Palaeontologia Electronica
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REMOTE SENSING APPLIED TO PALEONTOLOGY: EXPLORATION OF UPPER CRETACEOUS SEDIMENTS IN KAZAKHSTAN FOR POTENTIAL FOSSIL SITES

Dmitry V. Malakhov, Gareth J. Dyke, and Christopher King

ABSTRACT

Here we show that low-cost analysis of satellite image data (derived from Landsat ETM+) can be used efficiently for the 'remote prospecting' of a large field area, in this test case in Kazakhstan. By developing a spectral library to characterize the sedimentary profiles in our field area, we outline a simple method that can be used to quickly identify the locations of potentially fossiliferous strata that can subsequently be prospected first-hand by paleontologists on the ground. We have successfully tested this remote approach to search for fossils in the Lower Syrdarya Uplift in southern Kazakhstan – an area that encompasses more than 17,000 square kilometers. As image capture and analysis technologies develop, remote prospecting (sensing) applications are likely to become more and more prevalent in paleontology, especially in the development of remote field areas.

Key Words: Spectral analysis; GIS; Remote Sensing; sedimentology; Kazakhstan; dinosaurs; Syrdarya Uplift

Dmitry V. Malakhov. Laboratory of GISs Geological Institute, Almaty, Kazakhstan. d_malakhov_73@mail.ru
Gareth J. Dyke. School of Biology and Environmental Science, University College Dublin, Belfield Dublin 4, Ireland. gareth.dyke@ucd.ie
Christopher King. C/O University of Greenwich, United Kingdom. chrking@globalnet.co.uk

INTRODUCTION

Satellite images acquired from a range of different kinds of sensors are now commonly used as sources of data across the geological sciences. Indeed, procedures for the identification and remote analysis of rocks, minerals and tectonic structures have been developed in recent years based on a number of algorithms and approaches (e.g., Akhir and Abdullah 1997; Poursaleh 2007; Smith et al. 2007; Tangestani 2007) and have even included methods for recognizing potentially fossiliferous strata and predicting the location of new paleontological sites (Oheim 2007). If applicable, such methods could be hugely useful for paleonto-

PE Article Number: 12.2.3T

Submission: 28 May 2008. Acceptance: 23 April 2009

Malakhov, Dmitry V., Dyke, Gareth, J., and King, Christopher, 2009. Remote Sensing Applied to Paleontology: Exploration of Upper Cretaceous Sediments in Kazakhstan for Potential Fossil Sites. *Palaeontologia Electronica* Vol. 12, Issue 2; 3T: 10p;
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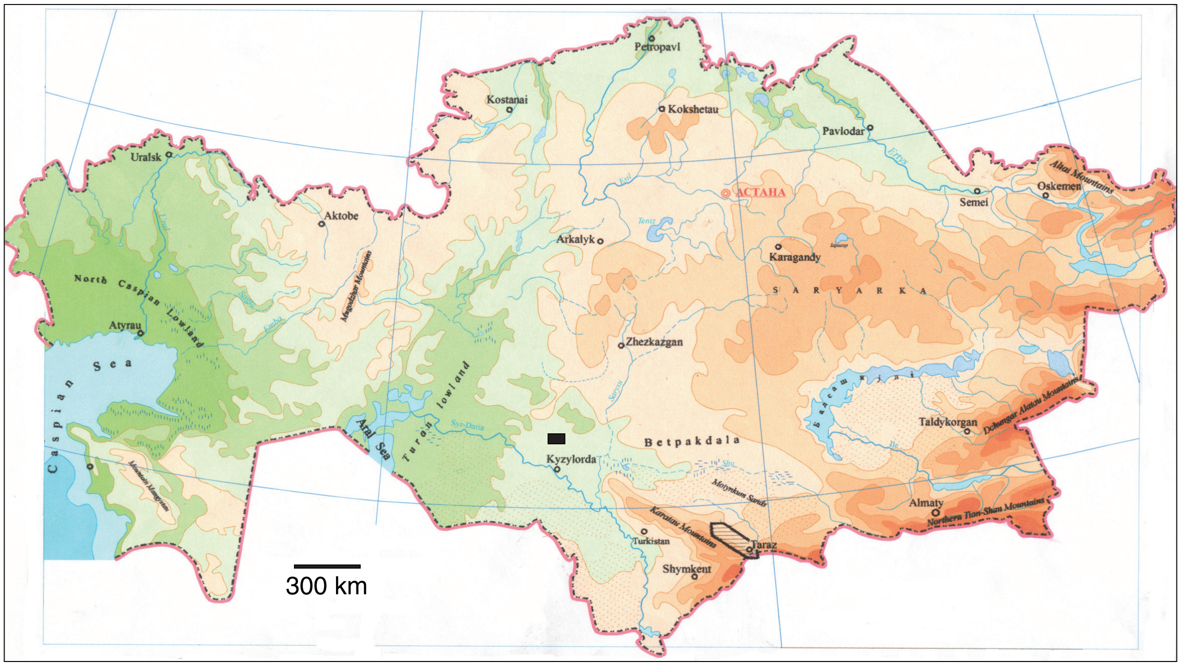

FIGURE 1. Sketch map of Kazakhstan. Field area is denoted by filled black box.

logical field studies where hundreds of hours are typically spent 'prospecting' land areas searching for fossil-bearing horizons. However, remote approaches to image data analysis have yet to be widely applied in paleontology.

