Dunes on planet Tatooine : Observation of Barchan Migration at the Star Wars film set in Tunisia

Ralph D. Lorenz[a], Nabil Gasmi[b], Jani Radebaugh[c], Jason W. Barnes[d], and Gian G. Ori [e]

[a] Space Department, Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723, USA

[b] Nabil Gasmi, Laboratoire de Cartographie Géomorphologique des milieux, des Environnements et des Dynamiques (CGMED), University of Sousse, Tunisia

[c]Department of Geological Sciences, Brigham Young University, Provo, UT, USA

[d] Department of Physics, University of Idaho, Moscow, ID, USA

[e]International Research School of Planetary Sciences, Universita' d'Annunzio, Pescara, Italy

Submitted to Geomorphology 30 July 2012.

Accepted for publication 16 June 2013.

contact ralph.lorenz@jhuapl.edu for additional information and figure permissions

Abstract

Sand dune migration is documented with a readily-available tool (Google Earth) near Chott El Gharsa, just north-west of Tozeur, Tunisia. As fiducial markers we employ a set of buildings used to portray the fictional city Mos Espa. This set of ~20 buildings over roughly a hectare was constructed in 1997 for the movie Star Wars Episode 1 – The Phantom Menace. The site now lies between the arms of a large "pudgy" barchan dune, which has been documented via satellite imaging in 2002, 2004, 2008 and 2009 to have moved from ~140 m away to only ~10 m away. Visits by the authors to the site in 2009 and 2011 confirm the barchan to be in a threatening position : a smaller set nearby was substantially damaged by being overrun by dunes circa 2004. The migration rate of ~15 m/yr decreases over the observation period, possibly as a result of increased local rainfall, and is consistent with barchan migration rates observed at other locations worldwide. The migration rate of this and two other barchans suggest sand transport of ~50 m^3/m/yr, somewhat higher than would be suggested by traditional wind rose calculations: we explore possible reasons for this discrepancy. Because of the link to popular science fiction, the site may be of pedagogical interest in teaching remote sensing and geomorphic change. We also note that nearby playa surfaces and agricultural areas have a time-variable appearance. The site's popularity as a destination for Star Wars enthusiasts results in many photographs being posted on the internet, providing a rich set of in-situ imagery for continued monitoring in the absence of dedicated field visits.

Keywords

Dune dynamics; Remote Sensing; Tourism; Barchans; Tunisia

Highlights

- Barchan movement at Star Wars film set is shown by satellite imaging and field photos
- Dune movement may have imminent economic impact on this popular tourist site
- Touristic appeal provides collateral field imaging on the Web

1. Introduction

The migration of barchan dunes is one of the most rapidly occurring examples of geomorphological change. Barchans are crescentic dunes that form where sand supply is modest and winds are fairly unidirectional (e.g. ; Fryberger, 1979; Lancaster, 1995). The rapidity of motion (typically several meters per year) makes it comparatively easy to observe, and barchan movements have been documented now for over a century since Beadnell (1910) reported field measurement of the movement of five barchans at Kharga in Egypt. Two recent factors have now made the ability to measure barchan movement from space rather straightforward to the general public. First is the unrestricted availability of high spatial- (<1 m) and high temporal-resolution commercial satellite imaging (considered "one of the most significant developments in the history of the space age" (Broad, 1999)) starting with the Ikonos satellite in 1999 and then a proliferation of other platforms since such as Worldview-2, Geoeye, etc. (see e.g. Webber and O'Connell, 2011). The second factor is the access to data afforded by the internet and the ability to examine it with convenient tools such as Google Earth with which to browse such data without the use of specialized photogrammetric software or Geographical Information Systems (GIS).

Here, prompted by a field visit in 2009, we describe barchan movement in the Tunisian desert at the film set used in 1997 to film the movie "Star Wars Episode 1: The Phantom Menace" (Lucas, 1999), released in 1999 (e.g. Bowen, 2005). The buildings in the film set serve as convenient fiducial markers with which to measure barchan migration. The site is also of interest because it is a significant tourist attraction, and its apparently imminent burial under the barchan may therefore have an economic impact on the area.

We are aware of only one other measurement of dune migration in Tunisia (Khatteli and Belhaj, 1994) and none published in English, thus much work remains to be done to characterize aeolian geomorphology in this region and present it to a global audience. We hope that this paper may encourage others to visit and monitor the site as the dunes continue to move.

2. Geomorphological Setting

The site is in the south-west of Tunisia (Fig. 1). The town of Tozeur is a popular tourist destination and has an airport that receives flights from several European destinations as well as domestic flights. In remote sensing data, the location is usually easy to determine due to the distinct albedo of the Chott el Jerid, a large ephemeral lake whose appearance from space can change dramatically due to episodic flooding (Bryant and Rainey, 2002).

A closer view is shown in Fig. 2, showing the relation of the site to the smaller Chott el Gharsa (sometimes transliterated as Chott el Rharsa) playa, and the town of Tozeur which is 26 km away. The area has widespread Neogene evaporitic deposits (e.g. Swezey, 1997, 1999; Blum et al., 1998) which extend west from the southern Atlas mountains: some of these evaporite-rich clay deposits (50-150 m thick) are attractions in themselves (e.g. the 'Camel Neck' or 'Oung el Jemal') are well-known film locations. Large plates of gypsum are often found and the assemblages of such gypsum plates into 'desert roses' (many 'cultured' by locals) are a popular tourist souvenir. The large salt concentration, especially at the southern edge of the Chott el Gharsa (this area to the south being referred to locally as El Ghadayers), often forms a crust and thereby inhibits growth of halophytic plants that might otherwise stabilize the soil.

The movie set is on a clay-rich pan in an isolated field of barchanoid dunes (Figs. 3, 4). The flatness of the pan probably encourages sand mobilityby acting as a surface with a high coefficient of restitution (allowing saltating grains to bounce efficiently). These dunes - the most significant aeolian features in the area - are fairly closely-spaced so their dynamics may be complicated by mutual interactions affecting wind or sand supply (e.g. Hersen et al., 2004). The dune sands in this area are quartz with a high proportion (>~70%) of gypsum, the latter with grain size from 0.1 to 1.5 mm, with a mean of 0.3-0.4 mm. The winds, as measured for example at the Tozeur airport (see section 5), are overwhelmingly from the east (see later) and are sufficiently constant in direction that the resultant duneforms are transverse barchanoid ridges and barchans (e.g. Fryberger 1979; Lancaster, 1995).

3. Mos Espa and the Barchan Dunes

The site is located at 33°59'39.78"N, 7°50'35.21"E (these coordinates are of the circular building at the northeastern corner of the complex, building 'B' in Fig. 5). The film set comprises around 20 structures of wood frame and plaster construction. The structures were used to portray the town of Mos Espa on the planet Tatooine and include Watto's shop, Sebulba's café and Qai-Gon's Alley (note that in the movie, computer-generated imagery and other cinematographic techniques are used to introduce background to scenes that are not present at the site itself). In addition to the conventional buildings and wall segments there are several tall antenna-like structures, referred to in the movies as 'moisture vaporators' (sic). Since these structures are not fixed firmly to the ground it is not clear if these might be moved and thus may be less reliable as fiducial markers. Several nearby locations were also used in the movie, notably Oung el Jemel and a field of yardangs ('D' in Fig. 4, where the silver spaceship of the protagonists lands).

The clay salt pan on which the structures are erected is very flat and smooth. Sand dunes are not especially evident in the movie itself but can be detected by alert viewers, and the site is at the southern edge of the dunefield (see Figs. 3, 4) comprising principally barchanoid ridges. The set was in a clearing when it was constructed. However, sand movement from east to west means that clearings are ephemeral and a large barchan is now approaching the site.

The principal dimensions of the barchan are the length of the windward slope (a) i.e. the apex to crest and the distance between the tips of the horns (c), ~90 m and ~107 m respectively in 2009. As discussed by Bourke and Goudie (2009) following Long and Sharp (1964), the ratio between these two lengths (a/c) is used to determine a planform categorization of the dune. For our measurement of (a/c) ~0.84 the barchan planform is 'Pudgy' (although is borderline 'Fat', a category that applies for (a/c) >0.87).

The height of the dune was estimated from field photographs (e.g. by comparison with persons of known height ~1.7 m in the image: the persons are 35 pixels high, the dune is ~135 pixels and the image is taken from far enough away that allows these features can be considered equidistant from the camera. Thus the dune height is simply 1.6*135/35 = 6.5 m in 2009 (Fig. 6a). This height-to-width ratio of about 1/12 is consistent with the typical barchan morphometry found in Hesp and Hastings (1998).

4. Barchan Movement

We examined commercial satellite imaging, initially with the Google Earth historical imagery tool. The native resolution of the color image data is ~1.6 m. The images were acquired by the Geoeye satellite on (a) 11 July 2004, (b)21 January 2008 and (c) 25 September 2009 and are shown in Fig. 7. The fixed buildings make the dune movement very easy to detect. There is also some small change in barchan planform between images, and vehicle tracks are prominent in the 2008 image. These observations are

essentially enabled by the high resolution of commercial satellite data, and would be at the threshold of detection by the 30 m resolution typical of Landsat or most imaging radars that were the best data freely available in the past. The buildings are nonetheless crucial as fiducial markers in that experiments at other locations show ~20 m jitter in geolocation of many images with the tool used in this study.

We can extend the time baseline for migration study with a 10 m-resolution image (Fig. 8) from the NASA Earth-Observing 1 (EO-1) Advanced Land Imager (ALI) acquired in 2002. Although individual buildings cannot be resolved, the overall pattern of the set is visible and a useful distance measurement to the dune slipface can be made (14 pixels, +/-1) or 140 m.

Inspecting the images in Fig. 7, we measured the distance from the southern corner of building B due east to the slip face of the dune using the Google Earth ruler tool: distances of 93, 35 and 24 m, respectively, were determined, with an estimated precision of ~2 m. When plotted against the time of acquisition (Fig. 9) these data yield a migration rate of about 15 m per year. Additional measurements from building C due east to the dune yield rather similar results (89 m in 2004, 38 m in 2008, 22 m in 2009).

The 2002 ALI imager measurement of 140+/-10 m would be too inaccurate to contribute for a measurement period of just a couple of years, but does appear (Fig. 9, large white circle) broadly consistent with the trend in subsequent years.

