appropriate data analysis

Whether age data are derived from based on high-density sites, low-density sites or off-site contexts, it is clear that each produces different datasets and thus potential interpretations of cultural landscapes (Rhoads, 1992; Stern et al., 1993). Further, only when archaeological or age distributions are analytically separated from the effects of post-depositional processes do they become useful data (Dunnell & Dancey, 1983, p. 270). Time-dependent degradation of chronological data cannot be dealt with through statistical analysis alone Torfing (2015b) - it requires appropriate knowledge of geographic context and sedimentary history (see also Silva & Steele, 2014; Robins et al., 2015).

It has been suggested that time-dependent preservation bias might be measured and removed from archaeological SPD analyses through comparison with measured ages of related geological surfaces (Surovell & Brantingham, 2007; Surovell et al., 2018) such as tephras. Whilst worthwhile to provide contextual inform and inform interpretations, this concept of "correcting" the data relies on two assumptions: i) there is post-depositional equivalence between the site and related geological surfaces, particularly for erosion (Johnson & Brook, 2011) and ii) there are constant preservation conditions over time (Ballenger & Mabry, 2011). For arid southwestern Australia, Davies & Holdaway (2017) use lithic and combustion features to neatly demonstrate that neither assumption is valid. Regardless, the data analyses of Williams et al. (2013; 2014a; 2015a, 2015b; 2018) used neither this correction nor any alternative (e.g. Ballenger & Mabry, 2011).

As noted by Williams et al. (2018, p. 3), SPD analyses are likely to be more robust for time periods or geographic regions that are more well-studied (i.e. are more visible and/or have more radiocarbon data). There is also an implicit view that a larger sample size provides a more complete record and/or reduced error, leading to arguments for more targeted dating of specific chronological or culturally-transitional periods, or of understudied areas (e.g. Delgado et al., 2015; Abe et al., 2016). However, as well as

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2 Timpson (2015) similarly pointed out that a strong correlation may exist, say for example between ice-cream sales and murder rate, or shark-attack rate and sandal-wearing, because each are affected by temperature, but this does not justify either as a good proxy because neither is the direct cause of the other and the relevant processes are ignored.
depending on the number and accuracy of the dates themselves, reliability also depends on precisely how the dates are associated with their depositional and cultural contexts (Phillips, 2013). This analytical problem becomes larger for data derived from studies that lack such context – this might be a particular issue for studies that use ages obtained by data mining.

Bevan et al. (2017) compiled 30,000 archaeological dates and numerous high-resolution palaeo-ecological archives to explore human population dynamics across four different geographic regions during the middle and later Holocene. Compared to the AusArch dataset, this equates to six times the number of dates for a landmass only 20% of the size of Australia, and for a much shorter time window. Very significantly, the dataset includes a variety of independent botanical and faunal evidence, and such a multi-proxy approach has many distinct advantages to help assess human activity. However, interpretations made from even this impressive dataset could be improved greatly by analysis that takes some account of the different sedimentary environments and deposits and of the surrounding non-archaeological (off-site) contexts. Thus, even in this case, the degree to which the data reflects true demographic change remains uncertain.

4.5 Undertaking data interpretation in the clear light of the uncertainties and limitations and forming conclusions and commenting on the broader significance of the work.

As noted above, the power of identifying uncertainties and limitations is in using them to realistically influence data interpretation and assess the overall significance of the research. In a series of papers, Williams et al. (2013; 2014a; 2015a, 2015b) correctly acknowledge a series of limitations of their analyses, including those associated with sample size, spatial bias and preferential preservation (together forming preservation bias) stating that these “cannot be readily corrected” (Williams et al. 2018, p. 146). Unfortunately, these limitations were largely overlooked in the associated analyses, unaccounted for in their interpretations and conclusions, and unacknowledged in remarks regarding the work’s significance (Phillips, 2013; Attenbrow & Hiscock, 2015; Larcombe & Ward 2018, p. 501). By contrast, a recent case study of Jomon archaeology by Crema & Kobayashi (2020) specifically tried to account for uncertainty. Using data for the period 8,000 - 3,000 cal BP, they compared the relative-age of ceramics and pit-dwellings against SPD of radiocarbon data, concluding that these relative and absolute proxies cannot be compared more closely than 500–1000 years. Whilst noting that the results were context-specific, they argued that similar studies could help explore “the limits and the potential of the so-called “dates as data” approach”.