In this short paper we demonstrate that even relatively low resolution satellite image data (in this case derived from Landsat ETM+) can be efficiently and beneficially used for low-cost evaluation of geological terrain for paleontological field exploration. Remote techniques work in spite of the fact that differences between sedimentary lithologies often cannot be discerned from satellite image data alone. The study area for our preliminary analysis is the extensive territory of the Lower Syrdarya Uplift in southern Kazakhstan, an exposed area of more than 17,000 square kilometers increasingly well-known for the preservation of a rich Late Cretaceous fossil vertebrate fauna (e.g., Shilin and Suslov 1982; Nessov 1995; Kordikova et al. 2001; Malakhov and Dyke 2003; Dyke and Malakhov 2004; Averianov 2007) (Figure 1). On successive field expeditions (2006, 2007) we have analyzed and applied Landsat ETM + image data to guide our prospecting efforts on the ground, saving time and money. In addition to spectral analysis, we have also developed a detailed map of this region based on Landsat image analysis. This approach has made our field logistics very effective, and in particular, allowed us to locate two fresh-water artesian wells in good positions relative to our basic camp for future long-term field work.

RATIONALE, BACKGROUND AND ANALYSIS

Terminology. Landsat ETM+- Landsat Enhanced Thematic Mapper: sensor that provides imagery at 28.5 meter spatial resolution (14.5 meters after image sharpening in three visual [blue, green and red] and four infrared bands). RSI ENVI: software developed for processing satellite images. ISODATA**:** algorithm that classifies pixels evenly distributed in the dataset and combines them into separate classes based on statistically significant minimum distances. Spectral Angle Mapper - SAM: physical spectral classification that uses the n-dimensional angle (one pixel characteristic) to match pixels to their corresponding reference spectra. This algorithm determines the spectral similarity between two spectra by calculating the angle between them, treating them as vectors in a space with dimensionality equal to the number of bands. Supervised classification: a set of methods for image classification that require a "region of interest" (ROI), or spectral library, created by the researcher. All pixels within the image are considered along with those included in the ROI. Unsupervised classification: does not refer to any predefined criteria to make a statistical consideration of all pixels and to distribute them into classes.

