Manuscript Details

Manuscript number	GEOMOR_2016_457
Title	Morphodynamics, boundary conditions and pattern evolution within a vegetated linear dunefield
Article type	Research Paper

Abstract

The controls on the evolution of linear dunefields are poorly understood, despite the potential for reactivation of dunefields currently stabilized by vegetation by 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 analysis was 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.

Keywords	Dune; Geomorphology; Self-organization; Pattern coarsening
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Figure2_site_maps_revised.jpg [Figure]

Figure3_OSL_detail_figure.jpg [Figure]

Figure4_dated_profiles_w_particle_size.jpg [Figure]

Figure4_dated_profiles_w_particle_size_colour.jpg [Figure]

Figure6_LOI_TiAl.jpg [Figure]

Figure9_aira_detail.jpg [Figure]

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13th February 2017

Re: GEOMOR_2016_457: Controls on the evolution of linear dunefields: A test of the pattern-coarsening hypothesis

Dear Editors,

This letter serves to cover the accompanying revised manuscript, renamed to reflect the contextual changes and conceptual frameworks suggested by the reviewers; “Morphodynamics, boundary conditions and pattern evolution within a vegetated linear dunefield”.

We thank the reviewers and editorial team for an especially constructive set of comments, which we believe we have addressed in the attached manuscript. Please accept my apologies (MT) for the delay in getting this resubmission to you. Attached to this resubmission is a detailed commentary on how we have addressed the points raised by the reviewers which have, we believe, substantially improved this manuscript. In almost all cases we have acted upon the suggestions made, and in the process significantly reframed and tightened the manuscript.

We look forward to your response in due course.

Kind regards,

Matt Telfer

Dr Matt Telfer, Dr Paul Hesse, Dr Marta Perez-Fernandez, Dr Richard Bailey, Dr Szilvia Bajkan and Dr Nick Lancaster.

-Reviewer 1

In their manuscript, " Controls on the evolution of linear dunefields: A test of the pattern coarsening hypothesis" Telfer et al. used chronological measurements paired with dune morphometric analysis to test the hypothesis that poorly organized dune-field patterns represent younger patterns and simple, organized dune-field patterns represent older patterns. The authors have hit on an important and difficult geomorphological problem in the spatial analysis of dune fields. Indeed, robust theory and even observational data show that dune field patterns evolve through pattern coarsening where by dune-dune interactions give rise to more organized patterns through time. Testing this model in older dune fields, as this paper set out to do, is difficult for some of the reasons outlined in this paper.

The paper's lengthy and sometimes indirect discussion of why the ages between the two patterns differ makes it somewhat difficult to draw firm conclusions from.
We have thoroughly restructured the discussion, along the lines proposed here, and we are grateful to the reviewer for this synthesis.

The two most important factors that I see and that were discussed in some depth in the paper are the morphodynamic influence on mixing OSL ages and boundary conditions of pattern evolution. The former is simply that dune-dune interactions as an autogenic process and variations in scour depth occur and inevitably make OSL ages difficult to compare.
The final model for the paper that offers some hypothesis related to morphodynamics is interesting and more discussion is needed around this idea. The latter is to say that the boundary conditions affecting pattern formation vary wildly between and within dune fields, and thus patterns are expected to be different.

In the examples given in the paper, one area is flanked by a large pan and another is not, yet there is little discussion of how the local surroundings might affect the pattern.
This is now included as a limitation in the introductory section on site selection, and is included in discussion of the idea of dune transport corridors switching ('avulsing'; a term we defend in more detail in this revision).

While both topics are somewhat discussed in the text, I think the authors could make a better argument by focusing on a few targeted arguments in depth, rather than the diffuse approach here.
We hope that the restructuring here addresses the concerns about the diffuse nature of the discussion, and we thank the reviewers for suggestions as to how we can make this more focused.

For example, the topography discussion makes a point, but it doesn't directly explain any differences in the ages. It could be lumped into 'boundary conditions', but as a standalone part of the paper, I thought this could be removed unless there is more discussion around it.
We have removed this section of the paper entirely, and concur that it is at best marginally relevant to the core of this paper.

The authors don't mention the possibility of dune field un-coarsening or degradation of the dunefield that might reorganize one part of the pattern while leaving other areas untouched. A process that could be related to wholesale shift in climate conditions or local shifts in boundary conditions.
We mention briefly that prospect of dunefield degradation with reference to McFarlane et al (2005) (Original ms line 477-479), but whilst this is an interesting point, and we note it as a possibility –

potentially for future studies – extensive discussion of this point is, we feel, beyond the scope of this paper.

Lines 19-50: Abstract is lengthy, multi-paragraphed, and reads like an introduction. It would benefit the readership to shorten this.
We have reduced the word count for the abstract from 430 to 320.

Line 50: Avulsion is a weighty term to describe this behavior and easily confused with its fluvial meaning. Could the authors use deformation or interaction if another dune is involved? This is one of the most interesting aspects of this paper and more discussion of this process is needed.
Avulsion is indeed a weighty term, and although it is not commonly used in this context, the parallels with fluvial systems are quite deliberate. The data appear consistent with a switch in preferred transport and deposition along the dune, although we note that more data are needed to properly confirm this hypothesis. We clarify the use of our term here to ensure there is no scope for confusion with fluvial geomorphology by making this analogy more explicit – after all, fluvial geomorphologists do not have exclusive rights to the words (which occurs commonly, for instance, in medicine).

Line 61: What does "...linear dunes are formed laterally..." mean? Suggest rephrasing.
We have rephrased this as "Whilst some linear dunes may be formed by sediment transport orthogonal to the dune trend by lateral deflation from local sands"

Line 62: Suggest Lucas et al., 2015, Rubin et al., 2008
References now added as suggested

Line 83: Capitalize Earth
Corrected, with thanks

Line 90: Beveridge et al. (2006) uses pattern morphometrics and OSL to reconstruct the history of the Gran Desierto Sand Sea in Mexico. Suggest also referencing Ping et al. (2014) for a growth sequence of dunes and Ewing and Kocurek (2010) show a time-for-space substitution. More substantively, given that the paper centers on coarsening, a more thorough examination of previous work is warranted. The author may be correct that coarsening hasn't been tested directly with chronological methods, but OSL and other dating methods in aeolian systems are typically a coarse method itself. Would modern observation not be better? Moreover, very little is known about pattern coarsening in linear dunes. Included in this much needed examination of coarsening would be a discussion of the possible hypotheses beginning with Werner and Kocurek, 1999.
I think the statement that 'very little is known about pattern coarsening in linear dunes' sums up the situation well. We are grateful for the suggestion that Kocurek and Werner (1999) ought to be brought in more explicitly at this stage. Beveridge et al.'s (2006) work was an inexcusable omission, and we have included this citation quite rightly now, although we do note that the dune morphologies here are very different, and also that there is marked evidence for changes in wind regime in the Gran Desierto, which is a somewhat different situation to that of that of the Strzelecki. This discussion overall now has its own section, including highlighting that the long timescales of vegetated dunefield development, modern observation is challenging, requiring either landscape-scale experimentation or space-time substitution, which has raised questions of its own (Telfer and Hesse, 2013).

