

Morphodynamics, boundary conditions and pattern evolution within a vegetated linear dunefield

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Highlights

- Adjacent linear dunes can preserve radically different records of accumulation.
- Boundary condition variability is more significant than morphodynamic pattern coarsening.
- The concept of ‘pattern dating’ requires further validation.
- Avulsion of sand transport pathways accounts for rapid accumulation in one dune.

Abstract

The controls on the evolution of linear dunefields are poorly understood, despite the potential for reactivation of dunefields, which are currently stabilized by vegetation, under the influence of 21st century climate change. The relative roles of local influences (i.e. boundary conditions) and morphodynamic influences (i.e. emergent properties) remain unclear. Chronostratigraphic and sedimentological analyses were conducted on two pairs of linear dunes exhibiting different spatial patterning in the Strzelecki Desert of central Australia. It was hypothesized that morphodynamic

influences, via pattern-coarsening, would mean that dunes from the simpler pattern, defined in terms of the frequency of defects (i.e. junctions and terminations), would be more mature, older landforms. Optically Stimulated Luminescence (OSL) dating of full-depth, regularly-sampled profiles was used to establish accumulation histories for the four dunes, and supported by sedimentological analysis to investigate possible compositional differences and similarities between the dunes. Whilst three of the dunes (the two more simply-patterned dunes, and one of the more complex dunes) have accumulation histories beginning between ~100 ka and 150 ka, and document sporadic net accumulation throughout the last interglacial/glacial cycle to the late Holocene, one of the dunes (with relatively complex patterning) reveals that the majority of the dune accumulation (> 7 m) at that site occurred during a relatively short window at ~50 ka. There is no clear sedimentological reason for the different behaviour of the younger dune. The data suggest that small-scale and essentially stochastic nature of the aeolian depositional/erosional system can overprint any large-scale morphodynamic controls. The concept of dating landscape change by pattern analysis is thus not supported by this study, and would require very careful interpretation of the scales being considered. This further suggests caution when interpreting dune chronostratigraphies palaeoenvironmentally, as different dunes are able to respond very differently to the same external stimulus (e.g. climate). In the case studied here, a mechanism is proposed to account for the rapid accumulation of the anomalous dune by avulsion of the local aeolian accumulation from one dune ridge to another.

1. Introduction

Linear dunes, when viewed from above in planform, are one of the world's most strikingly organised landscapes, yet the controls on patterning within dunefields in general and, in this case, linear dunefields are still poorly understood. In addition to being found in some of the world's hyper-arid deserts (e.g. Sahara), linear dunes are a widespread component of the landscape across many semi-arid and arid lands, such as central Australia and central southern Africa, in less-active forms. Yet

understanding of the formation and evolution of linear dunes at the landform and landscape scale is still far from complete. Absolute dating with luminescence methods has revealed that these landforms often maintain their position on the landscape over $>10^4$ years, yet may still experience substantial aeolian activity and reworking at decadal to centennial timescales (Telfer, 2011; Roskin et al., 2014). Whilst some linear dunes may be formed by sediment transport orthogonal to the dune trend by lateral deflation from local sands (Hollands et al., 2006; Rubin et al., 2008; Fitzsimmons et al., 2009), it is also evident that they can grow by downwind extension (Telfer, 2011; Lucas et al., 2015); and can also migrate laterally (Nanson et al., 1992a; Bristow et al., 2000). Some of these apparent contradictions may be resolved by consideration of the concept that linear dunes are self-organising phenomena, operating within the complex morphodynamic system formed by interactions within and between the turbulent atmospheric boundary layer and an erodible loose-sand substrate. As such, it is not to be expected that such landforms necessarily have singular and unique formational routes, but that the observed planform patterns might be the result of equifinality; part of the non-equilibrium worldview of Philips' 'perfect landscape' concept (Phillips, 2007). The concept of dune morphologies as attractor states within the phase-space of this system was proposed by Werner (1995), and has since been developed by numerous others (e.g. Eastwood et al., 2011; Ewing et al., 2006; Kocurek and Ewing, 2005). Different dunefield patterns may thus represent the outcomes of different trajectories, or different stages along a trajectory, through the phase-space of the complex aeolian system. The concept of attractor states can be extended not just to differences between gross dune morphologies (e.g. between transverse, barchans and linear forms), but also between different patterns within linear dunefields.

Understanding the development of linear dunefields is important for a number of reasons. Firstly, there have been suggestions that some of the world's linear dunefields (e.g. the Kalahari), which are currently largely inactive and host to extensive rural pastoralism, could be subject to intense aeolian reactivation by the end of the current century under the influence of anthropogenic climate change (Thomas et al., 2005), and yet the processes of dune remobilisation are poorly understood.

Secondly, attempts to use linear dunes as archives of palaeoenvironmental change have been hindered by poor understanding of the geomorphology of these landforms (Chase, 2009; Hesse, 2010; Thomas and Burrough, 2012; Zarate and Tripaldi, 2012; Telfer and Hesse, 2013). If there is to be hope of exploiting linear dunes as geoproxies of useful past environmental information, improved understanding of their landscape-scale behaviour is needed.

1.1 Morphodynamic effects: Pattern coarsening within linear/longitudinal bedforms

Modelling and experimentation suggests that the concept of pattern coarsening, whereby highly disorganised patterns become simpler over time, is likely to be a dominant control (Ewing et al., 2006; Andreotti et al., 2009; Ewing and Kocurek, 2010; Fourriere et al., 2010). Rubin and Ikeda (1990) observed pattern coarsening in linear ripples in flume experiments. Studies from other components of the Earth system which demonstrate self-organizing characteristics, ranging from semi-arid vegetation (Barbier et al., 2006; Kefi et al., 2007; Scheffer et al., 2009), to fluvial geomorphology and channel form (Hooke, 2007) also suggest that pattern coarsening can affect systems as diverse as vegetation patchiness and fluvial sedimentation (Seminara, 2009). In linear dunefields, pattern evolution results from the formation, migration and annihilation of defects, and typically results in upwind-branching (or downwind-converging) networks of junctions, although the evolution of pattern is complex due to the highly inter-related nature of defect location and movement (Werner and Kocurek, 1999). Using a probabilistic numerical model, these authors were able to demonstrate that defects migrate through the dunefield (upwind-facing defects migrating downwind, and vice-versa), and that in their simulation, 50 ka was sufficient to eliminate all defects. Such rates, however, are likely to be highly dependent on additional factors stabilizing the dunes, such as vegetation.

Although there is sound theoretical justification for expecting pattern coarsening to be observed in the remarkable spatial patterning of desert dunes, there is little field validation of the phenomenon in comparison to the wealth of observations from models. Beveridge et al. (2006) is a notable

exception and demonstrated changing wind regimes during the late Pleistocene and Holocene have resulted in multiple generations of dunes of different morphologies. In part, this is due to the timescales involved in pattern reorganisation within dunefields. Whilst landscape-scale experimentation of unvegetated dunefield has revealed that they may form and organise on timescales of months-years (Ping et al., 2014), vegetated linear dunefields are known to have formed over Late Quaternary timescales (e.g. Telfer and Hesse, 2013). As landscape-scale experimental plots such as that of Ping et al. (2014) have substantial logistical challenges, space-time substitutions offer another solution to the challenge of investigating such slow-forming landscapes (Ewing and Kocurek, 2010). Qualitatively, pattern coarsening has been observed in some linear dunefields; the widely spaced, rarely-branching dunes of the northern Kalahari are known to be in general older, more mature landforms (Thomas et al., 2000; Thomas et al., 2003; McFarlane et al., 2005) compared to those of the intricately-patterned southern Kalahari (Telfer and Thomas, 2007; Stone and Thomas, 2008). Indeed, this raises the further question as to whether such landscapes are prone to de-coarsening, or pattern degradation, either locally or at a regional scale. However, comparisons of globally available data on dune pattern morphometric analysis with geochronological data from the published literature suggest that pattern coarsening alone does not appear to explain the diversity of morphologies observed (Telfer and Hesse, 2013).

1.2 Boundary controls: Local spatial variability within the dunefield

Whilst models such as Werner and Kocurek's (1999) are able to entirely control boundary conditions, in reality the process of pattern evolution is likely to be influenced by a wide range of boundary conditions. Beveridge et al. (2006) note the role of heterogeneity of sediment supply, which has long been recognised as a control on dune morphology. Sediment supply, along with topography has also been recognised as being implicit in linear dunefield pattern evolution in the vicinity of dry valleys in the southwestern Kalahari (Bullard and Nash, 1998; 2000). The southwestern Kalahari also demonstrates localized variability which has been attributed to vegetation, and the role of both

grazing and fire on the landscape (Bullard et al., 1995). Throughout the Strzelecki dunefield, there is also more localized variability related to topographic and hydrological obstructions, as well as the nature of the substrate (Fitzsimmons, 2007). Whilst we have attempted to minimize such variability in our chosen study sites in order to explore the relative roles of autogenic and allogenic influences, it is not possible to entirely control such factors in reality.

1.3 Aims and rationale

This study therefore aims to investigate the relative roles that internal (morphodynamic) and external (boundary condition) factors play in process of pattern development over time in linear dunefields. It is hypothesized that morphodynamic pattern coarsening might exert a first-order control on the age and nature of linear dune accumulation. Two nearby (~15 km) pairs of linear dunes from the Strzelecki desert, central Australia, each pair from an area with markedly different planform patterning, were therefore sampled for geochronological (using Optically Stimulated Luminescence, OSL, dating) and sedimentological analyses. Pattern complexity is defined here in terms of the number of defects to pattern (i.e. junctions and terminations) per unit area (and is thus also influenced by dune spacing). Sites were selected in close proximity to each other in order to minimize the possible effects of other controlling variables, such as past variations in climate; it can be assumed here that such changes are synchronous between the pairs of sites.

[Approximate location of Figure 1]

[Approximate location of Figure 2]

1.3 Study area

The Strzelecki desert is characterized by vegetated linear dunes and occasionally other dune forms, at the eastern edge of the Lake Eyre basin (Fig. 1) (Fitzsimmons, 2007). Interdunes are sometimes sandy, sometimes have clay soils and pans (both of which are seen at the study sites; Fig. 2), and some are composed of stony (gibber) pavement (Fitzsimmons, 2007). The main Strzelecki dunefield

is centred around the tri-state boundary of New South Wales, South Australia and Queensland, to the south and west of the town of Innamincka. As part of the whorl of continental dunes that characterize the continental interior of Australia, it consists primarily of linear dunes with net annual sand-transporting wind from the south and southwest (Jennings, 1968; Hesse, 2010). Ash and Wasson (1983) noted the asymmetry of the dunes, and Rubin (1990) interpreted this as evidence of lateral (eastward) migration under present-day wind regimes different from those when the dune trends were initially emplaced, although Fitzsimmons et al. (2007) concluded that, at present, it was not possible to recreate past wind fields from currently available data. Luminescence dating has shown that many Strzelecki dunes have basal or near basal ages in excess of 100 ka, so that lateral migration, if it occurs, can only have progressed at a very slow pace (Fitzsimmons et al., 2007b; Cohen et al., 2010; Hesse, 2016). The dunes towards the northern (i.e. downwind) margin, however, are more disorganized (that is, have more complex patterning) and are more closely spaced. Dominant crest orientations swing from ENE in the far south of the Strzelecki dunefield to NE and NNE further north, and finally due north and NNW in the far north. The linear dunes are low and indistinct in the south but over much of the eastern Strzelecki they average around 10 m in height, with distinct crests, many junctions and tend towards an oriented network, or reticulate, pattern (Hesse, 2011). In the north and west they form much simpler, longer dunes with relatively few junctions. Another characteristic of the Strzelecki Desert is the dominance of source-bordering dunes on the fan of Cooper Creek, west of Innamincka (Cohen, 2010), where the dunes can be considered sediment transport-limited, but elsewhere in the dunefield, including in the study area, the dunes are sediment availability-limited due to the vegetation cover. The extent to which this has been true during the late Quaternary is unclear, but it is apparent that much of the Australian interior maintained a largely vegetated surface throughout most of the last glacial cycle (Hesse, 2016).

The dunes of the Strzelecki have previously been dated by a number of studies with primarily palaeoenvironmental foci (e.g. Lomax et al., 2003; Fitzsimmons et al., 2007b; Fitzsimmons and

Telfer, 2008). Cohen et al., 2010; Both Lomax et al. (2003) and Fitzsimmons et al. (2007) reported ages of 160-210 ka (Marine Isotope Stage, MIS 6-7) for the fluvio-lacustrine or alluvial substrate of the dunefield, and both also support a record of sporadic dune accumulation throughout the last 75 ka. Telfer and Hesse (2013), reanalysing the data of Fitzsimmons et al. (2007) in an attempt to account for the stochastic nature of the preservation of dune sands, suggested enhanced periods of accumulation at 10-14 ka and 28-32 ka, with a hiatus in accumulation at 36-32 ka, as being particularly significant. Fitzsimmons et al. (2007) also sampled aeolian sands dating from around the MIS7 termination at ~190 ka, and note that there is no evidence to suggest that the dunefield was initiated at ~75 ka; older sediment is simply not preserved, or has not been sampled. The meta-analysis of Hesse (2016) showed there is a distinct sampling bias in the Strzelecki dune age dataset, as there is for the entire Australian dunefield; namely that both deep and very shallow samples are often not collected. In addition, while the luminescence ages tend to show distinct clusters, or peaks, in time series, most peaks cannot be distinguished from that expected by random processes and those which may be in part due to the depth bias in the dataset. This finding reinforces the need for strategic sampling, at regular intervals over the full height of dunes, to answer questions concerning the formation and history of dune construction.

Four sites were selected for analysis in the northern sector of the eastern Strzelecki dunefield, and paired sites were chosen to represent two different degrees of dunefield patterning and organisation (Fig. 2). All sites were named after the nearest oil/gas wells, which are part of the Moomba oil/gas field lying beneath the Strzelecki, and have been classified using the metrics of Fitzsimmons (2007). Representing more disorganized dunefield patterning, Tarwonga I (28° 21.084'S 140° 42.578'E) and Tarwonga II (28° 21.617'S 140° 42.629'E) are characteristic of closely-spaced (mean spacing ~360 m), disorganised (1.50 – 1.62 defects km⁻², or ~7-8 defects 10 km⁻¹ dune length) dunes. Located around 15 km south, Caroowinnie (28° 29.850'S 140° 42.097'E) and Airacobra (28° 29.098'S 140° 42.049'E) are typified by widely-spaced (mean spacing ~630 m) and more highly organized (0.83-0.86 defects km⁻², or ~4 defects 10 km⁻¹) dunes. The dunes at Caroowinnie and

Airacobra are also more spatially variable in that the linear dunes tend to occur in patterns that have been varyingly referred to as ‘clustered’ (Goudie, 1970), ‘coalesced’ (Thomas, 1986) or ‘stringers’ (Breed et al., 1979), and which have been considered to form a type of compound linear dune (Lancaster, 1988). The location of the sites was selected to provide dunes away from the immediate margins of the dunefield, and close enough to each other to ensure that the pairs of sites have as similar as possible boundary conditions. Although all will have experienced the same climatic forcings over late Quaternary timescales, it was not possible to entirely control for boundary conditions due to the nature of the sites being investigated. For instance, at the more organised and well-spaced dunes at Airacobra and Caroowinnie, the underlying substrate is more widely exposed (Fig. 2). All of the dunes and interdunes are usually vegetated, although the Tarwonga dunes had been burnt by a rare wildfire in 2011, following fuel build-up after the 2010/11 La Niña wet period.