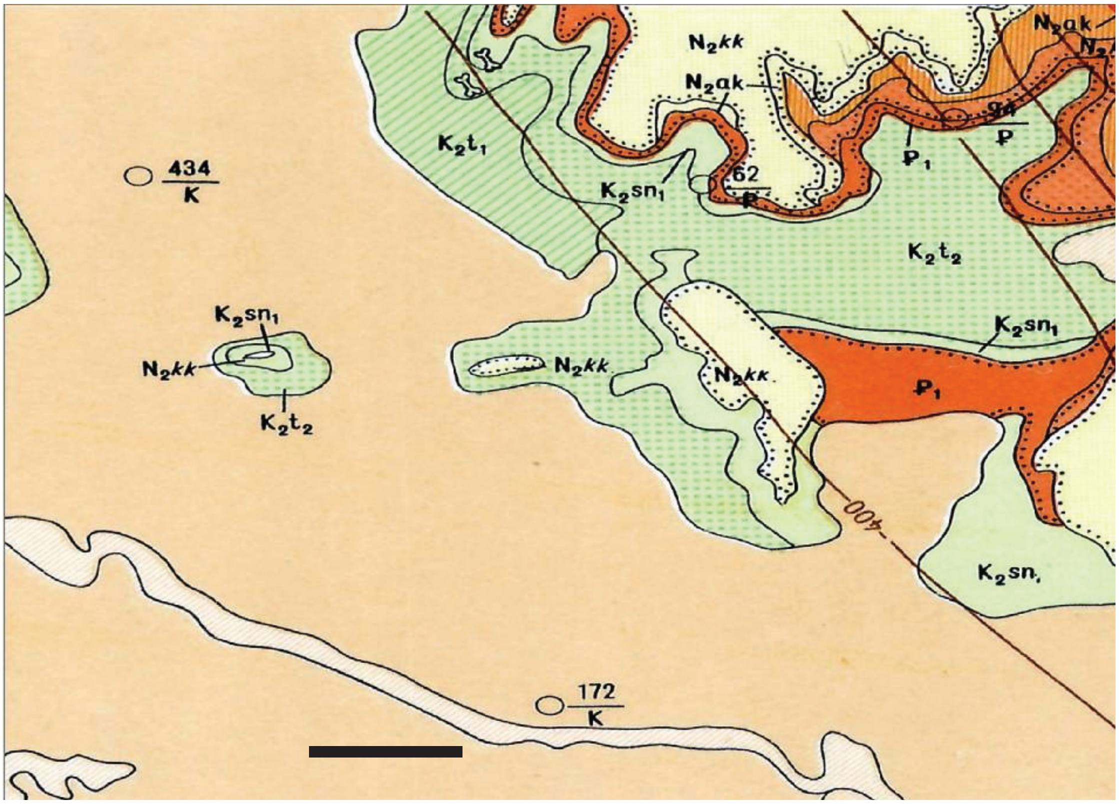

FIGURE 2. Outline geological map of one region of the Syrdarya area (Dyke and Malakhov 2004). This is the region within which we have focussed our attention searching for fossils in the field, the same area as the other maps presented in this paper (Figures 3-9). Scale bar is 20 km.

Study rationale. In contrast to the recent study of Oheim (2007), who analyzed a series of environmental factors considered useful for the prediction of likely fossil-bearing sites using GIS software (ArcInfo 9.1), we have focused our attention on the characterization of the spectral parameters of already known fossil sites identified by our earlier field work in the Syrdarya area (Dyke and Malakhov 2004). Once characterized, spectral parameters can then be re-applied to other regions to predict locations of fossiliferous sites. There are a number of logistical reasons for this: (1) Our study area is remote (the closest village is 90 km away; Figure 1) and not easily accessible; and (2) Previously collected fossil remains have been found at high abundances but concentrated in small areas scattered across the field area (approximately 17,000 square kilometers). These factors highlight the need for precise determination of likely sites rather than indeterminate prospecting effort (at high cost). For large land areas in particular, the development of spectral libraries as an aid to identifying likely fossiliferous strata seems a reasonable approach, albeit not as precise as the analysis of local environmental variables using GIS (Oheim 2007). Spectral analysis, however, can produce sets of ROIs for prospecting paleontologists especially in distant and poorly known land areas.

Thus for us to repeat the analysis of Oheim (2007) in the Syrdarya field area would require a complete database of environmental conditions, and these kinds of data simply do not exist for this region of Kazakhstan (which has very poorly developed local infrastructure). In addition, we do not believe that environmental factors significantly affect the presence and/or preservation of fossils across the Syrdarya area: for more than 17,000 square kilometers across this region of Kazakhstan, the terrain is very smooth and uniform (without rivers or significant water-bodies) and is covered with poor xerophilic vegetation that does not change significantly throughout the summer and thus does not affect the spectral reflectance of the area.

Paleontological and geological background. Since 2002 we have spent a series of field seasons in the Syrdarya field area and so have 'ground-truthed' fossil collection and distribution data (e.g., Dyke and Malakhov 2004; Averianov 2007). These data have enaled us to test the predictions of remote spectral analyses via exact GPS coordinates from earlier fossil finds. We have also used geologic maps (1:500 000) (e.g., Figure 2) to validate the results of image classification. Note that original geological maps for this area of Central Asia are of little value for planning field work because they indicate that Upper Cretaceous sediments are developed across a wide area: this is not the case.

The geological and paleontological context of the Syrdarya area has been reported in earlier papers (Kordikova et al. 2001; Dyke and Malakhov 2004; Averianov 2007) (Figure 3). In general, the fossiliferous strata across the area are color-mottled alluvial clays (Figure 4) of the lower Bostobe Formation [Bostobinskaya Svita] interbedded with thin overbank siltstones and channel-filling fluvial sands and sandstones (Figure 3). The fossil fauna of the Bostobe Formation comprises many common vertebrate groups (Dyke and Malakhov 2004) and includes abundant dinosaur bones, crocodile teeth and turtle carapaces as well as other taxa represented in smaller quantities (i.e., sharks, lizards, pterosaurs and urodelans as well as bivalves and fragments of petrified wood). Faunal composition also varies through the Bostobe Formation as the sediments change from semi-aquatic in the lower portion (i.e., bony fish, sharks, amphibians, turtles, crocodiles, small theropods and hadrosaurs) to more terrestrial (i.e., wood fragments, large theropods) in the upper portion of the sequence. Cretaceous sediments in this area are mostly almost flat-lying and are overlain by Paleogene marine clays and localized Neogene sediments of the Paratethys in some upland areas. Quaternary alluvial and fluvial sediments cover extensive low-lying areas across the Syrdarya Uplift.

Analytical protocol. All procedures, except compilation of basic maps, were performed with RSI ENVI 4.2. The following manipulations were used to preprocess the original Landsat fileset downloaded from http://edcsns17.cr.usgs.gov/EarthExplorer/: (1) Bands 1 – 7 (including thermal bands 6.1 and 6.2), originally represented separately in GeoTIFF format, were stacked into a single multiband file with pixel size set to 28.5 m; (2) The file was further ‘pansharpened’ to 14.5 m resolution; (3) The total image was cropped to delimit the study area; and (4) Several band combinations were visually tested (compare Figures 5 and 6). Note that recovered images were subject to atmospheric and geometric correction.

