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Isotopes and isoscapes for Australian archaeology: A review

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ABSTRACT

Both stable and radiogenic isotope analyses are widely applied in archaeological science to examine questions related to geochronology, diet, mobility, provenance and trade. Increasingly, measurements from materials of archaeological interest are used in conjunction with 'isoscapes' – spatially explicit maps of isotope composition from regional to continental scale. Comparison of analytical results to the spatial information available from isoscapes provides more nuanced interpretive power, particularly when several isotope systems are used in combination. Several isoscapes have become available for part or all the Australian continent in the last decade, generally developed for users in ecology, hydrology and mineral resource exploration. Here we review the development and interpretation of Australian isoscapes for hydrogen, carbon, nitrogen, oxygen, sulfur, strontium, neodymium and lead. We then assess the possibilities and limitations of these isoscapes to address contemporary challenges in Australian archaeology.

1. Introduction

1.1. Isotopes and isoscapes

An isotope of a particular element contains the same number of protons but a different number of neutrons in their nuclei. Consequently, isotopes of an element differ in relative atomic mass but not in chemical properties. An 'isoscape' represents the modelled or interpolated spatial distribution—a map—of the isotopes of an element in a material (rock, soil, water, vegetation, fauna). The term was first coined by West et al. (2008), and founded initially in biogeochemistry and ecophysiology, extending rapidly to applications, for example, in tracing animal migration and forensic science (West et al., 2009; Bowen, 2010). The potential application of isoscapes to archaeology was recognised at a similar time (e.g. Fenner and Frost, 2009).

Isotopes have been used in archaeology for decades, for example to match metal artefacts to Bronze Age mine sources (Gale and Stos-Gale, 1989) or infer the diet of prehistoric populations (Hobson and Collier, 1984). Over the last decade, the number of elements for which detailed isoscapes are available has increased dramatically. In some cases these were developed initially for application in other areas as diverse as biogeochemical cycling (Bowen and Good, 2015), geology (Osei et al., 2021) and materials authentication (Driscoll et al., 2020), but are increasingly being developed for use in archaeology (Lü et al., 2023; Wang et al., 2024; Huisman, 2025) and cultural heritage studies (Nord and Billström, 2018). Thus, for example, at least regional, sometimes global isoscapes are available for hydrogen (H), carbon (C), nitrogen (N), oxygen (O), sulfur (S), strontium (Sr), neodymium (Nd) and lead (Pb). Isotopes and isoscapes for all elements can potentially find use in archaeology for provenance, trade, mobility and dietary studies (e.g. Nord and Billström, 2018; Ditchfield et al., 2023; Stevens et al., 2025). Increasingly, combinations of isoscapes are being developed to enable

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finer-grained spatial resolution of the likely origin of a sample that has been measured for more than one isotope system, for example: Sr, Nd and Pb in Korea and South America (Jung et al., 2024; Frigolé et al., 2024) and O, S and Sr in Europe (Bataille et al., 2021). In the case of Australia, there are multiple national and regional-scale isoscapes available, produced for application primarily for ecological, hydrology and mineral exploration applications. Although there has been some application of combined isotope systematics, and in some cases isoscapes, to archaeological and geoforensic questions (e.g. Westaway et al., 2004; Theden-Ringl et al., 2011; Kristensen et al., 2016; Adams et al., 2019, 2023; Roberts et al., 2019; Koutamanis et al., 2021) there remains considerable potential in the use of isoscapes for understanding the movement of people and materials through the continent. Here we review the development of isoscapes in an Australian context, and their potential applications in archaeology.

1.2. Australia and Sahul

Much of the currently exposed Australian landmass is old, flat, weathered and tectonically stable. Rocks of Precambrian age (4600—540 million years; Ma) make up the underlying geology of most of western and central Australia. Eastern Australia is dominated by generally younger (Palaeozoic 541—252 Ma) rocks associated with the mountain-building activity that formed the Great Dividing Range, running along the entire eastern seaboard of the continent. Periods of high relative sea-level particularly in the Mesozoic (252—66 Ma) and younger, blanketed the low-lying older strata with dominantly marine sediments through central eastern Australia and the Great Australian Bight. Basalt volcanism was widespread along the Great Dividing Range during the Tertiary (<65.5 Ma) and during humid periods all rocks at the surface were subject to intense deep weathering (Bird et al., 1989) leading to the widespread formation of thick regolith (soil and weathered rock), including laterites and silcretes. As the climate became more arid from the Tertiary into the Quaternary, extensive sandy deserts formed in the continental interior. During humid periods rivers draining south from northern Australia and west of the Great Dividing Range delivered sediments into the major river basins of the Murray-Darling and Lake Eyre (Kati Thandi). For a general review of Australian geology see Blewett et al. (2012) and for geomorphology see Pain et al. (2012), with the major geological provinces shown in Fig. 1.

Sahul is the continent that comprises the Australian mainland, Tasmania, New Guinea and the Aru Islands that emerged during times of lowered sea level during the Glacial-Interglacial cycles of the Quaternary Period (2.58 Ma to the present). During the last Glacial Maximum (~20,000 years ago) sea level was up to 130 m lower and Sahul was 21.6% larger than the current land areas (Williams et al., 2018). For most of the time of human presence on the continent (since ~ 65,000 years ago; Clarkson et al., 2017) sea level was lower than it is now, with considerable additional land likely utilised by inhabitants on the now-flooded continental shelf (Norman et al., 2024). The additional land

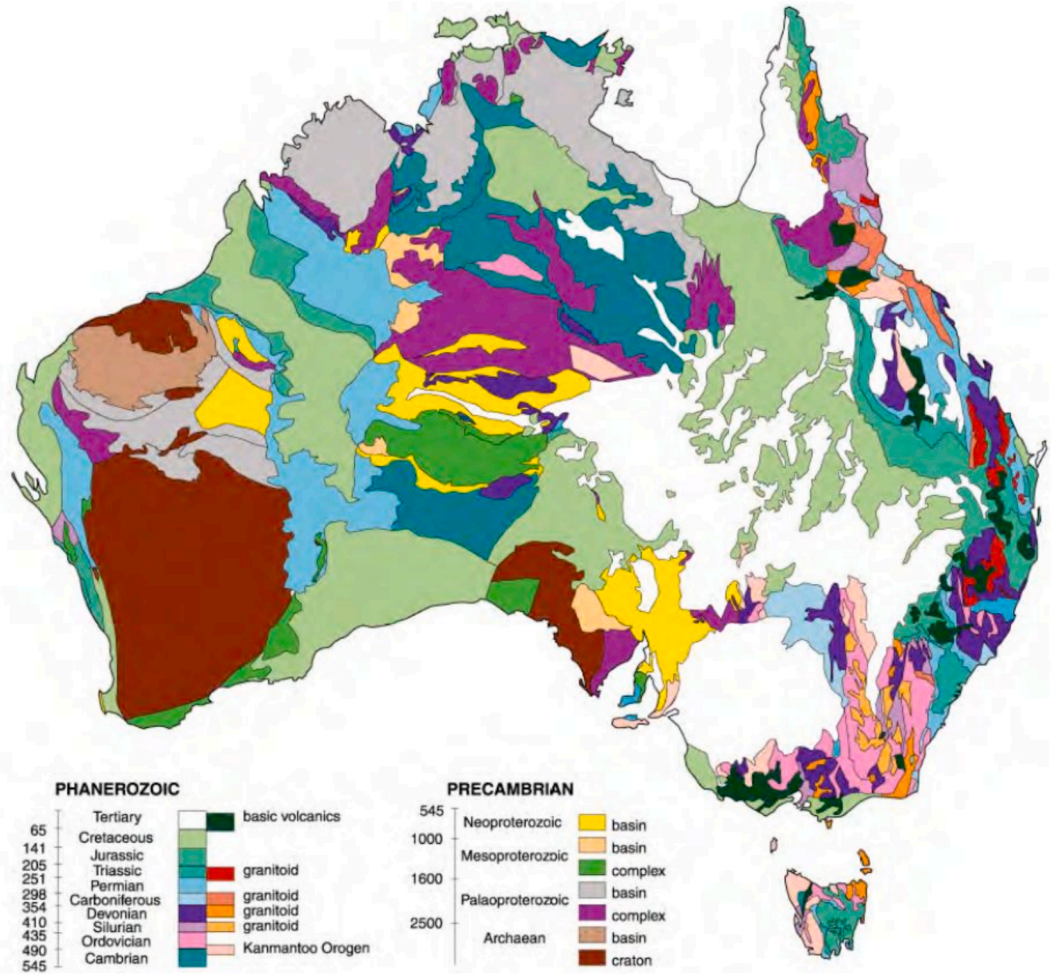

Fig. 1. Major geological provinces of Australia. Archean: 4000–2500 million years (Ma); Palaeoproterozoic: 2500–1600 Ma; Mesoproterozoic 1600–1000 Ma; Neoproterozoic: 1000–541 Ma; Palaeozoic 541–252 Ma; Mesozoic: 252–66 Ma; Cenozoic 66–0 Ma.
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on the continental shelf was relatively narrow along the southeast coast of Australia. In contrast, up to 300 km of additional continental shelf was exposed beyond the modern coast of northwestern Australia with northern Australia becoming contiguous with New Guinea, a mountainous region thrust up in the later Tertiary by collision of the Australian plate with the Pacific plate. The sediments deposited on the continental shelf at times of high sea level are marine, and likely have S, Sr, Nd and Pb isotope compositions similar to modern marine sediments, not to the rocks that underlie them.