Although most of the dunefield is of continuous barchanoid ridges which lack definitive features to track from one year to the next, we have made additional measurements of two other barchans. One we refer to as the 'large' barchan, which lies a few hundred meters due east of the film set and is labelled 'E' in Fig. 4. We measured its position relative to building 'B' over the three years and determined a migration rate of 5.8 m/yr. This dune is visible (just) in the background in Fig. 6 and is commonly used as a dramatic approach route to the film set by tourist vehicles, as evidenced by the abundant vehicle

tracks. A second barchan (labelled 'F' in Fig. 4 and 'North Barchan' in Fig. 5) is just north of the movie set: we documented its movement by measuring the distance and angle of bearing (again using the Google Earth ruler tool) from building B and computing the east-west coordinate. We obtain a migration rate of 10.8 m/yr. These position data are shown in Fig. 10. The slip face height for these dunes was estimated by measuring the maximum horizontal extent of the slip face in the Google images and multiplying by $\tan(30^o)=0.577$, resulting in heights of 16 m for the large barchan and 4.5 m for the north barchan. The horizontal extent of the barchan directly threatening the set was measured at 10.5 m; multiplying by 0.577 yields a height of 6.1 m, which is reasonably consistent with the estimate from field photos.

The migration rate of 15 m/year is quite typical for barchans of this size (6.5 m height). Various texts (including, of course, Bagnold, 1941) present compilations of data and analytical fits: the migration rate is usually described as proportional to the reciprocal of a dimension such as height or width. Sometimes the reciprocal is modified such that the migration rate, c, is written as a function of height H from the expression $c=Q/(H+H_o)$, where Q is a volume sand flux (typically 100-1000 m^3/yr/m) and H_o is a cut-off height (typically 1-10 m) (see e.g. Andreotti et al., 2002). Fig. 11 shows a simple reciprocal curve with $H_o=0$ and a couple of candidate sand fluxes against literature values of migration rate and our present measurements. The migration rates we observe appear consistent with a sand flux of the order of 40-100 m^3/yr/m.

We have analyzed wind speed and direction data from Tozeur airport in 2011 to construct a sand rose (Fig. 12), following the methodology of Fryberger (1979) - note also the caveat by Bullard (1997) on the use of units in constructing these diagrams. It is seen that the transport-effective winds are overwhelmingly from the ENE, consistent with the westwards migration of the dunes. The drift

potentials have been computed using an assumed threshold speed of 11.6 knots (e.g. Fryberger, 1979) and the resultant drift potential is 236 vector units (formally, these are knots-cubed). From Fig. 92 in Fryberger (1979) the corresponding sand transport is ~25 m^3/yr, which seems to be lower than that we have observed above. One possible reason for the discrepancy may be a lower saltation threshold than the assumed value of 11.6 knots (i.e. a friction speed of 16 cm/s): the sand composition may be partly responsible, in that gypsum has a lower density than quartz - all else being equal, the threshold would be lower by a factor equal to the square root of the density ratio.

5. Migration Rate : Possible factors

Dune movement requires that wind exceed the saltation threshold - which depends on particle characteristics but is typically assumed (e.g. Fryberger, 1979) to be ~12 knots (6 m/s) at typical anemometer height. There is no instrumentation at the site, but meteorological data is available from the Tozeur airport, about 26 km away (33°55'N, 8°06'E, elevation 87 m). Daily mean wind and daily maximum gust speeds over the period 2008-2011 are evaluated in Fig. 13: it is seen that gusts frequently exceed the threshold.

As shown in Fig. 9, the position points for the threatening barchan form a somewhat curved profile, possibly indicating a varying migration rate. The rates for each the two periods of high resolution imaging (2004.52-2008.06, and 2008.06-2009.73) are 16.6 m/yr and 6 m/yr, respectively, indicating a possible slowdown in recent years. A subtle indication of slowdown is noted for the big barchan, but little curvature in the points for the north dune is seen. If we do indeed interpret the threatening barchan as actually slowing down, rather than due to measurement error, three physical possibilities can be considered. First, it may be that a change in wind characteristics is responsible, but this is very difficult to demonstrate given the strongly time-variable character of windspeed (for example, if most

movement occurs during a few brief but intense storms, the interpreted average migration rate over an interval may depend on the stochastic number of such events within the interval. Thus there may be an apparent variation, even though the underlying long-term transport rate is formally constant). A more straightforward, and perhaps more likely, explanation would be the sand mobility. Damp sand does not saltate as easily, e.g. data summarized by Greeley and Iversen (1984, p.86) shows that 0.3%-0.6% moisture content can double the saltation threshold speed for sands, compared with their dry values. Furthermore, suppression of sand motion by moisture may be more extended for gypsum-rich sand, where flat particles may have high cohesion and some cementation may occur. Rainfall records from the National Institute of Meteorology of Tunisia (Fig. 14) show that 2009 was an exceptionally wet year. Indeed, the Chott El Jerid became flooded, which is historically somewhat rare. The average annual rainfall of ~100 mm (188 mm in 2009) may be compared with the mean annual pan evaporation at Tozeur of some 2750 mm (see also the discussion on precipitation in Tunisia in Bryant and Rainey, 2002). The additional rainfall likely kept the ground damp or wet for at least a month, although dampening for several months would likely be needed to suppress the annual sand transport appreciably. It is noteworthy that the fiming of the movie was in fact interrupted by a rainstorm (e.g. Bowen, 2005). Finally, it is possible that the slow-down of the threatening dune (which is not as apparent in the position data of the other two dunes) is spatially-determined rather than temporally-determined. It is possible that the influence of the buildings on the airflow and sand transport may have slowed its migration, and/or is causing the dune to erode. Another factor may be the effects of many tourists walking on the dune; once the dune is close to the film set, the number of tourists climbing the dune might increase.

Further observations may elucidate whether the migration rate has significant temporal variability on a year-to-year basis, and/or whether the threatening dune migration is affected by its proximity to the buildings.

6. Barchan Movement and Damage to Structures

Extrapolating the simple linear trend in Fig. 9 would indicate the site is already being overrun. However, the recent decline in migration rate may offer a reprieve. A visit by one of us (NG) in May 2011 showed that the 'town' had considerably more sand deposits among the buildings. However, the barchan appears not very much closer, and indeed appears to be somewhat lower in height. Clearly, further monitoring would be of interest.

There are no official statistics on the frequency of tourist visits to the site, but the informal testimony of a caretaker at the site suggests it is highly variable - between 50 and 150 4x4 vehicles per day, with most frequent visits in winter (especially December). With roughly 4 tourists per vehicle, this implies about 100,000 visitors per year. Apparently in 2010 only about 10% of visitors climbed the dune, although this fraction may rise now that the dune is essentially at the site.

Should the barchan that forms the focus of this paper overrun the Mos Espa set, many buildings will be temporarily buried. Their rather flimsy construction will mean roofs will likely collapse, degrading the attraction of the site when the dune moves on. This has already been seen at a smaller film set ('Repro Haddada', point 'C' on Fig. 4, sometimes referred to online as the 'slave quarters'), as documented in Figs. 15 and 16. This structure was overrun by a barchan around 2004, and has been substantially demolished, although it is still an object of pilgrimage by Star Wars fans, who also admire the barchans a few hundred meters to the south, which are prominent in several scenes of the movie.

Interestingly, the present barchan threatening the Mos Espa set appears not quite large enough to submerge the whole site, so visitors may still be drawn there. Mitigation measures may also be

effective. However, a field visit in May 2012 indicated that the horn of the barchan is virtually at the shade pavilion, and the slip face just a meter or two from building 'C' - see Fig. 17. During the revision of this paper in January 2013, an acquaintance of the first author happened to visit the site and took typical tourist photographs - e.g. Fig. 18 - demonstrating the 'citizen science' (e.g. Hand, 2010) potential of the site - the person concerned was not informed a priori of our project nor instructed to take any pictures, yet obtained geomorphologically-useful images. A challenge in interpreting the 'first contact' phase of migration where the slip face approaches the building is that scour may occur adjacent to the structure, forming an echo dune - we have accordingly not interpreted these field images as quantitative constraints on migration rate. However, in future, if the migration proceeds, both field and satellite images may show a trackable slip face relative to recognizable buildings. Within a couple of years, such migration through the set should be obvious.

In the long run, Mos Espa is still threatened: the large barchan (big enough to totally submerge the site) looms about 500 m to the east. In fact this dune is often driven over en route to the Mos Espa site, reportedly by ~80% of the visiting vehicles. Although the imminent threatening barchan and other effects may degrade the site on this timescale anyway, at the observed migration rate of ~6 m/yr, this large barchan will begin overrunning the site in about 80 years.

7. Discussion

The familiarity of the site in a popular movie may give it some appeal in teaching situations for geomorphic change and remote sensing. Consideration of a fictional planet can also stimulate discussion about similar features to those discussed here on other (real) worlds - for example, sand migration and dune movement has now been documented on Mars (e.g. Silvestro et al., 2010; Chojnacki

et al. 2011; Hansen et al., 2011; Bridges et al., 2012), and transient flooding of Titan's surface by (methane) rainfall has also been observed (Turtle et al., 2010).

An outstanding arena for further study is to assess the impact of moisture (and possibly gypsum reprecipitation as a result) on the migration rate. This, however, will require observations of rather higher time resolution than we have been able to derive from available data. The interaction of the migrating dune with the buildings will be interesting to observe in satellite imaging.

Given the importance of this site to the tourism industry of Tunisia, it may be that it is a candidate for mitigation measures, not being pursued at present. These could include erecting fences or walls, bulldozing the approaching dune (which would take considerable effort and would have to be repeated with each oncoming dune), or moving the site out of the path of the dunes. There would be some irony in such measures being adopted to protect a science fiction film set: it was exposure to aeolian transport concerns and countermeasures that inspired author Frank Herbert to write a science fiction novel set on a desert world ('Dune') that itself became an epic film.

8. Conclusions

We have documented, using commercial satellite imaging with ~1m resolution, barchan movement and its possible threat to a popular tourist site in Tunisia. The buildings here, used as a backdrop in the Star Wars movies, act as useful fiducial markers for measuring dune movement. A prominent barchan, 6.5m high, has moved at about 15m/yr over the last decade or so : a possible decline in movement may be due to meteorological variations or possibly the influence of the buildings. A nearby example of dune motion over a smaller set has already shown the potential for dune migration to damage these attractions.