Line 100: As is stated and the point of selecting these sites, it is unlikely that a site so close and within the same field would have experienced a dramatically different pattern evolution unless one pattern is associated with a source area. Thus, while one pattern may be less organized than

another within this specific area, it may well be within the distribution of a single population at the field-scale. Can the authors show how the defect densities of this area relate to the field scale pattern and that they fall within different populations?
We note that it may be the case that these populations may not be statistically distinct at the field scale in the discussion. However, we quantify the differences in pattern metrics in the section discussing the field site and they fall within different levels of organization by the classifications of Fitzsimmons (2008).

Figure 2: Are these availability-limited dunes? If so, it is not clear how availability-limited patterns respond to pattern coarsening and this should be acknowledged. For example, the more organized pattern is adjacent to a large pan and no large playa exists in the other pattern. So it seems that it may be the boundary conditions may be playing a strong role in the organization of the pattern. The more complex pattern also appears to have clustering of crestlines at wavelengths similar to that of the older pattern. Though this is referenced on Line 190-194 and again on Line 395, it isn't strategically used to explain why the pattern could vary.
These dunes are currently availability limited, but whether they were at the time of pattern emplacement is unclear. We have addressed this point in the introduction.

Could it be that local variations in the water table removed some of the smaller crest in the coarser pattern, but otherwise these began as similar patterns as suggested? That is just one hypothesis, but the point is that the authors should explore some alternative ideas to explain the pattern organization rather than inferring that these progressed through time along the self-organizing path in the absence of boundary condition controls on the pattern.
This is possible –as is the fact that the differing surface conditions (noted above, also). We raise this more explicitly in the section discussing boundary condition effects on dune geomorphology

Line 156: See Werner and Kocurek, 1999 for a model that predicts how the y-junctions should be oriented during coarsening. Suggest modifying that figure and presenting it in this paper in the introduction. This would benefit the readership to know what models are out there for linear dune pattern coarsening.
Whilst the conceptual ideas of Werner and Kocurek are excellent in this paper, the figure referred to here is not an easy one to interpret for a reader who might be unfamiliar with this model. Instead of incorporating this figure, we describe the process in the text, and refer the reader to this paper for further detail.

Line 331-338/Figure 4: The grain size data re difficult to read. Typical cumulative frequency plots would give the reader a more robust reading of the grainsize distribution.
I (MT) have thought long over how best to present grain size data within profiles such as these. It is true that cumulative frequency plots offer a potentially more detailed view of the data, but these must either be displayed as separate panels within a figure (in this case, 37 separate panels, which is unwieldy), or as stacked graphs on a single panel for individual profiles. In this case, up to ten individual cumulative profiles must still be stacked on a figure, and crucially, this figure must also retain stratigraphic information that is readily comparable (i.e. where, within the profile, each cumulative frequency line refers to). In my experience, such figures tend to be very hard to read. The method used here – essentially a variant on that used in traditional stratigraphic logs – retains all this information.

Line 356: What are those differing explanations for mobility? e.g., Rubin and Hesp (2009) Titan?
We have clarified and expanded upon this point, noting that not only is the degree of dune mobility likely to be affected, but, as Rubin and Hesp noted, potentially also the mechanism. The reader is directed to Rubin and Hesp's work for more detailed explanation of these mechanisms.

Line 383: Topography Section – Not clear what the point of the topography section is. Why is topography important in this analysis? The relationship of topography and coarsening was not mentioned earlier in the text and if there is one expected it should be discussed here. Is the idea that younger, more complex patterns should be smaller topographically along the coarsening trend.

We note that this section, whilst reporting some interesting findings, is not central to the aims of this paper, and thus have removed it.

Line 437: the authors don't make clear how the Bak model relates to pattern coarsening. Placing this discussion more directly in the context of dune-field pattern dynamics (i.e., interactions) would be more beneficial that the abstraction to Bak.

We have removed this analogy.

Line 476: The Werner and Kocurek, 1999 model explicitly suggests a model for coarsening in linear dunes; moreover, observations of coarsening in linear longitudinal ripple experiments (Rubin and Hunter, 1990) have been made. On top of those factors, bifurcations are a clear signature of interactions. Perhaps the best example of this is in the planetary literature Silvestro et al. 2016. The suggestion that linear dunes simply don't interact is incorrect, but the suggestion that we don't understand the mechanics of interactions for linear or any dunes is correct.

We concur that this was not worded well- we had used the phrase 'essentially independent existences', and yet, as the reviewer notes, dune bifurcations clearly indicate some interaction. We had meant that it might be that for the majority of the time, for the majority of their length, these dunes behave without synchronous response. This sentence has been reworded to remove the inference that dunes do not interact with their neighbours, and instead makes the point that compared to more mobile bedforms (e.g. barchans), opportunities for dune-dune interaction may occur less frequently. The references suggested have been cited, and discussion of the Werner and Kocurek model, and Rubin and Ikeda (I think this is the reference to which the reviewers is referring, and is certainly relevant; to the best of my knowledge, there is no 'Rubin and Hunter, 1990') observations, are now included in the extended introduction brought in response to the comment to line 156 above.

Line 484: I disagree. Some answer is needed. This is the first instance of the presentation of this data and thus a thorough exploration of its content should be presented.

I presume the disagreement lies with our statement: "It is a question to which the definitive answer is beyond the scope of this paper, but it is useful to consider some of the possibilities." I believe we do thoroughly explore this issue, and both reviewers note the interesting nature or sophistication of the discussion (which, we concur, could have been better organised and more tightly edited). We have removed this statement, though, as we concur it sets a somewhat negative tone at the outset of the discussion. We can, and do, propose hypotheses (noted by Reviewer ~2 as 'speculative but useful'), and offer a favoured hypothesis, but we cannot decisively prove it with the data here.

-Reviewer 2

This is an interesting study that used OSL dating in an effort to test a hypothesis on dune field development that is based largely on modeling and theory. Luminescence dating has been applied in many dune fields in recent decades, with the goal of paleoenvironmental reconstruction, but using these methods to test hypotheses on dune geomorphology has been rare and limited in scope. The paper also makes a contribution to the long-term problem of understanding linear dune growth and migration, and to the growing literature on issues in relating OSL dating results to what we know of *dune growth and migration in general. It is certainly within the scope of the journal, and it could be important in encouraging more work along these lines.*

I have one major issue with the paper, and a few comments on other points. It is clearly written for the most part, but could be more concise in a number of places. The paper could be acceptable for publication with moderate revision to address these issues.

The major issue is with how the study is framed. The title and most of the abstract suggest a simple story, that the pattern coarsening hypothesis has been tested and not supported, which will likely be the message to any reader who looks at this quickly and uncritically. Lines 42-44 in the abstract do suggest a more realistic and complex situation, but this is not enough, since they are followed by another sentence stating that dating landscapes based on the pattern coarsening hypothesis is not supported. It is not until the discussion starting on line 428 that the true nature of the problem is really addressed.
We have changed the title of the submission – whilst our aim was to provide a rigorous, hypothesis-driven approach, we agree that the data suggest a more complex interpretation than a straightforward 'yes/no' answer. Concurrently, we have developed the discussion and reorganized it into a framework in the light of reviewers' comments, and extensively reworked (and shortened) the abstract.