The complex distribution of different rock and sediment types across Sahul, of a variety of ages, often beneath a cover of regolith and/or more recent aeolian or fluvial sediments provides sources of S, Sr, Nd and Pb with a potentially broad range of isotope compositions. In turn, it is the spatial distribution of isotope compositions driven by the complex geologic and geomorphic history of Sahul, that underpins the potential use of isoscapes for provenance studies in Australian archaeology.

Modern Australia also encompasses a broad range of climate zones from tropical to cool temperate. Environmental conditions have changed dramatically since human arrival on the continent ~ 65,000 years ago (Clarkson et al. 2017), both gradually in response to glacial-interglacial cycles, and rapidly, in response to global climate phenomena associated with, for example, Heinrich events (Bird et al., 2025). Any change in environmental conditions will necessarily change the distribution of the isotopes of H, C, N and O in the terrestrial landscape. A detailed treatment of Australian palaeoclimate is beyond the scope of this review but general reviews of past environmental change for different regions and times in Australia are provided by Reeves et al. (2013), Petherick et al. (2013), Fitzsimmons et al. (2013), Bird et al. (2013) and De Deckker et al. (2019).

Of particular importance for some isoscapes is that Sahul, incorporating modern Australia, is largely old, flat and semi-arid to arid (with the exception of New Guinea and the eastern coast). As a result, there is likely a stronger imprint than on other continents, of elements (of most significance for S and Sr) that can be transported by wind from the adjacent ocean as 'cyclic salts'. In addition, at times of low sea level, large areas of continental shelf were exposed beyond the modern coastline and available for habitation (Williams et al., 2018). It is reasonable to assume that the isotope composition of the soils, developed on marine sediments, beyond the modern coastline had an isotope composition similar to modern marine sediments. It is also the case that the impact of an oceanic influence on the isotope composition of both S and Sr will be more signficant at the coast and decrease in importance inland. This cyclic salt component is bioavailable and will skew bedrock values to a variable degree away from the modern coast (e.g. Raiber et al., 2009 for Sr).

The largest component of cyclic salts deposited over the continent in rainfall is sodium chloride and Davies and Crosbie (2018) compile chloride deposition in rainfall data from 291 points across the continent, which ranged from < 1 to > 150 kg ha yr^{-1}. They used these data to model chloride deposition rate on a 0.05° grid across the continent. Fig. 2 shows high chloride deposition close to the coast, decreasing inland over a distance that is determined largely by wind direction and strength. As a result, whereas chloride deposition rates fall to < 10 kg ha yr^{-1} less than 50 km inland from the coast in southeast Victoria, the same decrease occurs over > 300 km in southwest Western Australia. The same pattern is likely true for marine-derived S and Sr deposition, and the implications are discussed in sections 5.3 and 5.4 respectively.

2. Nomenclature

It is difficult to measure the absolute abundances of the isotopes of any element and particularly the light elements. For this reason,

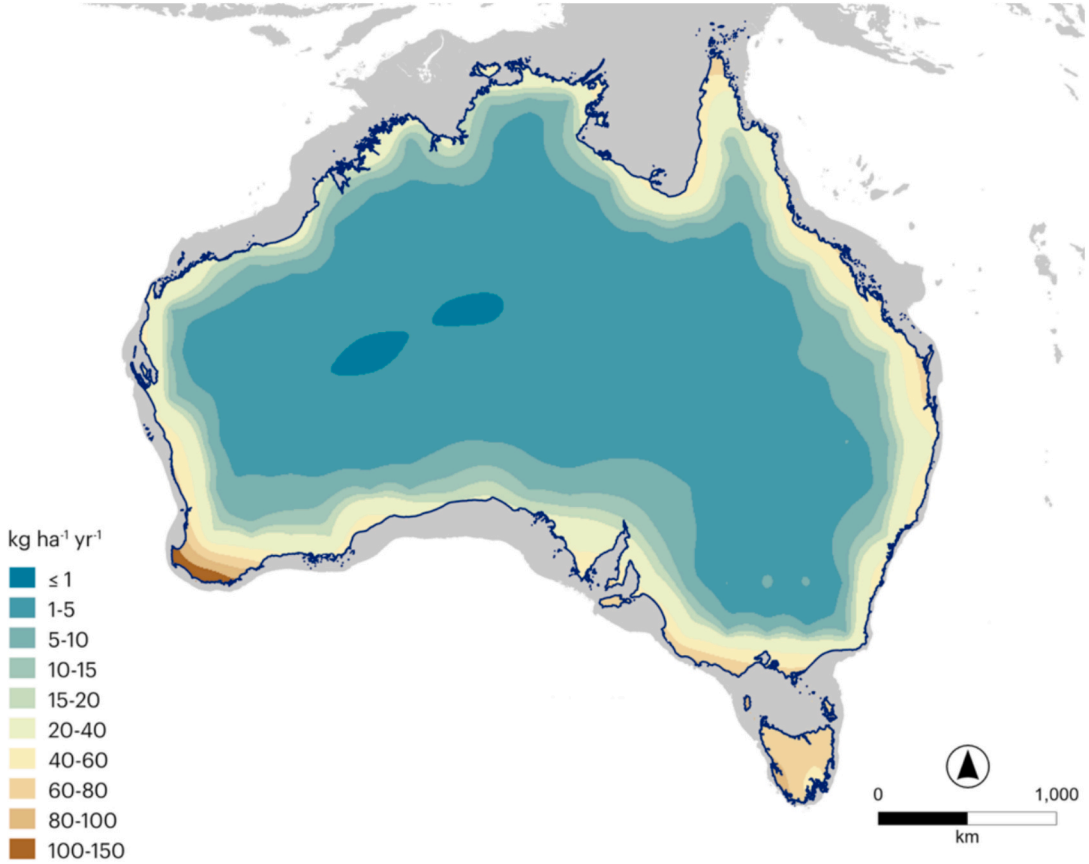

Fig. 2. Distribution of modern chloride deposition across Australia from Wilkins et al., (2022) who provide information on sample types, numbers, locations, analytical methods, the handling of uncertainty in extrapolation of point measurements and links to the dataset.

abundance of the rarer isotope of an element is usually measured as a ratio of the more common isotope of that element, with reference to a standard where the absolute abundance of those isotopes is precisely known. For the light stable isotopes (H,C,N,O,S) the abundance of the rare isotope relative to the more common isotope is reported in delta (δ) notation as parts per thousand (per mil; ‰) deviations in the ratio from that in an international standard that is defined for each element (e.g. $\delta^{18}O$ for oxygen; Table 1 and sections following). Isotope compositions are most commonly measured by converting a sample to a purified gas (e.g. organic matter to CO_2) for measurement by gas chromatography isotope ratio monitoring mass spectrometry (GC-IRMS). For further information see Sharp (2017).

For the heavy elements considered here, most of which are modified over time by radioactive decay, Sr, Nd and Pb isotopes are typically reported as absolute ratios normalised to agreed international standards (e.g. $^{87}Sr/^{86}Sr$ for strontium; Table 1). Additionally, however, Sr and Nd isotope compositions can also be reported similarly to light stable isotopes in epsilon (ε) values as parts per ten thousand deviations from an agreed standard value, a format which may be more accessible to the end user. Measurements of bulk material are usually made on dissolved and purified samples (e.g., Kochergina et al. 2022) by thermal ionisation mass spectrometry (TIMS) or inductively coupled plasma mass spectrometry (ICPMS).

The fundamental attributes of the isotope systems that are the subject of this review are provided in Table 1. It is important to note that all measurements are subject to analytical uncertainty, and the usual magnitude of these errors for each isotope system are also listed in Table 1.

3. Source, mixing, fractionation, decay and bioavailability

Where the material for isotope analysis is a lithic artefact, the composition of the artefact will be the same as the rock from which it was derived. Thus, for example, Weisler and Woodhead (1995) demonstrated that the Pb isotope composition of basalt artefacts could be uniquely ascribed to the island in Polynesia from which the raw material was quarried. For all other materials, organic or inorganic, the relationship between the isotope composition of the original source and the composition of the material analysed can be modified to a variable degree by multiple processes.

For the light isotopes, here up to and including S (relative mass difference 6.5%; Table 1), every chemical reaction will impart a difference in isotope composition between the source and the product. The magnitude of this difference is described by a fractionation factor (α; see Sharp, 2017 for definitions), which may be constant, or vary dependent on an environmental variable such as temperature. For most archaeological materials of interest (bone, teeth, keratin, collagen, vegetation, biogenic carbonate), these fractionation factors are known to a varying degree, with details provided in subsequent sections. As a result of the dynamic response of the isotope composition of the light isotopes to changes in environmental conditions on seasonal and longer timescales, and potential mixing between multiple sources, the isotope composition of the archaeological material analysed will change over time, and in some cases the material even preserves a temporal record of change in environmental conditions. Thus, molluscs contain a detailed seasonal record of environmental change that can be used to infer time of harvesting (e.g. Alidoostsalimi et al., 2025; Twaddle et al., 2016), and

Table 1
Nomenclature and characteristics for the major isotope systems use in archaeology and the development of isoscapes.