In many archaeological applications of SPD analyses, statistical corrections (e.g. Surovell & Brantingham, 2007; Surovell et al., 2009; Williams, 2012; Crema et al., 2016), are assumed to be able to account for time-dependent taphonomic loss. We think there is some clear overconfidence in the legitimacy of such corrections. Firstly, taphonomic effects are not limited to loss, but include processes
of redistribution and mixing, but no statistical approach, including the Bayesian statistical packages (e.g. rBacon, Clam, OxCal) can specifically account for reworking. Secondly, such corrections are mostly assumed to apply across regions and different site types (e.g. Barberena et al., 2017), whereas the differences in physical processes and stratigraphic resolution are real, significant and cannot be averaged away (see section 3.2 above). For example, the sedimentary history of cave and rockshelters are not only idiosyncratic (Farrand, 2001) but they vary widely across open sites and other depositional contexts (Ward et al., 2006). We should thus not be surprised that, Barberena et al. (2017) found that corrections produced an over-representation of the early Holocene record that was not supported by quantitative nor qualitative data, and concluded that the correction wasn’t valid. Thirdly, work rarely considers past changes in sedimentary regime to remove their effects. Recently, for South America, Riris and Arroya-Kalin (2019) used statistical procedures to “control for the global effects of taphonomy and first-order spatial processes such as sea level rise”, and chose to assert demographic regime change to explain where the modelling deviated from the ‘expected’. Their work did not consider sedimentary changes. Overall, the value of such work is diminished by these oversights.

As a concluding comment, many key interpretations in these SPD examples have been presented in a way that Terrell (2019a) might describe as ‘plug and play’, or ‘show and tell’, which is where analytical findings are presented and then it is stated how they are to be interpreted, without offering substantive explanation or explicit testing of alternative hypotheses (see also Larcombe & Ward, 2018).

5. HOW TO IMPROVE THE USE OF SPD AND ‘BIG DATA’ FOR EXPLORING CULTURAL CHANGE THROUGH TIME

As emphasised above and elsewhere, the most important step in understanding which processes have driven the patterns of temporal change observed in archaeological records - especially whether cultural or not – is to understand the deposits themselves and how they formed (Davies et al., 2016; Gouma et al., 2011; Karkanas & Goldberg, 2019). Such physical sedimentary understanding allows for appropriate archaeological project design, choice of sampling techniques, and vital context to data interpretation and the assessment of the results’ significance beyond the study site(s). Logically, other things follow, including various methods of delivering appropriate understanding of the preserved archaeological record. Focussing on improving future SPD analyses, below we describe ways to address some of the flaws outlined above, presenting these in order of importance. We summarise matters and indicate examples in Table 1, where we also note the variety of approaches to reduce uncertainties in SPD work, and give examples of international studies that incorporate the most useful approaches.

5.1 Increasing understanding of physical processes and their control on the archaeological record
Whilst spatial and temporal distribution of archaeological records vary through time, in the main, the physics, main mechanisms and signature of the relevant processes do not. Amongst other things, the variable sedimentary effects of mass wasting of rock and slope processes, of waves on coasts, of runoff and rivers upon sediment transport and of wind on dune sands are consistent across time periods, cultures and environments. Following Schiffer’s seminal (1987) book on formation theory, focus has gradually and necessarily shifted from the artefact to the deposit (Shahack-Gross, 2017) and towards the associated sedimentary and anthropogenic processes (Karkanas & Goldberg, 2019). Foci include studies of sedimentary processes themselves (e.g. Chlachula, 2012; Jazwa & Johnson, 2018) and the use of micromorphological techniques for context (Canti & Huisman, 2015; Shahack-Gross, 2017). Such sedimentary studies are critical to assess the scales of physical processes linking the various parts of the sedimentary system in which the archaeology sits (see also Tooth & Nanson, 1995; Woodward & Goldberg, 2001; Karkanas et al., 2015), and hence inform the nature of any correlative SPD analysis or regional modelling undertaken.