SPECTRAL ANALYSIS

Visualization of band combination 7-3-1 (R-G-B respectively) was used to define and to collect spectral signatures. Although the spectral parameters of all seven bands were taken for each pixel, these three bands were chosen because they show the greatest contrast. It is impossible technically to assign more than three bands at the same time in the viewer window, but our analytical procedure involves a complete set of bands: the central portion of this true color image comprises yellow and red patches – from geological maps and field observations we know that this map region corresponds to the Late Cretaceous deposits of the Bostobe Formation – while the remainder of the image has a more uniform coloration (Figure 5). Although in this true color (raw) image (Figure 5) differences between classes are not easily recognizable, the coloration of false color image 7-3-1 (Figure 6) contains more hues and contrasts making the discrimination of ‘color classes’ more precise. Thus, in order to evaluate overall class abundance and to delimit informative pixels into discernable ‘classes,’ we applied the unsupervised classification algorithm - ISODATA (with five to 30 classes over three iterations as conditions) to this full band false color image (Figure 6). Experience shows that three iterations are enough to allow the pixel classification to settle and become consistent; each additional iteration re-calculates and re-classifies pixels thus generalizing the statistics. Analysis of the resultant ISODATA images shows that topographic features are seen rather than geological ones (Figure 7). This preliminary step illustrates the general spectral homogeneity of the Syrdarya field area; this is also obvious in the true colored image (Figure 5). This image shows that the known localities fit into mixed classes (Figure 7) based on the ISODATA algorithm.

Our attempt to produce an image classification using the Band Ratio method resulted in the image shown in Figure 8. We calculated band ratios for clay minerals (red) and for ferrous minerals (bright green) (Figure 8): this supports the argument that the vertebrate fossils found to date in this region have been transported because ferrous minerals are usually determined by this algorithm as characteristic of weathered or disturbed areas.

Next we used a Z Profile (Spectrum) function in RSI ENVI to collect spectra from the most discernible pixel associations and applied Spectral Angle Mapper (RSI ENVI) to the whole multiband Landsat image (Figure 9). Although we use 7-3-1 visualisation to collect spectra, the full-band spec-