element	isotope	abundance	mass diff* (%)	reported as	standard	main drivers of change	temporal variation	applications
Hydrogen	^{1}H ^{2}H	99.985% 0.0155%	100	$^{2}H/^{1}H$ ratio as $\delta^{2}H$ (or δD) as ‰ deviations from a standard ±~3 ‰	VSMOW (Vienna Standard Mean Ocean Water) = 0 ‰	fractionation effects associated with climate, and with biosynthesis	potentially rapid in response to changes in environment and source of water assimilated	climate (potentially provenance)
Carbon	^{12}C ^{13}C	98.892% 1.108	8.3	$^{13}C/^{12}C$ ratio as $\delta^{13}C$ value as ‰ deviations from a standard ±~0.1 ‰	VPDB (Vienna Pee Dee Belemnite) = 0 ‰	fractionation effects associated with climate, and with biosynthesis	potentially rapid in response to changes in environment and in carbon source assimilated	diet, climate (potentially provenance)
Nitrogen	^{14}N ^{15}N	99.635 0.365	7.1	$^{15}N/^{14}N$ ratio as $\delta^{15}N$ value as ‰ deviations from a standard ±~0.2 ‰	AIR = 0 ‰	fractionation effects from biosynthesis and trophic level	potentially rapid in response to changes in nitrogen source assimilated	diet, climate (potentially provenance)
Oxygen	^{16}O ^{18}O	99.759 0.204	12.5	$^{18}O/^{16}O$ ratio as $\delta^{18}O$ value as ‰ deviations from a standard ± 0.1 ‰	VSMOW (water) or VPDB (carbonates) = 0 ‰	fractionation effects associated with climate, and with biosynthesis	potentially rapid in response to changes in environment and source of water assimilated	climate (potentially provenance)
Sulfur	^{32}S ^{34}S	95 4.21	6.3	$^{34}S/^{32}S$ ratio as $\delta^{34}S$ value as ‰ deviations from a standard ±~0.2 ‰	VCDT (Vienna Canyon Troilite = 0 ‰)	fractionation effects associated with source and biosynthesis	potentially rapid in response to changes in sulfur source assimilated	provenance
Strontium	^{86}Sr ^{87}Sr	~7.0 ~9.9	1.1	$^{87}Sr/^{86}Sr$ (ratio) (±~0.00004 ‰)	NIST SRM987 standard = 0.71034 ± 0.0003	geochemistry and age of source; mixing of sources and (very slow) decay of ^{87}Rb to ^{87}Sr	minimal – variations controlled by bedrock composition and mixing between sources	provenance
Neodymium	^{143}Nd ^{144}Nd	~12.2 ~23.8	0.7	$^{143}Nd/^{144}Nd$ ratio or εNd value (parts per 10,000) relative to Bulk Earth ±~0.5	La Jolla or JNd-1 Nd standards, or expressed as deviations from Bulk Earth (CHUR) values	geochemistry and age of source; mixing of sources and (very slow) decay of ^{147}Sm to ^{143}Nd	minimal – variations controlled by bedrock composition and mixing between sources	provenance
Lead	^{204}Pb ^{206}Pb ^{207}Pb ^{208}Pb	~1.4 ~24.1 ~22.1 ~52.4	1.9 1.4 0.5 0	most commonly $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios (±~1%)	NIST SRM981 (with some variation in accepted values)	geochemistry and age of source; mixing of sources and (very slow) decay of U to Pb isotopes	minimal – variations controlled by bedrock composition and mixing between sources	provenance

different parts of the human body preserve information on lifestyle at different times in the life of an individual (e.g. Lamb et al., 2014).

For the heavy isotopes (relative mass difference < 2%; Table 1), significant fractionation during chemical reactions can be discounted to a first approximation. While the isotope variations measured in rocks are generated by radioactive decay from an initial composition, the decay half-lives of the isotopes considered here are so long (billions of years) that radioactive-decay-induced variations in composition over the millennial timescales consider here can also be ignored. Variability in the isotope composition of materials of archaeological interest are driven primarily by variations in bedrock isotope composition and mixing between sources. The isotope composition of the bedrock is not necessarily the only source available for uptake by an organism. Therefore, a distinction must be made between bedrock isotope composition and the isotope composition of the bioavailable component in the regolith, which may also include material (dust, aerosols, water, exogenous sediment) not related to the immediate bedrock. The bioavailable component is generally determined by analysis of the isotope composition of soil leachate, local water or flora, or archaeological material of known provenance (Kootker et al., 2016; Bataille et al., 2018).

The impact of the multiple processes that can modify the isotope composition of a material of archaeological interest are considered for each isotope system described in section 5. It is also important to note that depending on the element and material being analysed, contamination and diagenetic modification of the primary composition can be a significant issue that needs to be carefully considered.

4. Australian isoscapes

There has been considerable work in Australia, particularly over the last decade, in developing national and regional isoscapes. The impetus for the development of these isoscapes has largely been derived from their utility in hydrological, ecological and mineral exploration research. Below we review the status of isoscapes for elements that are particularly useful in archaeology, demonstrated through their application in Australia and/or internationally.

In using any isoscape, there are several potential issues that must be considered in comparing individual analyses to results predicted by an isoscape. The first is that all isoscapes are extrapolations from point information, and this necessarily leads to larger uncertainties than the measurement error, and these tend to increase with distance from the nearest point measurement. The second as noted in section 3, is that the isotope composition of the bioavailable component of an element taken up by an organism may not be equivalent in composition to the material analysed to produce the isoscape. In addition, potentially useful or confounding depending on the application: (i) organisms may feed selectively, so will not necessarily encode an isotope composition that can be directly related to its position in an isoscape, and (ii) some isoscapes are dynamic and therefore will vary over time in response to changes in environmental drivers, particularly climate.

We review eight Australian isoscapes in the sections that follow. Within the limitations of this paper we cannot provide an exhaustive assessment of the potential uses and limitations associated with each isotope system, but further detail is readily accessible from the references cited in each section.

4.1. Oxygen and hydrogen isotopes

Hydrogen has two stable isotopes, ^{1}H (most abundant) and ^{2}H (deuterium) while oxygen has three stable isotopes, ^{16}O (most abundant), ^{17}O and ^{18}O (Table 1). The major physical processes controlling the $\delta^{2}H$ and $\delta^{18}O$ value of water, evaporation and condensation, manifest globally in a tendency to lower values in colder climates and higher values in hotter or more arid environments, and lower values as rainfall intensity increases, for example in the monsoon tropics (Bowen, 2010). Further variability in the composition of precipitation arises from changes in the source of water vapour and mixing between waters of different origin. The isotopic composition of rainfall can change dramatically even between individual rain events (e.g. Munksgaard et al., 2012) but on longer timescales it is possible to derive modern isoscapes for both elements as has been achieved at the global scale (Bowen, 2010).

The $\delta^{2}H$ and $\delta^{18}O$ value of water therefore contains a record of the environment that is encoded in many materials accessible to archaeologists, including wood, carbonates and the preserved remains of both people and fauna. In all cases, the isotope composition of the material analysed will be offset from the original rainfall water isotope composition by further changes in composition after the rain has fallen (e.g. through evaporation), the preferred source of water ingested by organisms (e.g. Ayliffe and Chivas, 1990; Lightfoot and O'Connell, 2016) and the fractionation effects associated with the chemical/biochemical reactions during formation, as noted in section 3. For many materials these fractionation factors are well known and are larger for H than for O, as a result of the greater relative mass difference between the isotopes of H than O (100% versus 12.5%), however, more studies focus on O than H as the systematics associated with fractionation are better known.

Hollins et al. (2018) have developed annual, and Falster et al. (2026) have presented seasonal isoscapes, for both the $\delta^{2}H$ and $\delta^{18}O$ composition of rainfall across Australia that can serve as a basis for interpreting the archaeological record, while McInerney et al. (2023) have developed leaf water isoscapes for Australia. Fig. 3 shows that there is considerable variability in rainfall isotope composition across the continent that relates largely to differences in annual rainfall amount, moisture sources and histories, distances from the modern coast and altitude. While it is possible that this isoscape might be somewhat applicable to the later Holocene, climate and sea level change on longer timescales mean that water isoscapes would have been dramatically different in the past. Thus the opportunities lie more in examining environmental change in the past through developing time series of water isotope proxy records, interpretable in the context of climate change and human response to climate change in the past (e.g. Brockwell et al., 2013; Long et al., 2021; Skippington et al., 2021), than in directly determining provenance.

In other countries, the $\delta^{18}O$ composition of teeth, for example, has been successfully used to identify individuals who had a composition that fell outside the range expected for the local population (e.g. Chenery et al., 2014). The approach has also been trialled in northern Australia on potential Macassan burials, through comparison with contemporaneous Indigenous burials (Theden-Ringl et al., 2011), and by analysing materials from historical burials of Indigenous individuals in the Gulf of Carpentaria (Adams et al., 2023) and Adelaide (Adams et al., 2022).

4.2. Carbon and nitrogen isotopes

Carbon has three isotopes, ^{12}C (most abundant), ^{13}C and ^{14}C (radiocarbon; unstable with a half-life of 5,730 years), while nitrogen has two isotopes, both stable: ^{14}N (most abundant) and ^{15}N (Table 1).