293 Because visitors often post pictures on the internet that can be found without much difficulty (the
294 search term 'Mos Espa' is effective), often with visit descriptions, it may be possible to continue to
295 monitor the site through the on-the-ground observations of others. Such 'citizen science' field imaging
296 can be a useful complement to the commercial satellite imaging which has readily demonstrated the
297 movement up to this point.

298

299

300 Acknowledgements

301 The September 2009 visit was part of the Planetary Analogs field excursion led by GO and NG and
302 associated with the Sedimentology 2009 conference in Sardinia. The participation of RL was supported
303 by the NASA Cassini project. We thank Stephen Slater for making available his holiday pictures, one of
304 which is shown as Fig. 18 in this paper. Figs. 7 and 16 are courtesy of Google Earth and
305 Geoeye/Digiglobe. We thank the editor and three anonymous reviewers for comments which improved
306 the paper.

307 References

308 Andreotti , B., Claudin, P. and Douady, S. 2002. Selection of dune shapes and velocities Part 1: Dynamics
309 of sand, wind and barchans, The European Physical Journal B, 28, 321-339.

310 Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Methuen, London. 265 pp

311 Beadnell, H.J.L., 1910. The Sand-Dunes of the Libyan Desert. Their origin, form, and rate of movement,
312 considered in relation to the geological and meteorological conditions of the region. The Geographical
313 Journal, 35, 379–392

314 Blum, M., Kocurek, G., Deynoux, M., Swezey, C., Lancaster, N., Price, D. M., and Pion, J.-C., 1998.
315 Quaternary wadi, lacustrine, aeolian depositional cycles and sequences, Chott Rharsa basin, southern
316 Tunisia. In Quaternary Deserts and Climatic Change, in A. S. Alsharan, K. W. Glennie, G. L. Whittle, and C.
317 G. S. C. Kendall, (Eds.), pp. 539-552. Balkema, Rotterdam/Brookfield.

318 Bourke, M. C. and Goudie, A. 2009. Varieties of barchan form in the Namib Desert and on Mars, Aeolian
319 Research, 1, 45-54

320 Bowen, J. L. 2005. Anticipation: The Real Life Story of Star Wars: Episode 1- The Phantom Menace,
321 iUniverse, ISBN 0-595-34732-0

322 Bridges, N., Ayoub, F., Avouac, J.-P., Leprince, S. Lucas, A. and Mattson, S., 2012. Earth-Like Sand Fluxes
323 on Mars, Nature, 485, 339-342

324 Broad, W. 1999. Giant Leap for Space Industry, New York Times, 13 October 1999

325 Bryant, R. G. and Rainey, M. P., 2002. Investigation of flood inundation on playas within the Zone of
326 Chotts, using a time-series of AVHRR, Remote Sensing of Environment, 82, 360–375

Bullard, J. 1987. A Note on the use of the “Fryberger Method” or evaluating potential sand transport by wind, Journal of Sedimentary Research, 67, 499-501, 1997

Chojnacki, M., Burr, D. M., Moersch, J. E., and Michaels, T. I., 2011. Orbital observations of contemporary dune activity in Endeavor crater, Meridiani Planum, Mars. Journal of Geophysical Research, 116, E00F19, doi:10.1029/2010JE003675

Fryberger, S.G., 1979. Dune forms and wind regime. In: McKee,E.D. (Ed.), A Study of Global Sand Seas. U.S. Government Printing Office, Washington, pp. 137– 160

Greeley, R. and J. D. Iversen, 1984. Wind as a geological process on Earth, Mars, Venus and Titan, Cambridge University Press

Hand, E. 2010. Citizen Science: People power, Nature, 466, 685-687

Hansen, C. J., M. Bourke, M., Bridges, N. T., Byrrne, S., Colon, C., Diniega, S., Dundas, C.,Herkenhoff, K., McEwen, A., Mellon, M., Poryaninia, A. and Thomas, N. 2011. Seasonal Erosion and Restoration of Mars’ Northern Polar Dunes, Science, 331, 575-578

Hersen, P., Andersen, K.H., Elbelrhiti, H., Andreotti, B., Claudin, P., Douady, S., 2004. Corridors of barchan dunes: stability and size selection. Physical Review E –Statistical, Nonlinear, and Soft Matter Physics 69, 113041–1130412.

Khatteli, H. and Belhaj, N., 1994. La dynamique des dunes dans le sud-ouest tunisien. Revue Secheresse, 5, 245-249.

347 Lancaster, N. 1995. Geomorphology of Desert Dunes, Routeledge,London

348 Long, J.T., Sharp, R.P., 1964. Barchan-dune movement in Imperial Valley, CA. Geological Society of
349 America Bulletin 75, 149–156.

350 Lucas, G. 1999. Star Wars Episode 1: The Phantom Menace, Lucasfilm, Marin County, CA.

351 Silvestro, S., Fenton, L.K., Vaz, D. A., Bridges, N. T., and Ori, G. G., 2010. Ripple migration and dune
352 dynamics on Mars : Evidence for dynamic wind processes, Geophysical Research Letters, 37, L20203,
353 doi:10.1029/2010GL044743

354 Swezey, C., Lancaster, N., Kocurek, G., Deynoux, M., Blum, M., Price, D., and Pion, J.-C., 1999. Response
355 of aeolian systems to Holocene climatic and hydrologic changes on the northern margin of the Sahara: a
356 high resolution record from the Chott Rharsa basin, Tunisia. The Holocene, 9, 141-148.

357 Swezey, C., 1997. Structural controls on Quaternary depocentres within the Chotts Trough region of
358 southern Tunisia. Journal of African Earth Sciences, 22, 335-347.

359 Turtle, E., Perry, J. E., Hayes, A. G., Lorenz, R. D., Barnes, J. W., McEwen, A. S., West, R. A., Del Genio, A.
360 D., Barbara, J. M., Lunine, J. I., Schaller, E. L., Ray, T. L., Lopes, R. M. C., Stofan, E. R., 2011. Rapid and
361 Extensive surface changes near Titan's equator: Evidence of April showers, Science, 331, 1414-1417

362 Webber, R. A. and O'Connell, K., 2011. Alternative Futures: United States Commercial Satellite Imagery
363 in 2020, Innovative Analytics and Training, LLC, Washington DC, 2012.

Figure Captions

Figure 1 : Location Map. The site is slightly northwest of the town of Tozeur, between the sometimes-flooded playas Chott el Jerid and Chott el Gharsa, which are readily visible from space. The background is a 1 km NASA MODIS image.

Figure 2. Regional context. A) Landsat 5 TM band 7 image (~2.1 micron wavelength, which shows dune sands as dark on brighter background, in contrast to the blue wavelength shown in Fig. 8) acquired in 1984. Note that the Chott surfaces continually change due to wetting and drying. In other data, the expansion of Tozeur and in particular its agriculture, are seen - prominent date plantations can now be found at the location marked (x). The study area is denoted by the dark square - displayed in Fig. 3).

Figure 3. Close-up of the dunefield from 1984: the overall barchan and barchanoid morphology is evident.

Figure 4. Commercial satellite image (Quickbird) acquired in 2004, showing the Mos Espa film set (A), the threatening barchan shown in Figs. 6 and 7 (B). Vehicle tracks (including circular segments) are evident on the interdune pan, as well as over the dunes themselves. Also indicated are the small Repro Haddada set (C) seen in Figs. 15 and 16 and several small yardangs (D). The 'large' barchan and a smaller 'north' barchan discussed in the text are labelled E and F respectively.

Figure 5 . Sketch map of the set identifying buildings of interest to Star Wars fans, with fiducial buildings A,B and C labelled. Tourist vehicles usually park near the shade pavilion and bathrooms, not part of the actual film set. The threatening barchan is visible at right.

Figure 6. Photos from site visit on September 26, 2009, one day after Fig. 7c. (a) A long view looking SSE showing barchan proximity to buildings A and B. Persons ~1.6 m tall atop the dune (~35 pixels) act as a

scale bar to estimate the dune height (135 pixels) as ~6.5 m high (b) A closer view with authors (l-r) JR, RL and JB and building B to the right. Tall structures are 'moisture evaporators' . The dark areas on the ground are seen to be wet from unusually heavy rains that summer. Many footprints are evident on the slip face of the barchan, also dark in color from the moisture and displaying the cohesive nature of the dune particles.

Figure 7. A sequence of commercial satellite images (GeoEye) visualized with the Google Earth historical imaging tool. The images were acquired on a) 11 July 2004, b) 21 January 2008 and c) 25 September 2009. Image (c) was acquired the day before our field visit - see Fig. 6b, where the dark band adjacent to the circular building is seen to be a temporarily wet area. Image (b) was acquired with a lower sun angle, and has more prominent shadows. In this image vehicle tracks are very evident on the barchan.

Figure 8. NASA Earth Observing (EO-1) Advanced Land Imager (ALI) scene about 12x10km across, EO1A1920372002122110KZ_SGS_01, acquired on day 122 of 2002. This imager acquires a superset of Landsat bands with a resolution of 10 m : shown is Band 1 at ~0.4 microns which shows the sand as bright (in contrast to Figs. 2-3). The east-west sand streaks are very evident in the lower half of the image. Although the image is not of high enough resolution to pick out individual buildings, it is possible to assess the approximate distance to the edge of the set as a whole and thus our fiducial - 14 pixels or 140 m - and extends the timebase beyond the commercial imaging.

Figure 9. Migration rate. Filled circles correspond to distance measured in Google Earth images due East from building B on sketch map to the slip face of the dune, while diamonds are measured from building C. The large open circle denotes the lower-resolution (+/- 1 pixel = 10 m) measurement from the 2002 EO-1/ALI image. Symbol size roughly indicates uncertainty in the measurement. The overall line fit to the circles is shown with a slope of 16 m/yr: the slopes for each the two most recent periods (2004.52-

2008.06, and 2008.06-2009.73) are 16.6 m/yr and 6 m/yr, and a parabolic fit (dashed line) to the distances, indicating a declining migration rate, has a significantly better fit to the data (R^2=0.999).

Figure 10. Migration of the three barchans described in the text. The large barchan (triangles, positions are offset by an arbitary constant to improve the aesthetics of the plot) moves at about half the speed of the threatening barchan seen in Fig. 9. The north barchan (squares) moves only slightly more slowly than the threatening barchan. Note that the large and north barchans seem to follow a quite linear position vs. time trend, without the upturn (i.e. a decline in movement rate) indicated for the threatening barchan.