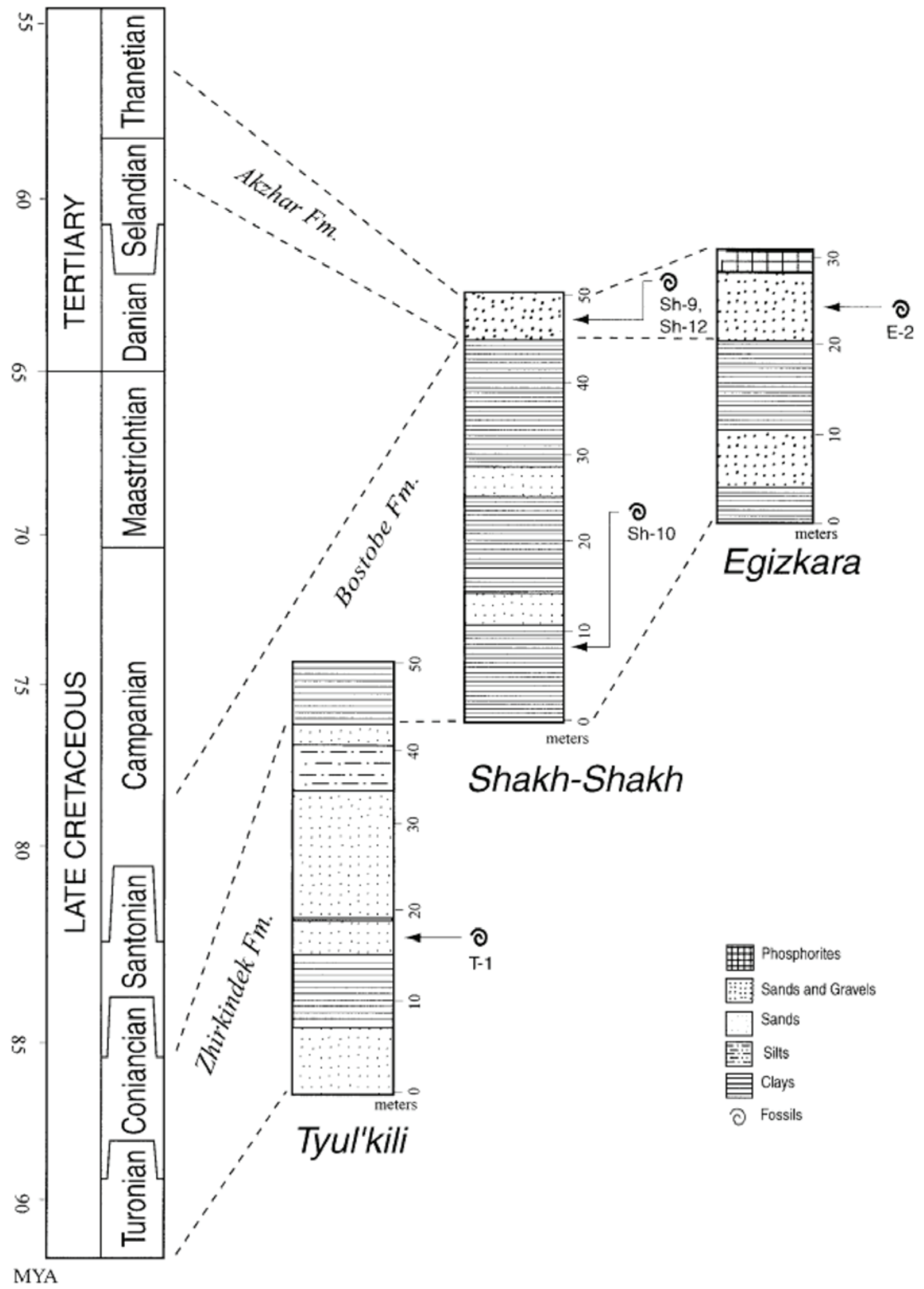

FIGURE 3. Composite geological section drawn through the Bostobe Formation (after Kordikova et al. 2001 and Dyke and Malakhov 2004).

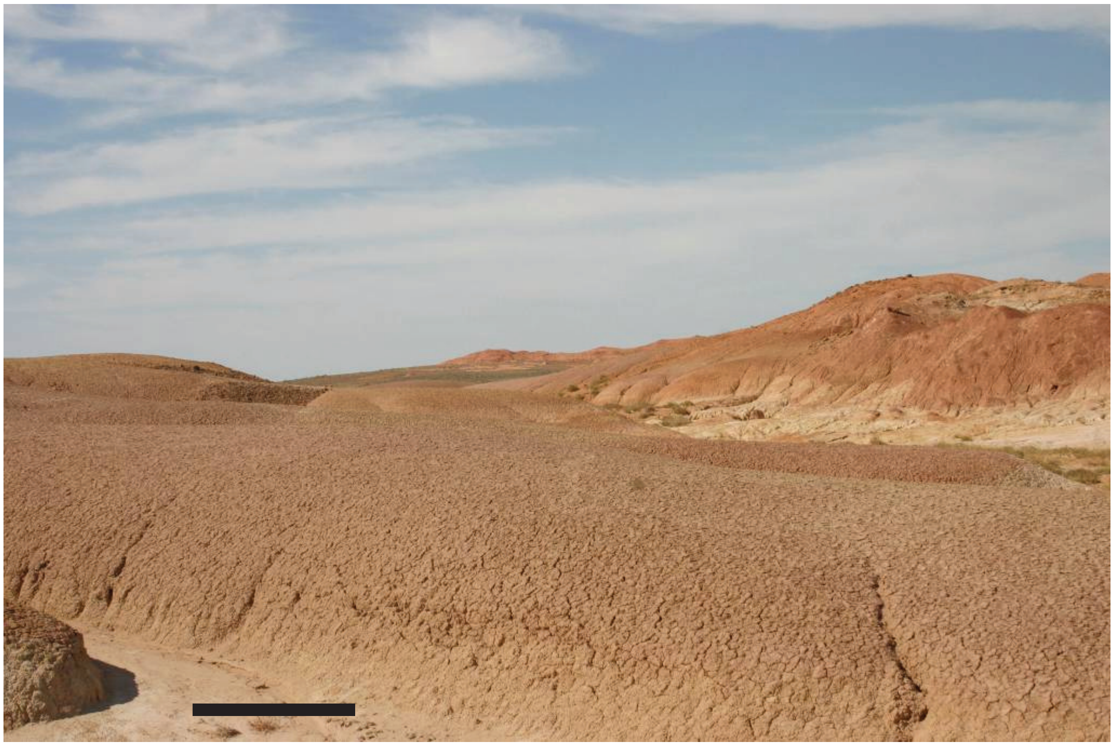

FIGURE 4. Color contrast of fossiliferous sediments on the ground. Ground photograph from the Syrdarya area (see Dyke and Malakhov 2004). Scale bar is 2 m.

FIGURE 5. True color visualization raw image file (bands 3-2-1) of the Shakh-Shakh field area. Black scale bar is 10 km. Site abbreviations: 1 – Shakh-Shakh 2; 2 – Shakh-Shakh; 3- Bird Site; 4 – Turtle Site; 5 – Forest; 6 – Forest 2; 7 – Shakh Shakh 3.