The $\delta^{13}C$ value of preserved organic and inorganic materials is ultimately linked via photosynthesis to the $\delta^{13}C$ value of the contemporaneous atmosphere (Bowling et al., 2008), and the $\delta^{15}N$ value of organic materials is ultimately linked to that of atmospheric nitrogen through fixation by some bacteria and plants (Craine et al., 2015). Both photosynthesis and biological nitrogen fixation, and subsequent transformations through the carbon and nitrogen cycles involve multiple fractionation effects that lead to a wide range of isotope compositions in archaeological materials. This range of compositions can provide information of use in archaeology, most commonly in relation to diet. In many cases the magnitude of these fractionation effects are well known, enabling dietary inferences to be drawn from a range of archaeological materials (e.g. France and Owsley, 2015; Ohkouchi et al., 2015;

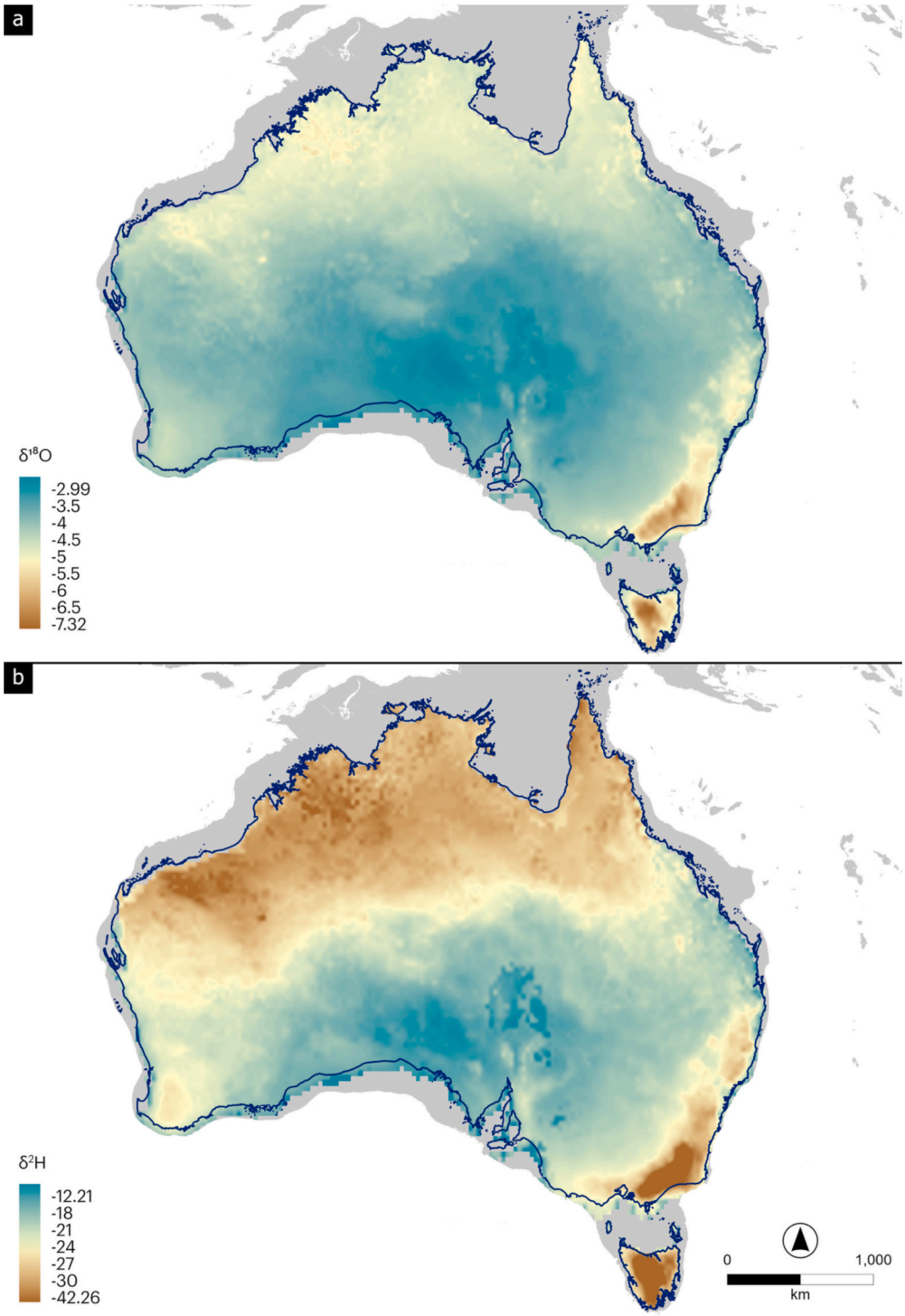

Fig. 3. (a) Oxygen and (b) Hydrogen isoscapes for modern Australian rainfall from Falster et al. (2026) who provide information on sample types, numbers, locations, analytical methods, the handling of uncertainty in extrapolation of point measurements and links to the dataset. Grey shading indicates no data.

Richards, 2020). In the terrestrial environment, the major cause of the range observed in dietary $\delta^{13}C$ values is related to whether the assimilation into plant matter was by C3 (trees, shrubs and cool climate grasses including temperate cereals such as wheat with low $\delta^{13}C$ values) or C4 (tropical grasses and sedges, including maize with high $\delta^{13}C$ values) photosynthesis (Bowling et al., 2008). Marine carbon tends to be intermediate in composition between the two terrestrial end-members at Australian latitudes (Magozzi et al., 2017; Ulm et al., 2023). The main driver of $\delta^{15}N$ values is the trophic level of an organism such that, at any location, $\delta^{15}N$ value increases with each increment in the position of an organism in a food web, with the magnitude of fractionation also being tissue specific (Stephens et al., 2023). In general terms, the $\delta^{15}N$ values of many marine food items tend to be higher than terrestrial foods. In addition, across terrestrial environments, $\delta^{15}N$ values tend to be higher in arid environments than humid environments (Bird et al., 2021; Stephens et al., 2023).

There are global isoscapes for the distribution of C3 and C4 terrestrial vegetation (e.g. Still et al., 2003) and the $\delta^{15}N$ value of soil which forms the baseline for further trophic increase in $\delta^{15}N$ value up a local food web (Zan et al., 2023). A carbon isoscape has been generated for

Australia by Munroe et al. (2022) and this shows that high $\delta^{13}C$ values from C4 vegetation dominate most of the interior and north of the country with low $\delta^{13}C$ values indicative of C3 vegetation in the temperate south and eastern coastal fringe (Fig. 4). There is no national nitrogen isoscape but the global isoscape of Zan et al. (2023) indicates a high $\delta^{15}N$ baseline pertains over much of the continent, except for the temperate west and southeast. As with O and H, these isoscapes are not static and vary with changes in climate, and the isotope composition of an organism other than a plant, is dependent more on dietary preference than the average isotope composition of an area.

The broad isoscapes presented in Fig. 4 may enable indications of habitat preference for fauna (e.g. Prideaux et al., 2009), evidence of mobility if a measured isotope composition is not commensurate with local conditions (Adams et al., 2021) and evidence of provenance for museum specimens of recent age but unknown origin (Pate et al., 2002). The major issue in using the 'total carbon' isoscape presented in Fig. 4, is that most organisms feed selectively, mostly obviously browsers versus grazers. This means that the isotope composition of most organisms is not equal to the biomass-weighted average $\delta^{13}C$ value of a location or region. Nevertheless, for common grazing species the climatically (and therefore geographically) mediated change in the proportion of C3, and C4 species in the grass biomass may be useful, for example for kangaroos (Murphy et al. 2007).

Other studies in Australia have focused on the use of C and N isotopes, often together, to infer the proportion of C3, C4 and/or marine foodstuffs in the diet of both human populations (e.g. Hobson and Collier, 1984; Pate, 1995; Adams et al., 2023) and archaeological fauna (Guiry et al., 2014; Roberts et al., 2019). Some studies have attempted to link observed variation in isotope composition to environmental parameters such as rainfall (Forbes et al., 2010; Gröcke et al., 1997) in order to develop records of environmental change in the past. Further studies have linked changes in the $\delta^{13}C$ values of pyrogenic carbon (charcoal) in lacustrine sediments to changes in climate and fire regime, including identifying changes from natural to anthropogenic fire regime (Bird et al., 2024).

4.3. Sulfur isotopes

Sulfur has four stable isotopes, ^{32}S (most abundant), ^{33}S, ^{34}S and ^{36}S (Table 1). It is an essential element for all living organisms and so is present in most materials of archaeological interest (Nehlich, 2015; Tarrant and Richards, 2024). The $\delta^{34}S$ value of bioavailable S reflects the balance between ultimately marine-derived sulfate with high $\delta^{34}S$ value and bedrock-derived sulphide, oxidised to sulfate by weathering, with low $\delta^{34}S$ value. Primary sulfate may also be present in some lithologies, particularly marine sedimentary rocks. The fractionation effects associated with incorporation into higher organisms are relatively small and reasonably well understood.

Because the $\delta^{34}S$ value of seawater sulfate itself, over geologic time, reflects the balance been sulphide oxidation and sulfate reduction globally, the $\delta^{34}S$ value of seawater sulfate has varied considerably in the past. Except for brief periods in the Phanerozoic, the $\delta^{34}S$ value of seawater sulfate has been lower than the modern value (Present et al., 2020, and references therein). This is relevant because large areas of Australia are covered by marine sediments of Palaeozoic to Cenozoic age resulting in all bedrock-derived sulfate having a $\delta^{34}S$ value that is lower than modern seawater sulfate. Section 4 demonstrates that there is a significant load of cyclic salt, including sulfate, delivered annually to the Australian continent from the adjacent ocean, and that this amount decreases inland.

Bataille et al. (2021) have developed a S isoscape for Europe, which shows the strong influence of marine sulfate on coastal regions, and Zazzo et al. (2011) have shown a strong relationship between the $\delta^{34}S$ value of sheep wool and distance to the western coast of Ireland. There is no S isoscape for Australia, but Chivas et al. (1991) have shown that the $\delta^{34}S$ value of sulfates, mostly from the terminal salt lakes that are characteristic of arid Australia, show a strong imprint from modern marine sulfate that decreases inland (Fig. 5). The pattern is very similar to the decrease inland that is evident in chloride deposition rates in Fig. 2. This suggests that the $\delta^{34}S$ value of archaeological materials can be linked to distance from the modern coast and thus be a useful indicator of mobility and trade. As noted in section 4, coastal position has changed dramatically in the past, but the marine sediments exposed by sea level fall will likely have $\delta^{34}S$ values that are similar to modern marine sulfate, or lower, depending on the proportion of oxidised sulphide contributing to the total bioavailable S from weathering of the marine sediments. In areas remote from the coast, there is likely to be more local heterogeneity in $\delta^{34}S$ values related to changes in bedrock type, as evidenced by the very low $\delta^{34}S$ values of gypsum related to sulphide oxidation of the underlying marine bulldog shale in central South Australia (Fig. 5).