2. Methods

2.1 Field sampling

At each site, at the dune crest, a Dormer Engineering sand auger was used to reach substrate (Munyikwa et al., 2011), or until clasts – presumably bedrock-derived – made further drilling impossible. After an initial sample at ~50 cm to capture the most recent activity as is practicable, samples were taken for OSL dating every metre where possible. Dry, unconsolidated sand made collection of one sample (at 5 m depth at Tarwonga II) impossible, and uncertainty about the degree of contamination from down-borehole collapse meant that another sample was not collected until 6 m depth. Samples for OSL and sedimentological analyses were collected via a steel tube hammered downwards into the sand, or via direct extraction from the intact inner portion of the augering head in cases where the steel tube would not hold dry sand. The base of the dune was reached at Tarwonga II (abundant calcium carbonate-cemented sand), Caroowinnie (an unidentified sudden hard layer) and Airacobra (a hard yellow clay), but not at Tarwonga I, where hole collapse prevented further drilling. A total station survey of each dune was performed orthogonally from the dune crest

from the sample site to the crest of each adjacent dune, to enable completeness of penetration to be assessed. If, as at Caroowinnie, no adjacent dune was present, the base of the interdune was used as an endpoint.

2.2 Sedimentology

The light-contaminated ends of the OSL samples were dried overnight at 105 °C and weighed to determine water loss. The dried sample was then ignited in a muffle furnace for four hours at 550 °C, and once more weighed to derive the Loss on Ignition (LOI). The sediment remaining after the organic matter had been burnt off was then analysed for particle size using a Mastersizer 2000 (version 5.60) laser diffractometer over a range from 0.1-2000 µm. No coarser material was present. Samples were dispersed in tap water with the aid of sodium hexametaphosphate. Additional analysis of the data was conducted using the Gradistat package (Blott and Pye, 2001). Carbonate content was calculated using the methods of Heiri et al. (2001), using sequential burns with a Carbolite AAF1100 muffle furnace of 550 °C for 4 hours, and 1100 °C for 2 hours, on samples which had been dried in an oven at 105 °C for three hours.

Geochemical analysis of the samples was conducted to a) provide dosimetric information for the OSL dating, b) assess similarities and differences between the dunes using a wider suite of elemental concentrations and c) investigate the causes of variance in elemental concentrations within the dune (e.g. sediment sources, illuviation, etc.). Geochemical analysis was conducted using Inductively-Coupled Plasma Mass Spectrometry (ICP-MS) and Optical Emissions Spectrometry (ICP-OES) at the ISO 9001-accredited Analytical Research Facility (ARF) at Plymouth University, to provide a suite of fifteen elemental concentrations. Samples were prepared using a modification of Haswell (1991) by lithium metaborate fusion at 950 °C and subsequent nitric acid dissolution. ICP-OES was conducted with a Varian 725-ES, and ICP-MS with a ThermoFisher X Series 2. Appropriate geological standards and blanks were used routinely through the analysis programme. Uncertainties on the derived elemental concentrations used for dosimetry were estimated conservatively on the basis of the

standard deviation of triplicate repeat analyses at 5% for K, and 10% for U and Th, as precisions reported from the ICP analysis (typically 1-2%) are not supported by the repeat analyses.

2.3 OSL dating

All OSL age determinations were conducted at the Oxford Luminescence Dating (OLD) laboratory at the University of Oxford. Sample preparation was conventional, using H₂O₂ to remove organics and HCl to remove carbonates. Samples were sieved to isolate the 90-180 µm fraction, and sodium polytungstate at 2.72 g cm⁻³ was used to isolate any heavy minerals. A 45 minute etch in 30% HF was used to remove the alpha-irradiated rind, as well as any feldspars, prior to a final HCl treatment and re-sieving at 90 µm.

For analysis, samples were mounted on either steel or aluminium discs (with dose rate corrected accordingly) with silicone oil using a 2 mm mask. All analyses were conducted on Risø TL-DA-15 automated luminescence readers, using modified single aliquot regenerative (SAR) protocols (Murray and Wintle, 2000, 2003) incorporating standard quality checks, including recycling, recuperation and post-IR feldspar purity checks. OSL characteristics were favourable, as has frequently been reported from Australian dune sands (e.g. Fitzsimmons et al., 2010), with a bright quartz OSL signal showing rapid decay (Fig. 3a). The very few aliquots which failed the quality tests were excluded from further analysis, and at least twelve acceptable aliquots were used for each sample. Individual equivalent dose (D_e) estimates were derived using the Central Age Model (CAM) of Galbraith et al. (1999), using an assumed time-averaged moisture content of 2 ± 1 % (Hesse, 2014). Dosimetry was derived from ICP-MS/-OES, using the conversion factors of Guerin et al. (2011). Disequilibrium in the U and Th series has rarely been reported for the Strzelecki (Lomax et al., 2003; Fitzsimmons et al., 2007b), and where present, is estimated to account for maximum error of ~10 % error on reported ages, although factoring this uncertainty into ages remains problematic due to the difficulty in establishing the onset of disequilibrium; for this study, thus, we assume samples are in equilibrium.

3. Results

3.1 OSL dating

As has commonly been reported for Australian dune sands, the OSL characteristics of the sands studied were, on the whole, highly favourable. Luminescence was typically very bright and decay very rapid, and dose-response curves typically demonstrated growth well-fitted with single saturating exponentials (Fig. 3a, 3b). Dose rates were highly variable, and ranged from very low (~ 0.4 Gy ka⁻¹) to moderately high (~ 2.5 Gy ka⁻¹); this is in accordance with similar variability reported by Fitzsimmons et al. (2007) and to a lesser extent by Lomax et al. (2003). The dose rate correlated strongly ($r^2 = 0.79$) with the proportional fine fraction ($< 63 \mu\text{m}$) of the samples (Fig. 3d). Dose rates are also correlated with the increased coarse fraction evident at the base of most of the dunes, though the correlation is weaker ($r^2 = 0.38$) and it seems more likely that the increase in dose rate is due to the finer fraction.

[Approximate location of Figure 3]

Thirty-six new ages are reported here, and they range from 50 ± 5 years to 145 ± 20 ka (Table 1, Fig. 4 and Fig. 5). In general, despite the highly variable dose rate, ages increase stratigraphically (within uncertainties), with one marked exception. The base of the core at Caroowinnie shows age inversion for the lowest two samples, with the basal sample, at 8 m yielding an age of 1.25 ± 0.30 ka, despite overlying sand attaining a maximum age of 116 ± 18 ka. This is accompanied by an increase in scatter within aliquots for the basal samples of the core, with overdispersion reaching 79 % and 92 % for the inverted samples. Two possibilities exist for this anomaly. Firstly, it may be due to borehole collapse, and internal contamination of the base of the core; indeed the basal age is within uncertainties of the age for 0.5 m within this core (1.46 ± 0.22 ka). Although much care was taken during augering and sample removal to avoid debris falling down the (unlined) hole, it remains a risk during this type of sampling (Munyikwa et al., 2011). Conversely, the subsamples used for grain size analyses, LOI

301 and elemental concentrations for the basal samples shows greater similarity with sands immediately
302 overlying the anomalous ages - and very little similarity to the uppermost samples - and this might
303 suggest the samples are indeed in-situ. In this case, the young ages are more credibly attributed to
304 daylight exposure during removal from the auger head, despite the precautions taken. As the latter
305 case is considered more likely, the lowest two ages from Caroowinnie (Strz12-3-8 and Strz12-3-9)
306 must be excluded from further discussion due to their untenable chronostratigraphic position;
307 however, they are retained in discussion of the physical and chemical properties of the sand

308 Despite their proximity, and overall similarity in dune morphology, there exists considerable
309 variability in the accumulation rates between profiles. Moreover, this variability is neither readily
310 explained by, nor limited to, differences between the degree of pattern complexity of the less
311 organized (Tarwonga I and II) and more organized (Caroowinnie and Airacobra) dunes. Tarwonga I
312 and II, and Caroowinnie, reveal similar accumulation patterns (Fig. 5); all reveal that the dune has
313 not migrated substantially in at least the past ~100 ka, and has been subject to accumulation – and
314 presumably reworking – throughout the late Pleistocene and Holocene. Airacobra, conversely,
315 reveals an accumulation history initiated by rapid accumulation between ~59 – ~42 ka, with net
316 Holocene accumulation accounting for just the top 1-2 m of sand. There is more subtlety in the dune
317 records preserved here, however. For instance, the deepest age of Tarwonga I (99 ± 7 ka) is
318 substantially younger than that of Tarwonga II (145 ± 20 ka), the latter being the oldest age yet
319 reported for non-source bordering dunes of the Strzelecki. As borehole collapse prevented the
320 retrieval of further samples at Tarwonga I (see Fig. 5a for the maximum drilling depth attained in
321 proportion to the height of the dune), an older basal age is likely. Previous studies of non-source
322 bordering dunes in the Strzelecki have not reached the dune base (see Hesse, 2016) and it is likely
323 that they also will have older bases. There is also much variation in the degree of recent dune net
324 accumulation. At least the top 2 m at Tarwonga I have been deposited or reworked in the past 2 ka,
325 whereas at Caroowinnie sands just 1 m below the surface were emplaced at ~ 16 ka.

326 [Approximate location of Table 1]

327 [Approximate location of Figure 4]

328 [Approximate location of Figure 5]

329 ***Sedimentology***

330 There is considerable sedimentological variation between the cores, but as with the net
331 accumulation profiles, this is not apparently a function of the spatial complexity of the dune
332 planform patterning. In all profiles (Fig. 4 and Fig. 6), the dunes are dominated by medium and fine
333 sands (125-500 μm) and, to varying degrees, both the fine and coarse fractions increase with depth.
334 This is especially marked at Tarwonga II and Caroowinnie, whereas variability down-core is less
335 apparent at Tarwonga I and Airacobra (Fig. 4). Overall, however, whilst there is a weak trend
336 towards fining down-core (Fig. 6a), there is no clear trend between dunes in terms of mean, sorting
337 (Fig. 6b), skewness (Fig. 6c) or kurtosis (Fig. 6d). At 6 m depth at Caroowinnie (the last sample which
338 is certainly in-situ), the dune is composed of ~14% silt with trace amounts of clay, as well as ~8%
339 very coarse sand (1-2 mm). The basal sample for Tarwonga II is composed of 10% silt, whereas the
340 adjacent Tarwonga I is <1.5% silt.

341 [Approximate location of Figure 6]

342 Geochemically, too, there is substantial variance within the dunes, and similarly it is not clearly a
343 function of the spatial patterning of the dunes. Organic matter increases with depth at all sites (Fig.
344 7a), with the lower part of the Caroowinnie core showing especially high values for a dune sand (up
345 to 5%). The adjacent Airacobra dune, by contrast, did not exceed 1% organic matter until the basal
346 sample (2.3%). Comparison with Fig. 4 suggests that organic matter concentrations in the dunes
347 closely mirror the fine (silt + clay) fraction. A similar depth-dependency – and lack of clear
348 differentiation between the dunes – is shown with the Ti/Al ratio (Fig. 7b), which shows a significant
349 negative correlation with depth (r^2 of all samples is 0.32; significant at >99.9% confidence with

n=36). This ratio is likely to reflect the proportion of detrital Ti-enriched heavy minerals (predominantly rutile and ilmenite (Pell et al., 2000)), and Al-bearing weathered feldspars and clays. This interpretation is supported by Fitzsimmons et al. (2009), who note the presence of heavy minerals in the dune sands, but not the interdunes, of the Strzelecki. It is also supported by the positive correlation between mean grain size and Ti/Al ratio (r^2 of all samples is 0.36; significant at >99.9% confidence with n=36); it is the finer grains which are relatively enriched in Al.

Carbonate contents are of interest as some Australian dunes are noted to be highly cohesive (Hesse, 2011), and thus differing levels of carbonate could provide an alternative explanation for differing mobilities of dunes. The presence of cohesive agents within sands has been suggested to not just alter the overall susceptibility of dunes to deflation, but also to alter the mechanisms of growth (Rubin and Hesp, 2009). However, as with the particle size and organic matter data, whilst carbonate levels vary by an order of magnitude between samples, there is no clear differentiation between the dunes (Fig. 7c); the overall trend is one of enrichment towards the base of the profiles. This is most marked at Caroowinnie, with the three basal samples exceeding 7% CaCO_3 . Whilst this may, in part, explain the relative immobility of Caroowinnie relative to the neighbouring Airacobra, it must be noted that field and laboratory observation suggests that much of carbonate in these samples is nodular, and thus its stabilizing influence is likely to be reduced.

To investigate the wider suite of elements, multivariate analysis was used. Non-metric Multidimensional Scaling (NMDS) (Oksanen et al., 2016) of the elemental data (Fig. 8a) shows the dominant axis (NMDS1) of variance in the data is dominated by position within the cores (younger samples from high in the profiles tend to low NMDS1 scores and thus plot to the left of the figure, whilst older, deeper samples in general have higher scores). There is no clear compositional difference between the samples from Tarwonga and Caroowinnie/Airacobra. This is supported by cluster analysis, using a Bray-Curtis dissimilarity matrix to construct the dendrogram (Fig. 8b) (Oksanen et al., 2016). Of the four high-level clusters identified by the method, three are dominated

by samples from lower in the profiles, whilst the other is predominantly comprised of near-surface samples. However, aside from one small cluster of three deep Caroowinnie samples, all of the other clusters contain a mixture of samples from Tarwonga and Caroowinnie or Airacobra.

[Approximate location of Figure 7]

[Approximate location of Figure 8]

Discussion

Morphodynamic behaviour of vegetated linear dunes

Pattern coarsening, whereby initially highly disorganised and complex spatial patterns become more organised and simpler over time, has been frequently proposed as a control on the dynamic evolution of dune and dunefield scale aeolian landscapes (e.g. Werner and Kocurek, 1997, 1999; Ewing et al., 2006; Andreotti et al., 2009; Kocurek et al., 2010; Zhang et al., 2012; Gao et al., 2015). The field expression of this concept might be that the simpler patterning of Caroowinnie and Airacobra would be expected to be older than the dunes at Tarwonga. However, not only does Tarwonga II yield the oldest basal date (145 ± 20 ka), Airacobra has the youngest (52 ± 3.5 ka). The difference in dune pattern development is not related to the date of initial dune emplacement; whilst Caroowinnie and the Tarwonga sites are characterized by steady net accumulation which accelerates towards the top of the cores (Fig. 4 and Fig. 5), Airacobra is constructed almost entirely at around 50 ka. If a single constructional period to account for the deposition at 2 – 8.5 m is posited, then the CAM would suggest a likely interval of 51 ± 4 ka (with an overdispersion of 22%) for this period of massive accumulation. The accumulation rate thus implied is likely a record for Australian desert dunes (Hesse, 2016). By contrast, Caroowinnie and the Tarwonga sites record the net accumulation of small sediment packages mostly less than 1 m in thickness throughout their profiles. Towards the top of the dunes, these packages are thicker, and the simplest explanation is

398 that reworking has not yet erased parts of these packages (Telfer et al., 2010; Bailey and Thomas,
399 2014).

400 A number of reasons can be suggested for the lack of evidence for pattern coarsening evident from
401 these data. Most simply, it might be suggested that these data do not support the idea of pattern
402 coarsening as a major control of dunefield evolution. The wealth of modelled and theoretical data in
403 support of this concept, however, merit a more nuanced consideration of the data presented.