Studies of South African Middle Stone Age sites, for example, demonstrate how microstratigraphic analysis can reveal temporal changes in site use and differences between local and regional trends in occupational intensity at resolutions greater than those achievable by radiocarbon dating (e.g. Goldberg et al., 2009; Miller et al., 2013; Karkanas et al., 2015; Romagnoli et al., 2018). This can be aided through comparison of onsite and offsite contexts. Included in this is a critical need to appreciate the sensitivity of different landforms to different drivers and the timescales over which they operate, thereby helping understand associated impacts on site distribution patterns (see also Brunsden & Thornes, 1979; Thomas, 2001; Attenbrow, 2006) and by inference radiocarbon distributions over space and time.

5.2 Improving the dataset – inclusion of geological and sedimentary information

A key step in improving SPD-based interpretation of the archaeological record is to expand age databases to promote a move beyond simple temporal correlation to more broadly based assessments. The various proxies used by archaeologists (e.g. radiometric, artefact, ecological and ethnographic data) are all filtered and biased in various ways (e.g. Castillo, 2018) by factors that themselves vary with depositional setting and time (e.g. see also Purnell & Donoghue, 2005). Even proxies derived from any one type of site (e.g. rockshelter, surface scatter, midden) are unlikely to form an appropriate representation for human activity (Ulm, 2013; French & Collins, 2015; Palmisano et al., 2017). Further, documented archaeological sites are not a random sample of all possible existing sites of their age (see also Torfing, 2015). As Robins et al. (2015) demonstrate for coastal Queensland, even with detailed data from a range of site types, it is a very complex and difficult process to establish the existence of trends independent of site-specific taphonomic and/or environmental factors. Therefore, the
consequences of preservation bias and research bias must be considered for each occupied sedimentary environment, and ideally every site.

As a first practical step, large-scale compilation of archaeological chronologies would benefit from i) information on sites and artefacts (e.g. Anderson, 1990; Faught et al., 1994), and ii) geological and sedimentary information (including palaeoenvironmental data) for context. A number of large datasets exist that do include contextual data, and they include data related to fossils (Peters et al., 2019), geological cosmogenic and luminescence\(^3\) data (Codilean et al., 2018), sea level (Hibbert et al., 2018) and palaeoclimate (AUS-INIMATE, SHAPE\(^4\); Lorrey, 2016). The only archaeological database we are aware of that specifically includes contextual data is that of Bevan et al. (2017).

Careful sedimentary assessment of terrestrial or marine deposits is a huge advantage in determining whether chronological records might be suitable for SPD correlation. One example is a study by Warden et al. (2017) that explored the transition from foraging to farming in northern Europe in the period 7,500 - 3000 cal yr BP. Multiple well-dated, high-resolution marine sedimentary records from the Baltic Sea were used to indicate past regional sea surface temperatures (SST). These records were then combined with SPD analysis of 1960 radiocarbon dates (from 608 archaeological sites) and with independent faunal and archaeological records to provide a convincing record of cultural change, with humans apparently responding to climate within two or three generations. Conversely Robinson et al. (2019) presented a database of 3571 radiocarbon dates from a complex system of catchments in the mountains of Wyoming, in a first-order spatial analysis of past social organisation. Each date was georeferenced, providing great potential to assess geomorphic influences on the deposits, and associated SPD analysis, but the sediments and depositional environments were not mentioned, so that the resulting conclusions on past population dynamics are subject to great uncertainty.

The general absence of contextual data limits our collective ability to interrogate the existing chronological and archaeological record (Phillips, 2013; Mökkönen, 2014; Ward et al., 2016) and to understand what the proxies represent and can reveal about human-environmental dynamics. Across the entire discipline, we recommend those methods of sampling, recording and analysis that specifically support the integration of archaeological, geological and sedimentary data in the interpretative process (see also Phillips 2013, p. 133). Such progress would begin to allow regional correlations or site comparisons i) to be founded on geomorphic and sedimentary principles, and ii) to include one or more sources of independent proxy data (e.g. Williams et al., 2009; Schüpbach et al., 2015), and/or (iii) one or more dating techniques (e.g. Bubenzer et al., 2007; Carleton & Groucutt, 2019; Pettitt, 2019), together providing greater confidence in the interpretations and their significance.