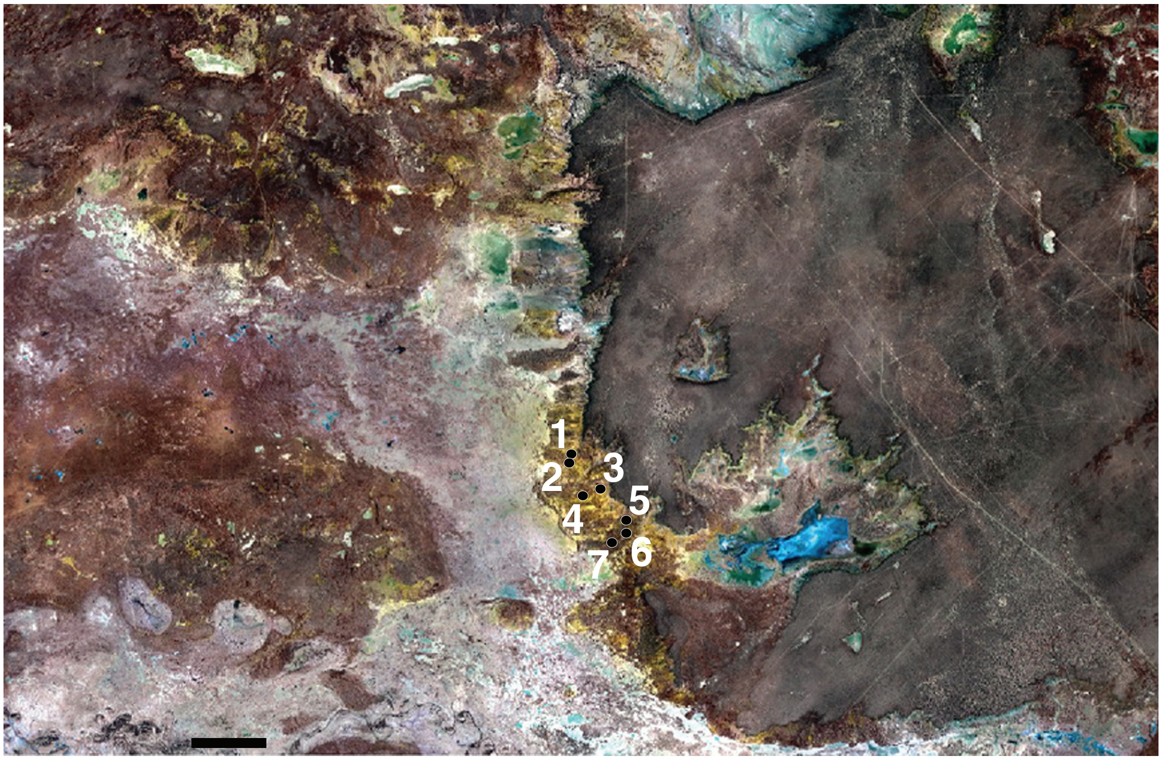

FIGURE 6. False color visualization raw image file (bands 7-3-1) of the Shakh-Shakh field area. Black scale bar is 10 km. Site abbreviations: 1 – Shakh-Shakh 2; 2 – Shakh-Shakh; 3 – Bird Site; 4 – Turtle Site; 5 – Forest; 6 – Forest 2; 7 – Shakh Shakh 3.

tral signatures were recorded for each pixel examined as the algorithm operates with a full set of bands. This approach defined the following numbered spectral classes: (1) Yellow Late Cretaceous Clays – shown in yellow pixels; (2) red Late Cretaceous clays – shown in red pixels; (3) overlying Neogene and Paleogene sediments – shown in blue pixels; (4) Quaternary clay beds – shown in white pixels; (5) dryed bottom of temporary lake – sea green pixels. All of these spectra were saved as a library for subsequent analyses.

Analysis of this image (Figure 9) shows that Quaternary and Neogene classes are distributed evenly through the entire image, and that the margins of outcrops in the field are unclassified in this approach (colored black). The central part of the plateau depression is occupied by a dried lake (which may be filled with water in the early spring), while the area to the south of the plateau is comprised of mixed soils, sometimes covered with vegetation. This explanation shows why the spectral characters of these Quaternary elements may differ from those of the Quaternary sediments, which are white in the spectral analysis. The red and yellow pixels (Cretaceous sediments) also fit very well into our geological understanding of this area; these image library data – groundtruthed in this small area – could be applied to other adjacent regions of Kazakhstan that are also covered by images available from Landsat ETM+.

Our fieldwork has shown that this combined map (Figure 9) is the most informative for pinpointing locations of possible fossil sites. Taken during the late summer of 2007, a transect from Shakh-Shakh hill along the western outcrops and then further to the west in the direction of Egizkara yielded almost perfect results - our research team found at least fragmentary fossil material in most places revealed by the Landast analysis. This compares very well to more traditional surface prospecting of sediments of the correct age where our teams found fossil material much less frequently.

