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Superimposed and Auxiliary Dunes of the Northern Namib Sand Sea: a Ground-Penetrating Radar Study

Clayton K. Chandler
Brigham Young University - Provo

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John H. McBride, Chair
Thomas H. Morris
Jani Radebaugh

Department of Geological Sciences

Brigham Young University

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ABSTRACT

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Clayton K. Chandler
Department of Geological Sciences, BYU
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Understanding modern features allows for their use as analogues for understanding the environments of the past and even environments on other planetary bodies. This study uses Ground-Penetrating Radar (GPR) to image the near surface sedimentary structures on a large linear dune in the northern Namib Sand Sea and image the sedimentary structure of an auxiliary dune. GPR data was collected using a 200 MHz antenna with a continuous scan method and was processed by removing direct arrival, gain balancing, migration and more which produced the highest resolution imagery from this region to date. Large dune data was analyzed to determine depositional process for different sedimentary patterns observed. Auxiliary dune data was analyzed to determine dune type and migration direction. Our results indicate five sedimentary process zones in the near surface of the large primary dune. These processes include motion of the dune crest as well as different phases of superimposed dune deposition. It is evident from our interpretation that there have been at least two phases of superimposed dune deposition separated by an erosional process boundary. These phases of deposition have produced a reversed succession of strata on opposing sides of the dune with deposits of 3D superimposed dunes beneath 2D superimposed dune deposits on the west and deposits of 2D superimposed dunes beneath 3D superimposed dune deposits on the east. This suggests a reversal of wind environment in the region in the recent past and could provide insight into the building and stability of linear dunes on Earth. Our results also indicate that the auxiliary study dune is oblique in nature with migration to the north-northeast and that it and other similar dunes in the vicinity are formed because of their proximity to Tsondab Vlei. The apparent dependence of these smaller scale features on interruptions in the dunefield like Tsondab Vlei suggest that the normal wind patterns within the dunefield are a combination of the regional wind patterns with significant influence from the large linear dunes themselves.

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Keywords: Namib Sand Sea, linear dunes, superimposed dunes, GPR, process sedimentology

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We would like to thank the Namibian government for allowing us to do field work in the sand sea. We also recognize the staff at Gobabeb; without them our field work would have been impossible.

I would like to thank my professors and committee for the guidance they have given throughout this project.

Finally and most importantly I want to thank my family for their support. My wife, Emily, most of all for the help and encouragement that it has taken to get to this point.

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INTRODUCTION

Linear dunes are a dominant landform in Earth's large deserts namely the Sahara, the Namib and the Arabian Deserts. They are unique and interesting landforms because on human timescales they appear to be stationary even though they exhibit a high level of activity. The long-term processes that build linear dunes are under discussion but likely involve multidirectional winds that act on the dunes and result in a sand transport vector parallel to the crest (Tsoar, 1983).

Several studies have been conducted on linear dunes generally (Rubin and Hunter, 1985, Rubin et al., 2008, Tsoar et al., 2004, Tsoar, 1982, 1983, McKee and Tibbets, 1964, McKee, 1979, Fryberger, 1979, Livingstone et al., 2007, Reffet et al., 2010), on dunes of the Namib Sand Sea (McKee, 1982; Lancaster, 1989, 1995), and the northern Namib Sand Sea specifically (Livingstone, 1989, 1993, 2003; Bristow et al., 2000, 2005, 2007). Studies in the northern Namib Sand Sea have focused on establishing that the Namib dunes are currently active and on what scale they have been active. For example, Bristow et al. (2005) found that part of a dune located ~5 km south of Gobabeb had moved an average of 0.12 m/year since ~432 AD andLivingstone (1989, 1993, and 2003) periodically monitored and surveyed a dune for twenty-one years (1980 to 2001) finding that, while the crest is active, there was no discernable movement of the dune margins. Some of these studies have used ground penetrating radar (GPR) and optically stimulated luminescence dating (OSL) to establish lateral migration and migration rate of these dunes (Bristow et al., 2000, 2005, 2007). While these studies are important for understanding large-scale processes, such as overall movement of the dunes, they do not address smaller-scale processes (superimposed dunes and auxiliary dunes). Furthermore, the GPR studies were performed very near the termination of the dunes and near the boundaries of the dunefield, which may have potentially introduced variations (due to edge effects) that would differentiate these areas from the sand sea as a whole.

Most studies in the Namib that include small-scale dune processes rely on visual observation and location measurements (e.g. Livingstone, 2003). This requirement means these studies only include a very short window into the time that superimposed dunes, crest avalanches, and other small features take to develop and change. Therefore, most field studies can only obtain a current picture of what is happening concerning small-scale processes (superimposed dunes for example), with little indication of how they might have changed in the recent or distant past.

This project investigates how small-scale processes, specifically superimposed dunes, affect the development, growth and overall architecture of linear dunes surfaces. We test the hypothesis that superimposed dunes develop concurrently with linear dunes and that superimposed dune deposition changes through time. This study uses 2D ground penetrating radar (GPR) to investigate the near-surface (~10m deep) deposits of a linear dune in the northern Namib Sand Sea, which allows us to analyze how deposition has changed in the recent past. We also show how small auxiliary dunes form across the interdune area between large linear dunes based on sedimentation patterns revealed by the new GPR data. These studies shed light upon the evolution of large, linear dunes, landforms comprising the largest proportion of dunes in Earth's big deserts worldwide (Lancaster 1995). Linear dunes of similar size cover ~15% of the surface of Saturn's moon Titan (Arnold 2014; Rodriguez et al. 2014), so this study reveals detailed aspects of those key landforms only visible from orbit at low resolution.

STUDY AREA

The Namib Sand Sea, located on the east coast of southern Africa (Fig. 1), overlies the earlier sandstone deposits of the Tertiary (pre-Miocene to quaternary) Tsondab Sandstone (Kocurek et al., 1999) and the Namib platform (McKee, 1982), an unconformity surface developed on late Precambrian bedrock (Kocurek et al., 1999). The majority of the sand in the Namib is from the Orange River which is near the southern edge of the sand sea (Vermeesch et al., 2010), and is mainly well-sorted and well-rounded quartz.

The dunes of the Namib Sand Sea can be up to 200 m tall, hundreds of kilometers long, 2 or more kilometers wide and spaced up to 4 km apart. The linear dunes of the Namib are regionally straight for tens to hundreds of kilometers, but on a local scale have a significant amount of crestline sinuosity. Furthermore there are superimposed dunes on the flanks of the primary dunes that are ~100 m across, up to 5 meters tall, and a few hundred meters long (in the area of our study) and are transverse in form. Also present in the sand sea are smaller auxiliary dunes that cross the interdune area between two primary linear dunes.

This study focuses on two sites within the northeastern part of the Namib Sand Sea, an area characterized by complex linear dunes (Lancaster, 1989), often over 100 m tall, trending north-south (Fig. 1). The first site (A) is a section of linear dune about 12 km south of Gobabeb Field Station where the dune is ~120 meters tall and 1200 meters wide (Fig. 2). This dune was chosen because its shape and size are characteristic of the large dunes throughout the center of the Namib Sand Sea (Fig. 3) and because it was farther into the dunefield where edge effects could be avoided. The dune crestline is highly sinuous and can have multiple crestlines, but it has a single and relatively straight crestline for about 250 m at the study site.

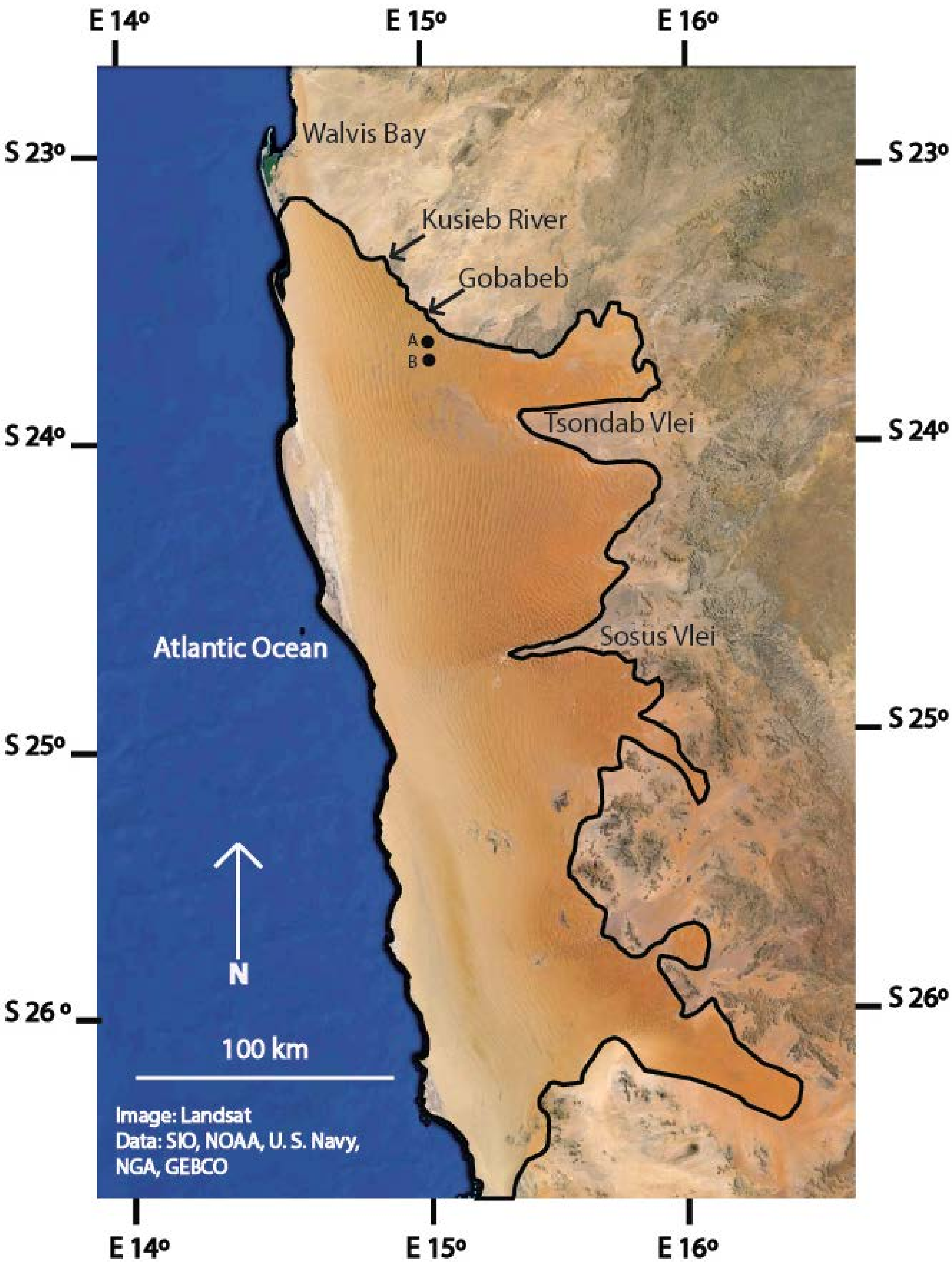


Figure 1. The Namib Sand Sea (black outline), located on the southern Atlantic coast of Africa. Linear dunes dominate the sand sea except for the vleis (washes) and the coastal plains. Black dots labeled A and B are locations of study sites. Base image from Google Earth.