\(^3\) [https://earth.uow.edu.au/](https://earth.uow.edu.au/)
5.3 Increase efforts to acknowledge dataset limitations

Work to increase understanding of the known limits of depositional and stratigraphic resolution is vital to improving the interpretation of the archaeological record. Every stratigraphic sequence and every archaeological site lie somewhere in a broad spectrum that ranges from complete preservation to complete loss, and patchy, low-density sites are likely the norm (Leppard & Runnels, 1997). However, this unevenness cannot simply be improved upon by adding more ages where the environmental record is already ambiguous (Thomas & Burrough 2016), and as Pettitt & Zilhão (2015, p. 527) comment, with large datasets even the smallest fault in assumptions can be magnified greatly.

We therefore promote careful assessment of the temporal characteristics of diastems (Kowalewski & Bambach, 2003) and studies to understand chronological gaps in the archaeological record, particularly because such gaps can be used as negative evidence regarding past human behaviour (Ward & Larcombe, 2003). Even when archaeological inferences from local absence are reasonably secure, generalisations to the broader region required separate justification (Wallach, 2019, p. 9). The above aspects can be aided by combining results from radiocarbon and OSL dating, plus other applicable dating techniques, to help distinguish cultural events from depositional events and to test apparent chronological gaps (e.g. Bubenzer et al., 2007; Hughes et al., 2017). Expanding the range of dating techniques has the further benefit of increasing our understanding of site formation processes.

Careful consideration also needs to be given to low-resolution stratigraphic contexts (Romagnoli et al., 2018), rather than merely applying perspectives from high-resolution sites to these contexts in which the formation processes naturally generate poorly developed palimpsests). Disturbed sites are more common than well-preserved ones and an apparently undisturbed sedimentary profile may not provide a true representation of the local or regional landscape used or occupied by past humans (Cook-Hale et al., 2018; Williams, 2019). Sampling needs to specifically include disturbed sediments and low-density patches of artefacts, because if samples are focussed only on apparently undisturbed stratified sediments and/or high-density patches of artefacts (including condensed deposits), the results are likely to be biased towards the recent (Stern et al., 1993; Ballenger & Mabry 2011; Knape & de Valpine, 2011). The resulting increased temporal and spatial understanding of both high- and low-density sites and their encasing sediments (Stern et al., 1993, p. 204) will improve moves towards developing regional syntheses.

If archaeologists are to use ‘big data’ to address some of archaeology’s most important questions (Kintigh et al., 2014), acknowledging the datasets’ limitations, working to improve them and considering alternative ways of evaluating the accumulated evidence will reduce the chance of misinterpretations. For some archaeologists this may constitute a paradigm shift in research approach.
As Stern et al. (1993, p 215) commented nearly three decades ago, it is only by coming to terms with
the limitations of current interpretive frameworks that archaeologists can begin to address these by
asking new research questions and considering alternative research strategies.

5.4 Simulation studies and understanding of process

Davies (2018) points out that archaeologists cannot experiment directly with many suspected
generative processes because they are long-term, cumulative, often variable over time and space, and
involve subjects that are logistically or ethically impossible to constrain (e.g. humans & ecosystems).
Whilst the use of analogues offers some help (but note the caution from Murray & Walker, 1988),
analogues are problematic applied at the landscape or regional scale and over long time periods.
Social, ecological, formational or other processes that operate at these scales generally rarely leave
discrete residues, although separation of these in archaeological palimpsests is always the ideal
(Romagnoli et al., 2018).

Whilst process-based field studies (e.g. Graf et al. 2019) and high-resolution analyses (e.g.
Kowalewski et al., 1998; Goldberg & Berna, 2010; Canti et al., 2015) are always preferable, we also
promote careful use of computer simulation studies - specifically computational models of change
through time – to help explore the potential influence of past and present physical processes on the
archaeological record. History only runs once but a simulation can run infinite times, allowing the
Present to be explored from a range of chosen past processes or states (Barceló, 2012). Contreras &
Meadows (2014) used simulations to critically evaluate SPD calibrations as a population proxy,
concluding that even if archaeological radiocarbon datasets could be corrected for taphonomic and
research biases, demographic signals would still be difficult to distinguish from statistical noise in any
SPD analysis.