There have been no studies of sulfur isotope composition in Australian archaeology. There have been studies internationally that have demonstrated the utility of S isotopes in understanding both diet and mobility in a range of contexts (see Nehlich, 2015 for a review) and based on the results of Chivas et al. (1991), the same is likely true in the Australian context.

4.4. Strontium isotopes

Sr is an alkaline earth metal with four stable isotopes ^{84}Sr, ^{86}Sr, ^{87}Sr and ^{88}Sr; of these ^{87}Sr is radiogenic and produced by the radioactive decay of parental ^{87}Rb (Table 1). Most studies, prior to the last decade, concern the 'radiogenic' $^{87}Sr/^{86}Sr$ ratio which records increase ^{87}Sr in a sample over time from the decay of ^{87}Rb relative to a primordial baseline (^{86}Sr); such measurements have both chronological and tracer applications. Recently, however, interest has also grown in so-called 'stable Sr isotopes' predominantly utilising the $^{88}Sr/^{86}Sr$ ratio which provides a measure of Sr isotope fractionation avoiding any time-integrated effects from ^{87}Rb decay. The $^{88}Sr/^{86}Sr$ ratio is proving to be a novel tracer of Sr cycling and, in biological systems, of dietary and physiological traits, with considerable application to the archaeological sciences (e.g. Knudson et al., 2010). The study of stable Sr isotope variation is, however, still very much in its infancy and so, in this contribution, we focus on the radiogenic $^{87}Sr/^{86}Sr$ ratio.

Because Sr is relatively soluble it has been utilised in provenance studies for many years based upon the key assumption that the $^{87}Sr/^{86}Sr$ ratio of mineralised tissues mirrors that of the underlying geology in areas where people and animals lived (Ericson, 1985). Isotopic analysis of bones and teeth can therefore provide information on regions of birth and track subsequent mobility and migration. With the advent of in situ analytical techniques, such studies can now also be conducted with very high temporal resolution (e.g. Lazzerini et al., 2021).

Recently, however, it has also been recognised that transport pathways from bedrock to biological systems can be complex and that, as such, simple isotopic mapping of bedrock geology may not be entirely adequate for use in provenance studies. This has led to the concept of 'bioavailable' Sr (e.g. Bataille et al., 2020) and, as a result, more recent efforts to produce isoscapes have favoured sampling of local groundwater (Scaffidi et al., 2020) or biological components (e.g. plants, snail shells, zooarchaeological enamel; Kootker et al., 2016; Bertacchi et al., 2025) over bedrock although this is not always feasible in an archaeological context. Potential complications can arise from the addition of Sr to locally-derived Sr from wind-borne continental dust, and seawater aerosols in nearshore environments (Raiber et al., 2009). The influence of these and other issues in the construction and use of Sr isoscapes has been recently reviewed by Holt et al. (2021) and Rossi et al. (2024). In an Australian context, spatial understanding of the distribution of chloride deposition, as discussed in section 4, provides a solid basis for evaluating the impact of marine strontium from aerosols on the isotope composition of bioavailable strontium across the continent.

Despite these issues, Sr remains a powerful tracer and Sr isoscapes

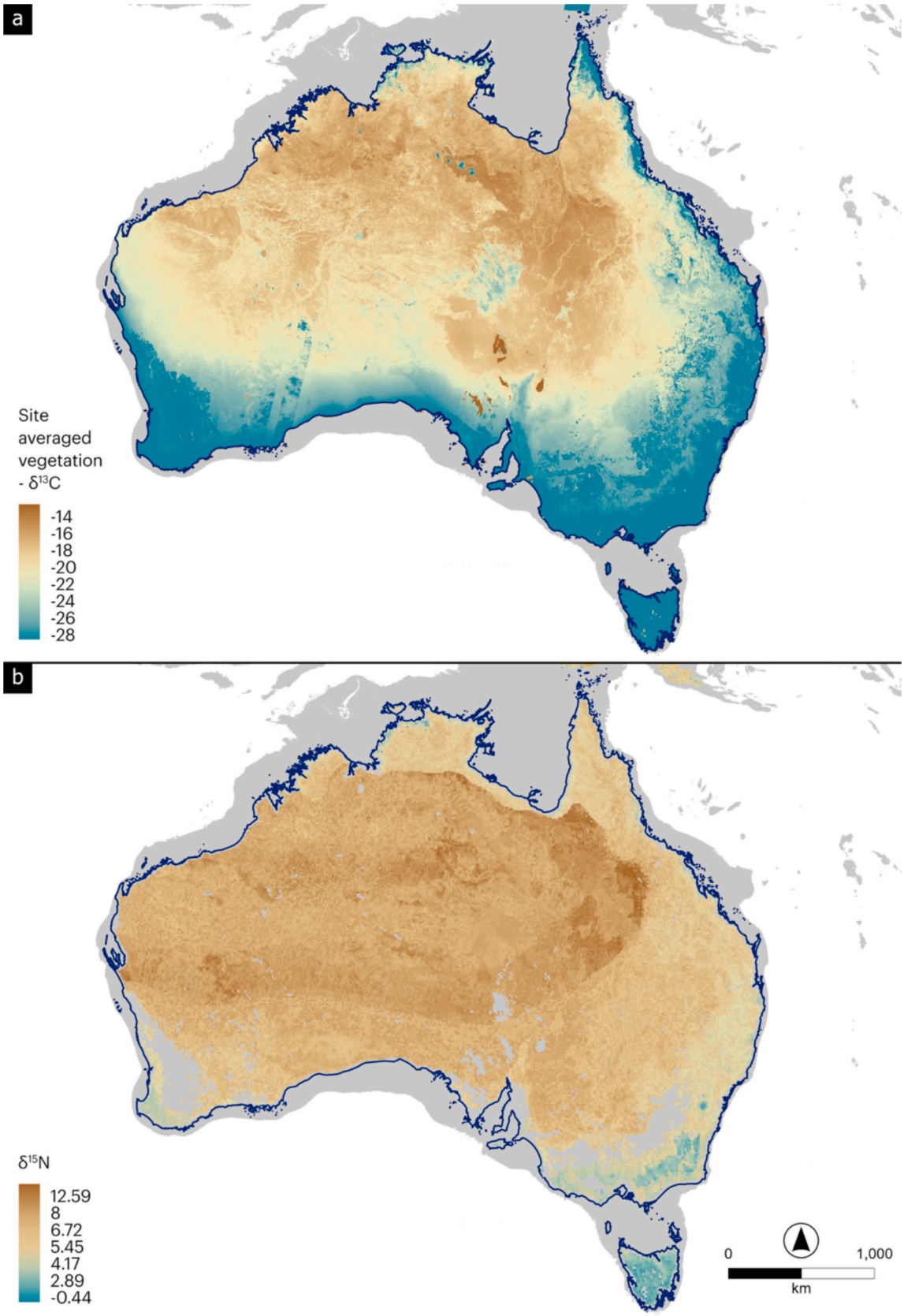

Fig. 4. (a) Carbon isoscape from Munroe et al. (2022) and (b) Nitrogen isoscape for the Australian part of the global model of Zan et al. (2023). Those two papers provide information on sample types, numbers, locations, analytical methods and the handling of uncertainty in extrapolation of point measurements and links to the dataset.

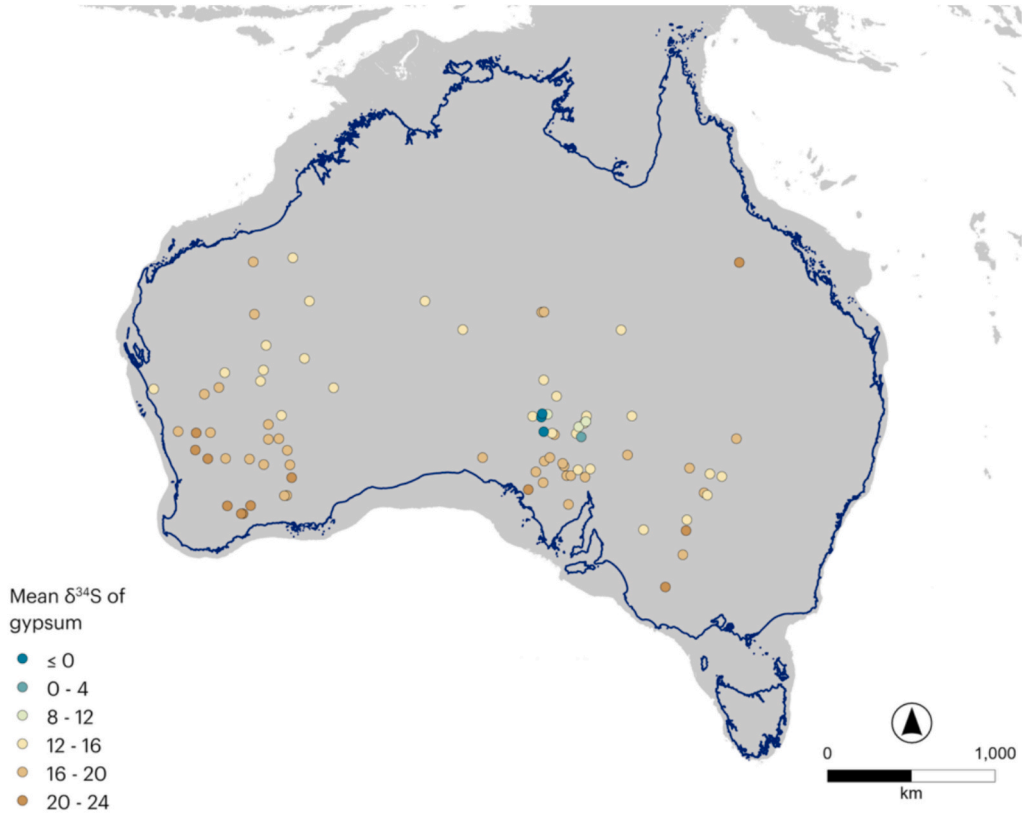

Fig. 5. Distribution of $\delta^{34}S$ values in gypsum from salt lakes across Australia (Chivas et al., 1991) augmented with new data from southwest Queensland (Singleton, 2024) who provide information on sample types, numbers, locations, analytical methods and the handling of uncertainty in extrapolation of point measurements and links to the dataset.