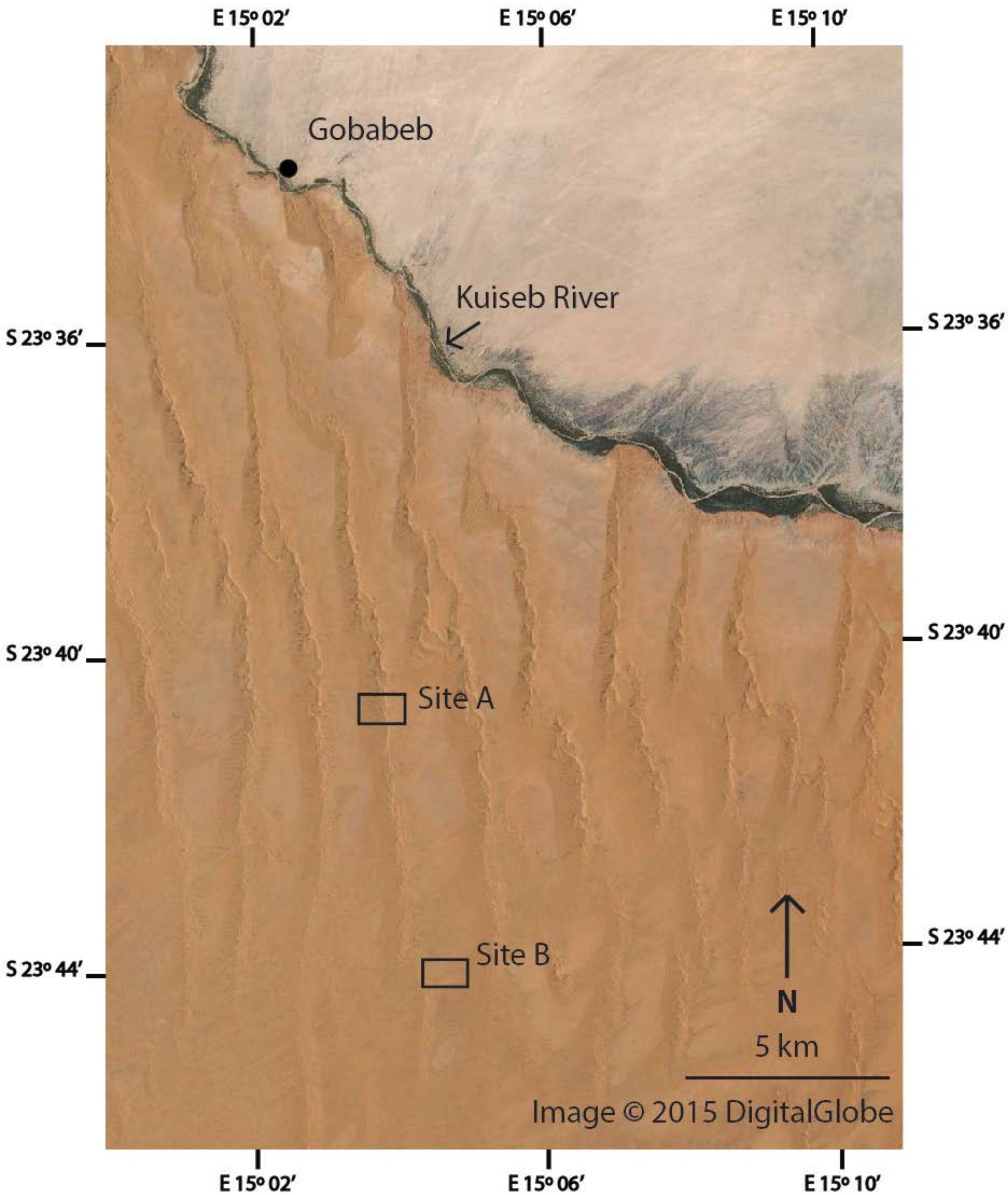


Figure 2. The northern Namib Sand Sea. Site A is our large dune site (see Fig. 3 for greater detail). Site B is our auxiliary dune site (see Figs. 4 and 5 for greater detail). Base image from Google Earth.

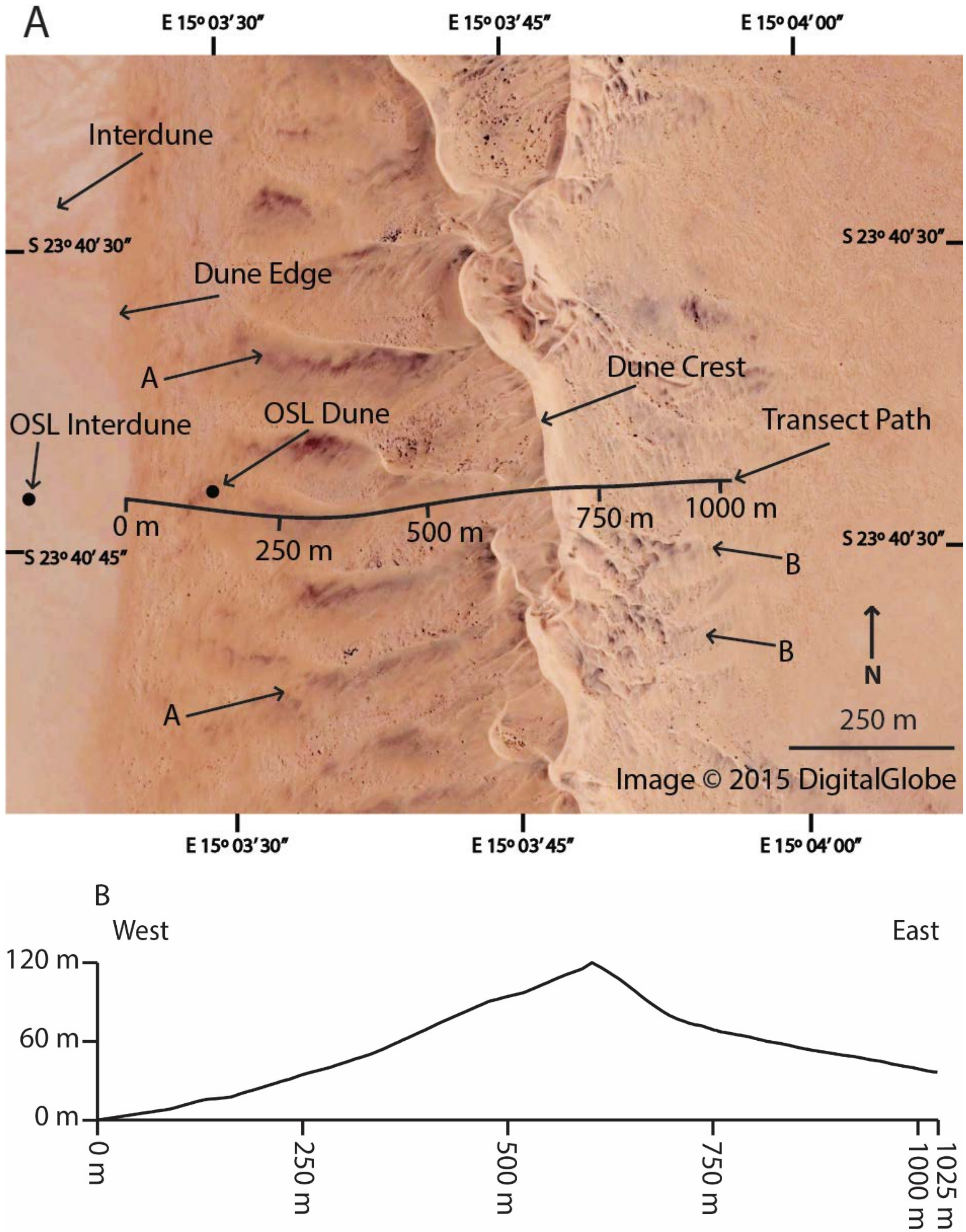


Figure 3. Our large dune area (Site A in Fig. 2), black line (labeled transect path) is the location of our GPR transect, the elevation profile of which is displayed as Fig. 3B. Arrow A is pointing

to superimposed dunes on the west side of the primary linear dune. These superimposed dunes are larger and simpler than those superimposed dunes on the east side of the dune, which arrow B is pointing to. Arrows labeled OSL dune and OSL interdune indicate locations where optically stimulated luminescence dating samples were collected. Base image from Google Earth.

The general morphology of the dune in this location is described here and can be seen in Fig. 3. The east margin of the dune, in its lower reaches, displays a gentle, uneven slope of shallow grade. The eastern slip face of the crest is near the angle of repose (~25 degrees) for ~90 m until the crest. The west side of the dune gradually slopes up from the interdune surface until ~15 meters from the crest, where the slope is near the angle of repose and forms the western slip face. This dune and other large linear dunes are referred to in this study as primary dunes or primary linear dunes. In much of the sand sea these primary linear dunes display smaller dunes on their flanks. In this study we refer to these smaller dunes found on primary dune flanks as superimposed dunes, features that are found on both flanks of our study dune.

The second field study Site (B) is about 7 km south of our large dune and is a section of a small auxiliary dune (Figs. 4 and 5) that extends east-northeast diagonally between two large linear dunes. This dune is ~10 m tall and ranges from 100 to 200 m wide (it is wider at the southwest end) and is 1.3 km long. This dune was chosen because it is representative of a number of dunes with similar characteristics in size, shape and relationship to the main linear dune. It is generally linear in form and is asymmetrical in cross section, with the northwest side steeper than the southeast side, and has a sinuous and discontinuous crest.