Four alternative interpretations are described, the first of which is stated as "the data do not support the idea of pattern coarsening." For comparison with the other three interpretations it would be better, I think, to just state the possibility that the pattern coarsening hypothesis is invalid and that's why the data aren't consistent with it.
We have removed this statement, and included an extended discussion of pattern coarsening in the introduction.

The second interpretation is essentially that the hypothesis cannot be tested by investigation at the scale of individual dunes. This idea does not depend at all on the study results, it could have been suggested before the study was carried out, and it would be just as much a possibility if the study had shown that the coarser-patterned dunes were older! Surely this is something that belongs in the introduction and perhaps even in the abstract; that is, the authors should raise this possibility and then make some arguments as to why it may not be true in order to justify going ahead with the study.
We thank the reviewer for this point, and upon reflection, this point was closely related to our following point (sample size). With the refocusing of the text away from a more deductive approach, which, as this reviewer rightly notes, did not quite work, and merging this with the subsequent point, we believe we have addressed this point.

The third interpretation is that the sample size is too small to adequately test the hypothesis, since dune reorganization is influenced by stochastic processes. This seems likely to me, and it leads quite well into the speculative but useful discussion in the following section on Geomorphological Mechanisms. The possibility that the sample size is much too small given the variety of mechanisms that could locally affect the age-depth profile in a linear dune is really more sound and important as an interpretation of the results than just saying the hypothesis is not supported. It should therefore be given much more emphasis in the abstract.
We have now refocused the abstract.

The fourth alternative interpretation, that pattern coarsening over long timescales is not detectable by this kind of study, is also a useful contribution, though it isn't developed in detail.

Further development of this idea, whilst we agree it is an interesting point, is, we feel beyond the core scope of this manuscript (we note that reviewer #1 already comments on the discussion as being 'lengthy'). We raise this as a point for further study.

The conclusion reiterates at least some of the useful points made in the discussion starting on line 428, but is a little vague. To summarize, the sophisticated interpretation of the discussion section is largely absent from the abstract, which will likely lead to misinterpretation of the study's outcome. The key points made in the discussion need to be highlighted better in both the abstract and the conclusions.
We have reworded both the abstract and parts of the conclusion.

Other issues:

While it is good to point out the contrast between the age-depth profiles at Airacobra and those at the other sites as a caution for paleoenvironmental studies, it is overdone in this paper. To say that just sampling the single dune at Airacobra would lead to misleading results is to set up a straw man: I can't recall any study that has sampled a single dune and drawn far-reaching conclusions from it. In many dune fields and semi-arid regions there are data from dozens of sites and it's not hard to find a few sections that seem pretty anomalous compared to the others nearby. The issue today is not that researchers are mistakenly focused on those few anomalous sites, it's more subtle issues such as sampling bias toward certain types of dunes or certain parts of larger ones, lack of deep samples, etc. I think you should note that this study adds one more example of the need to sample as many sites as is practically possible and leave it at that.
We (MT and PH) are afraid that given the frequency with which we are still getting sent manuscripts (as reviewer – including, in one case, a submission to Nature Geoscience - and/or editor) that draw wide-reaching palaeoenvironmental and/or palaeoclimatic conclusions from a minimal number of dune sections (and yes, in some cases, just one), we must disagree slightly with this comment. Perhaps – rightly – these studies are rarely making it into the published literature (or at least the more discerning journals) but there is still a lot of work *trying* to do exactly that. Whilst the points about sampling strategies are absolutely true, we would argue that this point is still valid – the 'straw men' are most definitely out there.

2. The discussion in lines 511-517 of higher silt, clay, and organic matter and more coarse sand in deeper samples (most obvious in Tarwonga II and Caroowinnie, but also evident to some extent in the other two cores), seems to miss some obvious possibilities. Addition of silt and clay to near-surface horizons of fully or partially vegetation-stabilized dunes through dustfall, or less likely, weathering. OM accumulation would occur under the same conditions. Why can't the deeper samples simply represent sands with longer residence time in the near-surface zone? This would be consistent with the low accumulation rates for the same deeper parts of the cores, especially at Tarwonga and Caroowinnie. I think this explanation works even if the low accumulation rates in part reflect more erosional truncation. I see hints of this idea in the section on paleoenvironmental reconstruction, but not earlier. As to the coarse sand content, does it have to do with greater transport of the coarser grains over a low-relief dune (or over a lower part of the dune, if the crest has shifted)?
We thank the reviewer for these observations, which might well be possibilities. We have included these within the brief discussion on paleoenvironmental implications; though it to be noted that this is not the main focus of this paper.

3. The observation that linear dunes near Caroowinnie and Airacobra are superimposed on larger topographic swells is interesting, but nothing is really done with it later. Is it necessary or appropriate to include this information, especially at such length?
We have removed this section

4. The methods section described estimation of organic matter content by loss on ignition. Later, results are reported in terms of % organic carbon. %LOI has to be multiplied by a factor around 0.6 to get %OC. Was this done, or are you actually presenting %LOI? Numbers like 6% would be much more realistic for dune sand if it's LOI; even well-developed, dark-colored soil A horizons rarely have more than 3% OC, and you would certainly have noticed a dark color in the field if your samples had the OC values reported.
Many thanks for attention to detail and spotting this error. We are indeed presenting LOI, and given the complexities of converting LOI to organic carbon content, we retain it as LOI.

5. Are any results from sieving reported, or are all the grain-size data shown from laser diffraction? If the latter, remove the reference to sieving, otherwise, note which data are based on that method.
Samples were pre-sieved at 2 mm prior to laser diffraction, but as noted, no coarser material was identified. We agree that the way this was written was confusing, and we have removed reference to sieving as it only complicated matters.

6. In regard to high Ca content interpreted as carbonates—it would be simple to test this with 10% HCl on remaining sample material, and better than speculating about it.
This would be ideal, and a 'simple' test confirming the presence of carbonate was done in the field. More rigorous quantification of carbonate is not so trivial, and the quantities of sample material available are limited. Given the dominance over carbonates over other possible sources of Ca (mainly trace calcic feldspars), we defend this position.

7. Much of the text could be made more concise with careful editing. A couple of examples are noted below.
We have extensively restructured and in places rewritten the text, with particular attention to the sections identified below.

Editorial and other minor notes (by line number):
98-99 Later, the two sampling areas are distinguished based on dune spacing as well as defect frequency.
This is a good point, and we have amended the definition here to reflect the fact that whilst spacing does not directly influence dune topological relationships, it does affect the potential for defect frequency.

99 Change "amount" to "number"
Amended as suggested.

173 State what the sampling bias is, more specifically (bias toward shallower samples/upper parts of the dune?)
We have clarified this with the addition of the clause "namely that both deep and very shallow samples are often not collected".

176 Delete "can"
Typo corrected.

212 Change to “no adjacent dune was present”

Amended as suggested.