are widely used in archaeological studies, especially as tracers of provenance and migration (e.g. Theden-Ringl et al., 2011; Price et al., 1994; Chenery et al., 2014; Copeland et al., 2016; Adams et al., 2021; 2023). Detailed isoscapes of bioavailable Sr have been established for many parts of the world, including Britain (Evans et al., 2010), New Zealand (Kramer et al., 2022), Europe (Hoogewerff et al., 2019), Italy (Lugli et al., 2022), the Amazon (de Almeida Mereles et al., 2025) and Sub-Saharan Africa (Wang et al., 2024). In the Australian context, Sr isoscapes are available for the northeast (Adams et al., 2019), southeast (de Caritat et al., 2022), northern (de Caritat et al., 2023) and southwestern (de Caritat et al., 2025) sectors. The latter three datasets are additionally compiled in Desem et al. (2025). Most of the samples contributing to these datasets can be considered bioavailable.

The continental distribution of observations remains incomplete but given that large areas of marine sedimentary rocks of known age form the surface cover, there is unrealised potential to map, within a broad range, the bedrock-derived $^{87}Sr/^{86}Sr$ ratio of bioavailable Sr for large areas of the continent (Fig. 1). This is because the $^{87}Sr/^{86}Sr$ ratio of seawater has changed dramatically in the past in response to changes in plate tectonics and weathering rates (Ingram and DePaolo, 2022). Dosseto et al. (2025) have presented a modelled bioavailable Sr isoscape for Australia, based on a spatially biased, but directly measured, set of Australian samples augmented by data from a much larger globally distributed set with well characterised geological, soil and climatic metadata (Fig. 6).

4.5. Neodymium isotopes

The rare earth element Nd has five stable isotopes ^{142}Nd, ^{143}Nd, ^{144}Nd, ^{145}Nd, ^{146}Nd and ^{148}Nd; of these ^{143}Nd is radiogenic and produced by the radioactive decay of parental ^{147}Sm (Table 1). The commonly reported ratio is $^{143}Nd/^{144}Nd$ which records isotopic growth in a sample over time relative to a primordial ^{144}Nd baseline.

Nd is little used in archaeological studies when compared to Sr and Pb largely because its bioavailability is less well studied but also because bioapatites such as teeth and bones, when buried, are highly susceptible to diagenetic overprints from sediment porewaters (e.g. Kohn et al., 1999). As such, Nd is better suited to the provenance studies of lithics, glass, ceramics and other non-biological materials where it can be combined with Sr, Pb and other isotopic tracers (e.g. Degryse and Schneider, 2008; De Bonis et al., 2018). Nd isotopes are beginning to be used on a regional scale to provide baselines for provenance studies (e.g. Lü et al., 2023; Štulc et al., 2024) but few actual isoscapes yet exist and most of these are limited in scale (e.g. Jung et al., 2024). In contrast, in the Australian context, considerable progress has been made in this regard. Nd isoscapes have been produced using both whole-rock analyses of largely igneous rock suites (Champion, 2013; Osei et al., 2021) and regolith samples (Desem et al., 2025), although the latter is based upon a small number of samples comprising three across-continent traverses. Together these studies cover large areas of the continent (Fig. 7).

4.6. Lead isotopes

The element Pb has one stable, primordial isotope (^{204}Pb) and three others (^{208}Pb, ^{207}Pb, ^{206}Pb) which are the stable daughter products from the independent decay of ^{232}Th, ^{235}U and ^{238}U respectively (Table 1). Over geological time this complexity—effectively 'three isotopic systems in one'—has produced a diverse array of isotopic compositions in different geological materials, providing significant potential for accurate source attribution (Komárek et al., 2008). When combined with a relative resistance to weathering overprints, and no observable fractionation during transit through the biosphere, this makes Pb isotopes a valuable provenance tool (e.g. Evans et al., 2022).

Pb isotopes have a long history of use in the archaeological sciences.

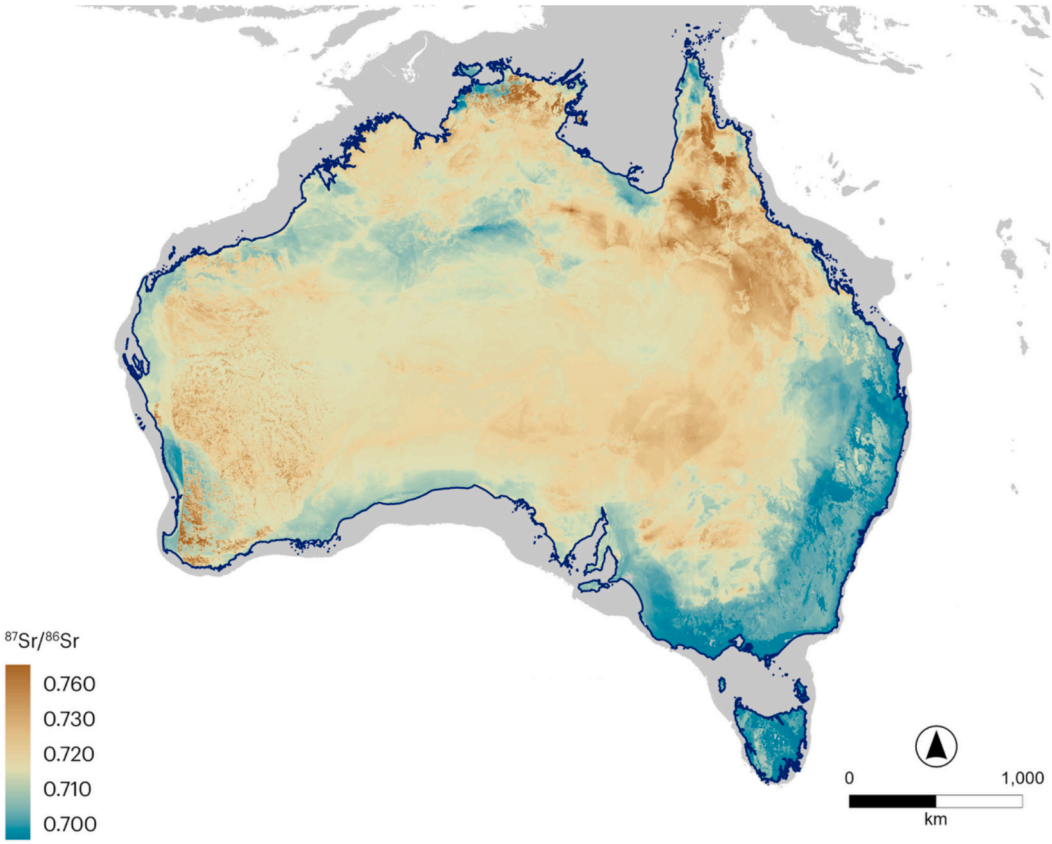

Fig. 6. Modelled bioavailable Sr isoscape from Dosseto et al. (2025), who provide information on sample types, numbers, locations, analytical methods and the handling of uncertainty in extrapolation of point measurements and links to the dataset.

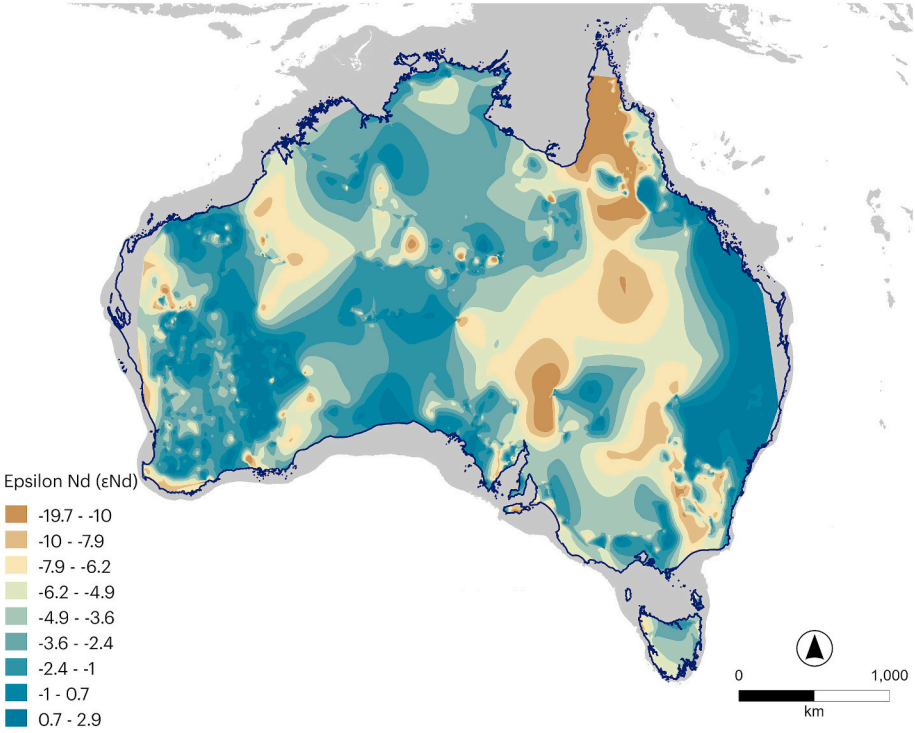

Fig. 7. Nd isoscape for Australia summarised in Desem et al. (2025), who provide information on sample types, numbers, locations, analytical methods and the handling of uncertainty in extrapolation of point measurements and links to the dataset.