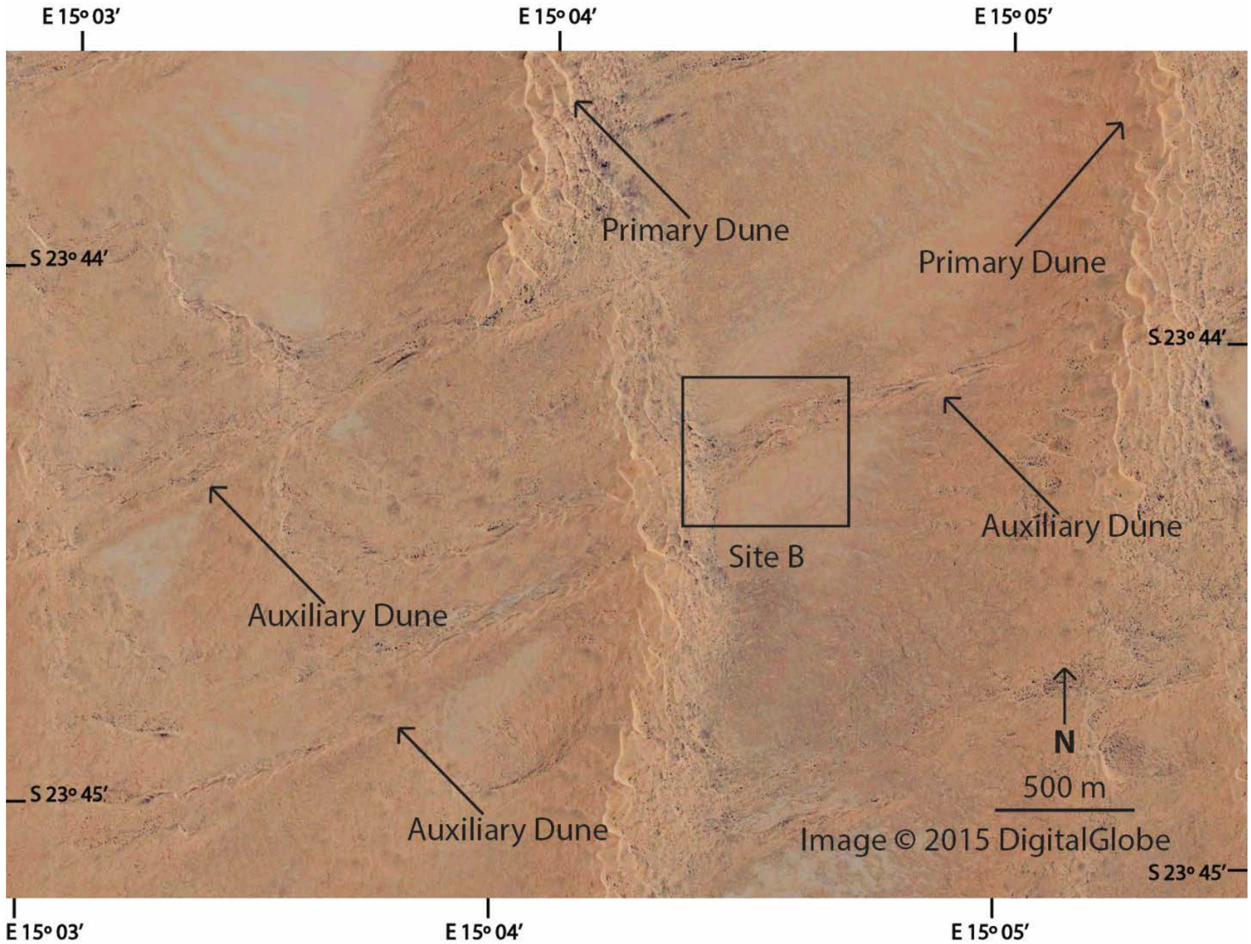


Figure 4. Location of auxiliary dune GPR site (B). The relationship between primary and auxiliary dunes are shown as well as the orientation of auxiliary dunes in this area. To the west of this location the auxiliary dunes are oriented at a more northward angle. Site B is the location where our auxiliary dune GPR was collected. Base image from Google Earth.

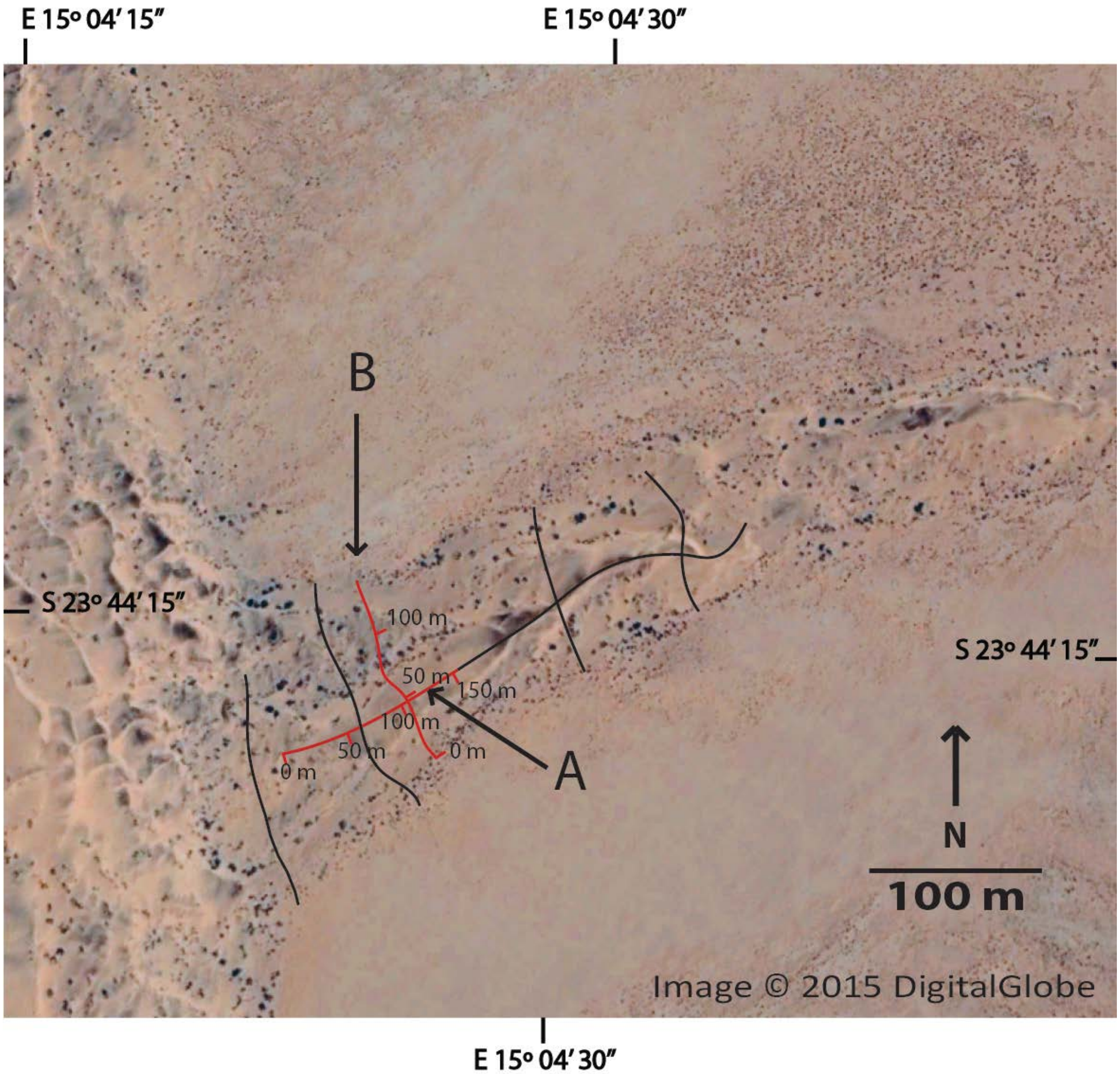


Figure 5. Close up of auxiliary dune site (B). Red lines show locations of auxiliary dune GPR data in Fig. 7. Black lines show where the rest of the data for this study was collected. Base image from Google Earth.

METHODS

Ground Penetrating Radar

GPR instrumentation and processing were chosen to balance depth of penetration with achieving high-resolution. Two GPR transect lines were collected on the primary linear dune. Additionally, one longitudinal line and five transect lines were collected on the auxiliary dune. These two datasets were collected using a Geophysical Survey Systems Inc. (GSSI) antenna with a central frequency of 200 MHz. Data were acquired in continuous mode with a trace every 0.06 m. Traces were collected over 200 ns and sampled every 0.20 ns.

The data were processed with a routine that included removing the direct arrival, exponential gain balancing, trace mixing, 2D phase shift migration, time to depth conversion, and topographic correction. Depth conversion was performed using a velocity of 0.122 m/ns (yielding resolution of 15 cm based on the Rayleigh criterion) calculated from a dielectric constant (ε) of 6 which assumes a mixture of quartz sand and air (23% porosity) with minor amounts of organic matter, iron oxide and moisture. This velocity is consistent with what is often used for dry sand (0.15 m/ns based on common midpoint surveys in the Namib from Bristow 2007) and it produced the best migration and flattened the interdune surface as we expected.

Optically Stimulated Luminescence (OSL) Dating

Optically stimulated luminescence (OSL) measures when quartz grains were last exposed to sunlight. Two OSL samples were collected to identify ages of deposits in our study, one on the flank of the large dune and one in the interdune area (see Fig 3). Samples were collected by digging down to a depth of ~1 meter at which a sample canister (pipe) was pounded into the sand

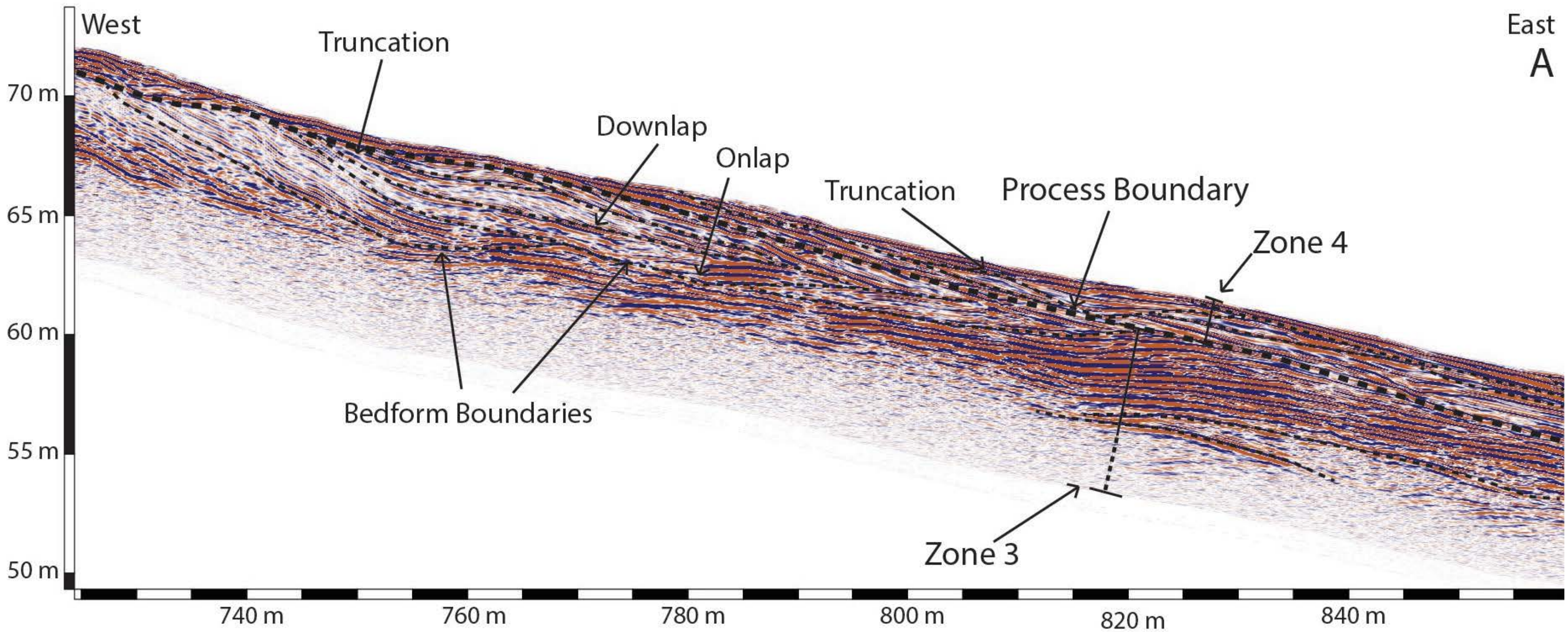
and extracted, retaining the sample. Samples were analyzed using single aliquot regenerative dose procedures for dating quartz sand (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006).