We think that the better use of simulations is in helping differentiate and understand the processes that
form the archaeological record, and ultimately improving interpretations of past human activity. Use
of such simulations should be intentionally experimental, aimed at developing a variety of model
scenarios that can assist hypothesis generation and also inform potential methods of hypothesis
testing. As an example, Davies & Holdaway (2017) and Davies (2018) explored the effects of
episodic surface erosion on the visibility of surface hearths in arid New South Wales (Figure 7) and it
is worth considering the detail of their work. Each of the 4x4 squares represents a plan view of the
same area, at the specified date. For the century 2000 BP - 1901 BP there are a series of surface
hearthers, formed across the area created by human activity, so that by 1901 BP there are 11 surface
hearthers represented across the area, with a median age of round 1950 BP. At 1900 BP a sedimentary
event occurs, which erodes some areas (red) and causes sediment accumulation (blue) elsewhere.
New surface hearths are made over the next century, so that by 1801 BP there are 14 surface hearths
present with a median age of 1850 BP, but no evidence at all of any older hearths. Another event at
1800 BP creates more sedimentary change, and with subsequent hearth formation, we arrive at 1701
BP, 300 years after the first hearth, which, if all surface hearths were dated, an apparent record of
hearth formation would indicate a few very old hearths (around 1900-2000 BP), and most of the
hearths formed between 1700 and 1800 BP (Davies & Holdaway, 2017, p. 140). This would be an
incomplete record, yet ripe for (mis-)interpretation. This simple model elegantly indicates that
patterns like those in the archaeological record (e.g. decreasing frequency of hearths through time, and
occasional gaps) might be produced in a number of ways, influenced by a number of sedimentary
events and processes, and also indicates that virtually any statistical taphonomic model is likely to be
misleading, and to an unknown, even unknowable extent. Another form of experimental simulation is
that of computer visualisation of coastal change, as used in northwestern Australia by Larcombe et al.
(2018), to help explain that a significantly wide range of sedimentary environments and
geoarchaeological outcomes might arise through time because of different dominant drivers of
physical change.

Two key messages arise: i) with increasing accessibility of faster computers, free and well-
documented software, and programming skills, simulations are best used as ‘tools to think with’
(Davies 2018), and ii) it is fundamental that researchers must always demonstrate that any interpreted
‘link between production, preservation, and analysis of datable organic material and population’ will
withstand scrutiny (Contreras & Meadows, 2014, p. 606).

6. CONCLUSIONS

Our review has considered the archaeological use of SPD analyses of aggregated radiocarbon data,
fockussing on the geoarchaeological issues of sampling bias and taphonomic bias, which are largely
controlled by sedimentary processes. The conclusion is clear – too often cultural inferences are made
from SPD analyses without due consideration of natural processes that may explain the data, or
otherwise constrain the use of SPD. With a few notable exceptions, studies have used SPD in a “plug
and play” mode (Terrell, 2019a, b), meaning that they produced a weakly or even untested tested
explanation of data rather than a means to generate testable hypotheses regarding causation. This is
especially important because such aggregated data do not and cannot relate to the processes that create
and preserve or disturb and/or destroy evidence of past cultural activities. In reality, the relationship
between chronology, sedimentary stratigraphy and archaeological stratigraphy is complex or obscure.
Lacking this recognition, many SPD-based archaeological interpretations have become divorced from
their sedimentary context, and their power diminished. This specific problem is exacerbated should
such information be combined across a wider region, such as time-averaging of radiocarbon dates to
infer human demographics (Attenbrow & Hiscock, 2015). Whilst the utility of SPD analysis may partly
depend on the chosen scale of analysis (Reide, 2009, p. 325), at present it is hard to see how it could ever be defensibly applied across a wider region or continent.