214 State the approximate grid cell size of 1 arcsecond data, in meters (~30 m)

This is now included in parentheses.

220-226 This description of methods is an example of text that could be shortened and at the same time made more accurate. For example: “Light-contaminated sediment from the ends of the OSL sample tubes was used for sedimentological analyses. Water content was measured by drying at 105 C, and organic matter content was estimated from loss on ignition at 550 C. The ignited sediment was then used for particle size analysis by sieving and laser diffraction using a…” [It is not the sample tubes that were used, it was the sediment in them. It is not water loss you are after, it is gravimetric water content. All LOI methods involved drying at 105 C first to account for water, I believe.]

We agree that this could be more concise and clearer. This section has been rewritten, reducing the word count by 30 within this paragraph:

“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.”

227 Rather than “fresh,” state whether it was DI or tap water

Clarified – it was tap water, as I believe is common for most laser diffractometry set-ups.

230 Shorten to “c) investigate the causes of variance…”

Amended from its previous ungainly form!

240 Mentioning repeat analyses here without any specifics is not very useful. Were they just duplicates or were larger numbers of replicates run for some samples? How did the range or sd compare to the +/- errors you used?

We have now clarified this with a statement in the methods; samples were analysed in triplicate and the uncertainties we used were based on the standard deviation of repeat analyses.

268-269 Shouldn’t there be a space between Gy and ka?

Yes. Many thanks for noting this. Now corrected throughout

360-365 Give references for NMDS and cluster analysis.

Citations to the R package used to provide these analyses, and thus the details of the methods employed are now included.

384-398 This is another section I think could be shortened considerably. See also comment above on whether a lot of this needs to be included at all.

We have removed this section entirely

498 Delete “of” before “common”

Typo corrected with thanks for the attention to detail

518-531. See above. I don’t think this adds much.

As noted, the section on topography is removed as peripheral to this story.

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

Telfer, M.W[1]*, Hesse, P.P.[2], Perez-Fernandez, M.[3], Bailey, R.M.[4], Bajkan, S.[4], and Lancaster, N.[5]

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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 currently stabilized by vegetation by 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 analysis was 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 (Roskin et al., 2014; Telfer, 2011). Whilst some linear dunes may be formed by sediment transport orthogonal to the dune trend by lateral deflation from local sands (Fitzsimmons et al., 2009; Hollands et al., 2006, Rubin et al, 2008), it is also evident that they can grow by downwind extension (Telfer, 2011; Lucas et al., 2015); and can also migrate laterally (Bristow et al., 2000; Nanson et al., 1992a). 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 are likely to correspond to one of a number of equifinal formational processes; 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; Telfer and Hesse, 2013; Thomas and Burrough, 2012; Zarate and Tripaldi, 2012). 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 (Andreotti et al., 2009; Ewing and Kocurek, 2010; Ewing et al., 2006; 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, and yet 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 (McFarlane et al., 2005; Thomas et al., 2003; Thomas et al., 2000) compared to those of the intricately-patterned southern Kalahari (Stone and Thomas, 2008; Telfer and Thomas, 2007). 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) and sedimentological analysis. 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 (Figure1) (Fitzsimmons, 2007). Interdunes are sometimes sandy, sometimes have clay soils and pans (both of which are seen at the study sites; Figure 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 (Hesse, 2010; Jennings, 1968). 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 (Cohen et al., 2010; Fitzsimmons et al., 2007b; 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, eventually 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 transport-limited, but elsewhere in the dunefield, including in the study area, the dunes are 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. Cohen et al., 2010; Fitzsimmons et al., 2007b; Fitzsimmons and Telfer, 2008; Lomax et al., 2003). 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 data set, 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 data set. 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 (Figure 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 boundary conditions as possible to each other. 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 (Figure 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.

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 Spectometry (ICP-MS) and Optical Emissions Spectrometry (ICP-OES) at the ISO 9001-accedited 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 H_2O_2 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 resieving 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 (Figure 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 (Fitzsimmons et al., 2007b; Lomax et al., 2003), 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 (Figure 3a and 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 µm) of the samples [Figure 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 and Figure 4). 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 and elemental concentrations for the basal samples shows greater similarity with sands immediately overlying the anomalous ages - and very little similarity to the uppermost samples - and this might suggest the samples are indeed in-situ. In this case, the young ages are more credibly attributed to daylight exposure during removal from the auger head, despite the precautions taken. As the latter case is considered more likely, the lowest two ages from Caroowinnie (Strz12-3-8 and Strz12-3-9) must be excluded from further discussion due to their untenable chronostratigraphic position; however, they are retained in discussion of the physical and chemical properties of the sand

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

[Approximate location of Table 1]

[Approximate location of Figure 4]

Sedimentology

There is considerable sedimentological variation between the cores, but as with the net accumulation profiles, this is not apparently a function of the spatial complexity of the dune planform patterning. In all profiles (Figure 4), the dunes are dominated by medium and fine sands (125-500 µm) and, to varying degrees, both the fine and coarse fractions increase with depth. This is especially marked at Tarwonga II and Caroowinnie, whereas variability down-core is less apparent at Tarwonga I and Airacobra. At 6 m depth at Caroowinnie (the last sample which is certainly in-situ), the dune is composed of ~14% silt with trace amounts of clay, as well as ~8% very coarse sand (1-2 mm). The basal sample for Tarwonga II is composed of 10% silt, whereas the adjacent Tarwonga I is <1.5% silt.

Geochemically, too, there is substantial variance within the dunes, and similarly it is not clearly a function of the spatial patterning of the dunes. Organic matter increases with depth at all sites (Figure 6a), with the lower part of the Caroowinnie core showing especially high values for a dune sand (up to 5%). The adjacent Airacobra dune, by contrast, did not exceed 1% organic matter until the basal sample (2.3%). Comparison with Figure 4 suggests that organic matter concentrations in the dunes closely mirror the fine (silt + clay) fraction. A similar depth-dependency – and lack of clear differentiation between the dunes – is shown with the Ti/Al ratio (Figure 6b), which shows a significant 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.

Ca content provides an indicative measure of the amount of calcium carbonate content of the sands. It must be noted that Ca might also be present in feldspars and clays, but is likely to be present in only small quantities, whereas on inspection of the cores in the field, carbonate precipitates, mostly powdery, were near ubiquitous. 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 Ca levels vary by an order of magnitude between samples, there is no clear differentiation between the dunes (Figure 6c); the overall trend is one of enrichment towards the base of the profiles. This is most marked at Caroowinnie and Tarwonga II.

To investigate the wider suite of elements, multivariate analysis was used. Non-metric Multidimensional Scaling (NMDS) (Oksanen et al., 2016) of the elemental data (Figure 7a) 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 (Figure 7b) (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 6]

[Approximate location of Figure 7]

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. Andreotti et al., 2009; Ewing et al., 2006; Gao et al., 2015; Kocurek et al., 2010; Werner and Kocurek, 1997, 1999; Zhang et al., 2012). 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 (Figure 4), 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 that reworking has not yet erased parts of these packages (Bailey and Thomas, 2014; Telfer et al., 2010).