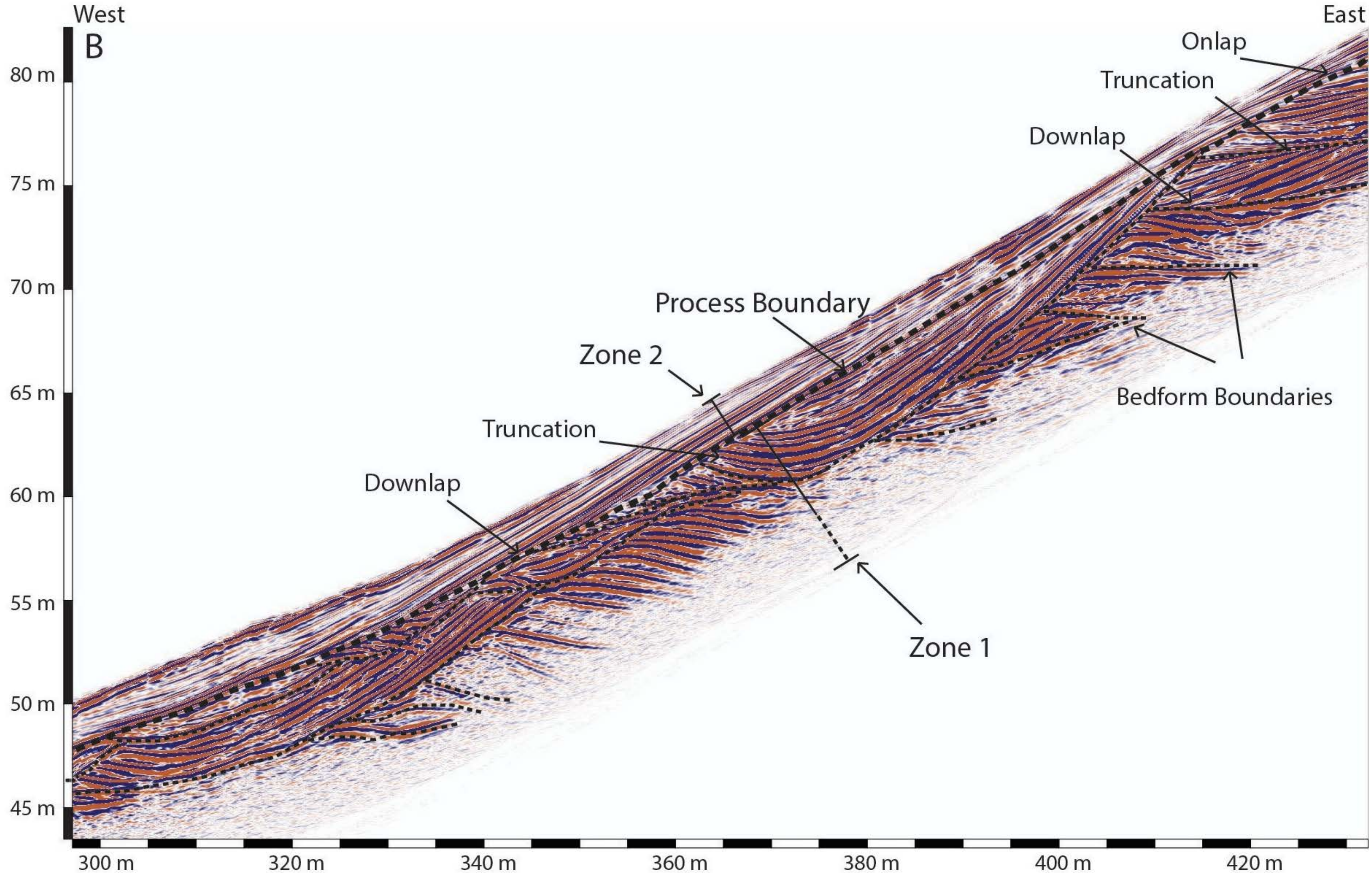
RESULTS

Linear Dune Ground Penetrating Radar

Our GPR data was able to penetrate into the dune sand about 12 m (ε=6). On the west flank of the primary dune (site A of Fig. 2) we see near the surface (to a depth varying from 1 to ~3 m) reflections that are nearly parallel with the surface of the dune (Fig. 6). These reflectors can often be followed for more than 100 m and terminate in gentle onlap, downlap or low angle truncation by the dune surface. Below these shallow reflectors exists a definitive surface that separates two distinct reflection patterns, this reflector is herein termed the process boundary. In the deeper part of the data (from the base of surface reflectors at 1 to 3 m to the penetration limit at ~12 m) on the west flank of the primary dune we see much shorter reflectors (rarely more than 20 meters long) that terminate in sharp truncations, high angle downlap, or onlap (rare; Fig. 6). Packages of reflectors in this part of the data often truncate other packages of reflectors. Several bowl-shaped packages of reflectors can be seen in this part of the data (Fig. 6, 10 m to 70 m on the horizontal axis in the center of the data).

On the east flank of the primary dune we see near the surface (to a depth varying from1 to ~3 m) reflections that are wavy nonparallel and in some areas discontinuous. These reflectors can usually only be followed for a few meters and terminate in onlap, downlap or low-to-moderate angle truncation by the dune surface or other reflectors. In the deeper part of the data (from the base of surface reflectors at 1 to 3 m to the penetration limit at ~12 m) on the east flank of the primary dune we see much longer reflectors (often 50 m or more) that terminate in gentle-to-moderate truncations, downlap, or onlap. Packages of reflectors in this part of the data often truncate other packages of reflectors. The shallow flank data and the deeper flank data on both sides of the primary dune are separated by a clear boundary (process boundary, ~1 to 3 m deep). Near the crest of the dune the long reflectors (up to ~90 m on the east side of the dune) are sub-parallel to the dune surface (shallower are more parallel, deeper are less inclined than the surface). These reflectors begin near the crest of the dune and terminate near the inflection point of the dune (where the slope of the dune decreases). At this inflection point the reflectors curve toward the surface and are truncated by the dune surface or overlying reflectors. Near the inflection point on both sides of the dune we see where reflectors with flank characteristics inter-finger with the terminations of the reflectors near the crest.


West
East
A
Truncation
Downlap
Onlap
Truncation
Process Boundary
Zone 4
Bedform Boundaries
Zone 3
70 m
65 m
60 m
55 m
50 m
740 m
760 m
780 m
800 m
820 m
840 m


West
East
B
80 m
75 m
70 m
65 m
60 m
55 m
50 m
45 m
Onlap
Truncation
Downlap
Process Boundary
Zone 2
Truncation
Downlap
Bedform Boundaries
Zone 1
300 m
320 m
340 m
360 m
380 m
400 m
420 m

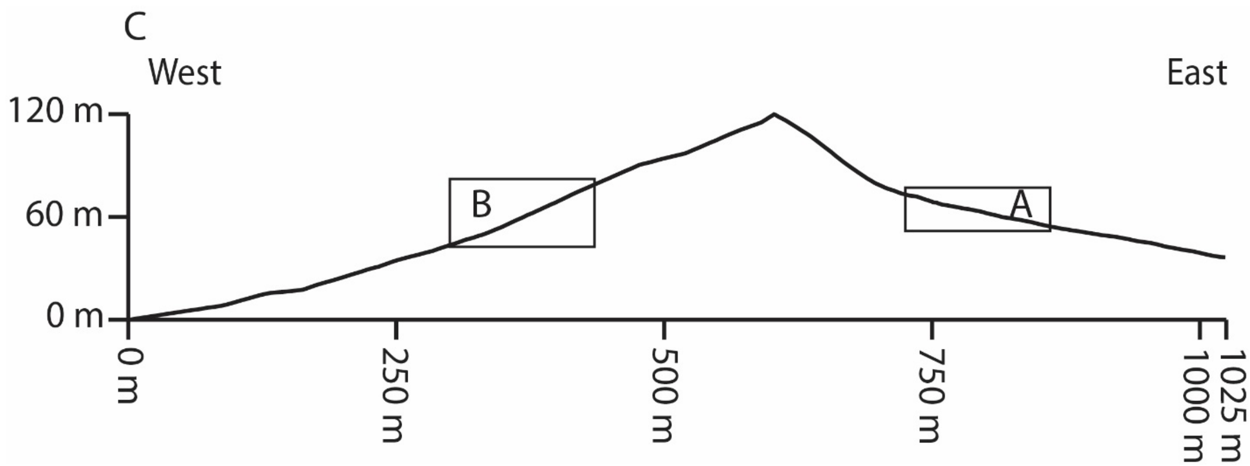


Figure 6. Excerpt of large dune GPR profile (site A of Figs. 1 and 2, transect in Fig. 3), A is from the east side of the primary dune and B is from the west side. Bold dashed line indicates location of process boundary. Other dashed lines indicate divisions in the trough cross-stratified unit. Labeled reflector termination types (onlap, truncation, downlap) were used to distinguish sedimentary packages.

Linear Dune OSL

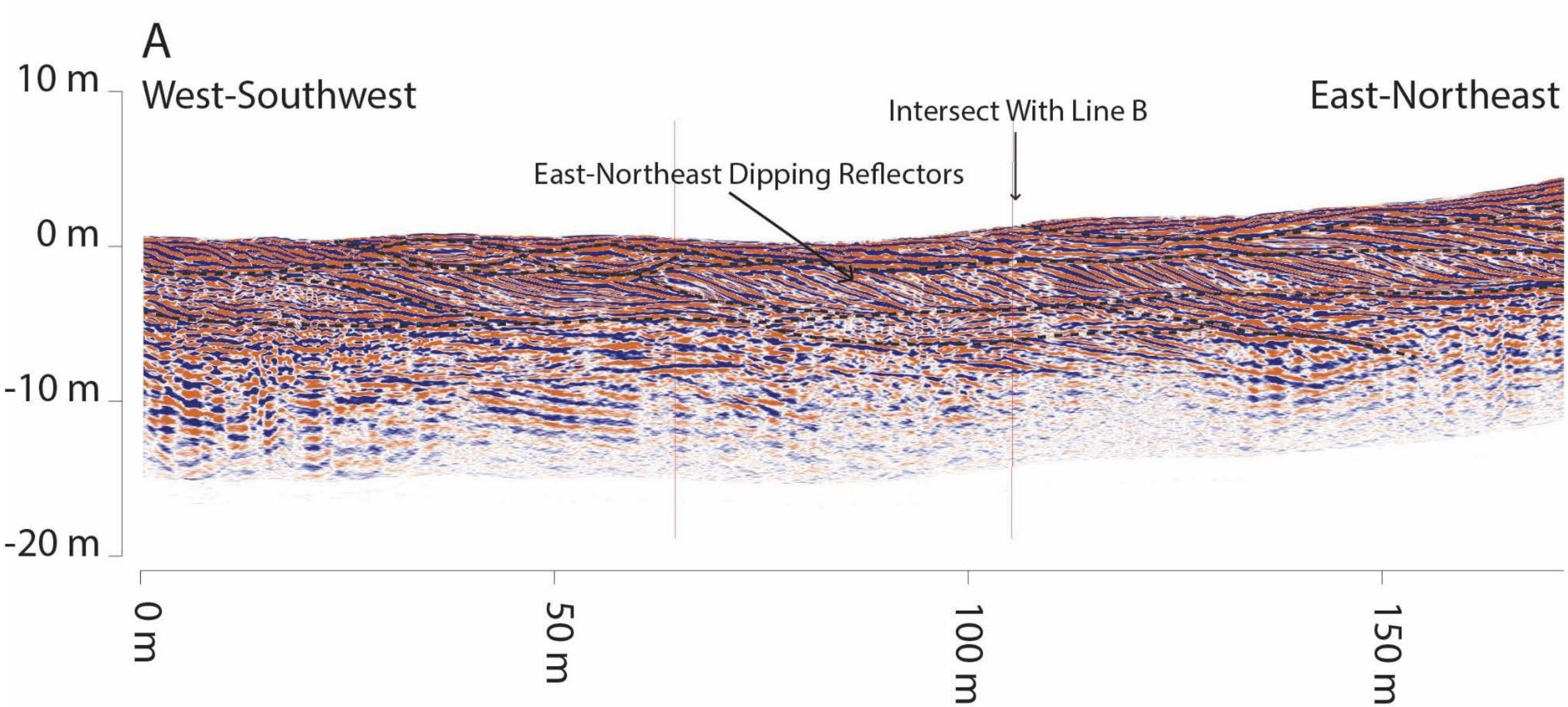
Our luminescence data shows that the interdune area is much older than the dunes. The data indicate that the last time the quartz sand in the interdune was exposed to light was 51 ka (± 7800 years). The age of the interdune deposits can be contrasted to the lower portion of the west side of the primary dune, which last was exposed to light 110 years ago (± 70 years).