Figure 11. Barchan migration rates (from a compilation by Andreotti et al., 2002): numbers after the dataset authors indicate the years over which migration was observed. The large circle with error bars is the measurement in this paper of the threatening barchan; the square is the north barchan and the triangle the large barchan. The curves are a simple reciprocal relationship, with sand fluxes of 40 and 100 m^3/yr/m.

Figure 12. Wind rose for Tozeur for the year 2011, computed according to the method of Fryberger (1979). The line segments indicate the transport-weighted fraction of winds from the direction shown, referred to as the drift potentials for each direction. The scalar sum of these is total drift potential (DP) indicating the overall sand mobility. The vector sum is the Resultant Drift Potential (RDP) and indicates (arrow) the expected migration of dunes over the long term. The ratio RDP/DP is a metric which determines dune morphology (e.g. Lancaster, 1995).

Figure 13. Histograms of daily mean wind and maximum daily gust recorded at Tozeur airport over a nearly 4-year period. It is seen that the saltation threshold of ~6 m/s (=11.6 knots) is frequently exceeded.

Figure 14. Precipitation record from the Tozeur airport since the mid-1970s. The 30-year period's second-highest rainfall occurred in 2009 when it appears dune motion declined somewhat.

Figure 15. Remains of the Repro Haddada set (point C in Fig. 4), also used in the filming of Star Wars Episode 1. The roof collapsed under the weight of sand when the building was overrun circa 2005 and serves as an indication of what damage may be incurred by barchan passage over the Mos Espa site.

Figure 16. Commercial satellite imaging via Google Earth of the Repro Haddada set ('C' in Fig. 4). In 2004 the structure was barely visible, being under a barchan dune which led to the damage shown in Fig. 15. The structure has emerged by 2009, although the sun elevation was evidently higher when this image was acquired, making the dune slopes and the yardangs less distinct.

Figure 17. Field photos from September 2009 (a) and May 2012 (b) from the barchans looking southwest to the shade pavilion and building 'C'. Several changes are apparent, despite the slightly different viewing geometry. First, the whole area appears more sandy in 2012, with the pan around the set covered with sand. Second, the space between the barchan and building 'C' has all but disappeared, suggesting the building is about to be overrun.

Figure 18. A photo (courtesy of S. Slater) from the threat barchan crest looking northwest towards buildings A and B. This photo (acquired in December 2012) shows that the edge of the barchan is essentially in contact with building B (compare with images in Fig. 6). This photo demonstrates the utility of tourist photos in monitoring the site.