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

Firstly, issues of spatial scale may be considered. Self-organising dunefield reorganisation over time is constrained by factors such as the defect density, with defects providing the means by which pattern changes are able to propagate (Werner and Kocurek, 1997, 1999). However, whilst predicting the behaviour of pattern evolution at a dunefield scale may be feasible, examining how such patterns will develop may be very difficult at a local scale. Since the process of reorganisation is strongly influenced by stochastic processes, it is possible that a sample of just four dunes may have simply missed the overall trend toward simplicity with time. These random factors, which may exhibit both quenched (i.e. stationary with regard to time) and annealed (i.e. time-dependent on the pattern evolution) disorder, stem from non-linear behaviour in the small-scale erosion and depositional potential within the turbulent boundary layer and the particulate bed. Indeed, quenched disorder has been suggested to promote pattern stability (Yizhaq and Bel, 2016). This stochastic behaviour in terms of preservation has been widely noted in both field (Leighton et al., 2013; Stone and Thomas, 2008; Telfer and Thomas, 2007) and theoretical (Bailey and Thomas, 2014; Telfer et al., 2010) studies; the net record of dune accumulation is highly spatially variable due to the repeated reworking of the upper dune sands. As well as surficial reworking, it has been suggested that defect development within linear dunes might be assumed to propagate at random locations within the dunefield (Werner and Kocurek, 1999). If this is the case, it may be that the 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 “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 (Bristow et al., 2000; Bristow et al., 2007a; Hesp et al., 1989; Rubin et al., 2008; Rubin, 1990); field studies demonstrating extensional growth under unimodal wind regimes due to cohesive sediments (Hesse, 2011; Rubin and Hesp, 2009); field monitoring and chronometric work showing predominantly vertical accretion within linear dunes (Craddock et al., 2015; Hollands et al., 2006); 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 (Hesse, 2016; Tsoar, 1989; Tsoar et al., 2004). Many (e.g. Bristow et al., 2007b; du Pont et al., 2014; Rubin and Hesp, 2009; Telfer, 2011) 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 (Figure 4), nor contains higher amounts of potential cementing agents (Figures 6-7), 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 (Figure 7). 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. Figure 8 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 (Figure 8a). 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 (Figure 8b). 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 ~2.3 x 10^6 m^3 of sand in the past 50 ka. Figure 8c 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. Cohen et al., 2010; Hollands et al., 2006) 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 Figure 8c 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 (~2.3 x 10^5 m^3) than a purely extensional model. Another possibility (Figure 8d), 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 Figure 8), 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 (Figure 9), 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 8]

[Approximate location of Figure 9]

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 accumualtion 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. Fitzsimmons and Telfer, 2008; Leighton et al., 2014; Stone and Thomas, 2008; Telfer and Thomas, 2007), 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. Wen and Dong, 2016; Wu and Guo, 2012) 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, and 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 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 folly of trying to recreate past environmental conditions from small numbers of samples. Although this observation is not new, the data presented here are perhaps the most dramatic example of how the stochastic nature of dune accumulation and reworking can overprint any evidence driven by external forcing.

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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 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) Loss on Ignition, b) Ti/Al ratios and c) Ca content for all samples.

Figure 7. 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 8. 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.

Figure 9. a) Detail of the high-resolution SPOT/CNRS imagery (courtesy of Google Earth™) suggests a possible explanation for the rapid accumulation at Airacobra; abandonment of a former transport pathway and the establishment of the present-day planform pattern at the site. b) An example of the inter-dune periodicity in the topographical profiles of the dunes at the clustered dunes of Caroowinnie and Airacobra. The relief of the dunes is superimposed on a longer wavelength relief, which is not obvious from the high-resolution imagery alone (courtesy of Google Earth™).

Table captions

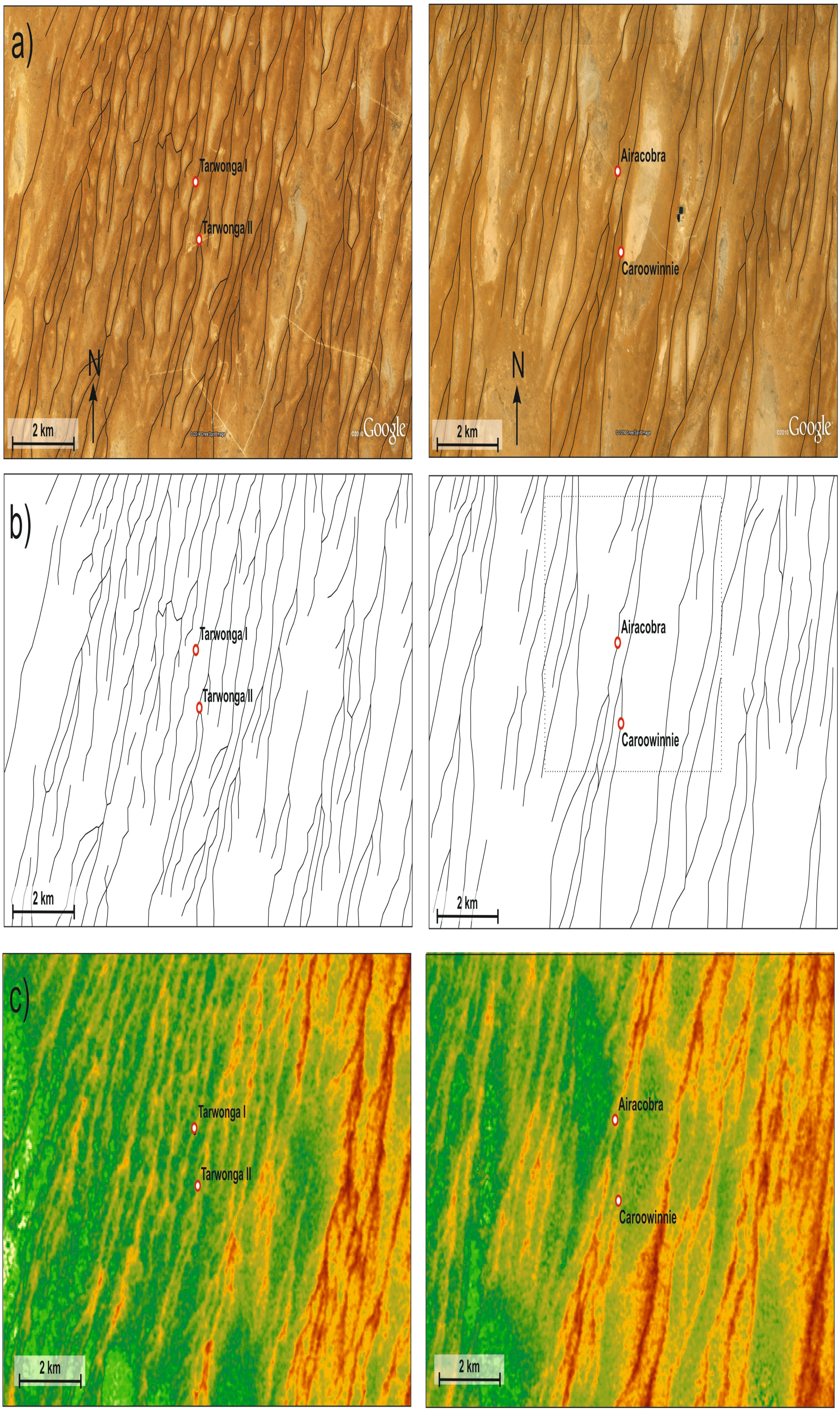
Table 1. OSL age data

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
	1	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 ±