Auxiliary Dune Ground Penetrating Radar

On the auxiliary dune the data penetration was limited to 10 m or less. The data set includes six GPR lines (Fig. 5), one along the crest of the dune (strike line) and the rest crossing the dune at different points (dip lines).

On the strike line (Fig. 7A) we see packages of reflectors bounded by downlap at the base and truncation at the top. These packages range in size from 1 to 5 m thick and 5 to 100 m or more long. The majority of these packages contain reflectors that dip to the east end of the line (a few have negligible dip and some within 2 m of the surface and, parallel the surface and dip to the west).

On the dip lines (Fig 7B) we see packages of reflectors bounded by downlap on the base and truncation at the top. These packages range in size from 1 to 5 m thick and up to 45 m long. The majority of these packages contain reflectors that dip to the north end of the lines with a notable exception of a package on the south side of the peak of the dune with reflectors that dip to the south.


A
West-Southwest
East-Northeast
Intersect With Line B
East-Northeast Dipping Reflectors
10 m
0 m
-10 m
-20 m
0 m
50 m
100 m
150 m

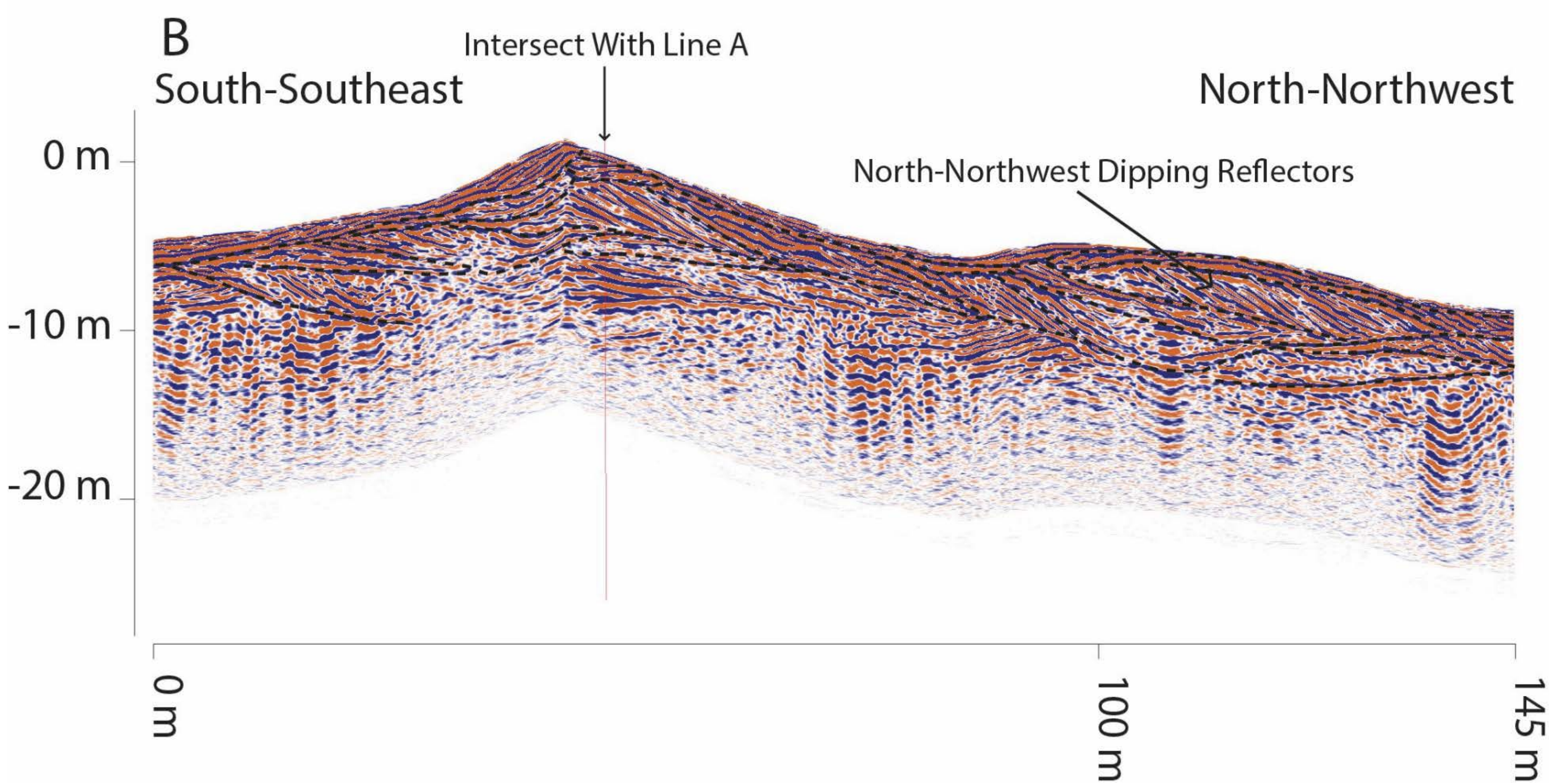

B
Intersect With Line A
South-Southeast
North-Northwest
North-Northwest Dipping Reflectors
0 m
-10 m
-20 m
0 m
100 m
145 m

Figure 7. Two of the GPR lines that were collected on the auxiliary dune (site B of Fig. 2). Map (Fig. 5) shows line locations on the dune marked A and B respectively. Line A was collected down the crest of the dune. Notice that most of the outlined packages show foresets dipping to the east-northeast. Line B is one of the cross lines collected. Notice that for this line most of the outlined packages contain reflectors indicative of foresets dipping to the north-northwest which is consistent between the transect lines. The combination of these observations indicates that motion of this dune is to the north-northeast at some vector between the orientations of the lines.

DISCUSSION

Meaning of GPR Reflectors

Ground Penetrating Radar (GPR) responds to changes in the electrical properties of the ground measured as the dielectric constant. In the case of dune sand we assume that the changes that the GPR is responding to are caused by small variations in porosity of the sand. In most cases we assume that these variations in porosity are equivalent to sedimentary structures like beds or foresets.

Large Dune GPR interpretation

We interpreted the GPR data by grouping different reflectivity patterns into zones representing distinct depositional processes. Starting from the base of the dune and heading to the peak of the crest we identified five depositional signatures. The description of the zones identified and their meaning are presented below.

Zone 1 – This is the deeper part (starting 1 to 3 m deep and continuing beyond the penetration of the data at 12 m) of the data on the west flank of the dune (Figs. 6 and 8). It is characterized by packages of reflectors that cross-cut each other and by bowl shaped packages of reflectors (scouring and fill). These reflectors can be interpreted as sedimentary structures and are consistent with trough cross-stratification (TCS). TCS results from deposition by turbulent flow of wind (in this case). The dunes formed by this kind of turbulent flow are three-dimensional (3D). This means that the dune fronts (crests) were sinuous, potentially discontinuous, and the peak of the crest varied in height along the dune.

In this location we interpret the TCS to be the deposits of 3D superimposed dunes on the flank of the primary linear dune. We envision these dunes to be similar to those seen in Fig. 9 in the area labeled "3D superimposed dunes," both in shape and in relationship to the primary dune.

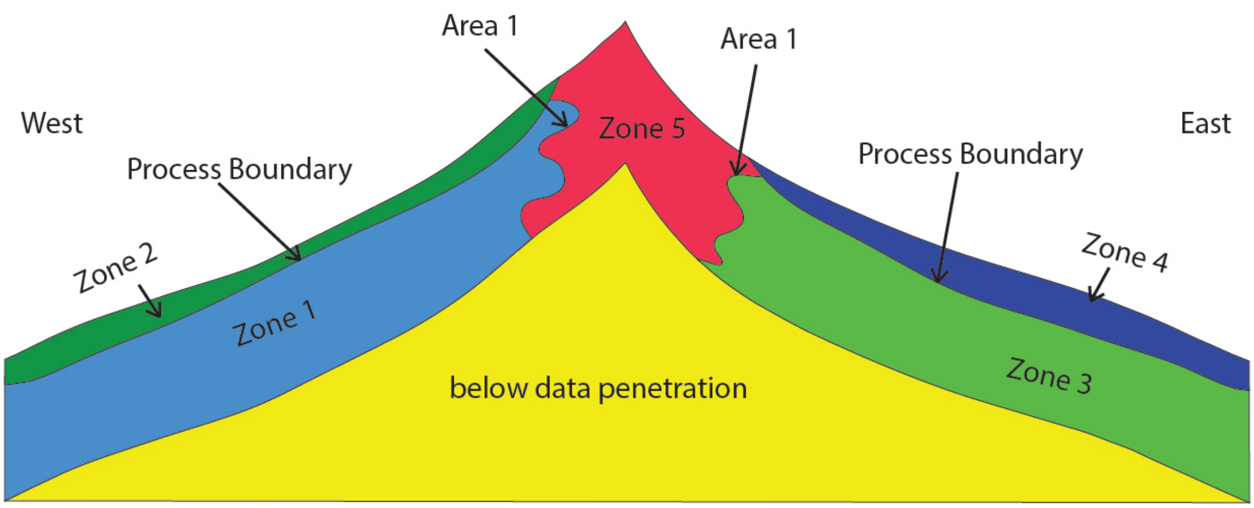


Figure 8. Cartoon of the interpreted depositional process zones. Note that area of interest is greatly exaggerated to be able to show relationship of interpreted features.