404 Firstly, issues of spatial scale may be considered. Self-organising dunefield reorganisation over time
405 is constrained by factors such as the defect density, with defects providing the means by which
406 pattern changes are able to propagate (Werner and Kocurek, 1997, 1999). However, whilst
407 predicting the behaviour of pattern evolution at a dunefield scale may be feasible, examining how
408 such patterns will develop may be very difficult at a local scale. Since the process of reorganisation is
409 strongly influenced by stochastic processes, it is possible that a sample of just four dunes may have
410 simply missed the overall trend toward simplicity with time. These random factors, which may
411 exhibit both quenched (i.e. stationary with regard to time) and annealed (i.e. time-dependent on the
412 pattern evolution) disorder, stem from non-linear behaviour in the small-scale erosion and
413 depositional potential within the turbulent boundary layer and the particulate bed. Indeed,
414 quenched disorder has been suggested to promote pattern stability (Yizhaq and Bel, 2016). This
415 stochastic behaviour in terms of preservation has been widely noted in both field (Telfer and
416 Thomas, 2007; Stone and Thomas, 2008; Leighton et al., 2013) and theoretical (Telfer et al., 2010;
417 Bailey and Thomas, 2014) studies; the net record of dune accumulation is highly spatially variable
418 due to the repeated reworking of the upper dune sands. As well as surficial reworking, it has been
419 suggested that defect development within linear dunes might be assumed to propagate at random
420 locations within the dunefield (Werner and Kocurek, 1999). If this is the case, it may be that the
421 small sample size simply selected dunes that exhibited, in one case, an unusually thorough degree of

reworking and/or an evolutionary trajectory not typical of the surrounding dunes. This idea is developed further in the next section.

Lastly, it might be that pattern coarsening does not occur at this spatial or temporal scale. For instance, it may be dune types selected for this study were simply not dissimilar enough in terms of spatial patterning to readily identify pattern coarsening. Alternatively, although this study has described dune evolution over the past ~100-145 ka, cosmogenic and OSL dating has suggested that the central Australian dunefields began to form at least 500 ka ago (Fujioka et al., 2009). It is conceivable, therefore, that the timescales investigated in this study are not sufficient for pattern coarsening to be evident. When compared to crescentic (migrating) dune systems, pattern evolution in vegetated linear dune areas may take much longer. In dunefields such as those in Australia and the Kalahari, where vegetation and soil stabilization plays a major role, successive periods of dune activation and reworking are likely to complicate the evolutionary trajectories, compared to systems which are unvegetated and evolve in a more uniform manner.

The data presented here suggest that a reconsideration of what the concept of pattern coarsening might mean in terms of linear dune systems is due. It is unclear, for instance, to what extent local instabilities in the dunefield pattern might emerge due to localized differences in boundary conditions (e.g. Fitzsimmons, 2007), and thus overprint regional pattern development. It is certainly evident that different patterns can currently co-exist. Pattern coarsening takes place as dunes interact and merge, which seems to be intuitive for dunes that migrate at different rates according to their size (e.g. barchans). However, for linear dunes, dominated by extension and/or vertical accretion, the scope for such interactions may be more limited (Werner and Kocurek, 1999). Alternatively, pattern coarsening could occur as detail to the pattern is lost to erosion following landform stabilization (McFarlane et al., 2005). In either case, further work is required.

Boundary conditions and geomorphological mechanisms of linear dunefield evolution

This study raises more questions than it answers concerning the long-term geomorphological evolution of linear dunefields. What mechanism accounts for the radical difference in accumulation at Airacobra, in comparison to the adjacent dune at Caroowinnie, and the paired cores at Tarwonga I and II? Here, we consider just the case of Airacobra and the almost-adjacent Caroowinnie dunes. The mechanisms by which linear dunes form are still poorly understood (Telfer and Hesse, 2013), and numerous, non-mutually exclusive models have been proposed. These include field studies demonstrating linear dunes growing by extension of foreset bedding downwind (Telfer, 2011); remote sensing, geophysical and chronometric studies demonstrating the capacity for lateral migration of linear dunes (Hesp et al., 1989; Rubin, 1990; Bristow et al., 2000; 2007a; Rubin et al., 2008); field studies demonstrating extensional growth under unimodal wind regimes due to cohesive sediments (Rubin and Hesp, 2009; Hesse, 2011); field monitoring and chronometric work showing predominantly vertical accretion within linear dunes (Hollands et al., 2006; Craddock et al., 2015); and field experimentation and numerical modelling revealing a dependence on sediment supply for dune orientation, with net extension sometimes parallel, and sometimes oblique to the net sand-transporting wind regime (du Pont et al., 2014; Ping et al., 2014). Compounding this is the recognition that despite some superficial morphological similarities, the sinuous seif dunes common in hyperarid deserts devoid of significant vegetation and the vegetated linear dunes of the semi-arid regions may be fundamentally different landforms (Tsoar, 1989; Tsoar et al., 2004; Hesse, 2016). Many (e.g. Bristow et al., 2007b; Rubin and Hesp, 2009; Telfer, 2011; du Pont et al., 2014) have noted that linear dune formation is likely to include multiple processes, operating and possibly co-existing at different temporal and spatial scales (Ewing et al., 2015). In short, when considering the possibilities for explaining the accumulation at Airacobra whilst the neighbouring dune records no net accumulation at ~50 ka, it is not possible to rule out extensional growth parallel or oblique to the wind, vertical accretion or lateral migration.

There is no clear evidence from the sedimentological or geochemical analysis to suggest that differences in sediment composition account for the differing behaviour of the Airacobra dune. It is

not markedly coarser (Fig. 4), nor contains higher amounts of potential cementing agents (Figs. 7, 8), which might account for its immobility. Indeed, it is not possible to separate, compositionally, the Airacobra dune from the others studied on the basis of the geochemistry of the sands (Fig. 8). Caroowinnie is the dune with markedly different properties in its lowest 2 m, with increased fines, and a coarse fraction, likely accounted for largely by increased carbonate nodules. The reasons for this local change in boundary conditions require further investigation, but could relate to the proximity of the dune to a large interdune area to the west (although it must be noted that a similar interdunal corridor is present to the east of Airacobra). Furthermore, at the time at which Airacobra was accumulating rapidly (i.e. ~50 ka), the carbonate-enriched base of Caroowinnie was already covered with overlying, carbonate-poor sands deposited ~20 ka prior. The only trend which is clear from both the physical and chemical characteristics of all the dunes is a change with depth (and thus time). Samples higher in the profiles (i.e. younger) are more well-sorted, geochemically less varied, and poorer in organic matter than their deeper counterparts. This may be a function of either eluviation of mobile elements and fine particles through the profile in-situ (Fitzsimmons et al., 2009), or may reflect sediment source variability over time, or, most likely, both. In short, despite their different temporal evolutionary pathways, the four dunes studied are all made of broadly the same material.

It is worth considering some of the possible scenarios which might explain the record of dune accumulation and dunefield evolution observed in this study. Fig. 9 shows schematically some possibilities to account for the observed pattern of dune evolution at Airacobra and Caroowinnie. The modern pattern of these dunes was established around 50 ka, and has remained essentially unchanged since (Fig. 9a). In considering these scenarios, it must be noted that strictly all that is known is the presence or absence of the dune at Caroowinnie and Airacobra before and after ~50 ka; other dune positions are shown for context, but must be regarded as speculative, especially in the light of the findings from this study. If a purely extensional mode for linear dune formation is adopted (cf. du Pont et al., 2014; Ping et al., 2014), the logical conclusion is that whilst Caroowinnie

was in place prior to 50 ka, the dune at Airacobra had not formed downwind of the sampling site (Fig. 9b). As this dune extends a further 5.1 km downwind before merging with the Caroowinnie dune (and terminating at 5.5 km), and assuming a typical dune width of 100 m, height of 9 m, and an isosceles triangular profile, this represents an accumulation of $\sim 2.3 \times 10^6 \text{ m}^3$ of sand in the past 50 ka. Fig. 9c depicts an alternative, in which a section of the Airacobra dune has either not yet formed, or has suffered a blow-out which has reworked the sand to the full depth of the dune. Similar reworking to half the depth of a similar dune in the Kalahari has been observed (Telfer, 2011), and shallow blowouts can be observed currently on the crest of the dunes at the field site, and have been reported elsewhere in the Strzelecki (Hesse and Simpson, 2006). Under the lateral accretion model favoured by some (e.g. Hollands et al., 2006; Cohen et al., 2010) for formation of Australia's linear dunes, the dune would then be rebuilt by accretion from sediment derived from adjacent swales at around 50 ka. The gap illustrated on Fig. 9c is ~ 1.5 km long, but it is conceivable that such a blowout could be much shorter; perhaps just ~ 500 m. This would require an order of magnitude less sand accumulation ($\sim 2.3 \times 10^5 \text{ m}^3$) than a purely extensional model. Another possibility (Fig. 9d), which could remain consistent with the pattern coarsening hypothesis, is that the Airacobra dune has moved laterally into place. With a width of ~ 100 m, lateral movement of half this distance would be sufficient to account for the observed chronostratigraphy at the crest, and net sand movement would be on the same order as the blowout model. Perturbations in the planform of the linear dune crests of the area are commonplace (note the kink in the dune to the east of Caroowinnie in Fig. 9), and most models of vegetated linear dune formation would suggest that such deviations will tend to straighten out over time. Indeed, close inspection of the high-resolution CNES/SPOT imagery provided by Google Earth for the site (Fig. 10), suggests that a low-relief (~ 3 m) dune immediately to the west is connected to the Airacobra dune to the north and south of the site. Speculatively, this may represent a relic of the former sand transport pathway through this part of the dunefield, before the preferred net accumulation switched to its present location. This might be thought of as being analogous to avulsion within an anabranching river channel; in effect, aeolian

sediment transport and depositional pathways could be thought of as having avulsed to a new route through the dunefield. Although the sites were selected as far as possible to minimize differences in boundary conditions, the more sparsely-patterned dunes at Caroowinnie and Airacobra may have influenced the dune's morphodynamic behaviour by facilitating a switch in transport pathways across bare interdunal corridors; there is more space here for dune migration to occur. Alternatively, localized variations in boundary conditions such as surface moisture might influence the stability of sediment transport pathways. Additional fieldwork is necessary to test these hypotheses.

[Approximate location of Figure 9]

[Approximate location of Figure 10]

Implications for palaeoenvironmental reconstructions

It is not the primary aim of this study to investigate the palaeoenvironmental nor palaeoclimatic signal recorded within the archives of dune sediment accumulation at these sites. Nonetheless, comment is required on how the ages presented here relate to existing studies, and the implications of the findings of this study. The ages are, in the broadest sense, in agreement with those presented for dunes of the Strzelecki by Lomax et al. (2003), Fitzsimmons et al. (2007a; 2007b), Nanson et al. (2008), Cohen et al. (2010), and summarized in Hesse (2016), in that they reveal sporadic net accumulation throughout the last glacial cycle. Few ages preceding the last interglacial have previously been reported for Strzelecki dunes (Gardner et al., 1987), and yet at least one of the dunes (Tarwonga II) studied here was emplaced during Marine Isotope Stage (MIS) 6. The age-depth profile suggests that it is likely that the base of Tarwonga may have a similar age. The most frequently occurring ages in the suite are those representing the late Holocene (n=9) surficial activity, and the period of rapid accumulation at Airacobra at 51 ± 4 ka (n=8). However, whilst the late Holocene (in many cases, essentially modern) activity is observed at all sites, no net accumulation at around 50 ka was sampled at two of the sites, and only a single sample close to this

range at the other site (57 ± 3.9 ka at Tarwonga II, although it must be noted that the missing sample at 5 m from this site is bracketed by ages at 57 ± 3.9 and 22 ± 1.9 ka). Of course, it is entirely possible that deposition from this interval occurred at all the sites, but if so, it has been entirely removed from the record at the other three sites. Although three of the dunes have broadly similar age-depth structures, they do not show simultaneous episodes of accumulation. While reworking could account for loss of some events at some sites, it would take a remarkable coincidence to remove all evidence of a simultaneous event at three out of four sites, whilst leaving it entirely intact at the other. There is no clear evidence of enhanced activity during the Last Glacial Maximum (LGM), with only two ages falling within this range (17 ± 2.4 ka at Caroowinnie, and 22 ± 1.9 ka at Tarwonga II). Hesse (2016) discusses the mounting evidence challenging the long-standing paradigm of the LGM in Australia as being a time of continent-wide aridity. Accumulation since the LGM is diversely recorded in the different dunes, but all show some signs of activity in the late Holocene, and two record accumulation within the past century at 50 cm depth.

The basal deposits of three of the sites date from MIS 5 or 6, and those samples deposited near the height of the last interglacial (especially at Tarwonga II and Caroowinnie, and considering that the true age of the two basal samples is not known, but is greater than 116 ka) do show some distinct sedimentological variations which may have palaeoenvironmental significance. Whilst the enhanced fine fraction (and accompanying geochemical diversity) may well be a post-depositional phenomenon, or might result from longer residence times in the near-surface zone due to lower accumulation rates, it is harder to rationalize a mechanism by which the fraction of very coarse sand could be due to eluviation within the dune body. Likewise, the organic matter fraction is markedly higher in samples deposited during this interval. Whilst the presence of a peak in organic C content at the base of Airacobra clearly cannot be attributed to an interglacial origin, and must result from illuviation, both Caroowinnie and Tarwonga II record the highest organic C levels at around ~108-~116 ka. In both cases, this is higher than deeper samples (of unknown age at Caroowinnie, and dating from MIS 6 at Tarwonga II). If this organic matter is indeed in-situ, as this might suggest, this

would corroborate arguments for enhanced vegetation cover, and, by inference, wetter conditions around MIS 5 (Hesse et al., 2004, and references therein; Nanson et al., 1992b). The increased coarse fraction may be attributable to a change in sediment supply, potentially via enhanced sediment supply due to increased regional fluvial activity (Nanson et al., 1992b), or may simply reflect accumulation of coarser grains over low-relief bedforms early in the dune's development.

The most obvious, and concerning, implication for palaeoenvironmental reconstructions from linear dunes, however, is the very substantial spatial variability in preservation evident. Whilst this is not a new observation (e.g. Telfer and Thomas, 2007; Fitzsimmons and Telfer, 2008; Stone and Thomas, 2008; Leighton et al., 2014), the data presented here represent perhaps the most dramatic example of the problem yet presented. If only the dune at Airacobra had been sampled, even using best-practice full-depth systematic sampling to avoid depth bias, the conclusion – with obvious palaeoenvironmental implications – would be that linear dunes of the Strzelecki had been emplaced in a single, rapid accretion period sometime around 50 ka, with minimal reworking of the crests since that date. Any of the other sampled dunes would, by contrast, suggest emplacement beginning prior to 100 ka, and net accumulation since that date occurring frequently throughout the whole of the last glacial/interglacial cycle.

Moreover, these data suggest that the concept of providing relative dating by assessing pattern complexity, proposed by Ewing et al. (2006) and applied in various forms by others needs to be treated cautiously. Whilst theory suggests that the broad concept ought to be applicable, and that very simple patterns such as those of Titan, might indicate maturity (Savage et al., 2014), using the technique to derive absolute age estimates (e.g. Wu and Guo, 2012, Wen and Dong, 2016;) without corroborating absolute age estimates (e.g. from OSL) may be prone to error due to the stochastic nature of accumulation demonstrated here.

Conclusions

This study has not found evidence to support morphodynamic pattern coarsening as being a first-order control of linear dune pattern evolution, at least for sites investigated here. Instead, small-scale, presumably stochastic local variability between dunes dominates the accumulation histories of the four dunes studied. Whilst three of the four dunes record broadly similar accumulation histories, the fourth (Airacobra) demonstrates a radically different age-depth profile. It is not clear exactly what aspect of the boundary conditions control this variability; sedimentological differences do not account for the distinct behaviour, and all the sampled dunes demonstrate down-core variability in chemical and physical sedimentary characteristics that likely reflect both changes in sediment source and in-situ modification of the dune sands. For linear dune systems, the degree of pattern organization may be more reflective of the spatial and temporal variability of boundary conditions relative to rates of sand transport, rather than the age of the system. Whilst the timing of dune emplacement, as well as the physical and chemical composition, of the dunes does not vary with the complexity of the patterning, a mechanism is proposed in this instance, in which one dune crestline is abandoned during a sudden avulsion in a sand transport corridor and a new adjacent dune is created.