CONCLUSION

The simple analysis and field verification reported in this paper show that it is possible – at least in the Syrdarya area of Kazakhstan – to use spectral image data extracted from Landsat ETM+ to assist in the search for fossils in the ground. Using image data we were able to locate areas of likely fossiliferous Cretaceous-aged sediment prior

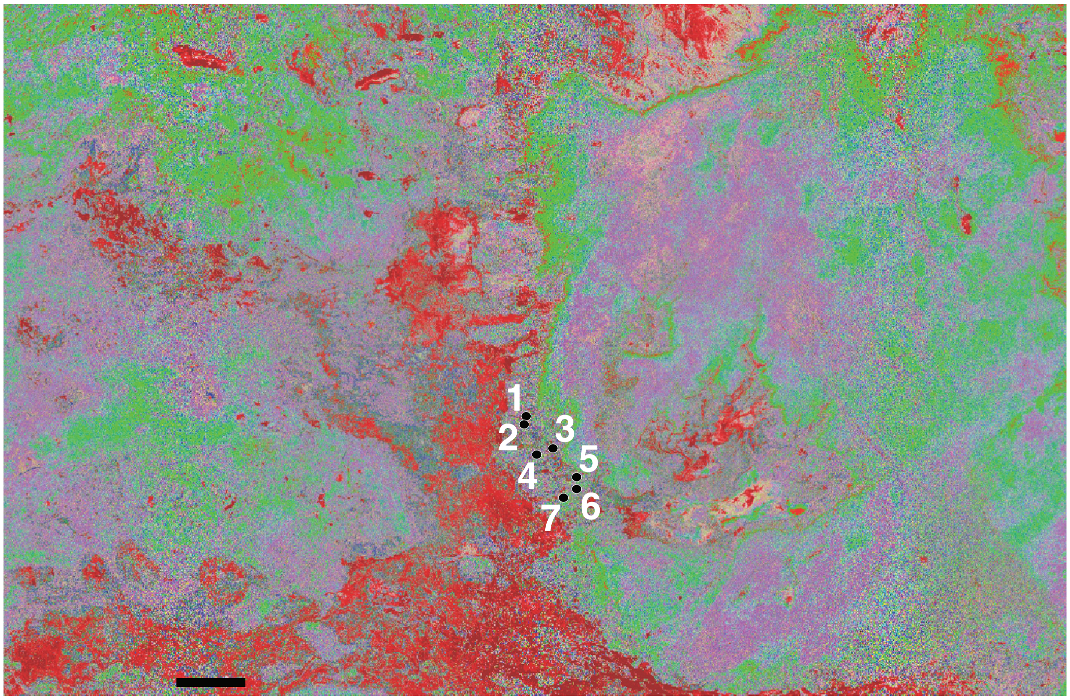

FIGURE 7. ISODATA classification image file of the Shakh-Shakh field area. Black scale bar is 10 km. Site abbreviations: 1 – Shakh-Shakh 2; 2 – Shakh-Shakh; 3 – Bird Site; 4 – Turtle Site; 5 – Forest; 6 – Forest 2; 7 – Shakh Shakh 3.

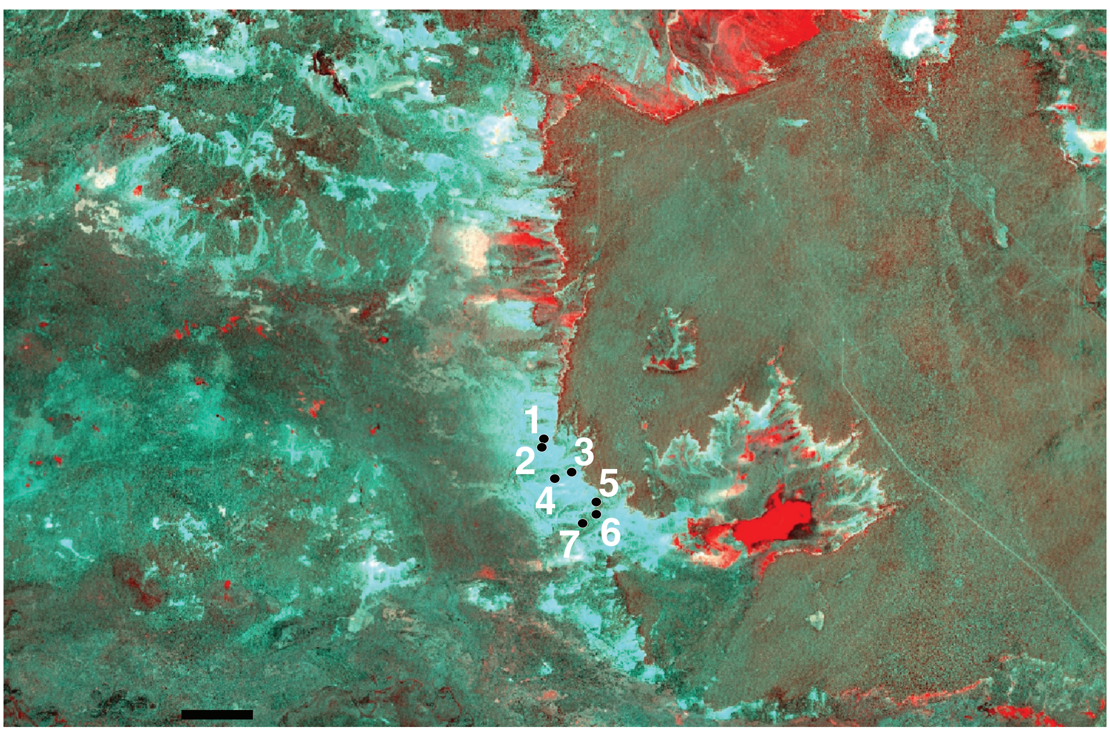

FIGURE 8. Landsat ETM+ classification image file of the Shakh-Shakh field area. Black scale bar is 10 km. Site abbreviations: 1 – Shakh-Shakh 2; 2 – Shakh-Shakh; 3- Bird Site; 4 – Turtle Site; 5 – Forest; 6 – Forest 2; 7 – Shakh Shakh 3.