Figure 1

Click here to download high resolution image

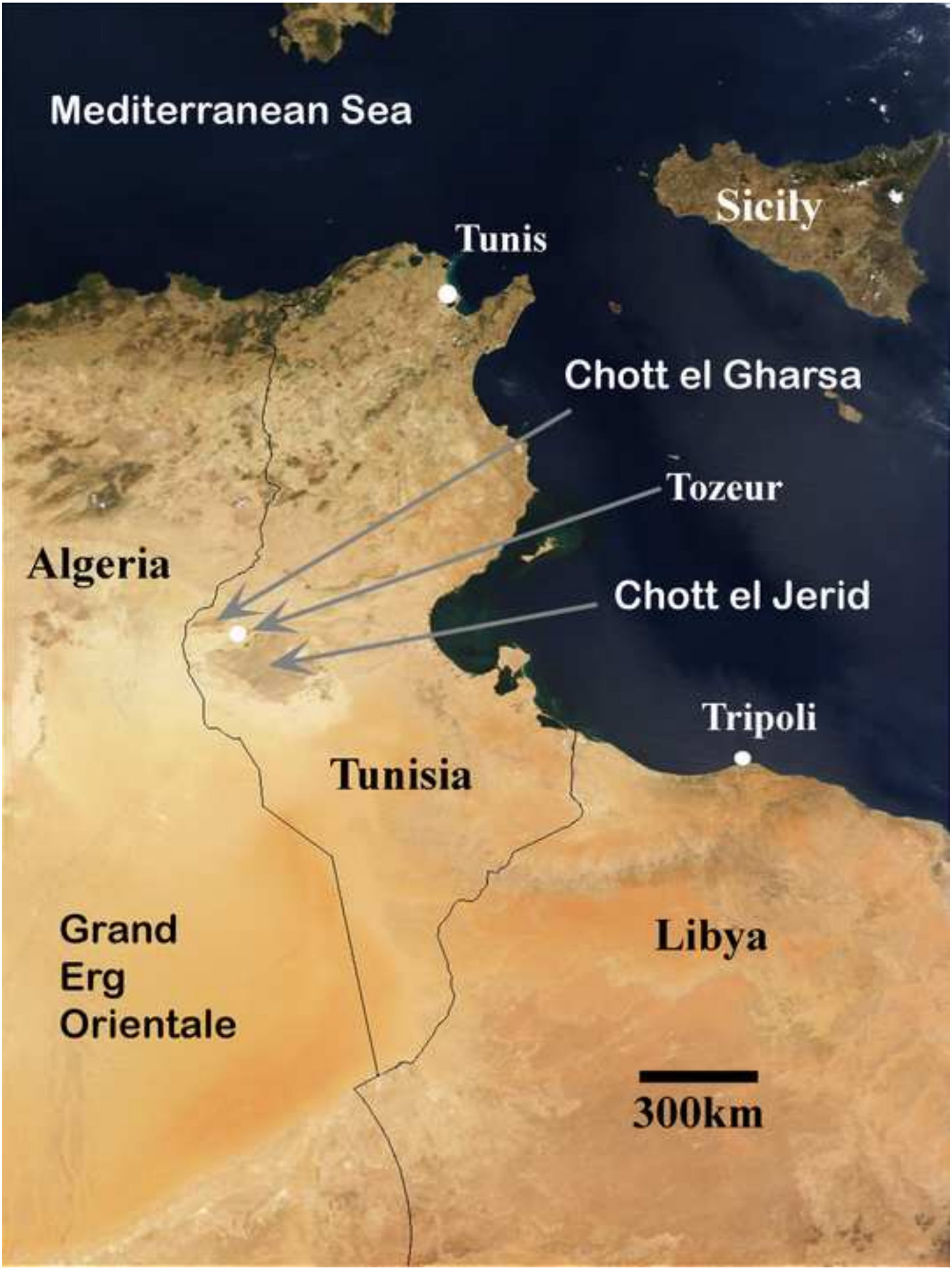

Figure 6

Click here to download high resolution image

Figure 7

Click here to download high resolution image

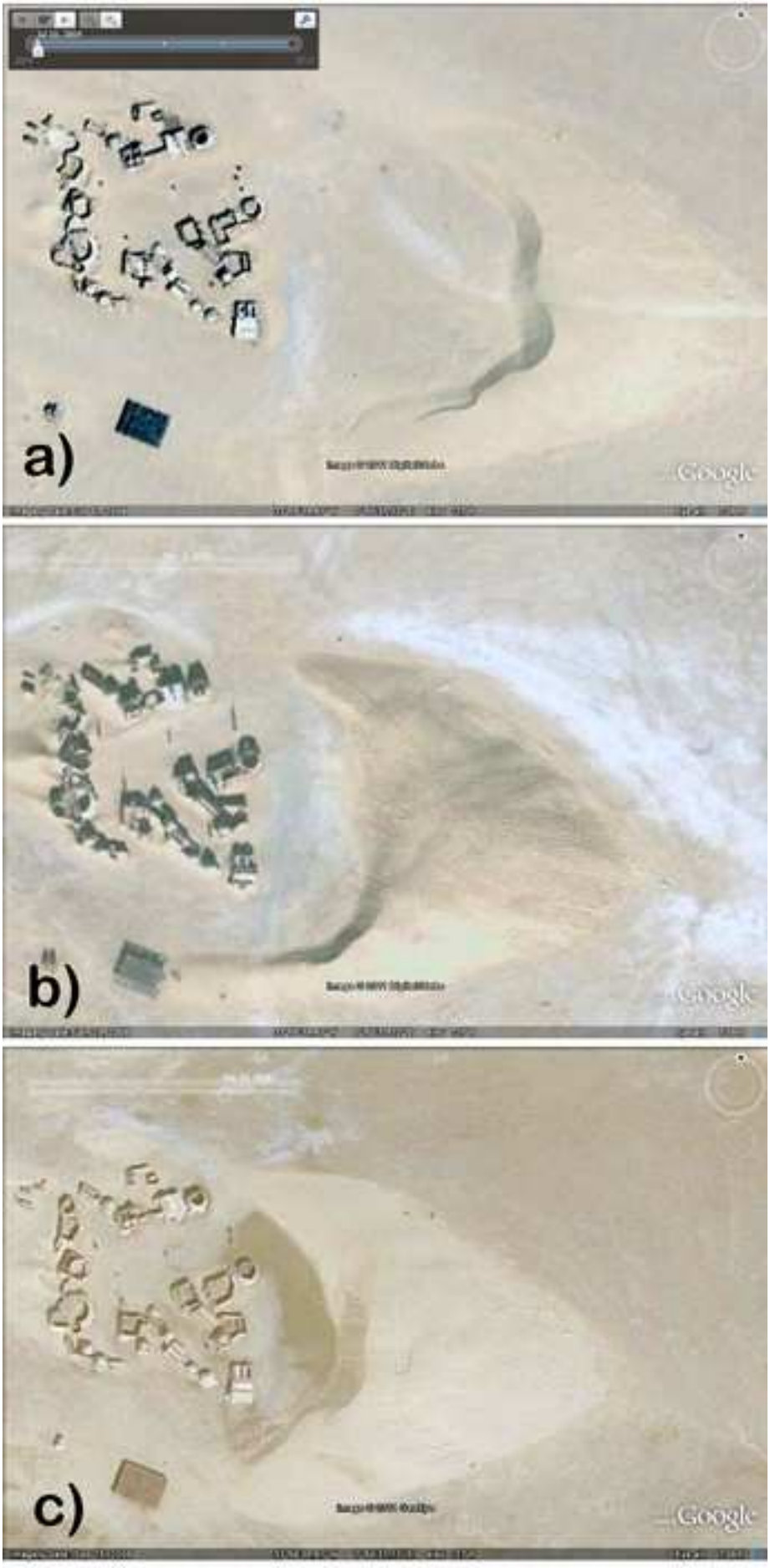

Figure 8

Click here to download high resolution image

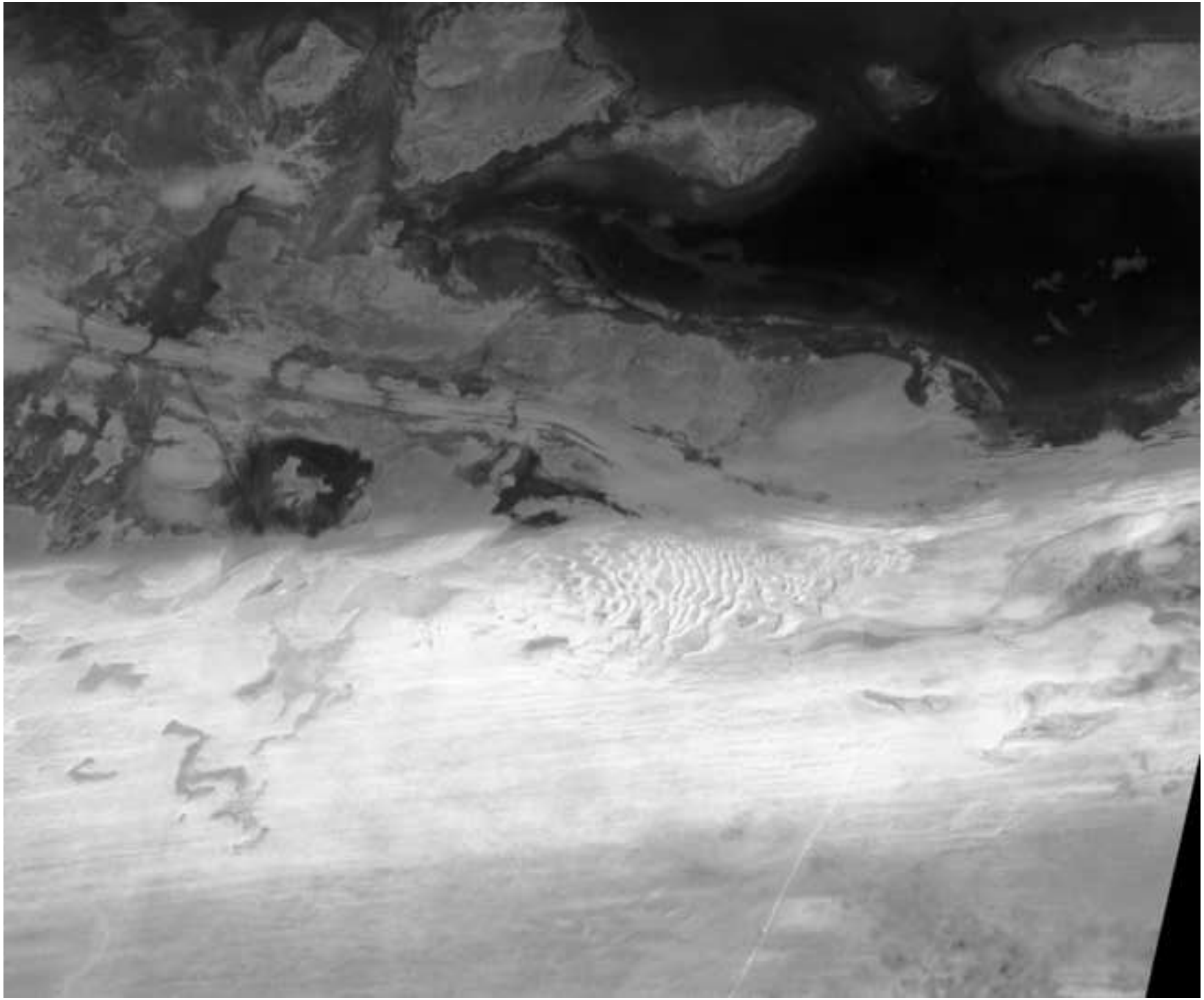

Figure 3

Click here to download high resolution image