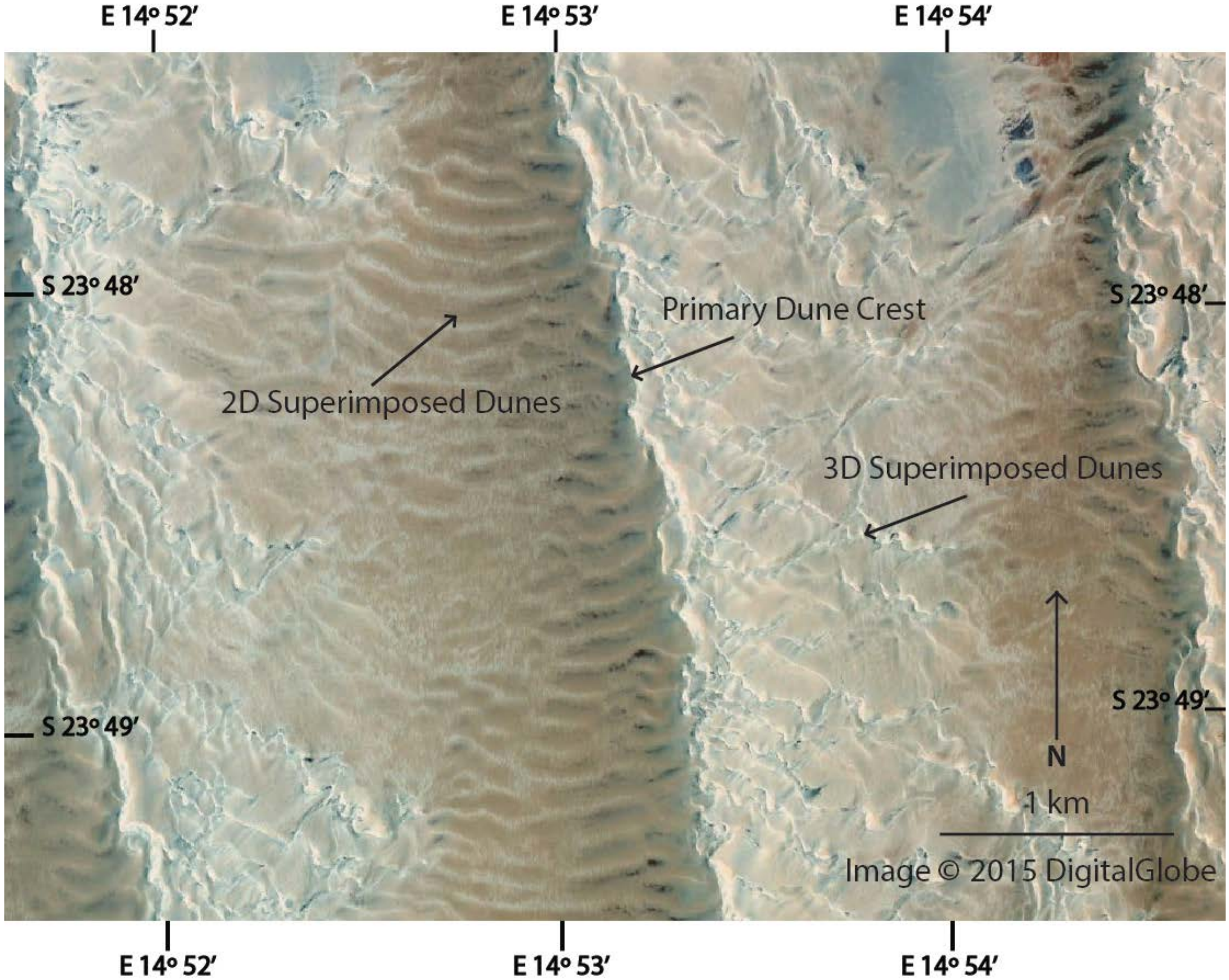
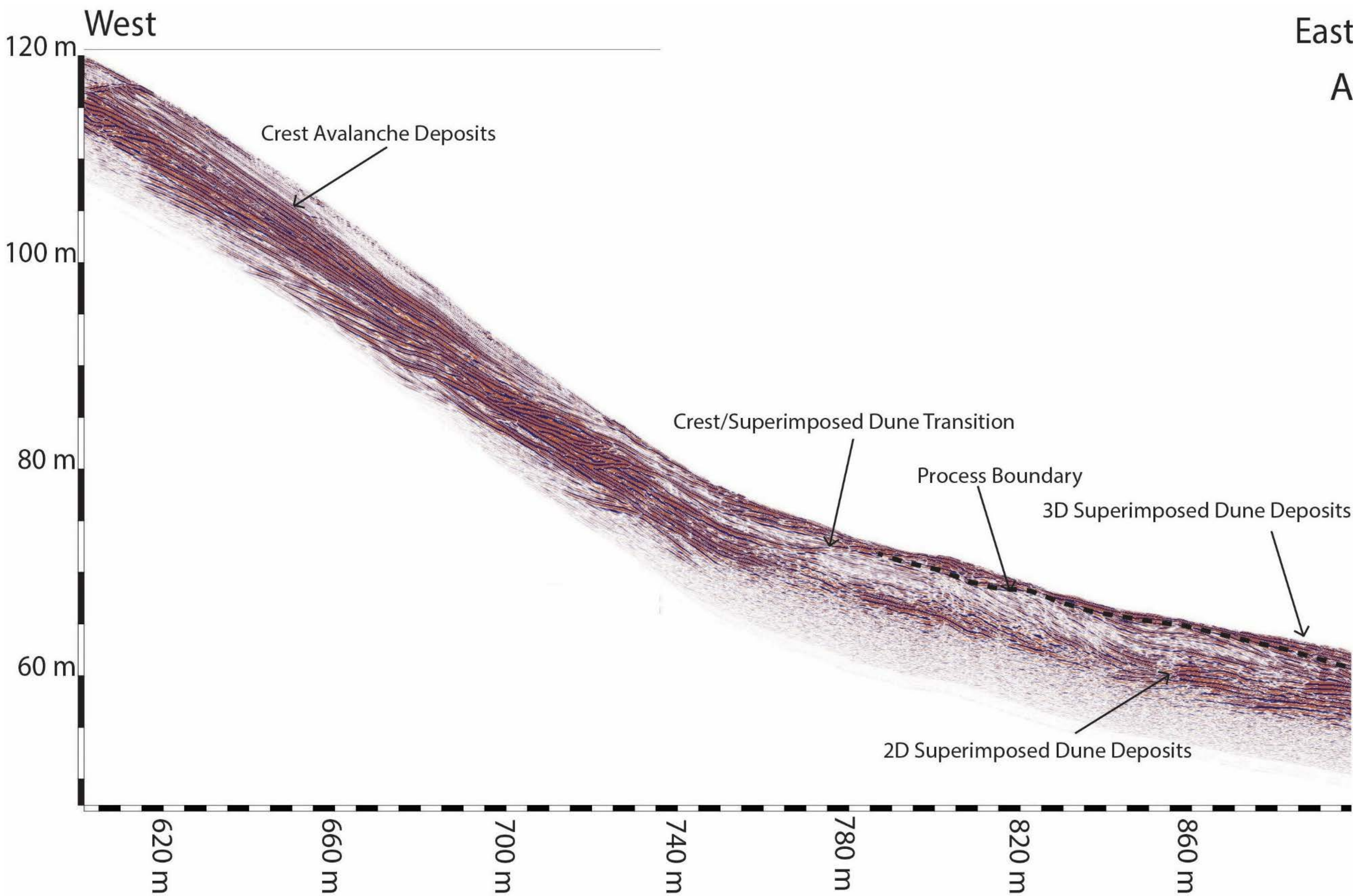


Figure 9. Area to the southwest of our study area. Labeled on the right of the image are 3D superimposed dunes similar to what we expect to have deposited the TCS patterns in zone 1 or the GPR data. The 2D superimposed dunes pointed out here are similar to what we expect to have deposited zone 2 in the GPR data. This image shows a distinct side-by-side contrast of what is meant by 2D and 3D dunes. Base image from Google Earth.

Zone 2 – This is the shallower part (from the dune surface to a range of 1 to 3 m) of the data on the west flank of the dune (Figs. 6 and 8). It is characterized by long reflectors (up to 100 m or more) that are nearly parallel to the surface of the dune with gentle terminations (low angle down lap and low angle truncation). These reflectors are taken to be laminar beds of sand and are consistent with planar stratification.

In this location we interpret the planar stratification to be the deposits of 2D superimposed dunes on the flank of the primary dune. We envision these dunes to be similar to those seen in Fig. 9 in the area labeled 2D superimposed dunes and in Fig. 3 A, arrow A.

Zone 3 – This is the deeper part (starting 1 to 3 m deep and continuing beyond the penetration of the data at 12 m) of the data on the east flank of the dune (Figs. 8 and 10). It is characterized by long reflectors (often more than 50 meters) that cross-cut each other and there are some bowl-shaped packages. Comparing this zone to zone 1, we see that the reflectors are much longer and terminate more gently. This reflector pattern is consistent 2D dune architecture with an element of sinuosity. A gently sinuous wave front would produce long, low-angle beds that cross-cut each other as is illustrated in Figs. 6 B and 10 B.


West
East
A
120 m
100 m
80 m
60 m
Crest Avalanche Deposits
Crest/Superimposed Dune Transition
Process Boundary
3D Superimposed Dune Deposits
2D Superimposed Dune Deposits
620 m
660 m
700 m
740 m
780 m
820 m
860 m

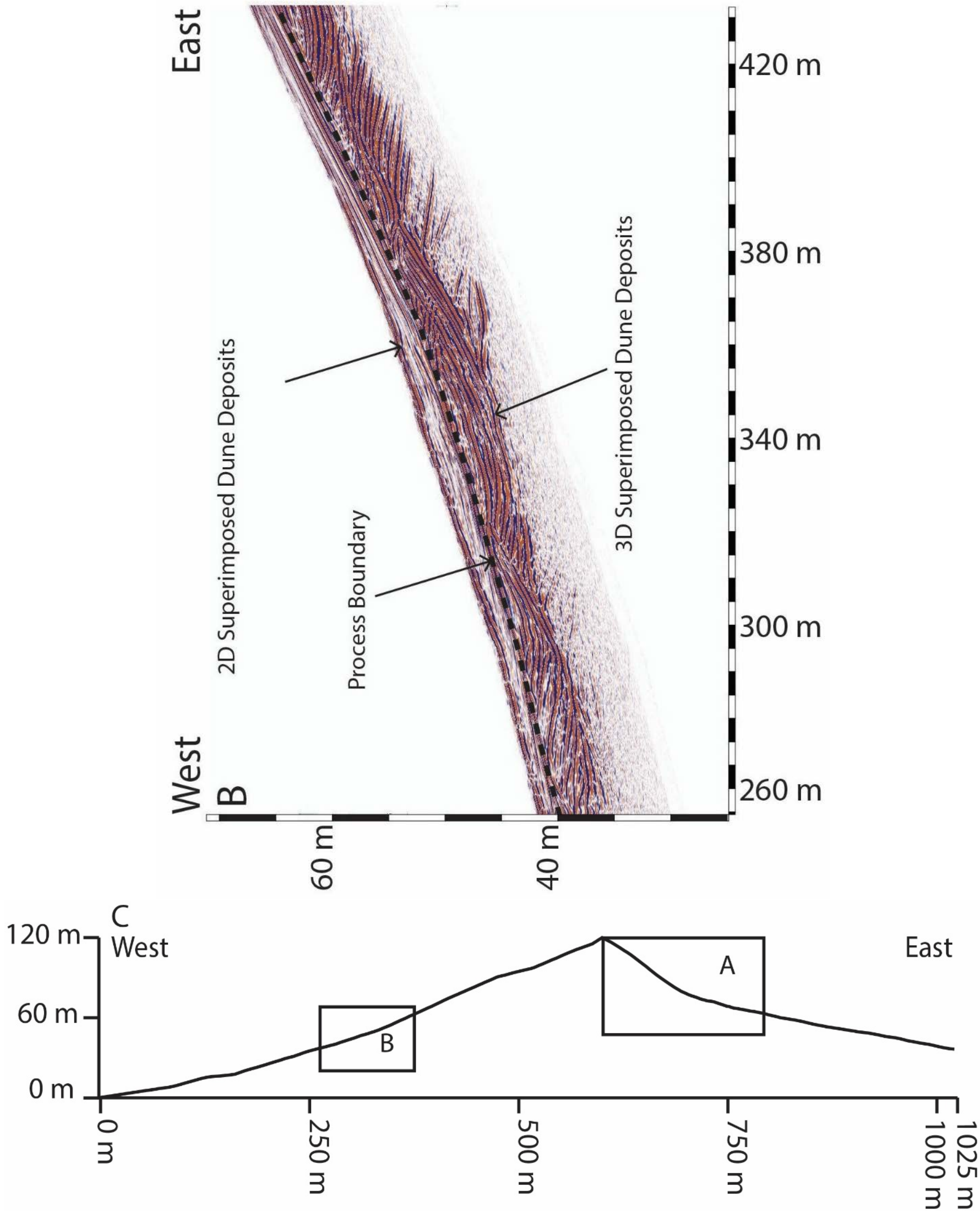


Figure 10. Selected portions of GPR profile showing different depositional features interpreted. A shows the data from the east side of the dune near the crest. This data includes crest avalanches (zone 5 of Fig 8), trough cross-stratification from 3D superimposed dunes (zone 4 of Figs. 6 and 8), planar stratification from 2D superimposed dunes (zone 3 of Figs. 6 and 8), the

transition from crest processes to superimposed dune processes (area 1of Fig. 8), and the boundary between 2D and 3D superimposed dunes (Process Boundary). B shows data from midway down the west side of the dune. This data shows trough cross-stratification from 3D superimposed dunes (zone 1 of Figs. 6 and 8), planar stratification from 2D dunes (zone 2 of Figs. 6 and 8), and the boundary between them (Process Boundary). C shows the profile of the cross section where data was collected the boxes labeled A and B are A and B shown above respectively.