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

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


a)
Tarwonga I
Tarwonga II
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Airacobra
Caroowinnie
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c)
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Caroowinnie
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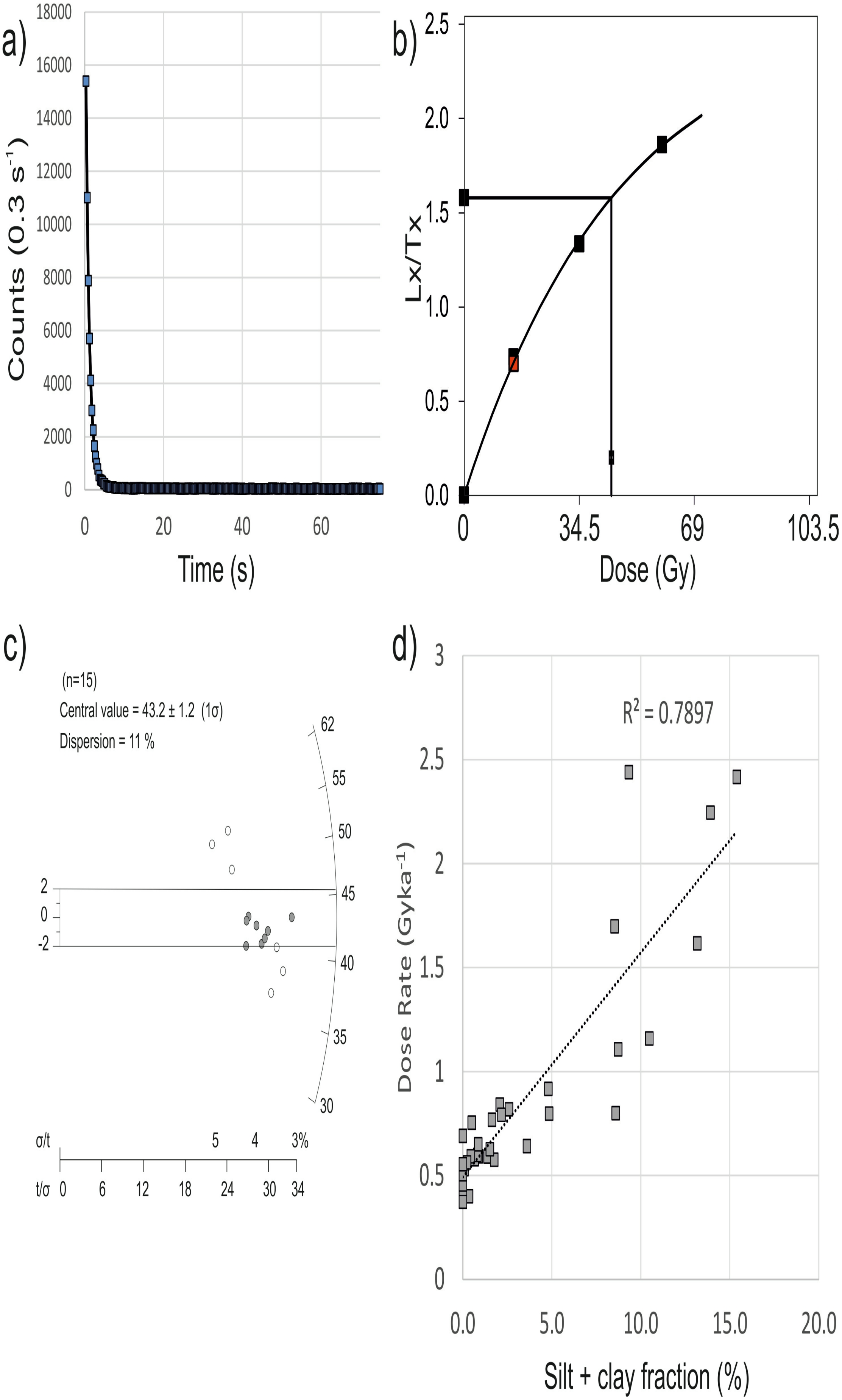
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16000
14000
12000
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8000
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2000
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60
Time (s)
b)
Lx/Tx
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2.0
1.5
1.0
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Dose (Gy)
c)
(n=15)
Central value = 43.2 ± 1.2 (1σ)
Dispersion = 11 %
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-2
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5