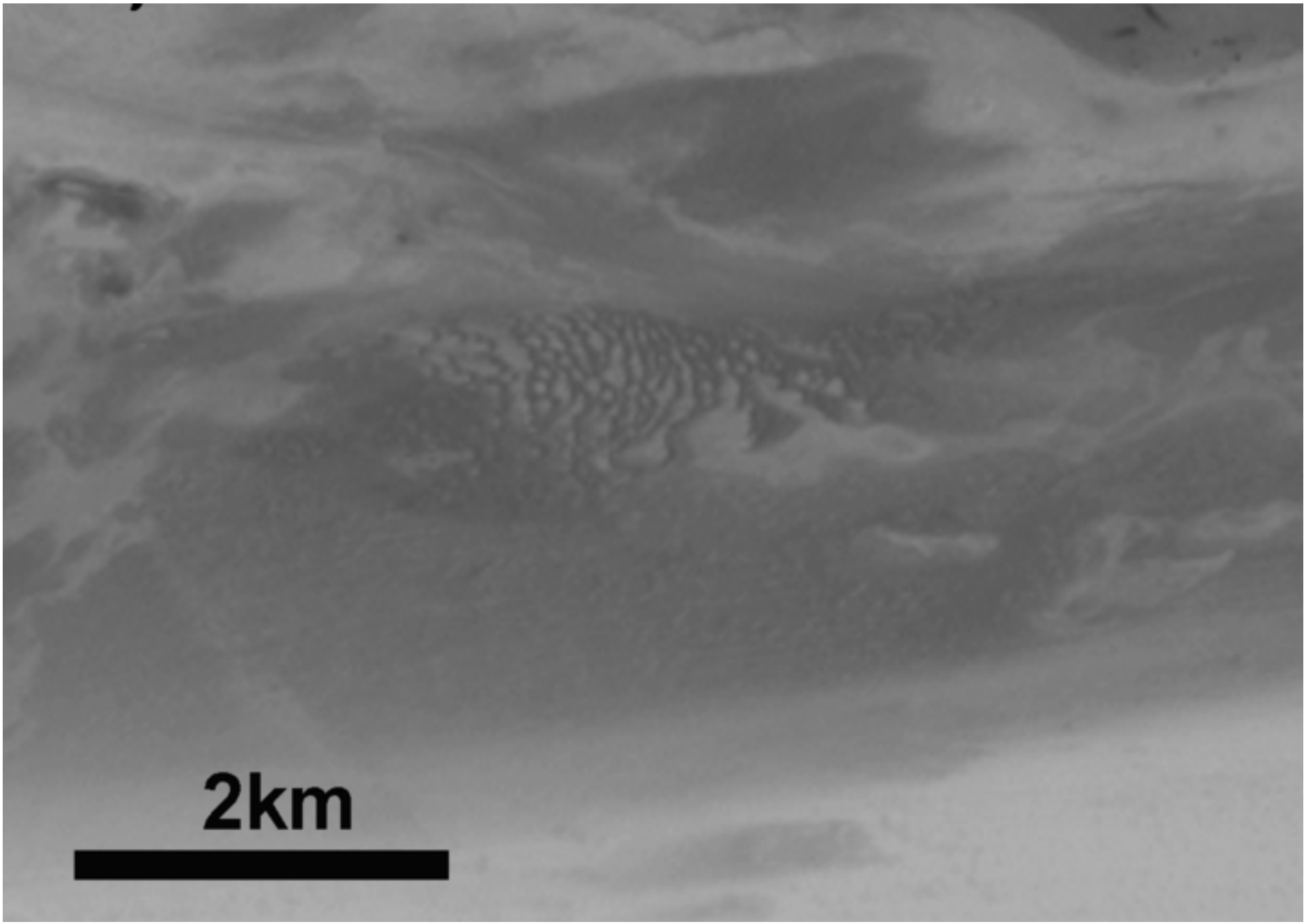

Figure 4

Click here to download high resolution image

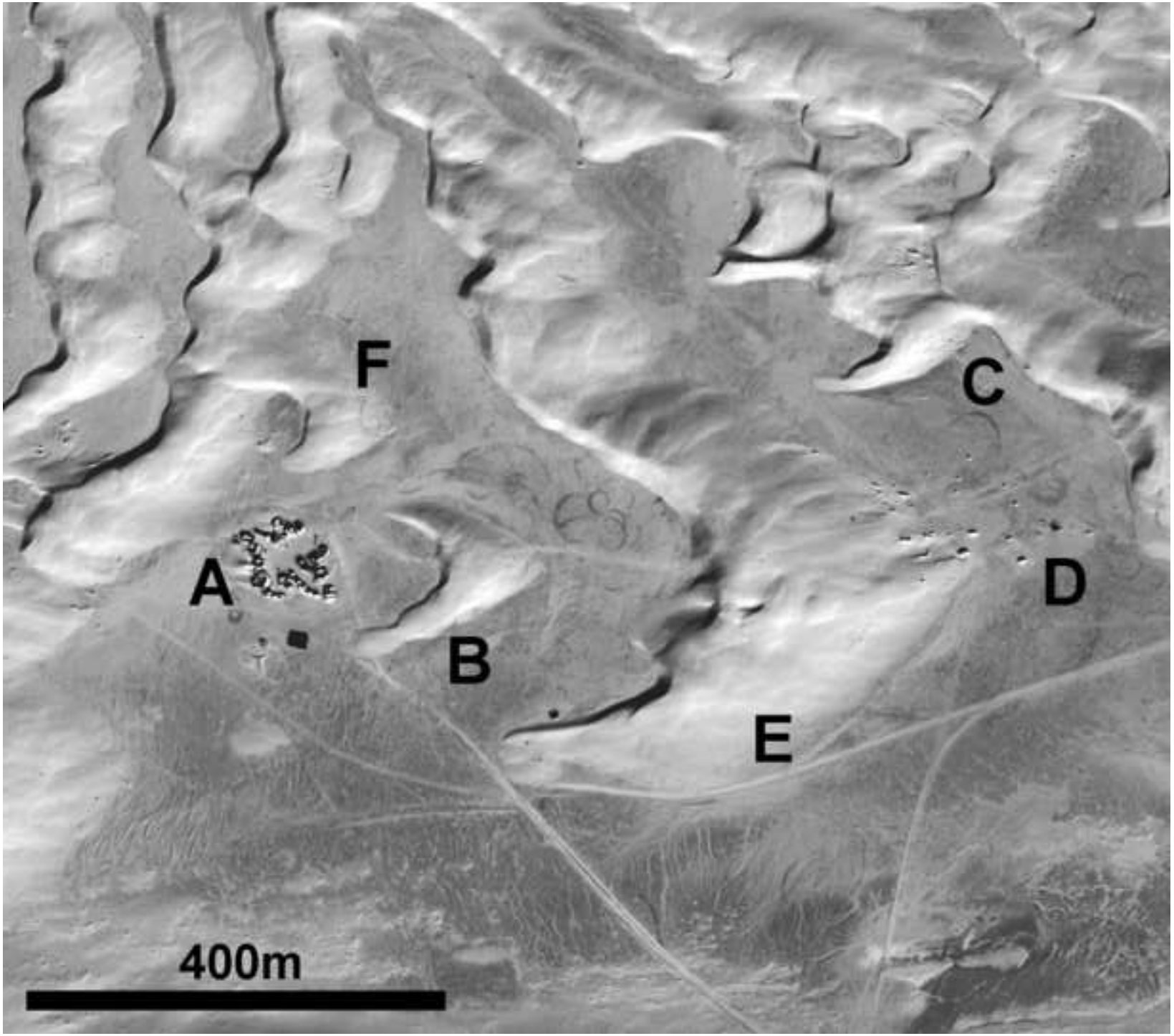

Figure 5

Click here to download high resolution image

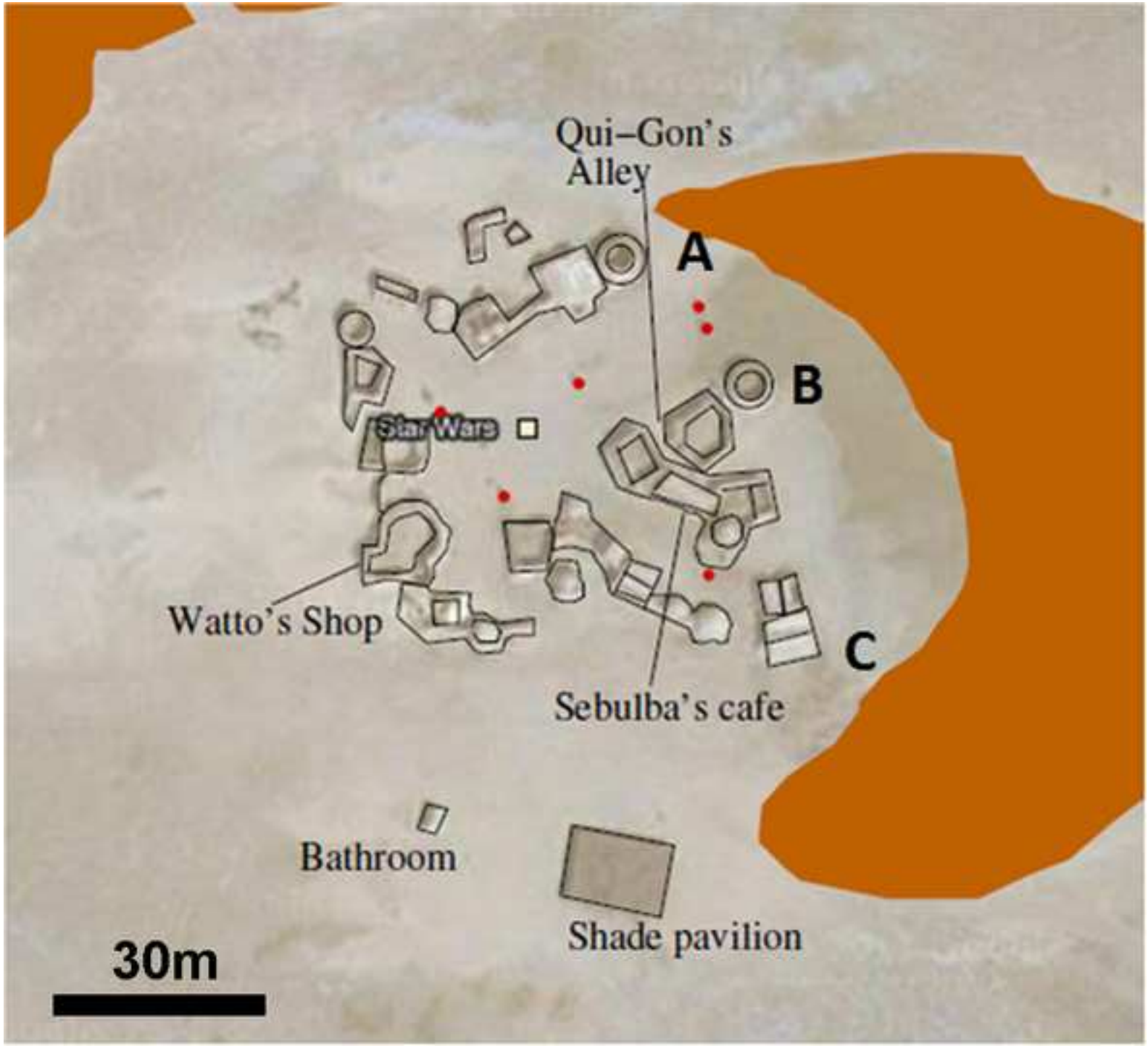

Figure 10

Click here to download high resolution image

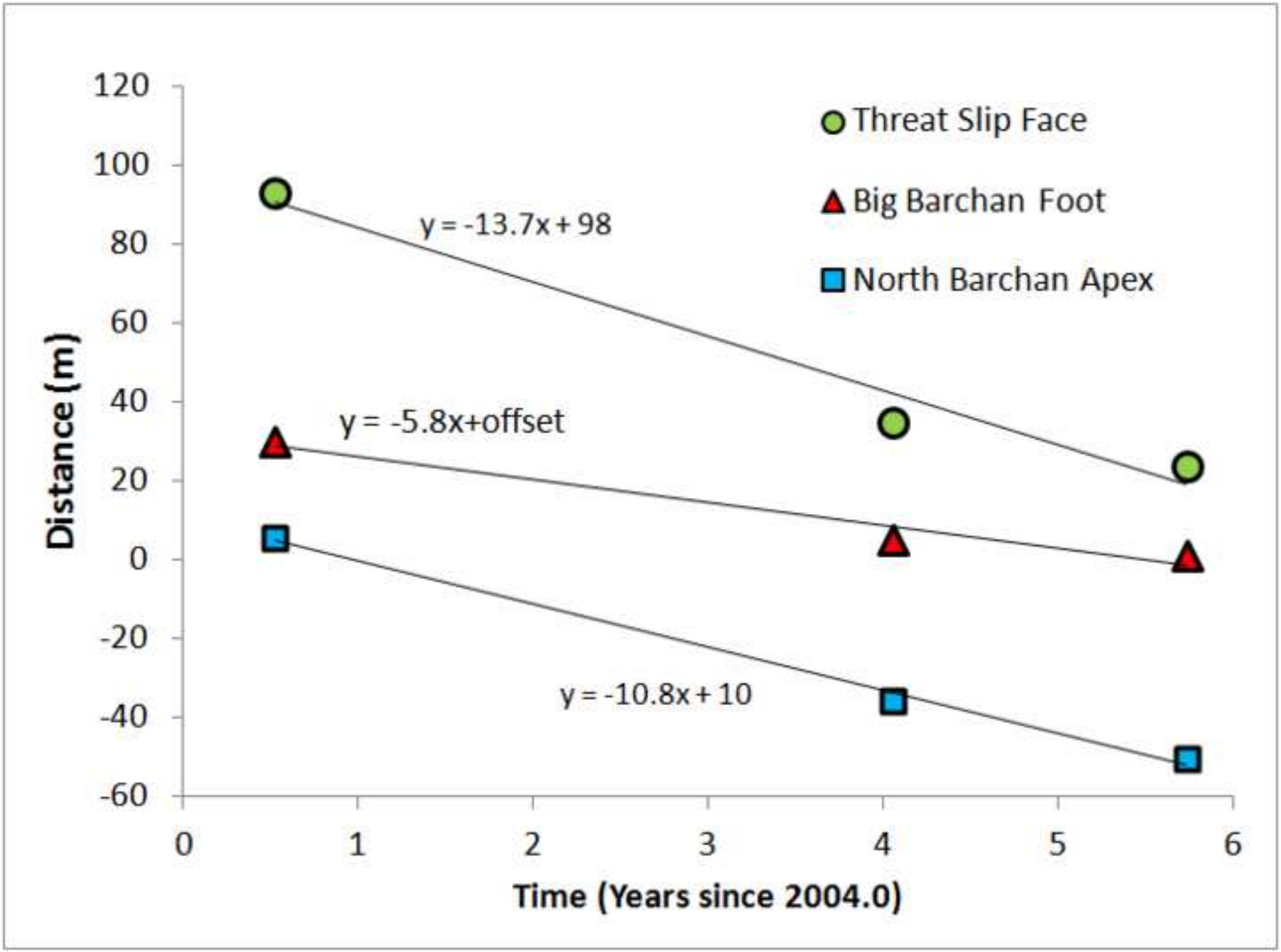

Figure 11

Click here to download high resolution image