Originally Pb isotope analysis was employed to determine the provenance of metallic artefacts, starting in the 1960s (e.g. Brill and Wampler, 1965) but then expanding greatly in the 1970s and 1980s (e.g. Gale, 1989). More recently, technological developments now allow for Pb isotopic analysis, and provenance studies, of many other materials including ceramics and glazes (e.g. Wolf et al., 2003), turquoise (e.g. Thibodeau et al., 2015) and even stone tools (e.g. Weisler and Woodhead, 1995).

Pb, is also a bioavailable element, with primary pathways into the body via ingestion/inhalation of dusts in addition to dietary intake (e.g. Kamenov and Gulson, 2014). As such it has been used to track the sources of Pb in both modern (e.g. Gulson, 2008) and ancient (e.g. Valentine et al., 2008) humans and animals. Munkittrick et al. (2023) provide a comprehensive review of this field.

These examples highlight an important feature of the Pb-isotope system. Pb found in most rocks and minerals (often termed 'common Pb') will in general have an isotopic composition reflecting a prolonged history of radiogenic accumulation. In contrast, processes of ore genesis often exclude the isotopes of U and Th and thus Pb isotopic compositions stop at the time of formation with no further radiogenic ingrowth (these are termed 'initial Pbs'). As a result, while provenance studies of non-metallic materials would typically reference common Pbs, studies of metallic artefacts must instead reference initial Pb compositions found in ores. Construction of Pb isoscapes then requires different sample types for different applications (Komárek et al., 2008; Evans et al., 2022).

Due to contamination issues associated with anthopogenic lead from gasoline (e.g. Rosman et al., 1994) and the time-consuming nature of sample preparation, early Pb provenance studies utilised background databases of Pb isotope analyses from individual sites (predominantly mines). These were painstakingly constructed over many years (e.g. Stos-Gale and Gale, 2009) with limited opportunity for the development of comprehensive isoscapes. Only in the last few decades have technological advances provided for higher throughput Pb isotope analysis, allowing the construction of large-scale isoscapes. Notable examples include an agricultural soil map of Europe (Reimann et al., 2012) and a Pb isotope map of Britain based upon geological datasets (Evans et al., 2022), with a number of other, smaller studies in areas such as China (e.g. Bing-Quan et al., 2002). Concurrent with these developments Pb isoscapes are now routinely being incorporated into archaeological studies; for example, Sharpe et al. (2016) used a Pb isoscape to study human migration and trade in the Mayan culture.

In the Australian context two large scale Pb-isoscapes have recently been published. Desem et al. (2024) employed 1219 regolith samples covering 5.6 million km^2 to establish the first continental-scale Pb isoscape (Fig. 8). This can broadly be equated with the 'common Pb' type noted above. In addition, Liebmann et al. (2024) published a dataset of 232 igneous samples of varying U and Th content, thus incorporating both 'common Pb' and 'initial Pb' types, covering 2.3 million km^2 in southeastern Australia. As such each database will likely find a different purpose.

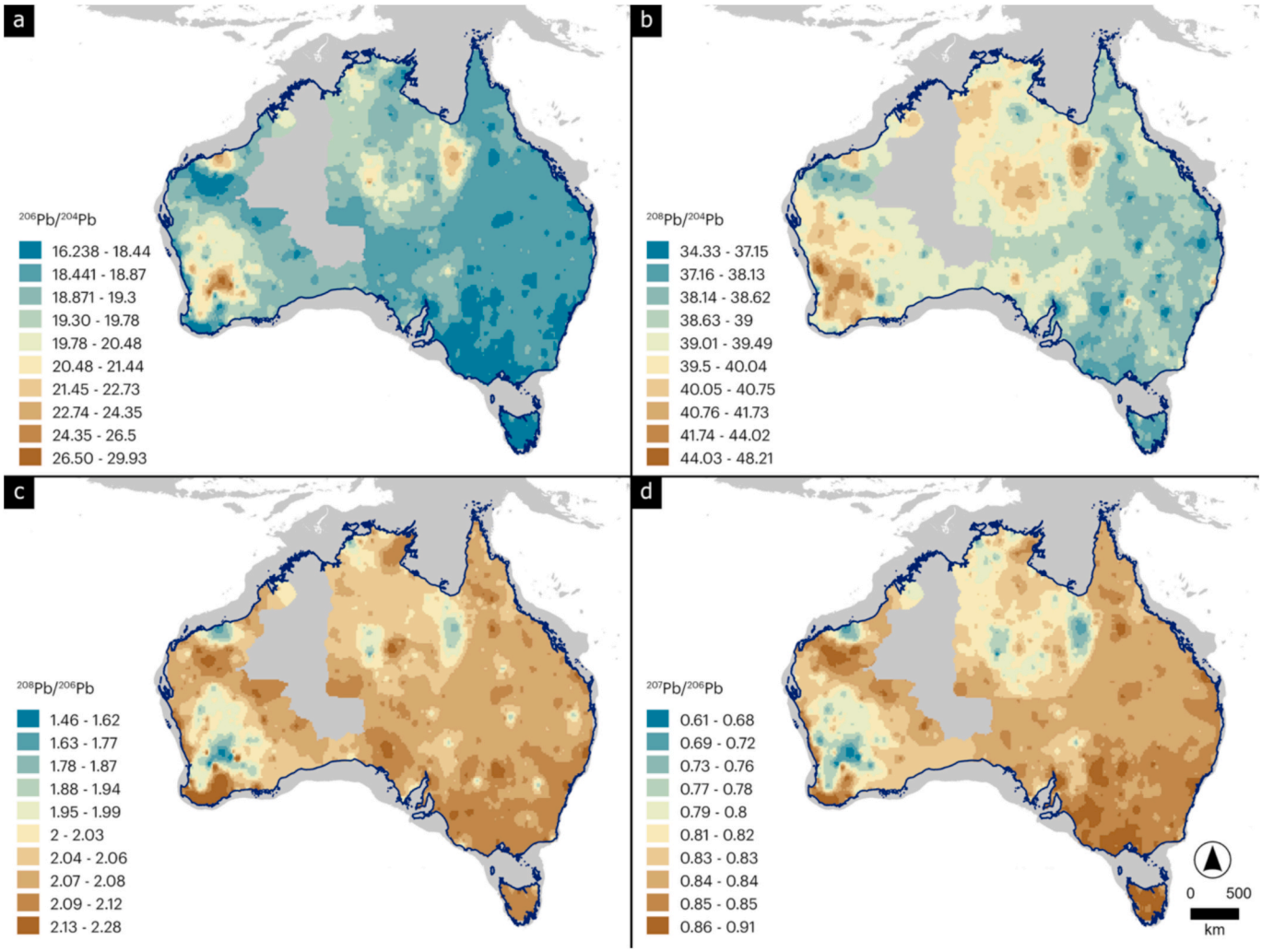

Fig. 8. Pb isoscapes of regolith from Desem et al. (2024, 2025), who provide information on sample types, numbers, locations, analytical methods and the handling of uncertainty in extrapolation of point measurements and links to the dataset. Grey shading indicates no data available.

5. Multi-isoscape overlays in archaeological applications

The forensic power of isoscapes is amplified as the number of isotope systems applied increases. It has now become common internationally for combinations of C, N, O, S, Sr, Nd and Pb isotopes, referenced to detailed isoscapes, to be applied to arrive at a nuanced interpretation of the diet, mobility and origin of humans (Chenery et al., 2014; Scorrer et al., 2021; Neil et al., 2023), the materials they carried and traded (Frigolé et al., 2024; Lü et al., 2023; Štulc et al., 2024) and fauna (Tschetsch et al., 2020).

Limited multi-isotope approaches have been used sporadically in Australia mainly to identify individuals who may not be of local origin (Theden-Ringl et al., 2011), inform on origins and lifeways of individuals from Indigenous and European skeletal material, in some instances in support of repatriation of ancestral remains (Adams et al., 2021; 2022; 2023). Repatriation of ancestral remains is an increasingly pressing issue for many First Nations communities in Australia and the Torres Strait islands with museums pursuing repatriation policies. To respect these ancestors any remains should be returned to the place from which they were removed; however, poor provenance information means that this is not always straightforward. Unfortunately, provenance studies of ancestral remains have heavily relied on Sr rather than multi-isotope systems (sometimes in combination with O, C and N) and most of these studies have been undertaken in coastal contexts where the distribution of Sr is heavily shaped by oceanic influence, dampening meaningful variation in Sr abundances in many regions. Adams et al. (2021; 2022; 2023) and Collard et al. (2019) have highlighted the problem of equifinality in relying heavily on Sr, a problem that can be directly addressed with multi-isotope systems approaches.