Zone 4 – This is the shallower part (from the dune surface to a range of 1 to 3 m) of the data on the east flank of the dune (Figs. 8 and 10). It is characterized by short, (only a few meters) wavy, discontinuous reflectors that cross-cut each other. The reflector terminations in this zone are more aggressive than those in zone 3. This is also consistent with TCS.

In this location we interpret the pattern to be the result of deposition by 3D dunes but less sinuous than those that deposited zone 1. We assume that this is the process happening here currently therefore the dunes at the surface on the east side of the primary dune would produce this type of deposit. It should be noted from the transect line in Fig. 3 that this part of the transect was probably collected in the deflationary trough between two wave fronts and this zone would likely be thicker if it were collected along the ridge of one of these dunes.

Zone 5 – This is the part of the data near the crest of the dune (~100 m to the east of the peak to ~35 m west of the peak) (Figs. 8 and 10). It is characterized by long reflectors (up to ~90 m on the east side and ~30 m on the west side) that originate near the peak of the dune and are truncated by shallower reflectors or the surface of the dune as they approach the inflection point. These reflectors are taken to be direct avalanche deposits from the dune crest.

Area 1 – This area is located at the inflection points on both sides of the dune (Fig. 8). This is where we see zone 5 interfingering with the other zones (Fig. 10A). In this area we can see the variation in the dominance of each process (superimposed dunes and primary crest).

Process Boundary – This is the boundary between zones 1 and 2 on the west flank of the dune and zones 3 and 4 on the east flank (Figs. 6 and 8). This boundary truncates reflectors below it. Reflectors above the surface onlap or downlap against it (Figs. 6 and 10). The boundary is continuous from where it begins near the inflection point on both sides of the dune until it meets the interdune surface on the west side of the dune and until the end of the data on the east side.

This surface (Process Boundary) is significant because it seems to indicate a change or reversal of primary wind regime. We can think of dunes, like the superimposed dune we see in the Namib, as existing on a spectrum. At one end of the spectrum we have 2D dunes and at the other 3D dunes (the dunes pointed out in Fig 9 are a good approximation of these end members). The deposits we see on the west side of the primary dune are nearly end members of this spectrum, with 3D below 2D. The deposits on the east side are not end members but are each more similar to one end than the other, with the lower zone (3) more strongly 2D and the upper zone (4) more strongly 3D. The implication from this is that at the time the west side was forming 3D dunes the east side was forming 2D. Currently the west side is 2D and the east side is 3D. The extension of this observation is that since the dune type flipped the wind patterns flipped also.

Superimposed Dune Morphology

The current morphologies of the superimposed dunes are not the same on each side of the primary linear dune. On the east side of the primary dune the superimposed dunes display a 3D waveform, are arcuate, and do not extend from the inflection point of the dune to the interdune surface. They are also oriented oblique to the primary dune crest. The superimposed dunes on the west side of the primary dune are less arcuate, usually extend from the inflection point to the interdune surface and display a 2D waveform. Also, the western dunes are oriented mostly normal to the crest of the primary linear dune. The difference in the shape of superimposed dunes between the sides of the primary dune suggests that there are different winds affecting each side of the primary dune.

Comparison with Previous Studies

Superimposed dunes have been noted in GPR data of lower resolution (in order to obtain greater depths of penetration; Bristow et al. 2000; 2007). Those studies noted TCS from superimposed dunes on their study dunes but did not recognize any 2D superimposed dune deposits. The superimposed dune deposits on our dune are at least 10 meters thick compared to a maximum thickness of less than 10 meters on the smaller portion of a large linear dune, at the northern margin of the sand sea (Bristow et al., 2000, 2007). The limit of penetration for our data is 10 to 12 meters, which makes it difficult to establish beyond doubt that the superimposed dune deposits on our dune are significantly thicker. Thus, while superimposed dune forms may be slightly thicker in the portion of the sand sea with taller dunes, indicating either a depth of process, mobility of sediment or age of process, we cannot say these are significantly thicker than at the margins of the sand sea.

We also compare OSL ages between samples from what we interpret as superimposed dune deposits. The samples (10 samples) from a previous study indicated an age of ~25 to 450 years (Bristow, 2007) while our sample indicated an age of 110 years (+/- 70 years). Therefore, superimposed dune sands seem to be of similar age in these two locations, which are from the dunefield margin and deeper in the dunefield, respectively.

Auxiliary Dune GPR Interpretation

In the data from the auxiliary dune we saw packages of reflectors with dips primarily to the east on the strike line and primarily to the north on the dip lines. We interpret these dipping reflectors to be depositional foresets. The dip of these foresets indicates direction of sand transport. If we consider the strike line and the dip lines separately, the strike line indicates sand transport to the east-northeast and the dip lines indicate sand transport to the north-northwest. The combination of these leads to the interpretation that the actual sand transport direction is somewhere between the orientation of the strike and dip lines, or to the north-northeast.

Relationship between Primary and Auxiliary dunes

Based on interpretation of the Auxiliary dune GPR data we determined that our auxiliary study dune is three dimensional and sand transport is oblique (neither transverse nor longitudinal) to the orientation of the crest (it is 3D oblique). In order to extend our interpretation, we looked at areas where similar dunes exist (Fig. 11). Concentrations of auxiliary dunes are found in the areas around Tsondab Vlei and Sossus Vlei and on the western edge of the linear dunefield. Our study dune and others in the surrounding area are near the margins of Tsondab Vlei, which is an area where the normal pattern of linear dunes is disrupted and, relative to the surrounding areas, there is very little sand. The majority of these auxiliary dunes are roughly parallel to each other with an east-northeast orientation (Fig.4); however on the northwestern and western margins of Tsondab Vlei, they seem to be more parallel to the margin of the Vlei (northeast orientation) than to the other auxiliary dunes.

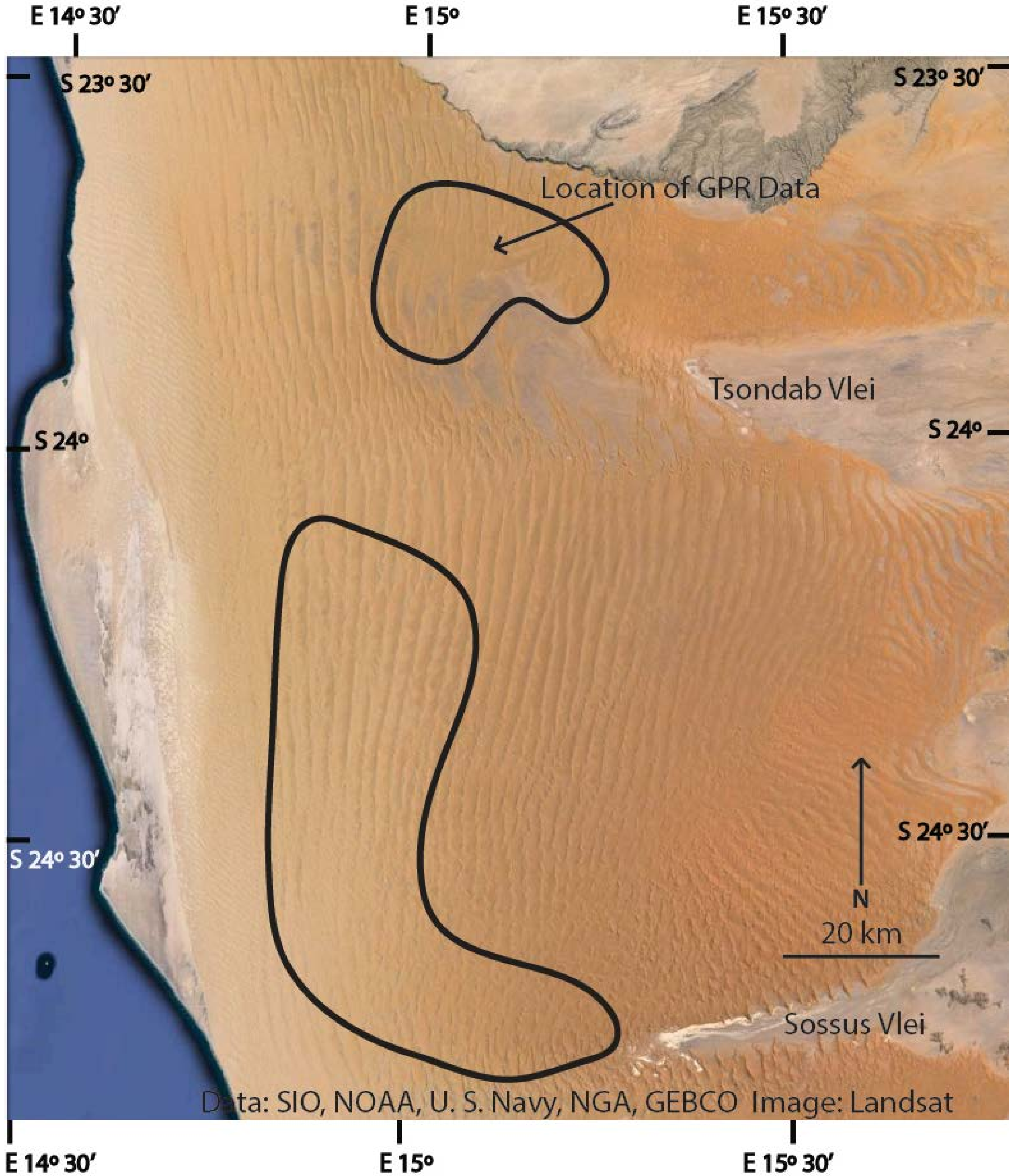


Figure 11. Northern half of Namib Sand Sea. Highlighted areas showing the range of dunes similar to our auxiliary study dune. Notice that the northern area of auxiliary dunes (where our study dune is located) are strongly associated with a large area with little sand (Tsondab Vlei). Base image from Google Earth.