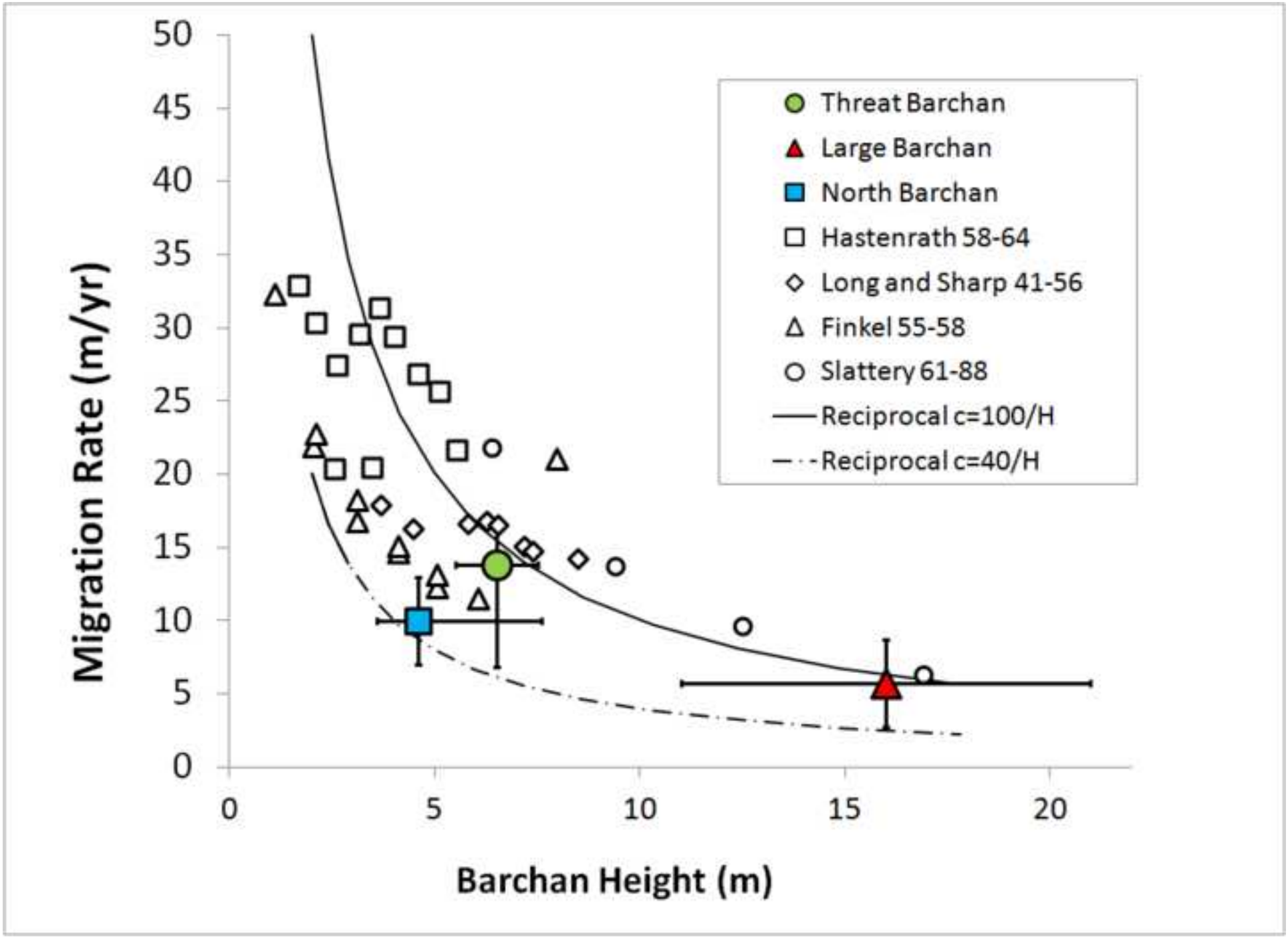

Figure 12

Click here to download high resolution image

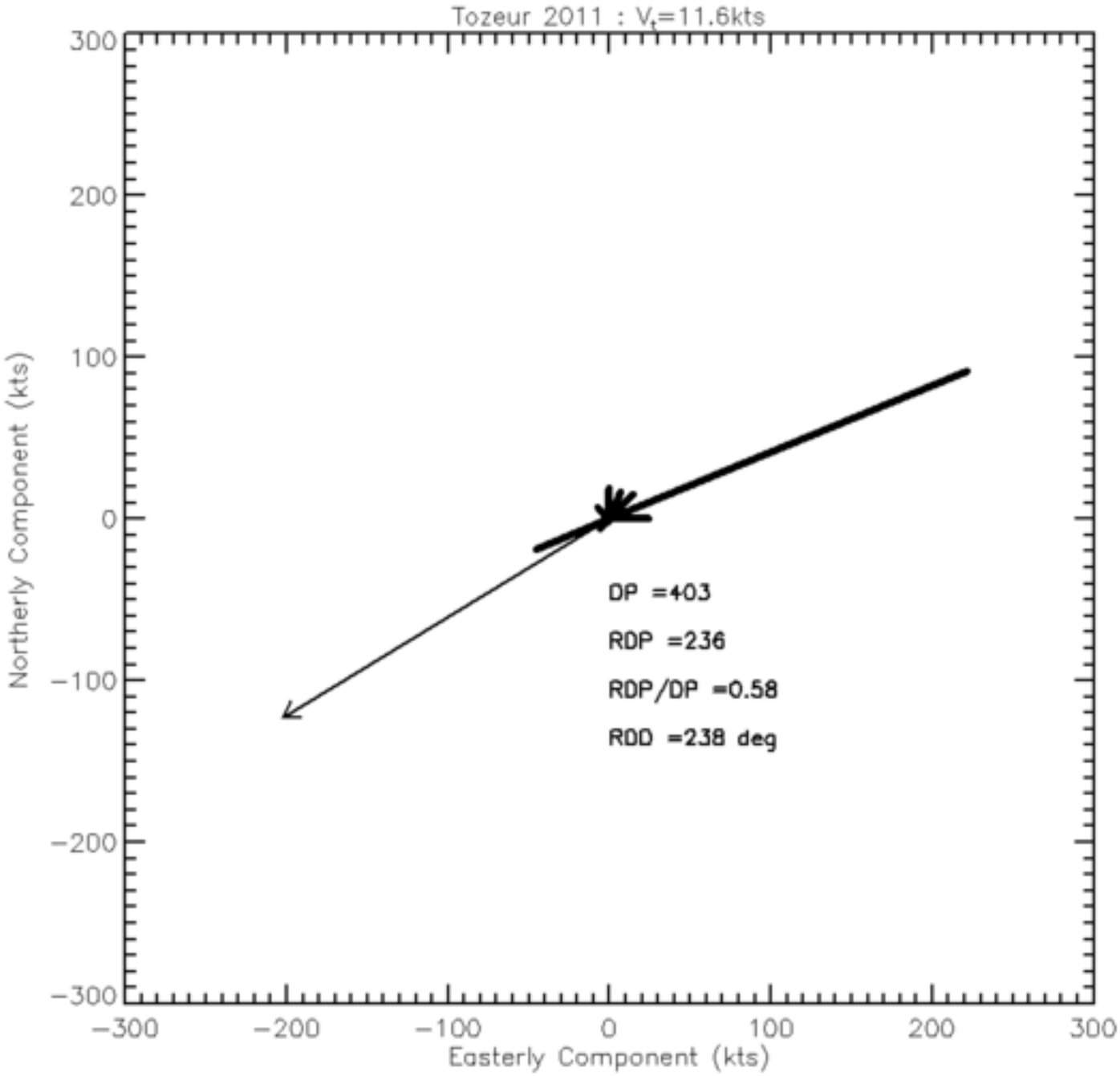

Figure 14

Click here to download high resolution image

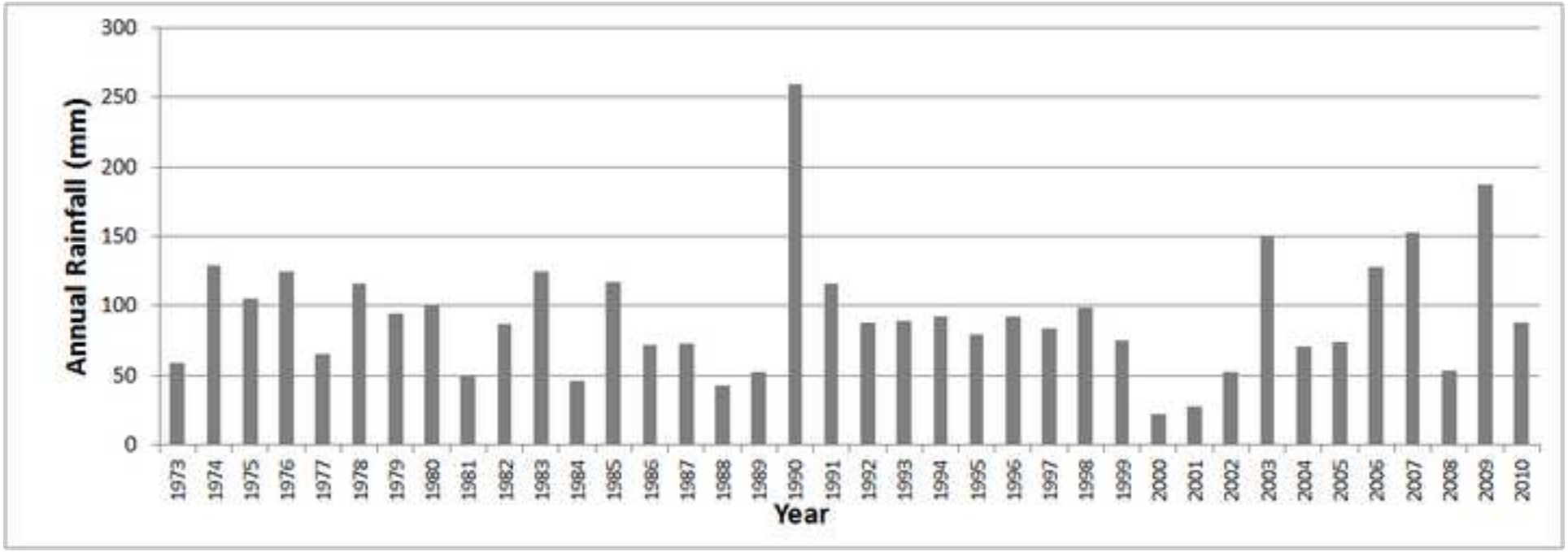

Figure 15

Click here to download high resolution image

Figure 16

Click here to download high resolution image