These findings imply that caution should be exerted with the concept of 'pattern dating' (Ewing et al. 2006). Whilst working at larger scales (i.e. considering the dunefield as a whole, rather than individual dunes), might negate the issue of individual dunes being unrepresentative of the whole dunefield, the data from this study suggest that further field validation is necessary if pattern analysis is used to extract geochronological information. There are further implications for the derivation of palaeoenvironmental information from dune accumulation records, and highlight the shortcomings in trying to recreate past environmental conditions from small numbers of samples. Although this observation is not new, the data presented here are a convincing example of how the stochastic nature of dune accumulation and reworking can overprint any evidence driven by external forcing.

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830

Figure captions

Figure 1. a) The study area set within the context of Australia and its dunefield (highlighted in orange), and b) the regional setting for the selected sites, in the northern Strzelecki Desert. The extent of the dunes is highlighted in orange, along with major hydrological features in the area.

Figure 2. Detail of the site locations from a) CNES/SPOT imagery courtesy of Google Earth, with b) manually digitized dune crests. Note that Tarwonga I and II are located in a region characterized by more disorganized patterning, with higher defect densities, than Caroowinnie or Airacobra, which lie ~15 km to the south in the northern part of the main Strzelecki dunefield. The outlined area in the lower schematic is the area of focus in Figure 8. c) Topographic data from the SRTM global 1-arcsecond dataset (NASA, 2004), whilst at the limits of resolution for the elevation expression of the dunes, highlights the dune trends.

Figure 3. OSL characteristics of the samples. a) All samples had a signal dominated by the quartz fast component, with very rapid decay, and b) growth was well-fitted with single exponentials. c) Overdispersion of samples ranged from 8 – 62%, with the majority of samples under 25% (see Table 1). d) The large variation in dose rates apparent in these samples ($0.4 - 2.5 \text{ Gy ka}^{-1}$) is attributable to variation in the abundance of fines within the sediment.

Figure 4. OSL ages (in thousands of years, ka) and grain size data for each site.

Figure 5. a-d) Age-depth profiles of the four sample sites, with surveyed transects of the dunes, with the depth of the cores indicated, shown inset. Note that the sampling at Tarwonga I does not reach the base of the dune as indicated by integration of the adjacent interdunes; basal ages here are thus likely to be a minimum for dune emplacement at this location. The flat plinth at Tarwonga II to the east of the dune is a road. e) Age-depth profiles overlain, highlighting the distinctly different profile of Airacobra.

Figure 6. a) Mean grain size (μm), b) Sorting, c) Skewness and d) Kurtosis for all samples. All descriptive statistics were calculated by graphical methods (i.e. according to the methods of Folk and Ward, 1957) using the Gradistat package (Blott and Pye, 2001). Note that, with the exception of a general trend towards fining down-core, and an increase in fine content (resulting in poorer sorting and negative skew) towards the base of the Caroowinnie core, the dune sands share very similar physical properties.

Figure 7. a) Loss on Ignition, b) Ti/Al ratios and c) carbonate content for all samples.

Figure 8. a) Non-metric Multidimensional Scaling of the elemental suite analysed. Samples are described with a prefix indicating site (T = Tarwonga, T2 = Tarwonga II, C = Caroowinnie, A = Airacobra), and a suffix indicating position downcore (thus the uppermost sample = 1, and the basal samples are 8 to 10). Note the tendency for the x axis (NMDS1) to separate samples based on their depth/maturity in the profile; uppermost samples tend to low NMDS1 scores, and older samples tend to high values. b) Cluster analysis confirms that samples are not grouped according to individual dunes, but grouping is more strongly controlled by depth (or age) within the dunes.

Figure 9. a) The current spatial arrangement of the dunes at the sampled sites at Airacobra and Caroowinnie was essentially established at around 50 ka. b) If a purely extensional mode of development were assumed, it would have to be assumed that the downwind dune formed subsequently. c) A brief interruption to patterning, such as a full-depth blow-out of the dune, could have subsequently been infilled by accumulation at around 50 ka. d) Lateral migration of a small section of the dune by more than half the dunes' width. Note that in all panels, the only points which can be confidently located at either of the timeslices presented (here simplified to just pre- and post- 50 ka, though the uncertainties surrounding this age should be noted), are the sampled sites themselves. Other dunes are shown in these schematics only indicatively and may, or may not, have been present at the times indicated. Where the dune is known to have been in place at this date, it is indicated with a black circle, and where it was not present, with a grey circle.

881 *Figure 10. a) Detail of the high-resolution SPOT/CNRS imagery (courtesy of Google Earth™) suggests*
882 *a possible explanation for the rapid accumulation at Airacobra; abandonment of a former transport*
883 *pathway and the establishment of the present-day planform pattern at the site. b) An example of the*
884 *inter-dune periodicity in the topographical profiles of the dunes at the clustered dunes of*
885 *Caroowinnie and Airacobra. The relief of the dunes is superimposed on a longer wavelength relief,*
886 *which is not obvious from the high-resolution imagery alone (courtesy of Google Earth™).*

887 *Table captions*

888 *Table 1. OSL age data*

889

890 *Table 1*

Site	Sample depth (m)	Sample ID	K (%)	Th (ppm)	U (ppm)	Cosmic dose (Gy/ka)	Dose rate (Gy/ka)	De (Gy)	Overdispersion (sigma, %)	Age (ka)
Tarwonga I	0.55	STRZ12-1-1	0.19 ± 0.01	1.2 ± 0.12	0.27 ± 0.03	0.18 ± 0.035	0.506 ± 0.04	0.03 ± 0	0.17	0.05 ± 0.005
		STRZ12-1-2	0.28 ± 0.01	1.98 ± 0.2	0.51 ± 0.05	0.169 ± 0.021	0.691 ± 0.036	0.17 ± 0.02	0.29	0.24 ± 0.03
	2	STRZ12-1-3	0.13 ± 0.01	1.07 ± 0.11	0.21 ± 0.02	0.147 ± 0.013	0.4 ± 0.02	0.7 ± 0.04	0.15	1.75 ± 0.13
	3	STRZ12-1-4	0.21 ± 0.01	1.38 ± 0.14	0.21 ± 0.02	0.129 ± 0.01	0.477 ± 0.023	1.46 ± 0.09	0.3	3.06 ± 0.24
	4	STRZ12-1-5	0.32 ± 0.02	1.42 ± 0.14	0.31 ± 0.03	0.114 ± 0.009	0.593 ± 0.029	18.69 ± 0.41	0.23	31.53 ± 1.69
	5	STRZ12-1-6	0.47 ± 0.02	1.61 ± 0.16	0.39 ± 0.04	0.101 ± 0.007	0.754 ± 0.039	21.88 ± 0.42	0.23	29.02 ± 1.6
	6	STRZ12-1-7	0.34 ± 0.02	1.28 ± 0.13	0.35 ± 0.04	0.09 ± 0.007	0.591 ± 0.03	43.2 ± 1.2	0.11	73.04 ± 4.2
	7	STRZ12-1-8	0.39 ± 0.02	1.99 ± 0.2	0.39 ± 0.04	0.08 ± 0.006	0.69 ± 0.035	68.3 ± 2.9	0.29	99.01 ± 6.57
Tarwonga II	0.5	STRZ12-2-1	0.11 ± 0.01	0.82 ± 0.08	0.14 ± 0.01	0.181 ± 0.038	0.373 ± 0.04	0.48 ± 0.02	0.13	1.29 ± 0.15
	1	STRZ12-2-2	0.17 ± 0.01	0.9 ± 0.09	0.18 ± 0.02	0.169 ± 0.021	0.435 ± 0.026	0.86 ± 0.09	0.35	1.97 ± 0.24
	2	STRZ12-2-3	0.22 ± 0.01	0.88 ± 0.09	0.18 ± 0.02	0.147 ± 0.013	0.458 ± 0.023	3.92 ± 0.14	0.12	8.57 ± 0.52
	3	STRZ12-2-4	0.24 ± 0.01	1.5 ± 0.15	0.29 ± 0.03	0.129 ± 0.01	0.531 ± 0.025	5.27 ± 0.18	0.1	9.93 ± 0.58
	4	STRZ12-2-5	0.33 ± 0.02	1.22 ± 0.12	0.25 ± 0.03	0.114 ± 0.009	0.578 ± 0.029	12.85 ± 0.9	0.24	22.22 ± 1.91
	6	STRZ12-2-6	0.46 ± 0.02	2.26 ± 0.23	0.48 ± 0.05	0.09 ± 0.007	0.798 ± 0.04	45.7 ± 2.1	0.16	57.28 ± 3.92
	7	STRZ12-	0.56 ±	1.57 ±	0.32 ±	0.08 ±	0.799 ±	91.9 ± 6.3	0.21	114.96 ±

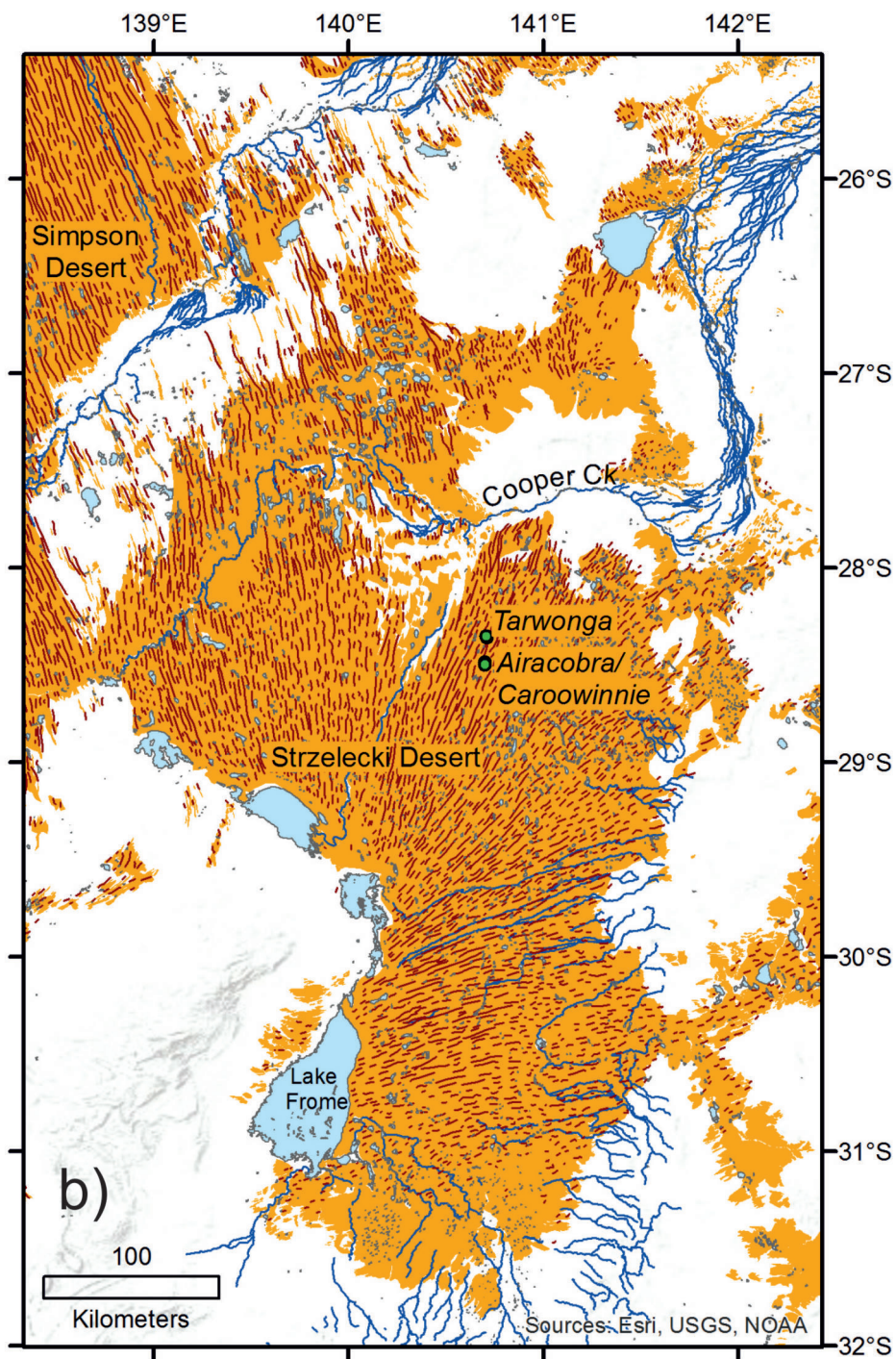
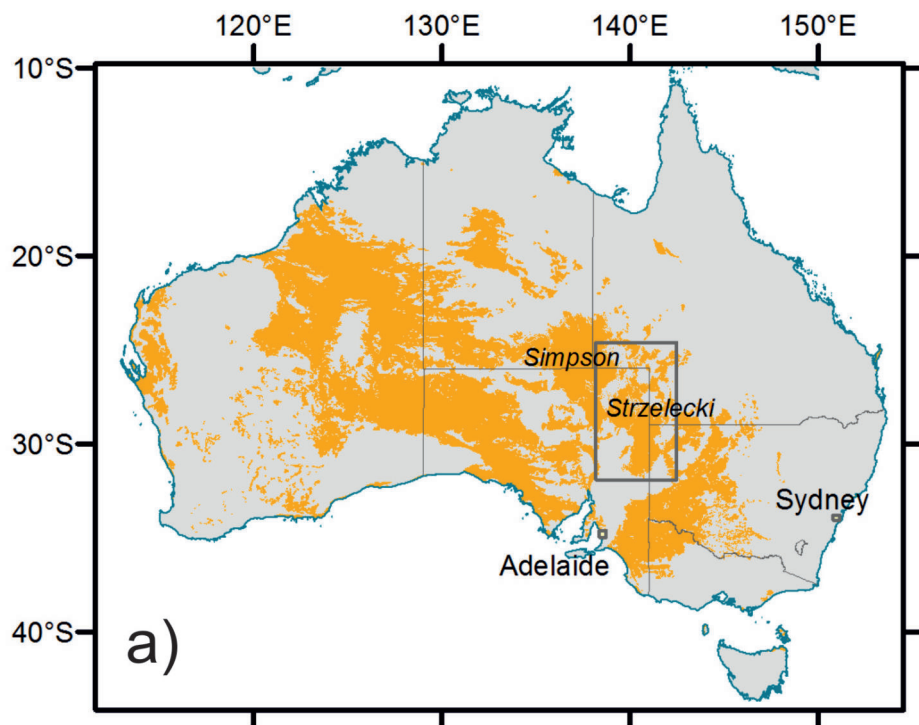
Caroowinnie		2-7	0.03	0.16	0.03	0.006	0.044		10.09
		STRZ12-	0.78 ±	2.16 ±	0.58 ±	0.072 ±	1.106 ±		108.47 ±
	8	2-8	0.04	0.22	0.06	0.005	0.061	120 ± 15	0.4 14.84
		STRZ12-	0.8 ±	2.69 ±	0.58 ±	0.065 ±	1.159 ±		144.91 ±
	9	2-9	0.04	0.27	0.06	0.005	0.064	168 ± 21	0.43 19.81
		STRZ12-	0.24 ±	0.78 ±	0.19 ±	0.181 ±	0.507 ±	0.74 ±	
	0.5	3-1	0.01	0.08	0.02	0.038	0.043	0.09	0.21 1.46 ± 0.22
		STRZ12-	0.29 ±	1.27 ±	0.27 ±	0.169 ±	0.599 ±	9.53 ±	
	1	3-2	0.01	0.13	0.03	0.021	0.032	0.71	0.23 15.92 ± 1.47
		STRZ12-	0.33 ±	1.3 ±	0.42 ±	0.147 ±	0.65 ±	7.79 ±	
	2	3-3	0.02	0.13	0.04	0.013	0.031	0.33	0.15 11.99 ± 0.77
		STRZ12-	0.32 ±	1.35 ±	0.28 ±	0.129 ±	0.593 ±	6.59 ±	
	3	3-4	0.02	0.13	0.03	0.01	0.029	0.35	0.18 11.12 ± 0.8
		STRZ12-	0.28 ±	1.6 ±	0.37 ±	0.114 ±	0.576 ±		
	4	3-5	0.01	0.16	0.04	0.009	0.027	9.9 ± 1.3	0.45 17.19 ± 2.4
		STRZ12-	1.08 ±	3.89 ±	0.88 ±	0.101 ±	1.616 ±		72.38 ±
	5	3-6	0.05	0.39	0.09	0.007	0.088	117 ± 22	0.62 14.17
		STRZ12-	1.36 ±	6.19 ±	1.79 ±	0.09 ±	2.245 ±		116.26 ±
	6	3-7	0.07	0.62	0.18	0.007	0.119	261 ± 37	0.47 17.6
		STRZ12-	1.69 ±	4.21 ±	1.88 ±	0.08 ±	2.44 ±		84.43 ±
	7	3-8	0.08	0.42	0.19	0.006	0.136	206 ± 47	0.79 19.83
		STRZ12-	1.95 ±	3.07 ±	1.1 ±	0.072 ±	2.417 ±	3.01 ±	
	8	3-9	0.1	0.31	0.11	0.005	0.147	0.69	0.92 1.25 ± 0.3
Airacobra		STRZ12-	0.23 ±	1.36 ±	0.28 ±	0.181 ±	0.563 ±	0.05 ±	
	0.5	4-1	0.01	0.14	0.03	0.038	0.044	0.02	0.36 0.08 ± 0.03
		STRZ12-	0.27 ±	1.08 ±	0.2 ±	0.169 ±	0.554 ±	2.08 ±	
	1	4-2	0.01	0.11	0.02	0.021	0.031	0.14	0.22 3.75 ± 0.32
		STRZ12-	0.34 ±	1.29 ±	0.26 ±	0.147 ±	0.626 ±		
	2	4-3	0.02	0.13	0.03	0.013	0.031	31 ± 0.76	0.085 49.5 ± 2.74
		STRZ12-	0.35 ±	1.44 ±	0.32 ±	0.129 ±	0.642 ±	26.96 ±	
	3	4-4	0.02	0.14	0.03	0.01	0.031	0.6	0.081 42.02 ± 2.26