4
3%
t/σ
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6
12
18
24
30
34
d)
R² = 0.7897
Dose Rate (Gyka⁻¹)
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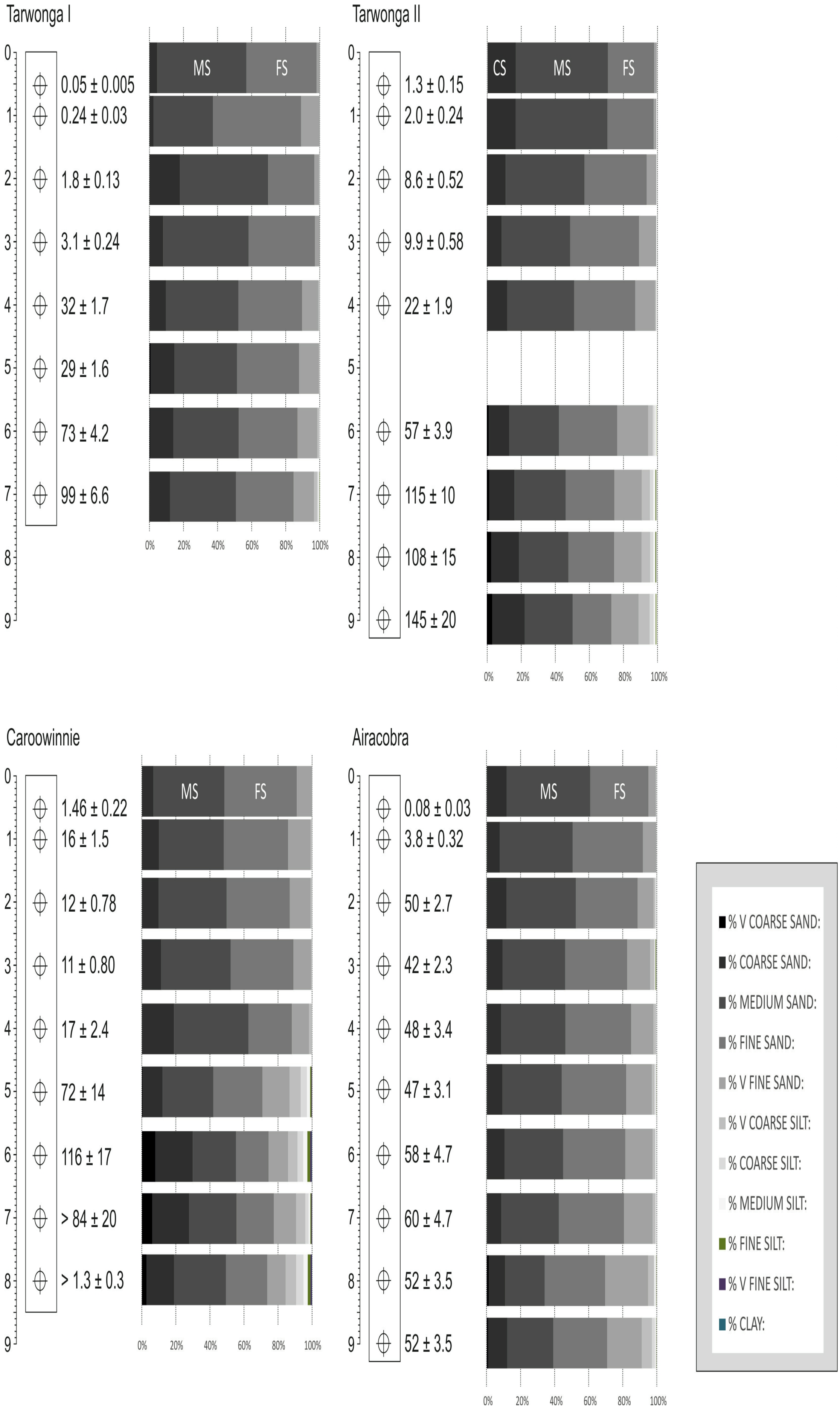
Silt + clay fraction (%)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3.1 ± 0.24
32 ± 1.7
29 ± 1.6
73 ± 4.2
99 ± 6.6
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FS
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40%
60%
80%
100%
Tarwonga II
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2.0 ± 0.24
8.6 ± 0.52
9.9 ± 0.58
22 ± 1.9
57 ± 3.9
115 ± 10
108 ± 15
145 ± 20
CS
MS
FS
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Caroowinnie
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16 ± 1.5
12 ± 0.78
11 ± 0.80
17 ± 2.4
72 ± 14
116 ± 17
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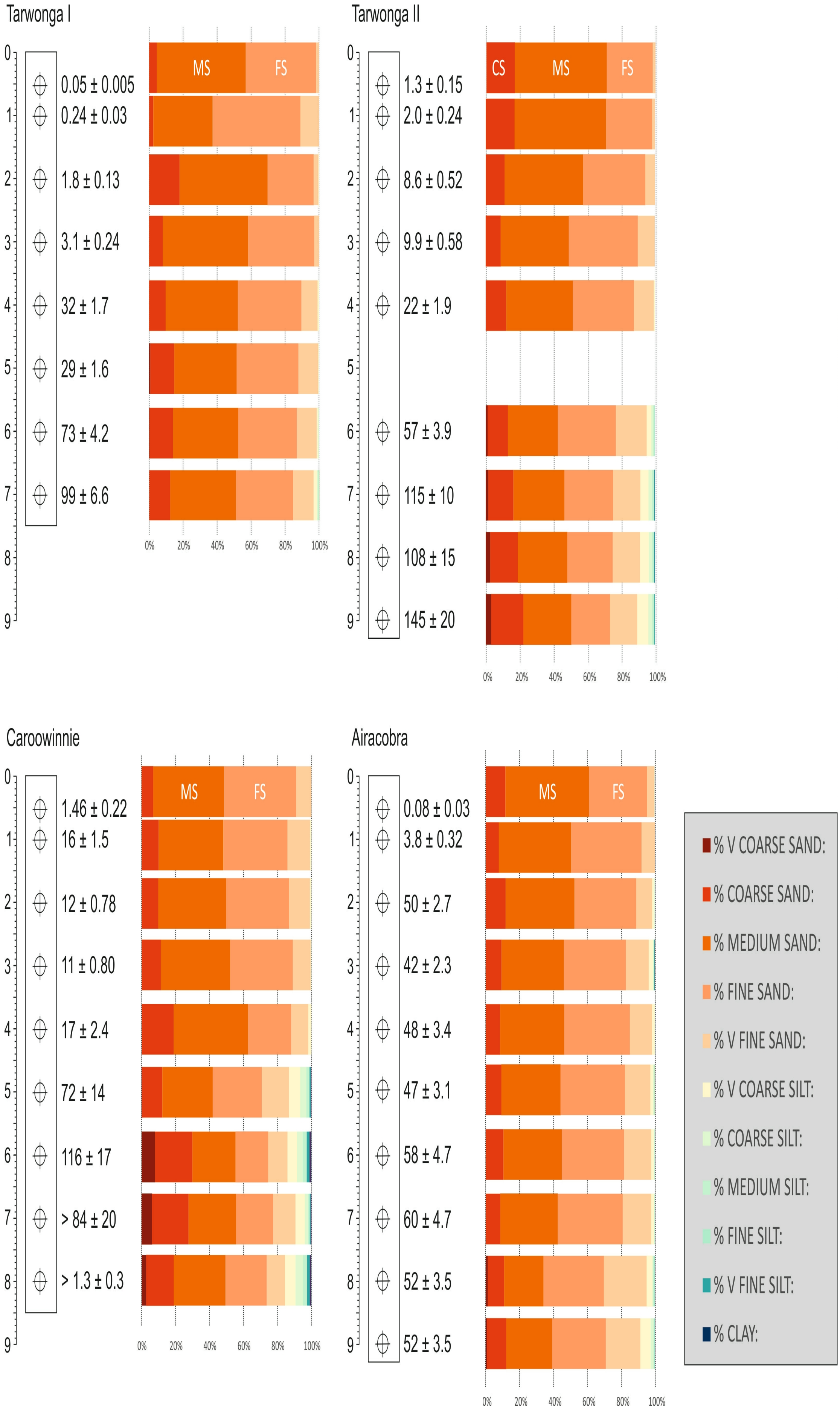
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Caroowinnie