The strong association of these auxiliary dunes with Tsondab Vlei leads us to believe that, at least near our study area, auxiliary dunes are primarily controlled by disruptions of the normal dunefield pattern. We speculate that this is because the bare area of Tsondab Vlei allows wind patterns to be established that affect the interdunes in the nearby area. These wind patterns pull sand from the primary dune flanks and draw it into these auxiliary dunes.

CONCLUSIONS

We obtained the highest resolution GPR data for this area that we know of, this data is also unique because it is imaging features that haven't ever been imaged before. This study adds to the validity of GPR as a tool for investigation of problems in sandy desert environments. Furthermore it demonstrates the importance of choosing appropriate collection and processing methods.

In relation to superimposed dunes, this study show that the process boundary that we see in our data involves some level of erosion. This is evident because of the truncation of reflectors below this boundary. The different superimposed dune morphologies (2D and 3D) on opposite flanks of the primary linear dune indicate a difference in flow regime from one side of the dune to the other. Opposing dune flanks display a reversed stratigraphic succession (Fig. 12). There was a change in flow energy and/or direction of wind from below the erosional process boundary to above the boundary. This change in energy is likely a regional forcing mechanism as its modern pattern is observable over great distances within the Namib Sand Sea. We speculate that the change in energy is oscillatory and that this change may be involved in the linear growth and lateral stability of large, complex, linear dunes on Earth. Further research may aid in determining whether the stratigraphic stacking pattern continues deeper into the dune and if it is found throughout the sand sea and even in other sand seas of the world.

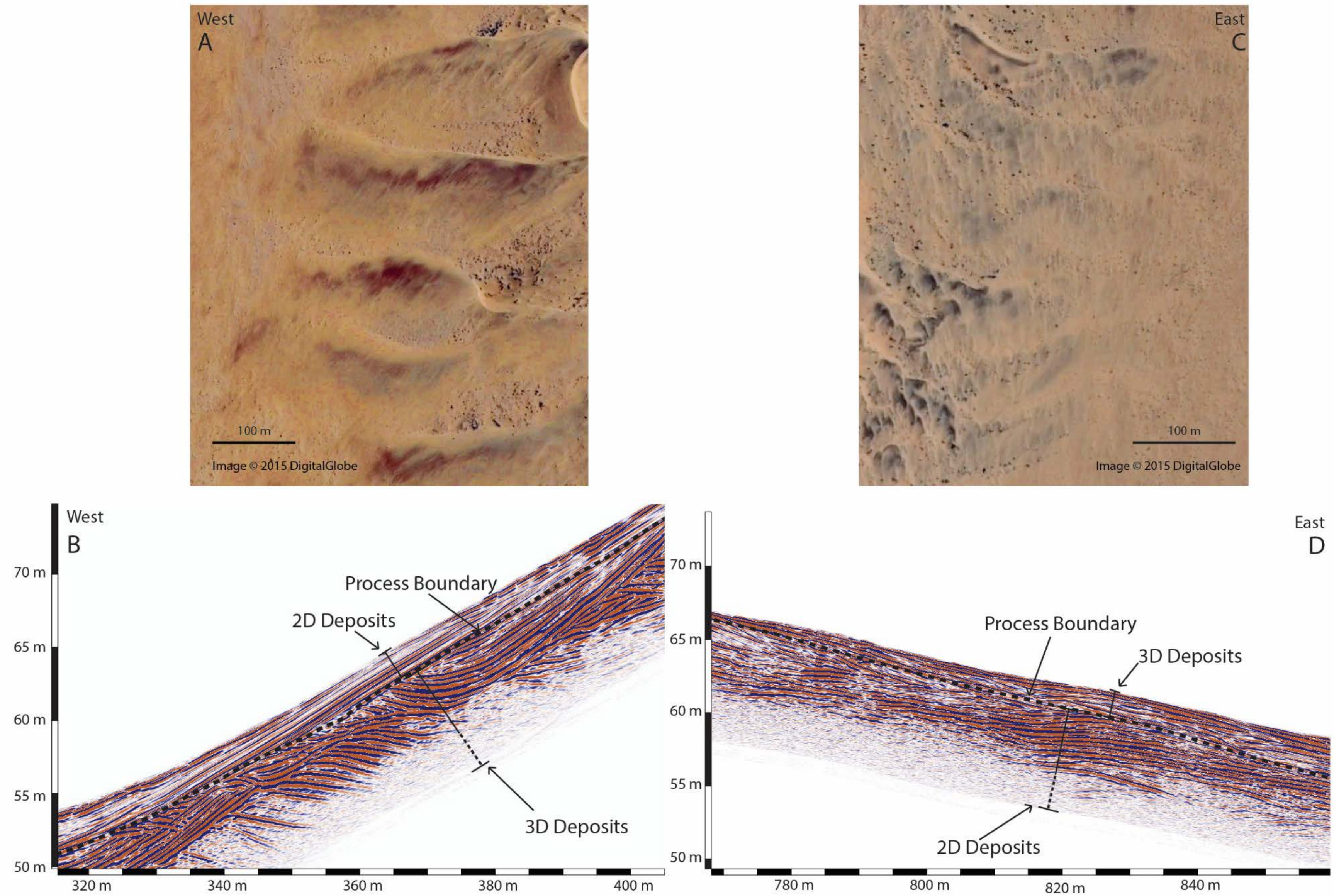

West
A
100 m
Image © 2015 DigitalGlobe
East
C
100 m
Image © 2015 DigitalGlobe
West
B
70 m
65 m
60 m
55 m
50 m
Process Boundary
2D Deposits
3D Deposits
320 m
340 m
360 m
380 m
400 m
East
D
70 m
65 m
60 m
55 m
50 m
Process Boundary
3D Deposits
2D Deposits
780 m
800 m
820 m
840 m

Figure 12. The difference between the superimposed dunes on opposing sides of the primary dune (A and C) compared to the observed stratigraphy of opposing sides (B and D). Note that the succession of the west side of the dune (B) is the reverse of the east side of the dune (D). Base image for A and B from Google Earth.

With regard to auxiliary dunes, this study shows that these dunes (in the region of our study) are primarily migrating obliquely to the north-northeast. This combined with the association of these dunes with Tsondab Vlei leads us to speculate that the barren area of Tsondab Vlei produces wind patterns in the nearby interdunes that draws sand from the primary linear dunes to produce auxiliary dunes. We further speculate that a similar process controls auxiliary dunes in other regions of the sand sea but would instead be controlled by proximity to the coastal plain or to Sossus Vlei. This may indicate that the surface wind patterns in the linear dune field are a combination of the regional wind patterns and a significant influence from the large linear dunes.

REFERENCES

Arnold, K. 2014. Sand Sea Areas and Sediment Volumes on Titan from Dune Parameters. Thesis, Brigham Young University

Bristow, C.S., Bailey, S.D., and Lancaster, N., 2000, Sedimentary structure of linear sand dunes: Nature, v. 406, p. 56–59.

Bristow, C.S., Lancaster, N., and Duller, G.A.T., 2005, Combining ground-penetrating radar (GPR) surveys and optical dating to determine dune migration in Namibia: Geological Society [London] Journal, v. 162, p. 315–321, doi: 10.1144/0016-764903-120.

Bristow, C. S., Duller G. A. T., Lancaster N., 2007, Age and dynamics of linear dunes in the Namib Desert, Geology, v. 35 p. 555-558.

Fryberger S. G., 1979, Dune forms and wind regime. In: A study of global sand seas (Ed. By E. D. McKee) professional paper U. S. Geological Survey, 1052 p. 137-170.

Kocurek, G., N. Lancaster, M. Carr, and A. Frank, 1999, Tertiary Tsondab Sandstone Formation: Preliminary bedform reconstruction and comparison to modern Namib Sand Sea dunes, Journal of African Earth Sciences, v. 29 n. 4 p. 629-642.

Lancaster, N., 1989, The Namib Sand Sea: Dune forms, processes, and sediments: Rotterdam, A.A. Balkema, 200 p.

Lancaster, N., 1995, Geomorphology of desert dunes: London, Routledge, 290 p.

Livingstone, I., 1989, Monitoring surface change on a Namib linear dune: Earth Surface Processes and Landforms, v. 14, p. 317–332.

Livingstone, I., 1993, A decade of surface change on a Namib linear dune: Earth Surface Processes and Landforms, v. 18, p. 661–664.

Livingstone, I., 2003, A twenty-one-year record of surface change on a Namib linear dune: Earth Surface Processes and Landforms, v. 28, p. 1025–1032.

Livingstone, I., Wiggs, G. F. S., and Weaver, C. M., 2007, Geomorphology of desert sand dunes: a review of recent progress: Earth-Science Review, v.80 p. 239-257.

McKee E. D., 1979, a study of global sand seas: professional paper U. S. Geological Survey, 1052

McKee E. D., 1982, sedimentary structures in dunes of the Namib Desert, South West Africa: special paper Geological Society of America, 188.

McKee E. D., and Tibbets (Jr), C. G., 1964, Primary structures of a seif dune and associated deposits in Libya: Journal of Sedimentary Petrology, v. 34 p. 5-17.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single aliquot regenerative-dose protocol. Radiation Measurements 32, 57-73.

Murray, A.S., Wintle, A.G., 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. Radiation Measurements 37, 377-381.

Reffet, E., Courrech du Pont, S., Hersen, P., and Douady, S., 2010, Formation and Stability of transverse and longitudinal sand dunes: Geology, v. 38, p 491-494.

Rodriguez, S., A. Garcia, A. Lucas, T. Appéré, A. Le Gall, E. Reffet, L. Le Corre, S. Le Mouélic, T. Cornet, S. Courrech du Pont, C. Narteau, O. Bourgeois, J. Radebaugh, K. Arnold, J.W. Barnes, C. Sotin, R.H. Brown, R.D. Lorenz, E.P. Turtle 2014. Global mapping and characterization of Titan's dune fields with Cassini: correlation between RADAR and VIMS observations. Icarus 230, 168-179.Rubin, D.M., and Hunter, R.E., 1985, Why deposits of longitudinal dunes are rarely recognized in the geologic record: Sedimentology, v. 32, p. 147–157, doi: 10.1111/j.1365 3091.1985.tb00498.x.

Rubin, D. M., Tsoar, H., and D. G. Blumberg, D. G., 2008, A second look at western Sinai seif dunes and their lateral migration: Geomorphology, v. 93 p. 335-342.

Tsoar H. T., Blumberg, D. G., and Stoler, Y., 2004, Elongation and Migration of sand dunes: Geomorphology, v. 57 p. 293-302.

Tsoar H. 1983, Dynamic processes acting on a longitudinal (seif) sand dune: Sedimentology, v. 30 p. 567-578.

Tsoar H. 1982, Internal structure and surface geometry of longitudinal (seif) dunes: Journal of Sedimentary Perology, v. 52 n. 3 p, 0823-0831.

Vermeesch, P., Fenton, C. R., Kober, F., Wiggs, G. F. S., Bristow, C. S. and Xu, S., 2010, Sand residence times of one million years in the namib sand sea from cosmogenic nuclides: Nature Geoscience, v. 3 p. 862-865.

Wintle, A.G. Murray, A.S., 2006. A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regenerative protocols: Radiation Measurements, v. 41, p. 369-391.