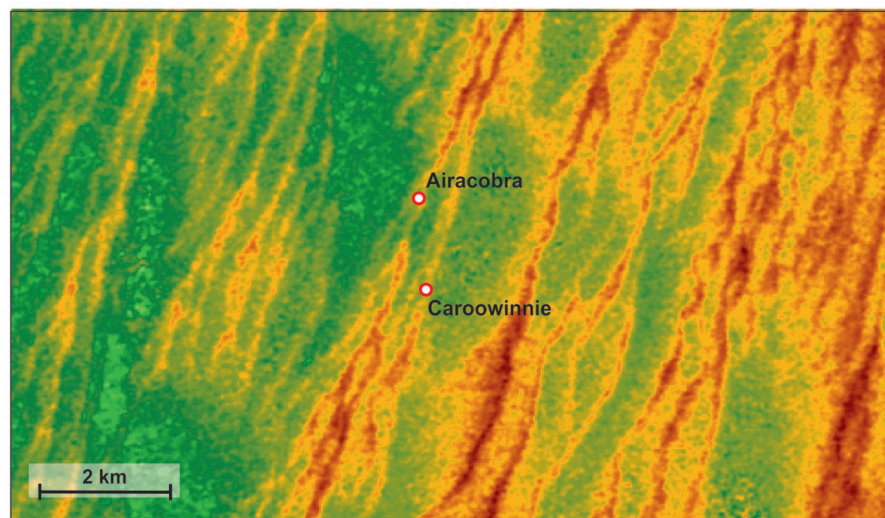
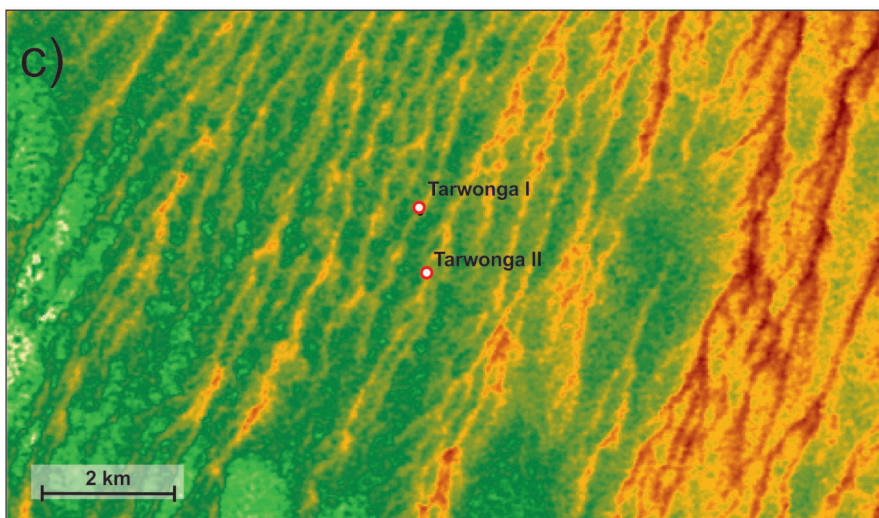
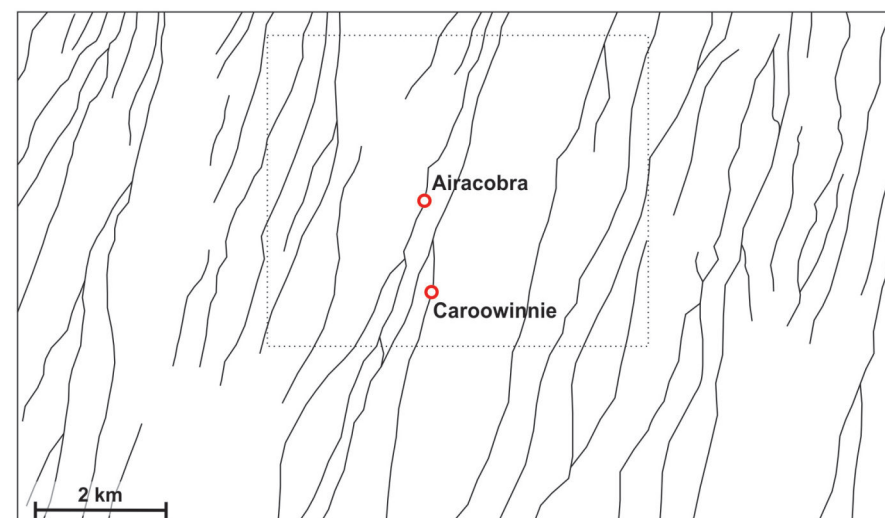
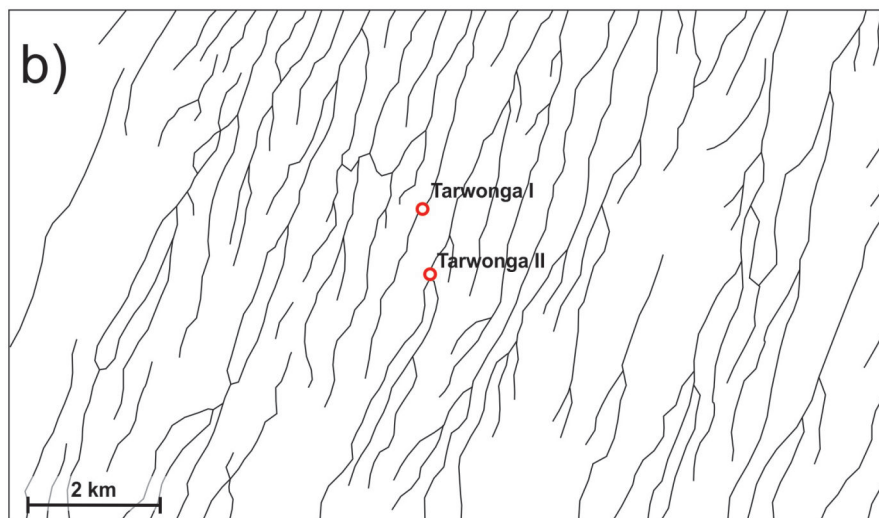
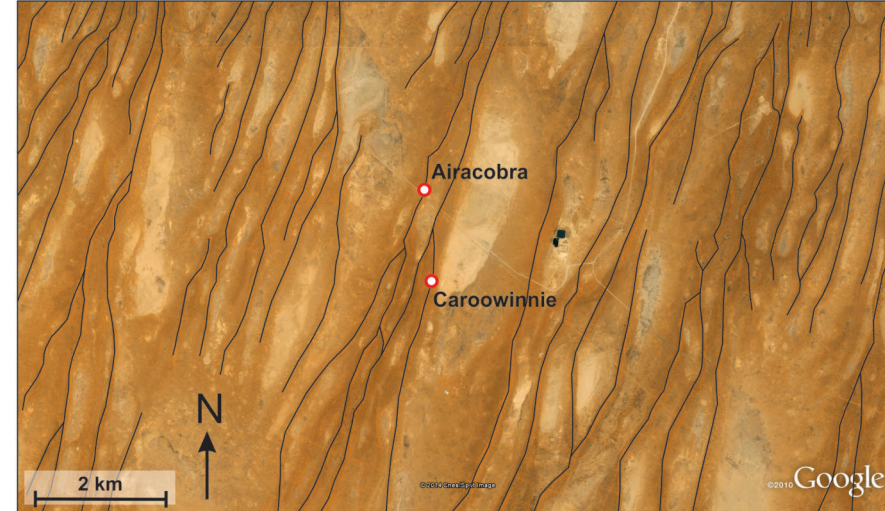
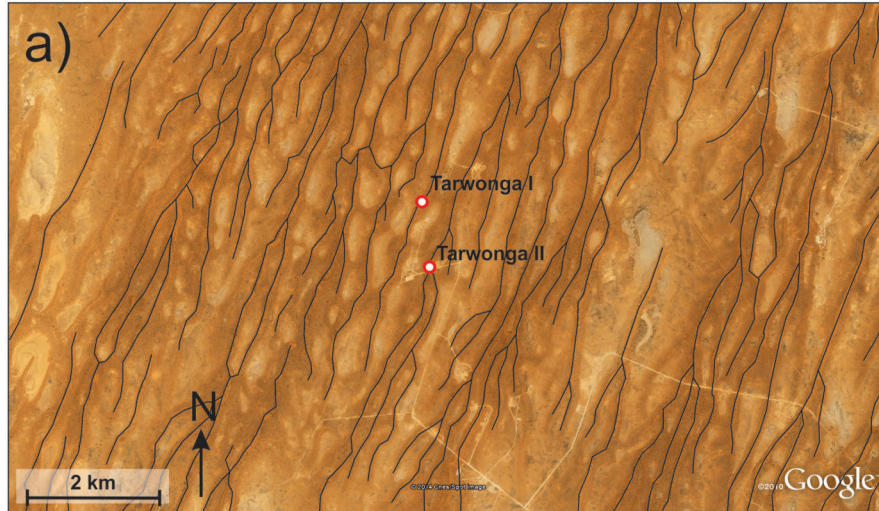
	STRZ12-	0.5 ±	1.45 ±	0.31 ±	0.114 ±	0.768 ±			
4	4-5	0.03	0.14	0.03	0.009	0.04	36.8 ± 1.8	0.16	47.94 ± 3.44
	STRZ12-	0.52 ±	1.69 ±	0.45 ±	0.101 ±	0.819 ±			
5	4-6	0.03	0.17	0.04	0.007	0.042	38.4 ± 1.6	0.14	46.9 ± 3.12
	STRZ12-	0.57 ±	1.61 ±	0.38 ±	0.09 ±	0.842 ±			
6	4-7	0.03	0.16	0.04	0.007	0.045	48.6 ± 2.9	0.2	57.74 ± 4.65
	STRZ12-	0.53 ±	1.51 ±	0.42 ±	0.08 ±	0.792 ±			
7	4-8	0.03	0.15	0.04	0.006	0.042	47.4 ± 2.7	0.19	59.85 ± 4.68
	STRZ12-	0.61 ±	1.98 ±	0.5 ±	0.072 ±	0.916 ±			
8	4-9	0.03	0.2	0.05	0.005	0.05	47.7 ± 1.9	0.13	52.07 ± 3.5
	1.19 ±	4.16 ±	0.84 ±	0.072 ±	1.698 ±				
8.5	0.06	0.42	0.08	0.005	0.095	87.6 ± 3.3	0.12	51.59 ± 3.48	