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72 ± 14
116 ± 17
> 84 ± 20
> 1.3 ± 0.3
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Airacobra
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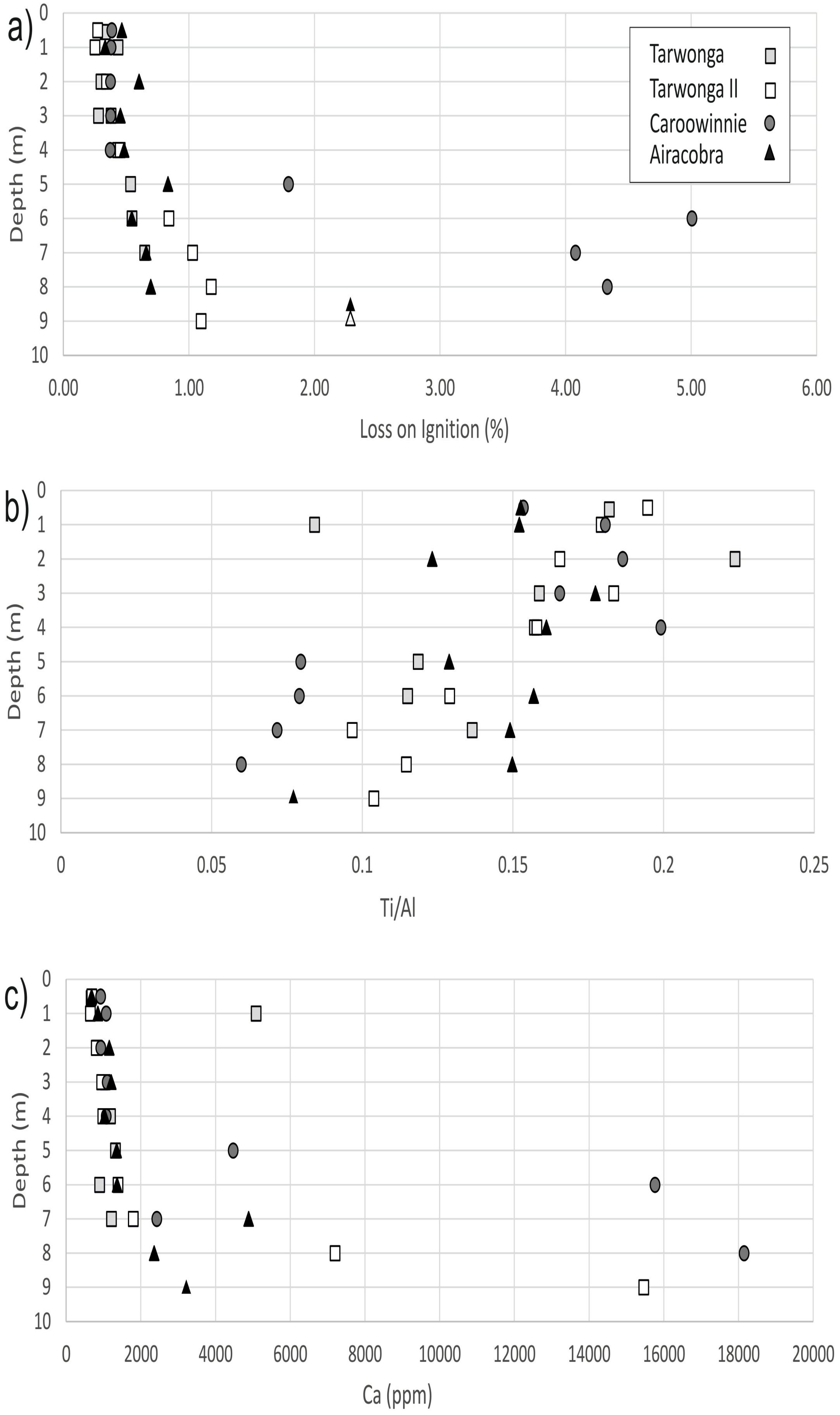
a)
Depth (m)
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4
5
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7
8
9
10
0.00
1.00
2.00
3.00
4.00
5.00
6.00
Loss on Ignition (%)
Tarwonga ▨
Tarwonga II ☐
Caroowinnie ●
Airacobra ▲
b)
Depth (m)
0
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10
0
0.05
0.1
0.15
0.2
0.25
Ti/Al
c)
Depth (m)
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6
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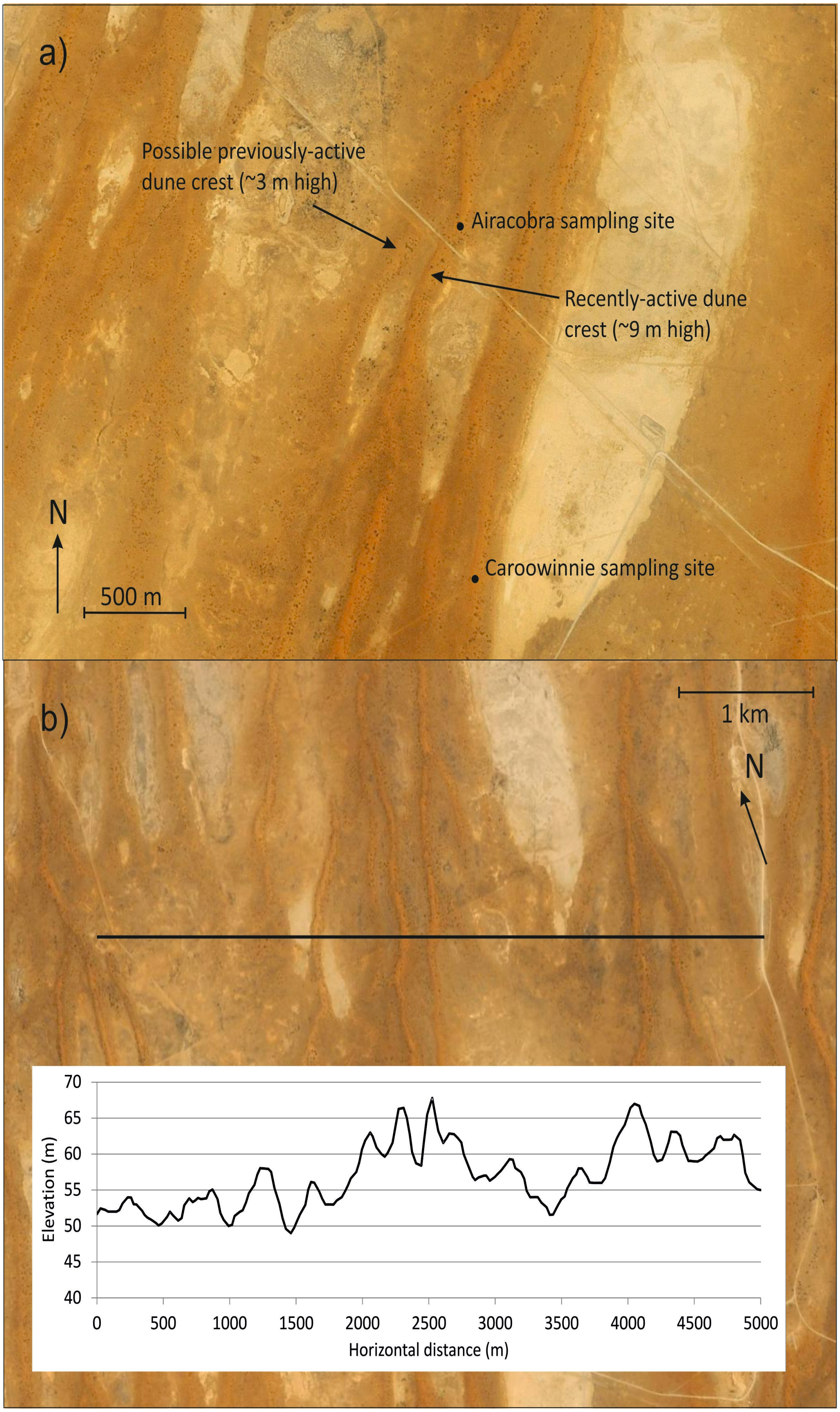
10
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Ca (ppm)


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
70
65
60
55
50
45
40
Elevation (m)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Horizontal distance (m)