Focussing on the influences of sedimentary processes in archaeology is far from new, but perhaps now more than ever, given the rapid growth in the use of the SPD technique in archaeology, it remains critical. At present, we see a mismatch, where the routine easy availability of big and seemingly powerful datasets is large, but that the necessary supporting contextual data is small or even absent. Thus, sedimentary context has become overlooked in attempts to generate grand syntheses of human behavioural dynamics through statistical analysis of large chronological (or other) datasets. Archaeology is better served in the long run by incorporating these fundamentals of geoarchaeology, rather than joining the rush towards “big science” and “fast science” (Cunningham & MacEachern, 2016). Although tempting to use SPD to investigate some of archaeology’s grand challenges, at present SPD analysis is best suited and eminently able to help establish hypotheses, rather than test them. Following Cunningham & MacEachern (2016; see also Pettitt, 2019), we therefore urge for a considered pause in SPD analyses, to allow time to carefully refocus on understanding those sedimentary processes which create the observed archaeological record. This is the more difficult route, but it is the correct one.

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8. REFERENCES


Arponen, V.P.J., Dörfler, W., Feeser, I., Grimm, S., Groß, D., Hinz, M., Knitter, D., Müller-Scheesel, N., Ott, K. & Ribeiro, A. (2019). Environmental determinism and archaeology. Understanding and
evaluating determinism in research design. *Archaeological Dialogues* (in press), 1–11
doi:10.1017/S1380203819000059

org.ezproxy.library.uwa.edu.au/stable/j.ctt24h8wg

Attenbrow, V. & Hiscock, P. (2015). Dates and demography: are radiometric dates a robust proxy for
long-term prehistoric demographic change? *Archaeology in Oceania*, 50 (Supplement), 30–36.


Archaeology*, 26(2), 198-223.

Southwest: taphonomic, paleohydraulic and demographic implications. *J. Archaeological Science*, 38,
1314 – 1325.

Bamforth, D.B. & Grund, B. (2012) Radiocarbon calibration curves, summed probability distributions,
and early Paleoinidian population trends in North America. *J. Archaeological Science*, 39 (6), 1768-
1774.

Barberena, R., Méndez, C. & de Porras, M.E. (2017) Zooming out from archaeological discontinuities:
The meaning of mid-Holocene temporal troughs in South American deserts. *Journal of Anthropological
Archaeology* 46, 68–81

Archaeology Review*, 3(5), 8 – 12.


post-depositional sediment disturbance in sandy deposits using optical luminescence. *Quaternary
Geochronology* 2, 57–64.

processing within radiocarbon dating and their impact in 14C-dates-as-data studies. *Journal of
Archaeological Studies*, 113, 105043.


Causation: Devils, Details and Demography. *Proceedings: Biological Sciences*, 273(1591), 1173-1181.

in human population demonstrate repeated links to food production and climate. *PNAS*, E10524 –
E10531, doi:10.1073/pnas.1709190114


Science Reviews* 36, 38 – 49

36, 38-49. https://doi.org/10.1016/j.quascirev.2010.11.012


Burg, M.B. (2017) It must be right, GIS told me so! Questioning the infallibility of GIS as a methodological tool. *Journal of Archaeological Science*, 84, 115-120


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Whitley, T., Berry, M. & Clayton, L. (2018). Visualizing 125,000 Years of Environmental and Landscape Change in NW Australia. DOI: 10.13140/RG.2.2.19934.95042


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Figure 4 Example of changes in biogeography around Australia between the Last Glacial Maximum and the present, which will also entail changes in geomorphic and other physical processes. Modified from Kearns et al. (2014).

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<th>Uncertainty introducers</th>
<th>Useful approaches and considerations to reduce uncertainty (see main text section 5)</th>
<th>Relevant studies (SPD where marked)</th>
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<tr>
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</tr>
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Summary of the number of publications that combine "summed radiocarbon" and "archaeology" from a Web-of-Science search supplemented by local academic library search for June 2020. The number of publications and citations of these have both increased significantly in the last 15 years.

80x54mm (300 x 300 DPI)
Examples of SPD analyses of radiocarbon dates interpreted to reflect demographic change over the last 10,000 years in (a) Belgium, from Crombe and Robertson (2014; modified after their Figure 2), and (b) Portugal, from Pardo-Gordo & Carvalio (2020; modified after their Figure 2).
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180x81mm (300 x 300 DPI)
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