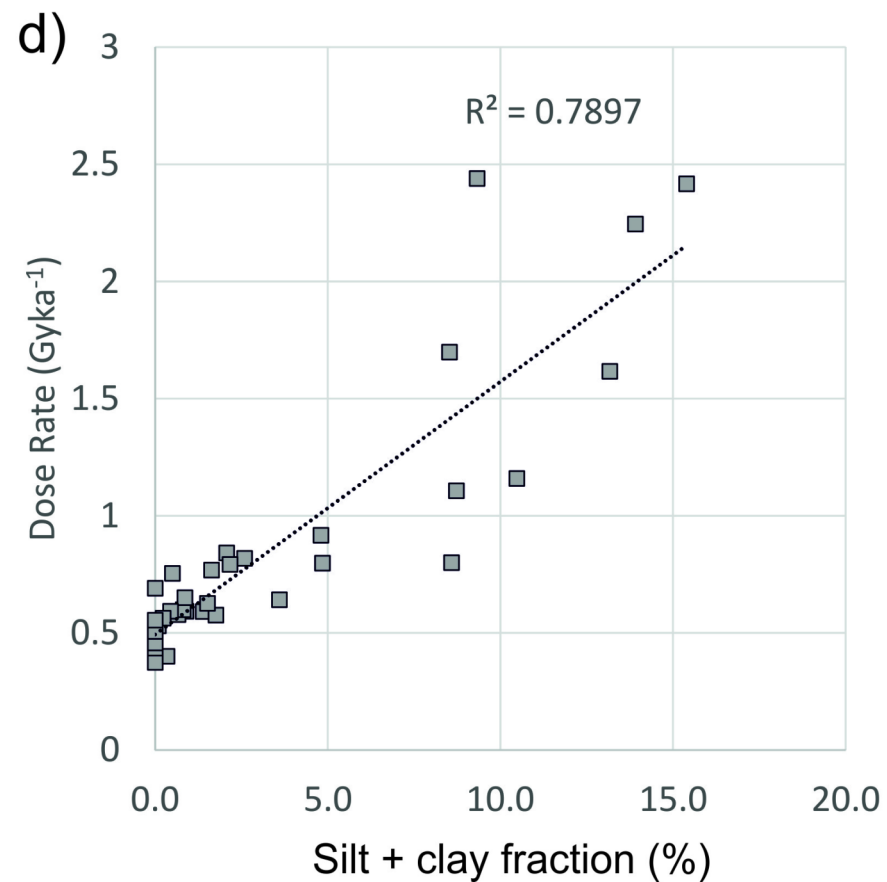
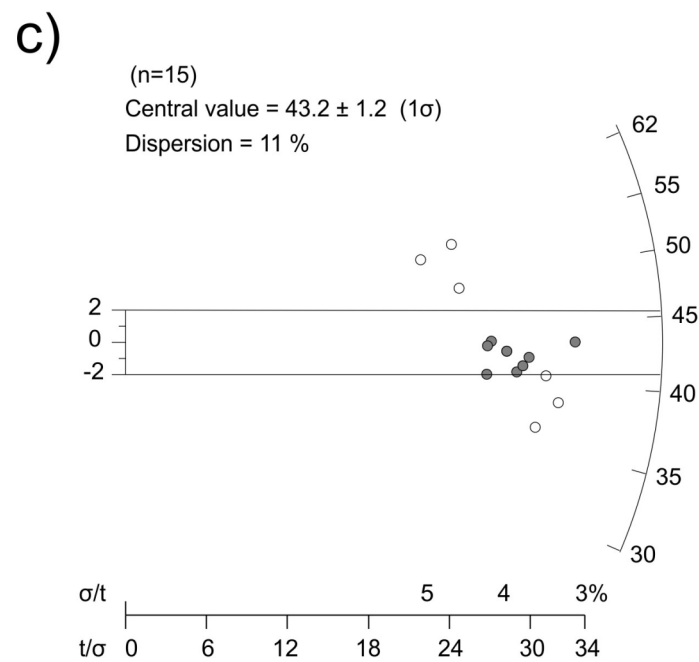
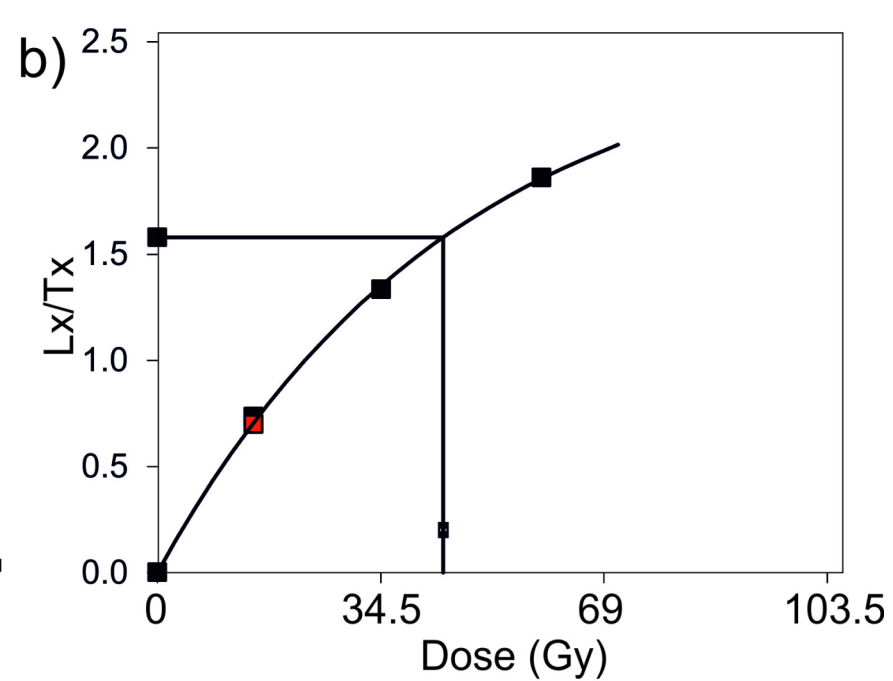
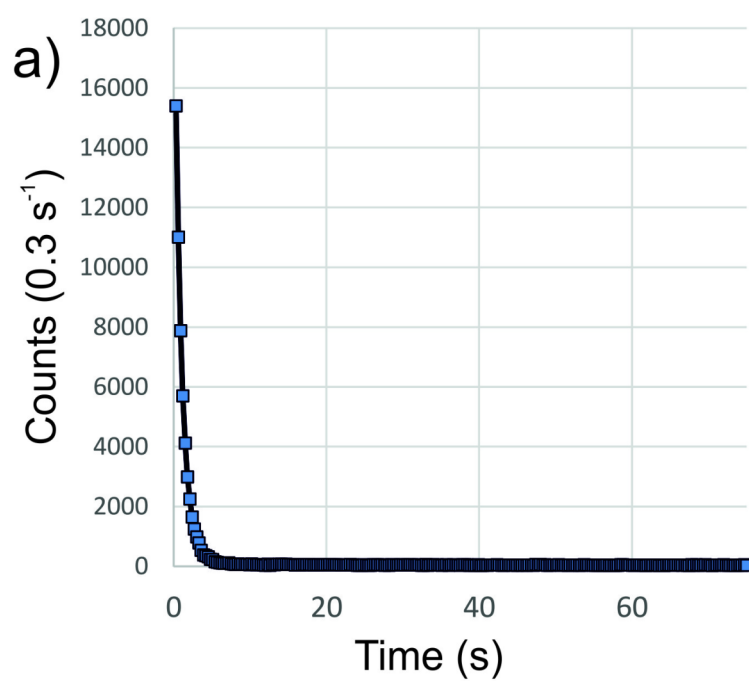
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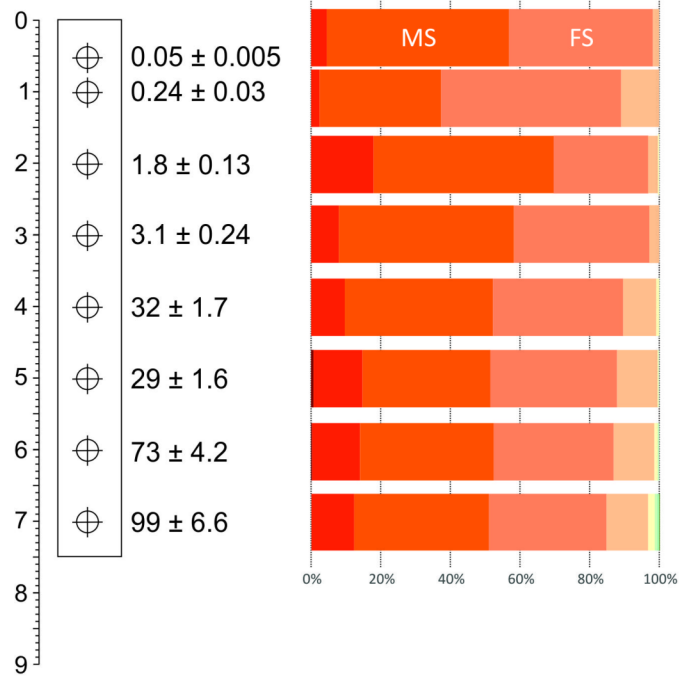
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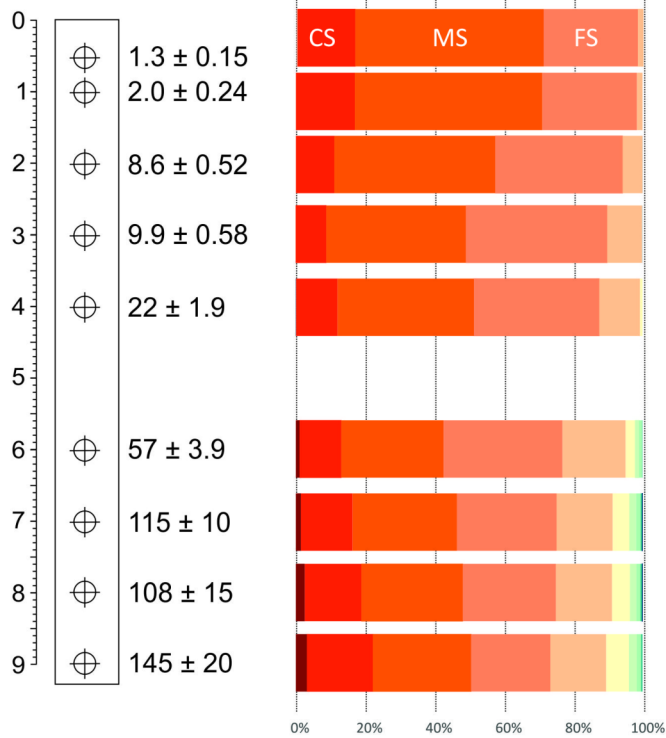




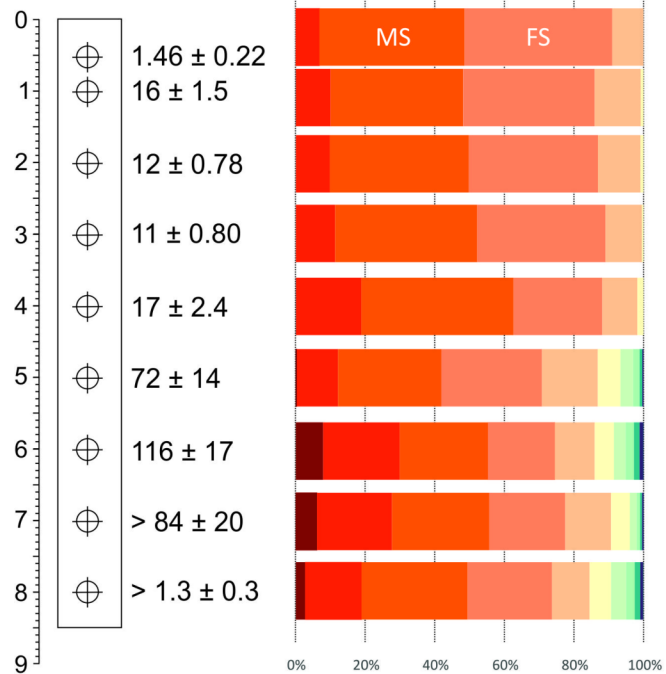
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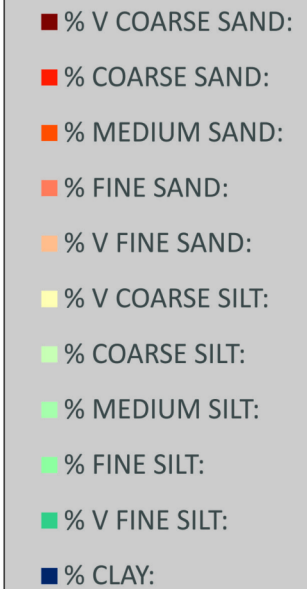
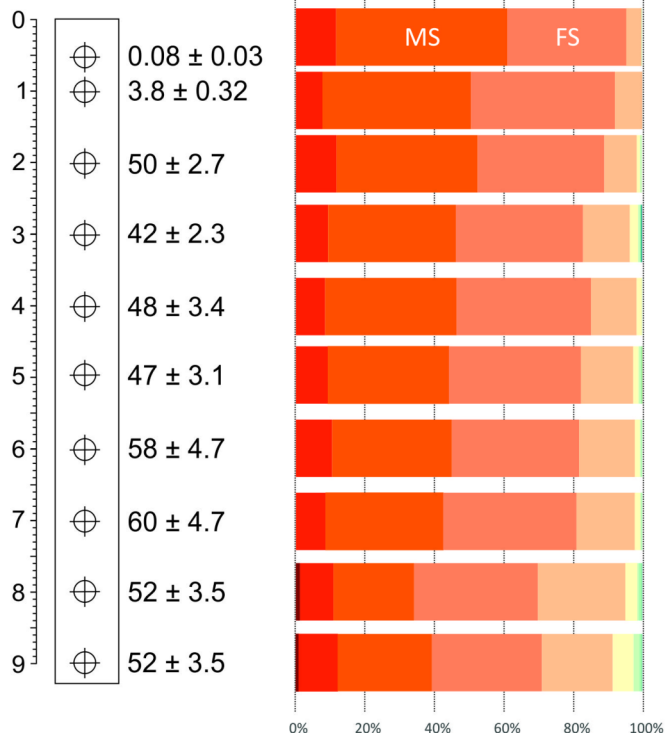
Tarwonga II