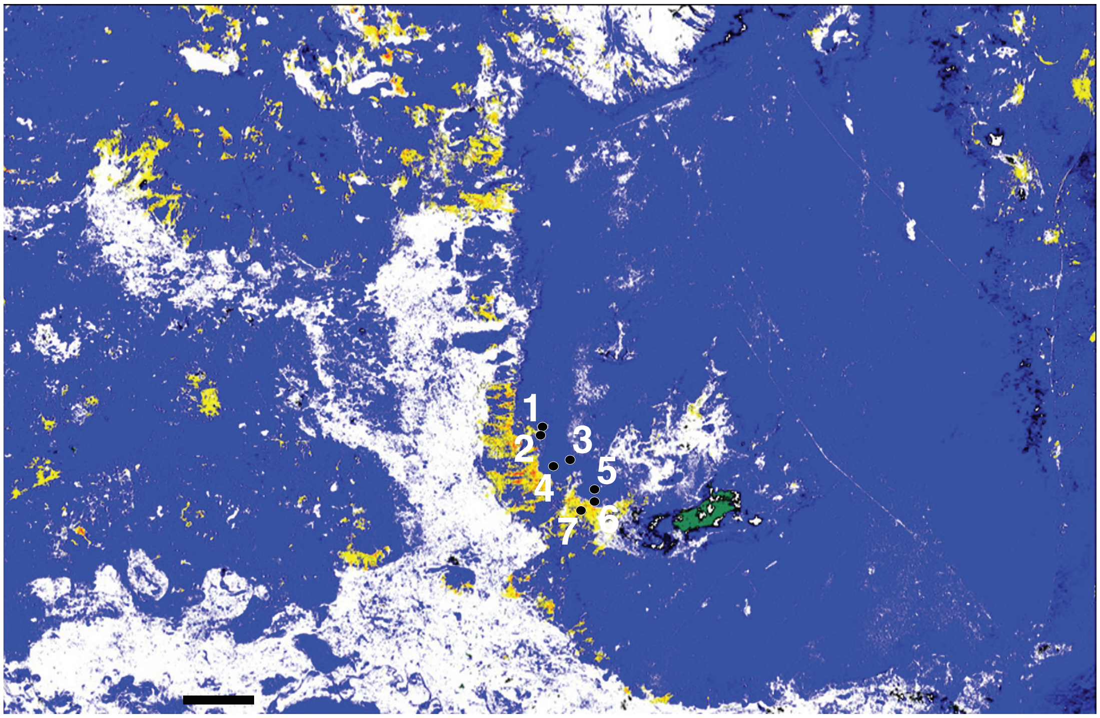

FIGURE 9. SAM (spectral libraries collected from Scatter Plot) analysis image file of the Shakh-Shakh field area. Black scale bar is 10 km. Site abbreviations: 1 – Shakh-Shakh 2; 2 – Shakh-Shakh; 3 – Bird Site; 4 – Turtle Site; 5 – Forest; 6 – Forest 2; 7 – Shakh Shakh 3.

to prospecting on the ground, saving both time and money. Limitations are implied, however, particularly in the accuracy of the spectral analysis and its ability to distinguish closely related spectral sets: for example, our attempts to recognize Zhirkindek Formation deposits within the field area with Landsat ETM+ images failed because these deposits are represented mostly by grey-colored clays that are hard to determine accurately from images. This is because the spectral characteristics of this unit are similar (in Landsat images) to those of the overlying Paleogene strata in the field area.

Nevertheless, if treated with caution, the classification and interpretation of satellite multispectral images could be very helpful to paleontologists in particular for determining likely areas for fruitful field exploration. The spectral libraries created for our approach are different from those used for other kinds of geological exploration in that they are created without reference to mineral compositions. Our approach uses just the reflected spectrum of beds exposed at the surface.

As this project develops, we will build spectral libraries for other fossiliferous locations across Kazakhstan that are of large enough thickness to be seen from space. Spectral libraries may potentially have a huge significance to the future extrapolation of prospective fossiliferous sites.

ACKNOWLEDGMENTS

We thank the members of the 2007 expedition to Shak Shak in southern Kazakhstan, two anonymous referees for their helpful comments and Mark Purnell for his patience with this manuscript. Our research was funded by University College Dublin and by the Leonard family (Dublin, Ireland).

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