As new isoscapes for the continent have become available only relatively recently there is considerable scope to expand multi-isoscape studies. Fig. 9 overlays the $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ isoscapes revealing regions with very strong gradients in the relative difference in values between these two systems. At the sub continental scale there is a very large difference between the southeastern coast and semi-arid inland regions to the west, useful for identifying long distance movement of people or artefacts. At the regional level Inset A in Fig. 9 indicates that the Pilbara and Yilgarn cratons (the Archaean areas north and south respectively, on Fig. 1) are isotopically very distinct from the surrounding regions that are mostly underlain by sedimentary units of a

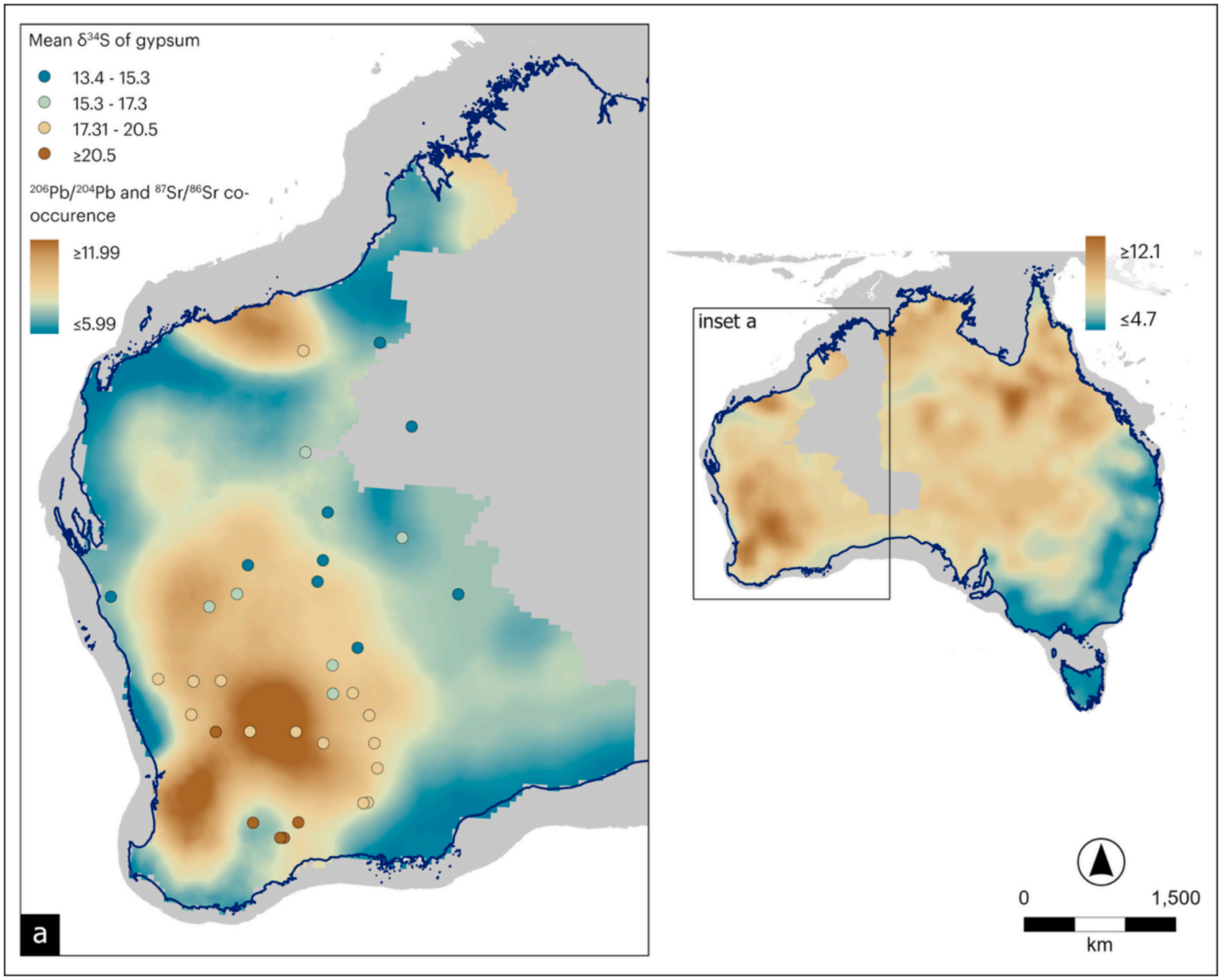

Fig. 9. Spatial co-occurrence of $^{87}Sr/^{86}Sr$ (from Fig. 6) and $^{206}Pb/^{204}Pb$ (from Fig. 8) isotope ratios. Z-scores for each isotope were reclassified into seven classes (±1σ intervals), subjected to focal statistics analysis (circle, 5 cells [~85 km radius]) to emphasize regional trends, and summed. The resulting summed values (range: 2–14) highlight spatial co-occurrence of isotopic signatures across the study area, with lower values (approaching 2) indicating co-occurrence of isotope ratios more than 3 standard deviations below their respective means, and higher values (approaching 14) indicating co-occurrence of isotope ratios more than 3 standard deviations above their respective means. Inset A focuses on Western Australia with an expanded colour ramp interval compared to the main map to highlight regional differences, and with available sulfur isotope data overlain from Fig. 5. Areas with no data shown in grey.

variety of ages. The Yilgarn craton alone is still more than twice the size of the United Kingdom, however the strong gradient in $\delta^{34}S$ value that occurs from SW coast of Western Australia inland to the NW across this region (Fig. 9 inset A) should enable more spatial specificity. In addition, there are currently strong gradients in C and N isotope compositions across the region (Fig. 4) that might provide further constraints on provenance, though these may have been different during periods of altered climatic conditions. Therefore, application of multiple isotope systems may well be able to provide relatively specific provenance for a range of archaeological materials, though not in all cases, at all places, or all times.

Some isotope systems, such as for S, Nd and Pb, have so far rarely been used in Australian archaeological applications. $\delta^{34}S$ isoscapes are likely to be useful in studies of coastal-inland mobility and exchange, based on the probable decline in the rate of marine sulfur accession with increasing distance from the coast (as shown for chlorine, Fig. 2), with an attendant decrease in the $\delta^{34}S$ value of bioavailable sulfur inland (Chivas et al., 1991). Nd is well-suited to non-biological provenancing studies, especially of lithics, but has not been used in Australia, despite the availability of regional-scale isoscapes. Pb holds much promise for informing provenance studies, including repatriation of ancestral remains (Kurpiel et al., 2019). Furthermore, the source material for the increasing numbers of pre-European ceramics reported for northeast Australia (Ulm et al. 2024) and Torres Strait (McNiven et al. 2006) could potentially be further discriminated using a multiple isotope system approach. Pb and Nd, for example, should easily discriminate between vessels manufactured on sediments in western Torres Strait (granitic) versus eastern Torres Strait (basaltic).

Most isotope analyses are destructive by their nature, and this is a consideration in any decision to apply isotope analytical techniques to potentially culturally significant material that may also be available in very limited quantities. Advances in analytical techniques mean that the sample required has been reduced considerably over recent decades, for example ion microprobe analysis of the $\delta^{18}O$ (Green et al., 2022) and laser ablation ICP-MS analysis of the Sr isotope composition (Willmes et al., 2016) of tooth enamel, utilize spot sizes measured in a few to tens of microns.

It is also important to note that, as isotope databases become larger, many of the simpler tools used for placing artefacts in an isoscape context (such as nearest neighbour interpolation) are now rapidly becoming somewhat obsolete and new tools for provenance analysis are required that include defined areas of doubt and uncertainty, for example in relation to Pb (De Ceuster et al., 2023) and Sr isotope mapping (Holt et al., 2021).

6. Conclusion

There are several well-established isoscapes in Australia, although some regions are better characterised than others and the spatial resolution varies between different isotope systems. Some isoscapes are developed from the direct measurement of large numbers of samples (Pb, Sr) whereas others are modelled based on an understanding of the drivers of fractionation in response to climate variations (C, N, H, O). For some isoscapes, clear contrasts and gradients exist across the continent while others are more ambiguous. Multi-isotope approaches therefore provide the most promising approach for determining the provenance of cultural materials for repatriation, identifying the likely origin of ancient and historic individuals, and identifying mobility, interaction and trade networks.

There is clearly considerable potential for the broader application of isoscape approaches in archaeology. There is also a clear need to extend some isoscapes (Sr and S in particular) to cover the entire continent. In the case of Sr, there are numerous studies of the Sr isotope composition of sedimentary basins, ground and surface waters (e.g. Raiber et al., 2024; Stoot et al., 2024), volcanic provinces (Raiber et al., 2009) and fauna (e.g. Rippon et al., 2020; Koutamanis et al., 2021) that could contribute to development of a more complete Sr isoscape for the continent. There are other isotope systems that also have application in archaeology; for example, silicon ($\delta^{30}Si$; Hodson et al., 2008) and calcium ($\delta^{44/42}Ca$; Koutamanis et al., 2021) but variations in composition are not generally relatable to spatial variables.

There are caveats to be considered in undertaking any isotope study in archaeology. First, the application of any isoscape requires consideration of the many processes that can impact the initial isotope composition recorded in an archaeological sample (e.g. Huisman, 2025) and potentially modify that composition following formation. These are specific to each isotope system but considerable research is now available to underpin robust interpretation of isotope data in an archaeological context. Second, most isotope analyses are destructive by their nature, and this is a consideration in any decision to apply isotope analytical techniques to potentially culturally significant material that may also be available in very limited quantities. Ongoing technical developments in mass spectrometry are likely to continue to increase the range of materials that can be analysed and decrease sample size. Concerted effort to 'fill in the gaps' in existing isoscapes has the potential to increase the granularity possible in the interpretation of isotope results on archaeological samples in Australia.

Author Contributions

MIB, SU and JW wrote sections of the initial manuscript, MH drafted the figures. All authors Contributed to interpretation and the final text.

CRediT authorship contribution statement

Michael I. Bird: Writing – review & editing, Writing – original draft, Project administration, Formal analysis, Conceptualization. **Matthew Harris:** Writing – review & editing, Visualization, Investigation. **Janet Hergt:** Writing – review & editing, Investigation. **Sean Ulm:** Writing – review & editing, Writing – original draft, Investigation. **Anna Willis:** Writing – review & editing, Writing – original draft, Investigation. **Jon Woodhead:** Writing – review & editing, Writing – original draft, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

all data is from published work, there is no new data

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