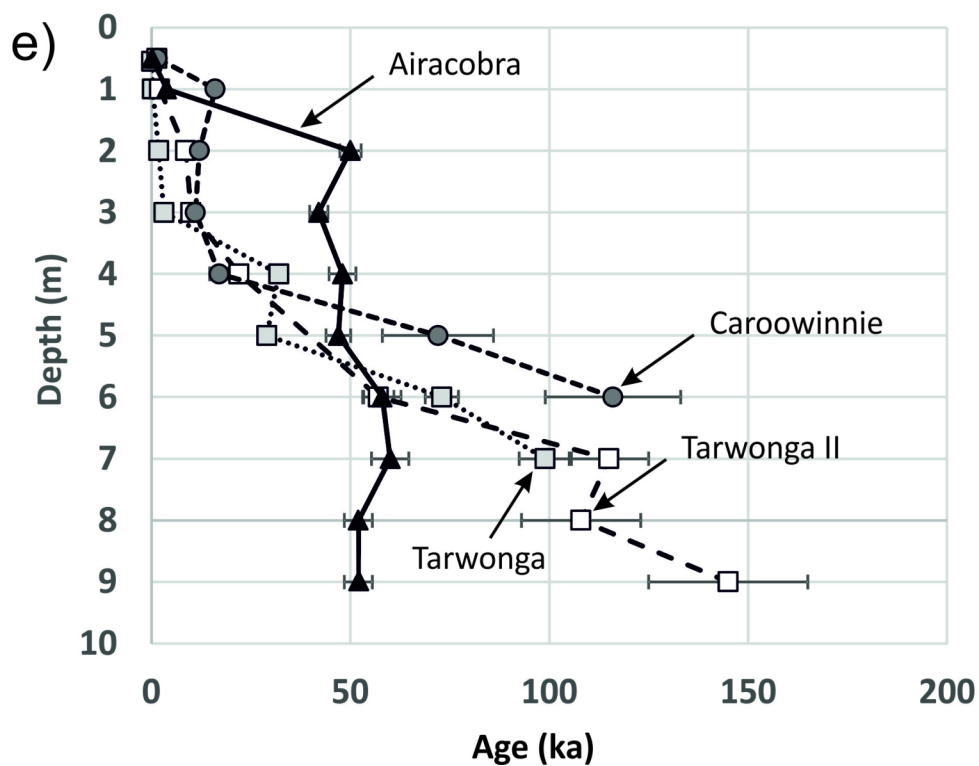
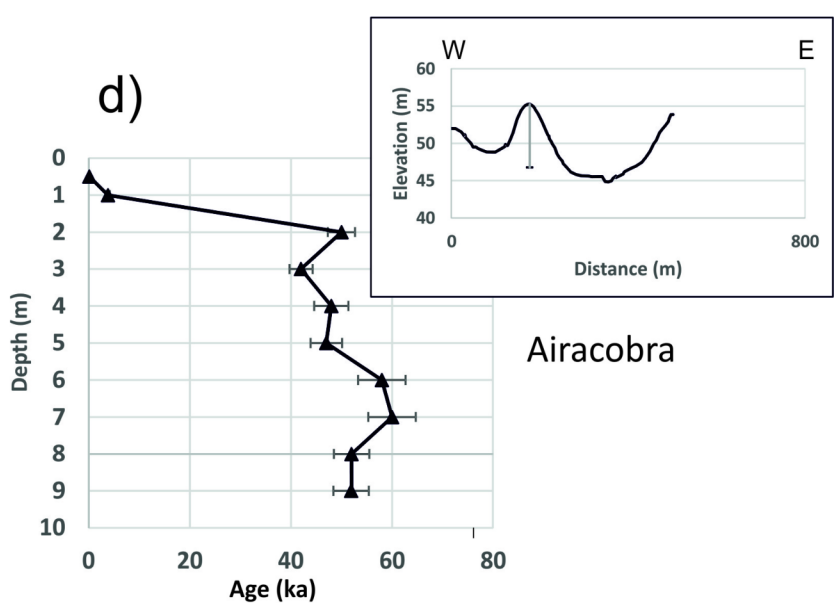
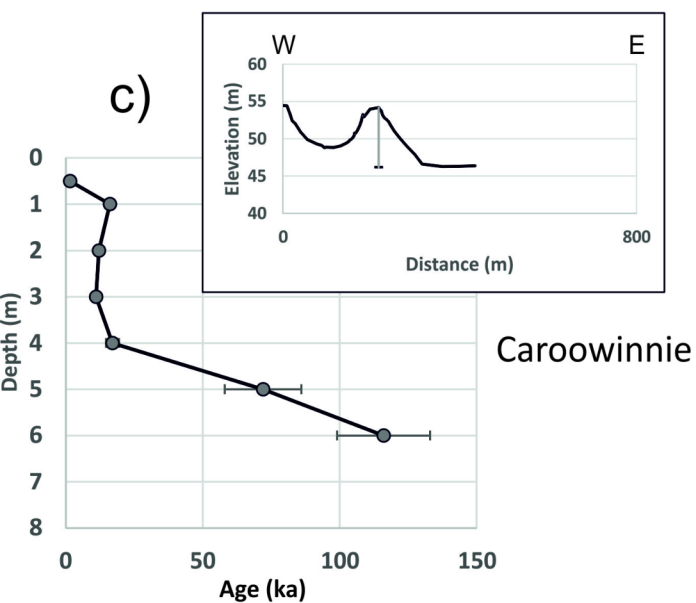
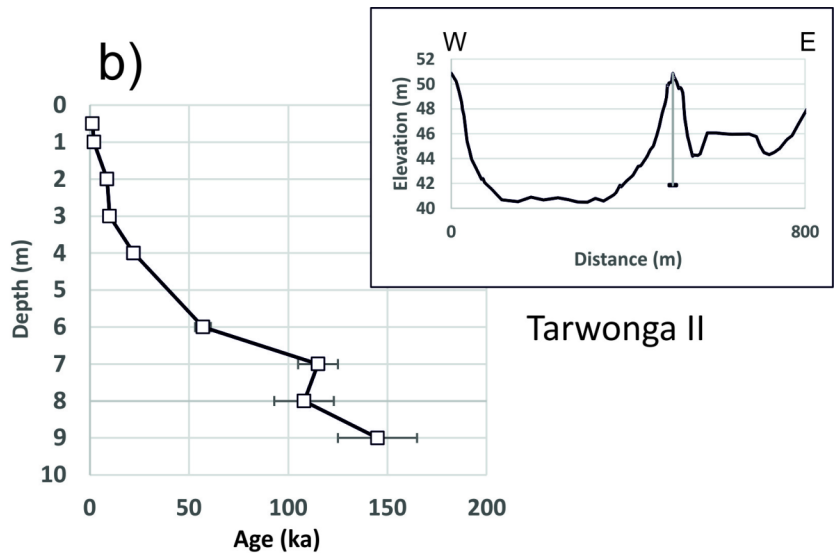
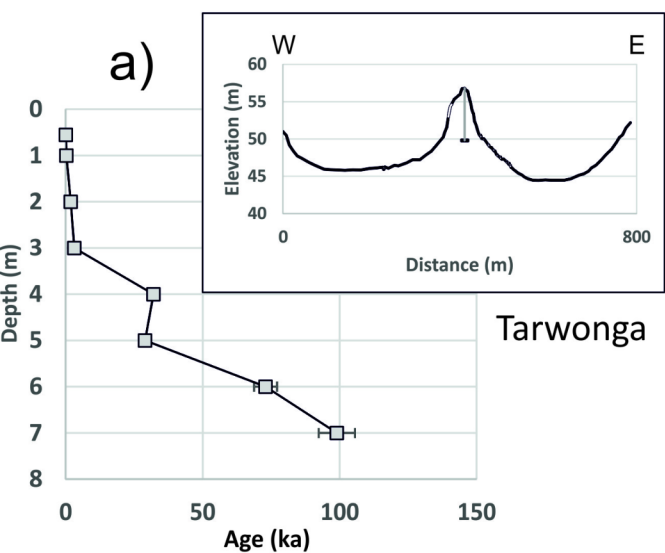


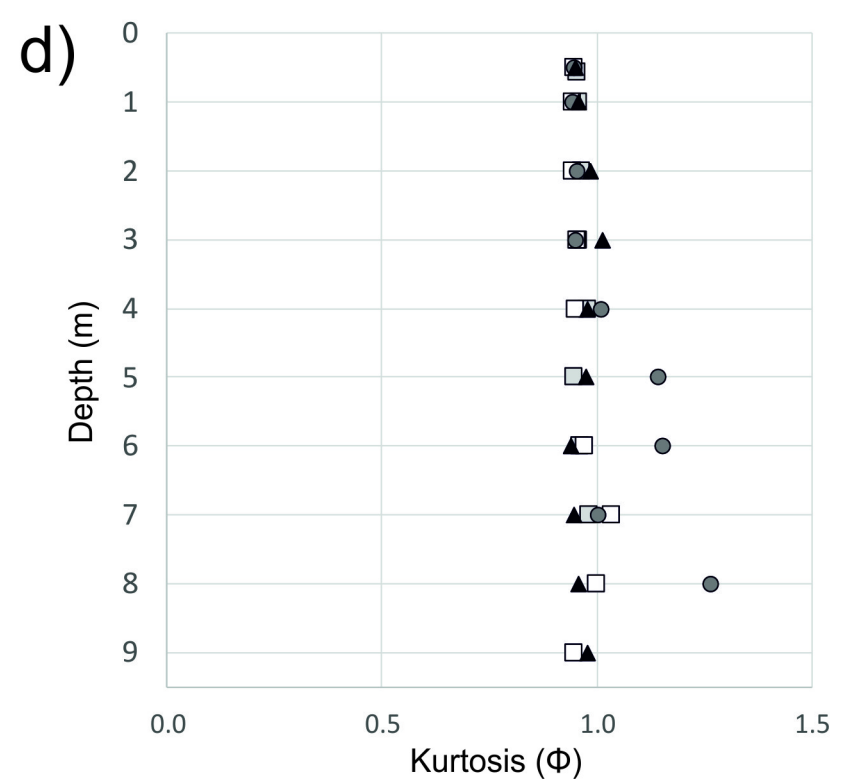
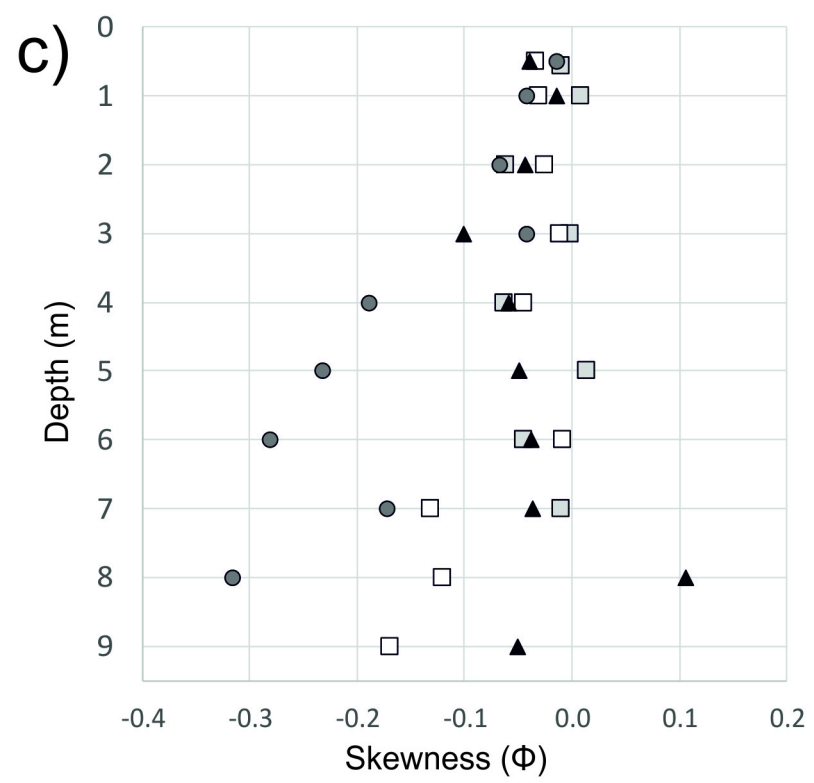
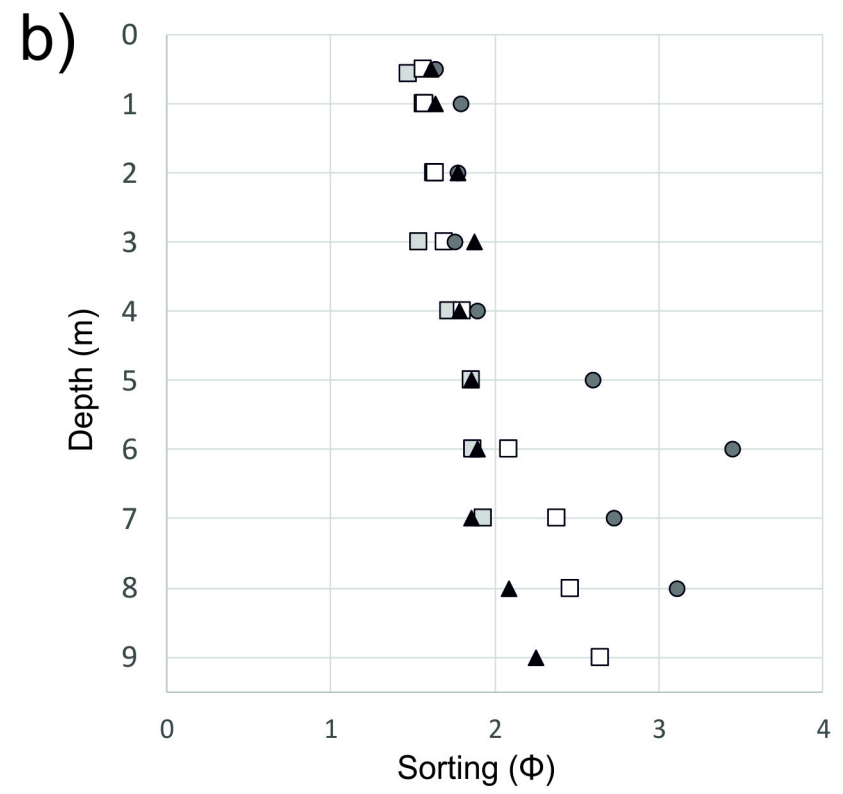
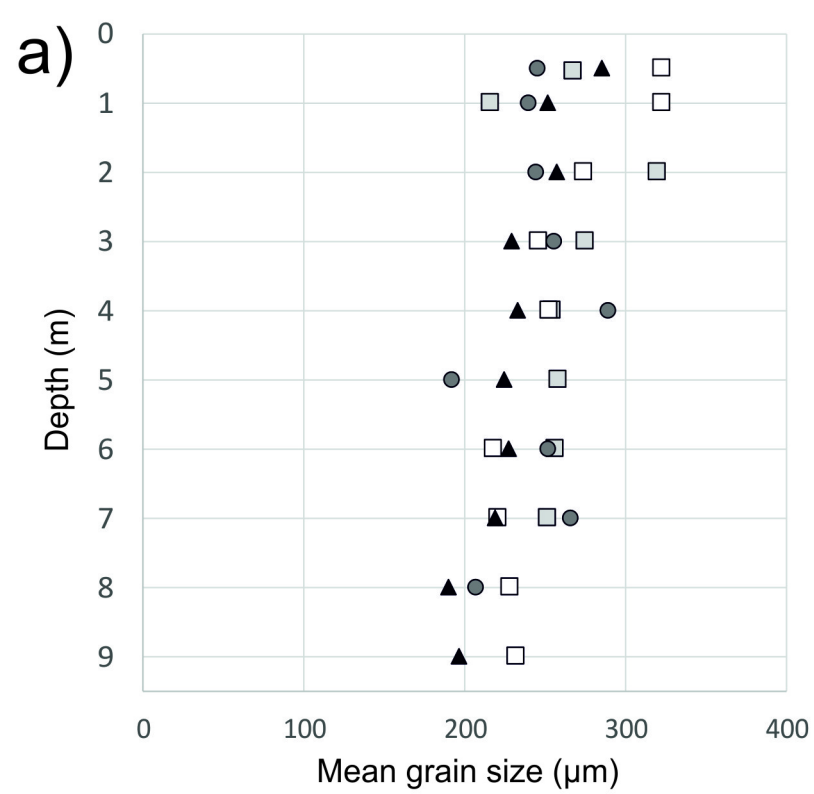
Caroowinnie