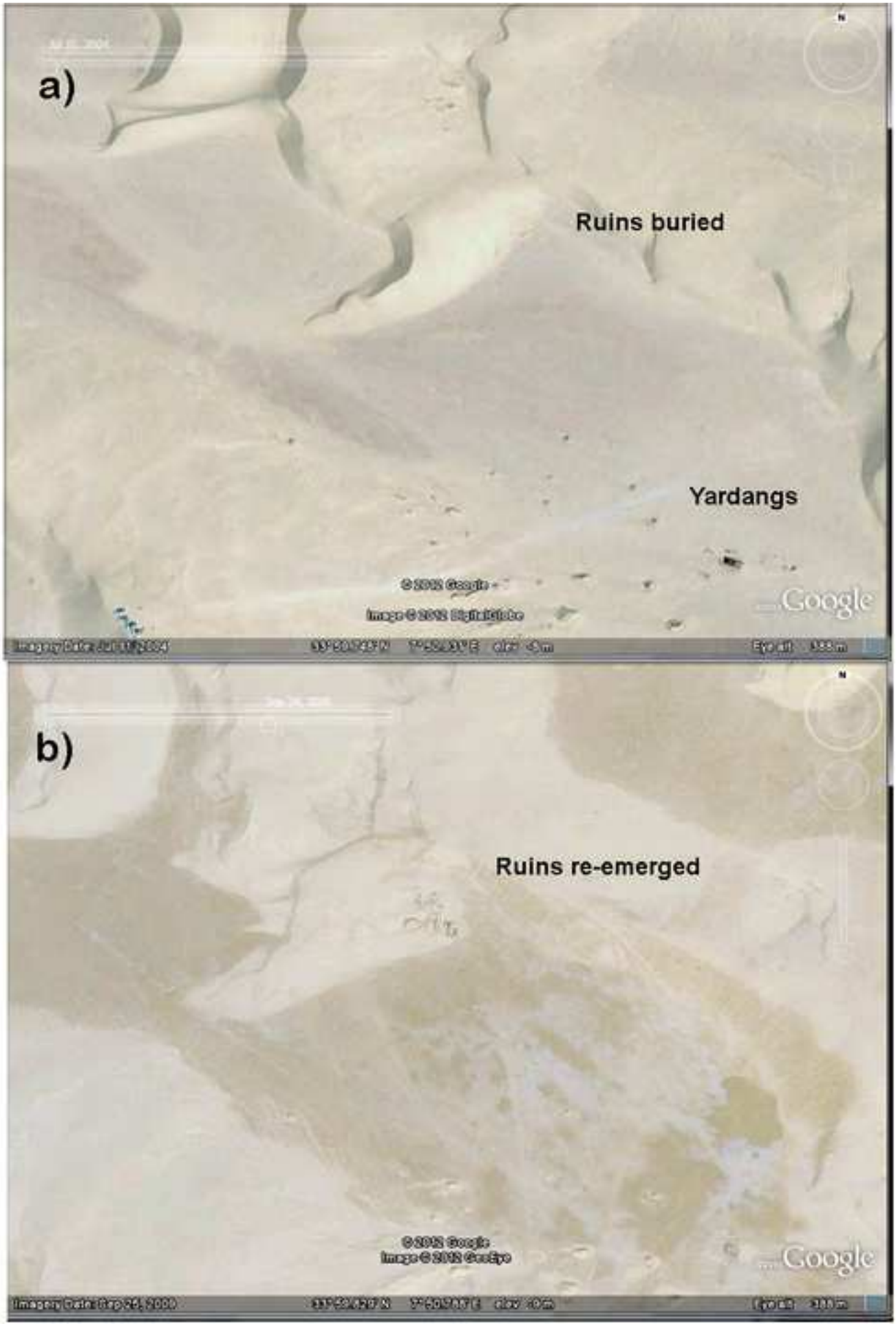

Figure 17

Click here to download high resolution image

Figure 18
Click here to download high resolution image

Figure 2
Click here to download high resolution image

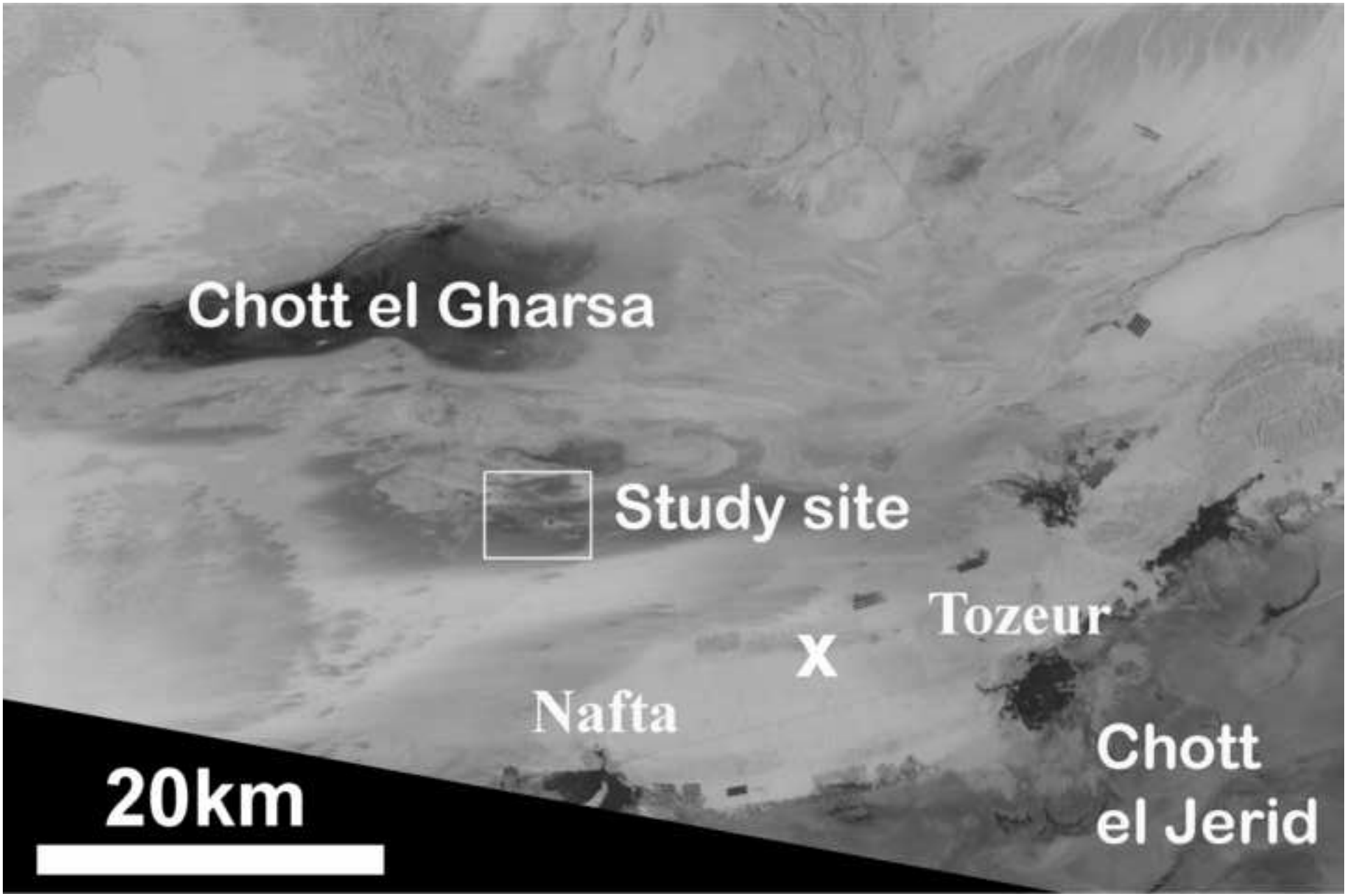

Figure 9

Click here to download high resolution image

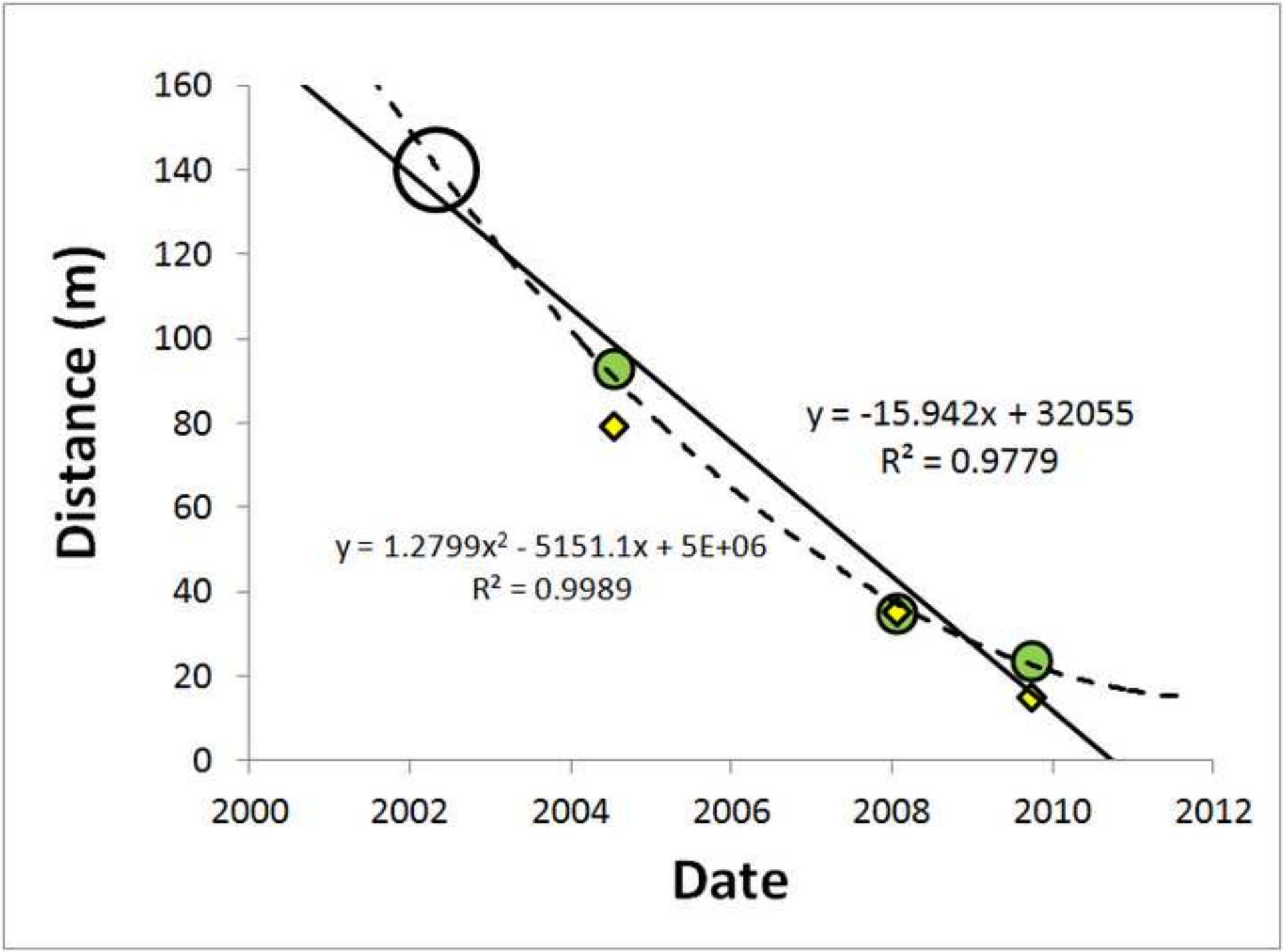

Figure 13

Click here to download high resolution image