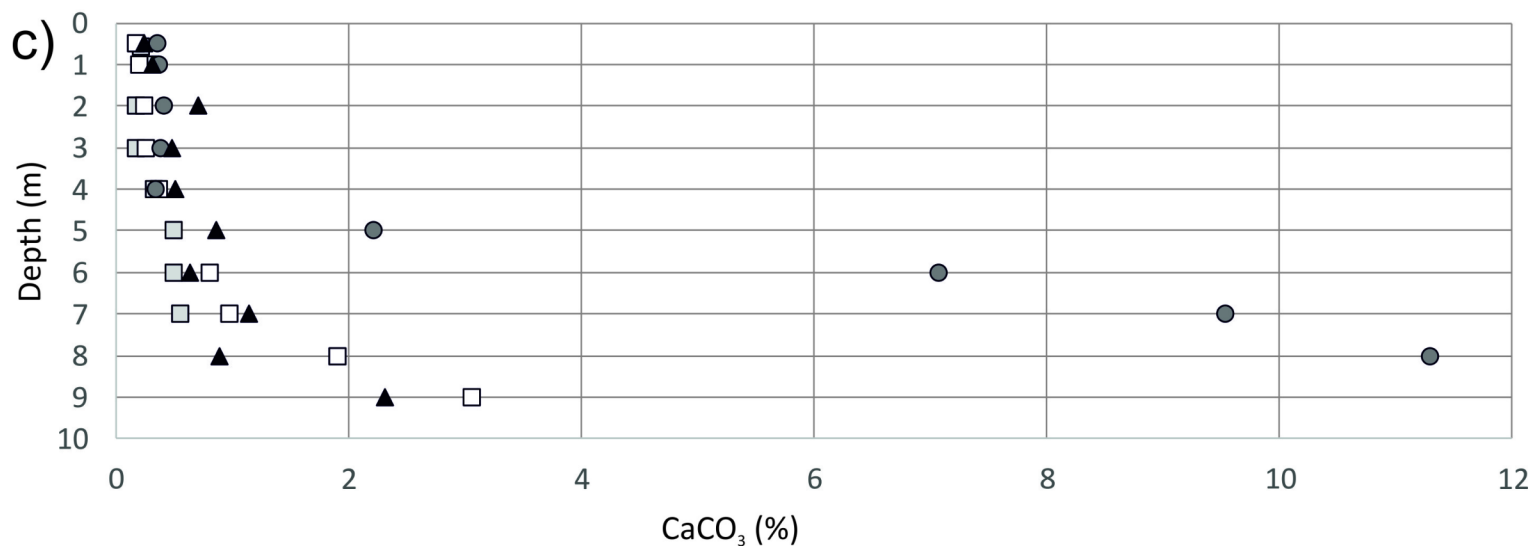
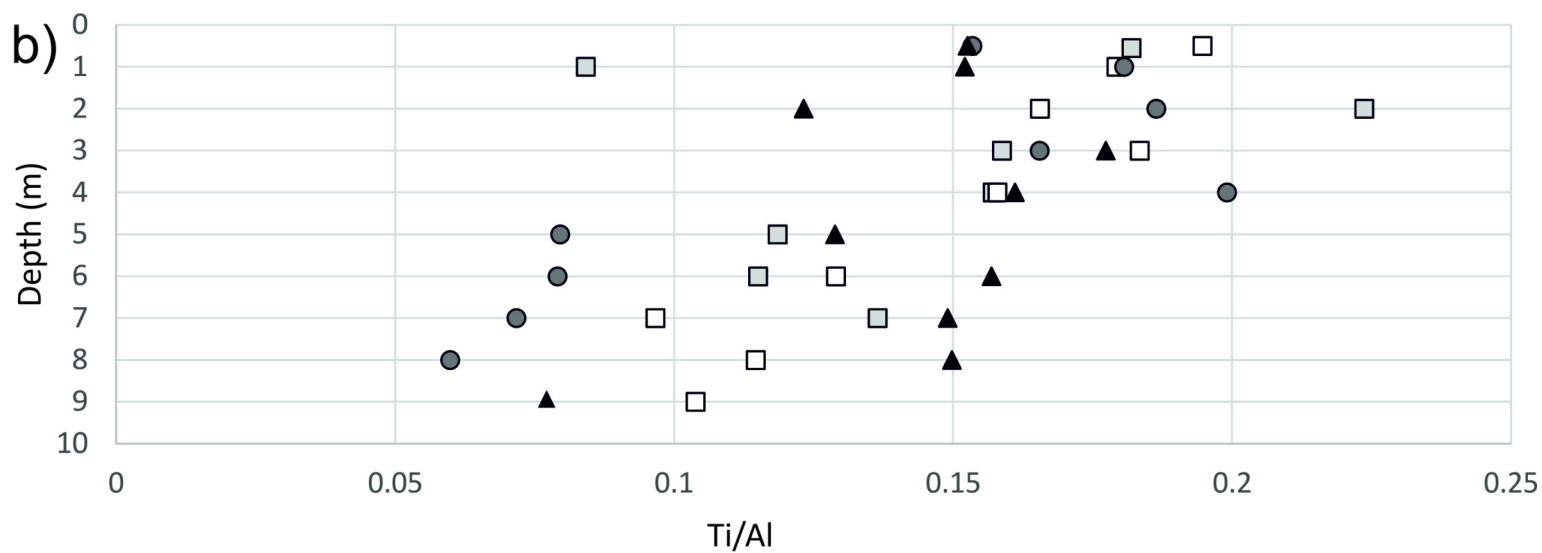
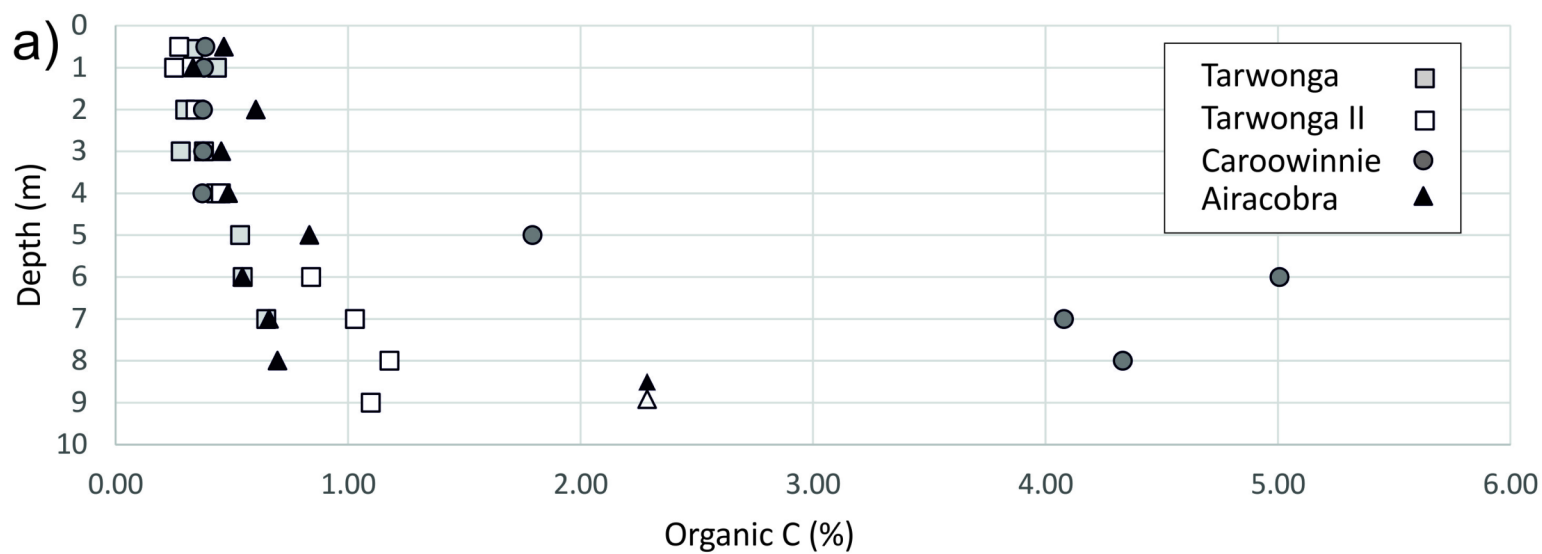


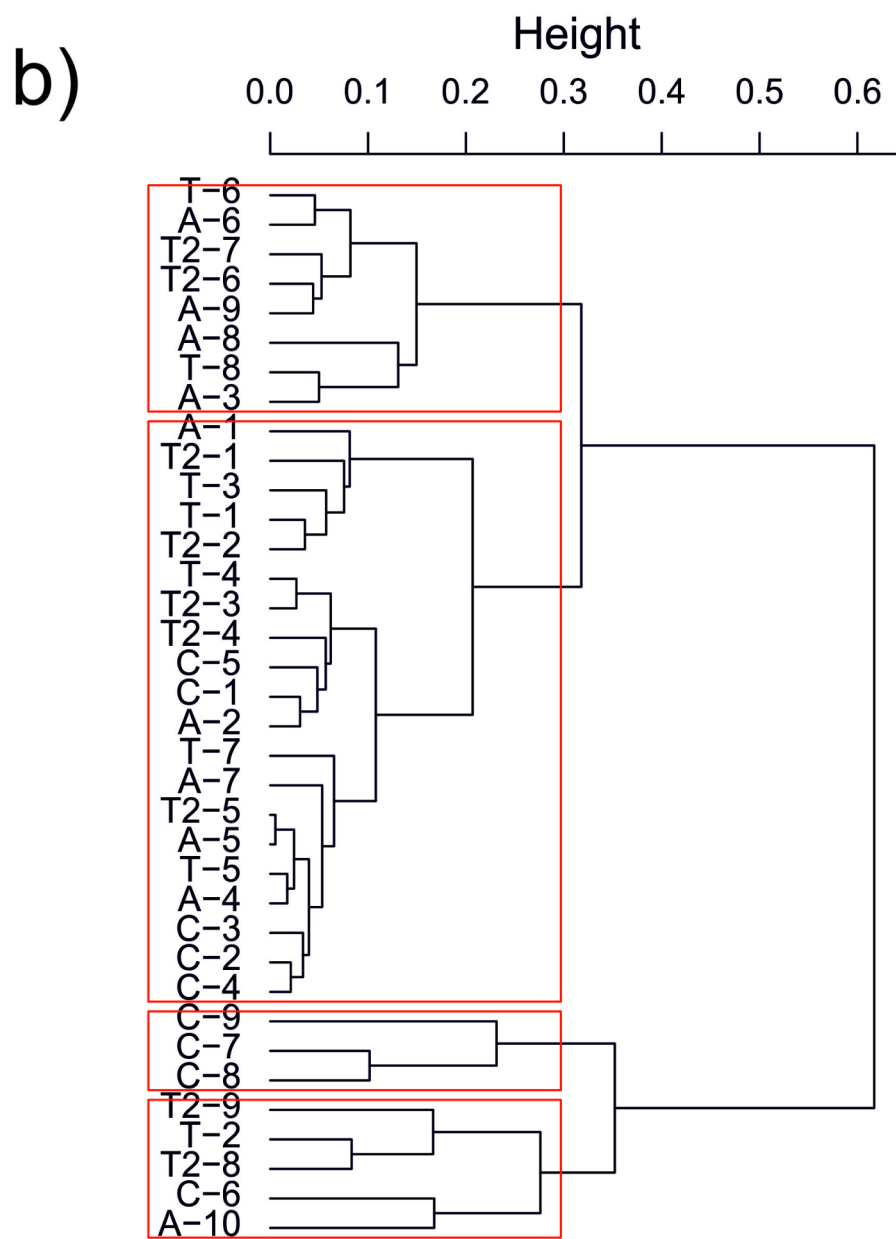
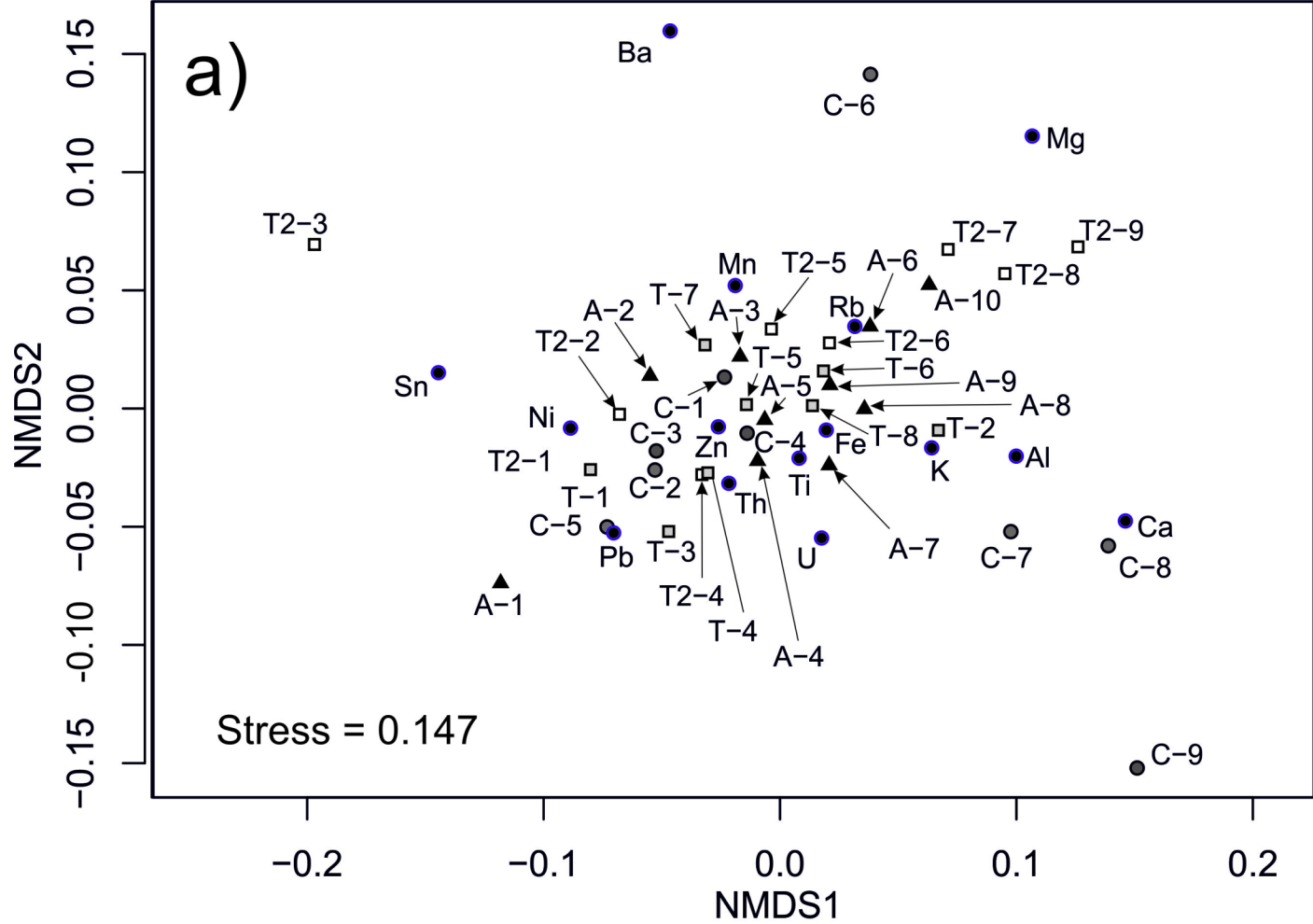
Airacobra

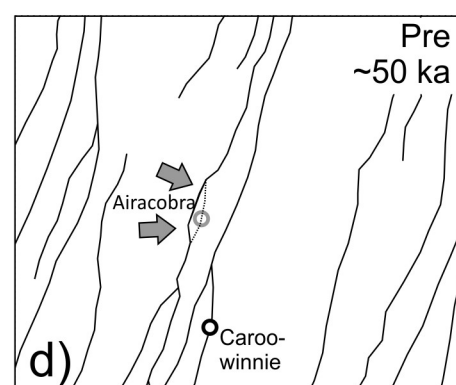
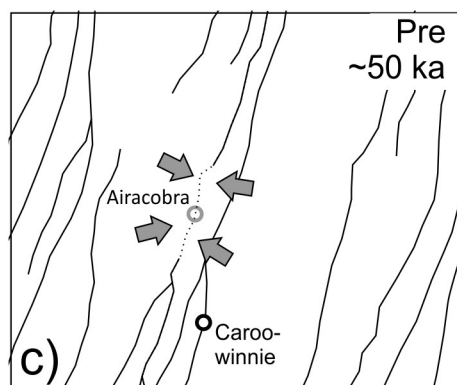
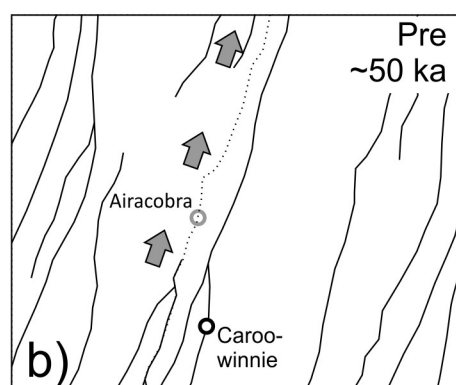
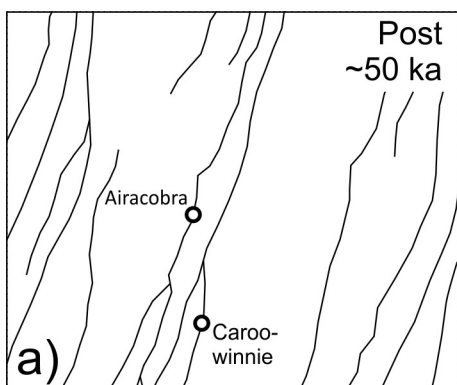












a)

Possible previously-active
dune crest (~3 m high)

• Airacobra sampling site

Recently-active dune crest (~9 m high)

• Caroowinnie sampling site

N

500 m

b)

1 km

N

