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Pan morphology, Distribution and formation in Kazakhstan and Neighbouring areas of the Russian federation

A. Goudie*, P. Kent, H. Viles

Oxford University School of Geography and the Environment, South Parks Road, Oxford, OX1 3QY, United Kingdom

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Abstract

In northern Kazakhstan and neighbouring parts of the West Siberian Plain of Russia is one of the world's biggest concentrations of pans. The area has thousands of them. Landsat imagery and Google Earth images indicate their distribution within this semi-arid area and their forms and associated lunette dunes. Many of the pans, most of which are small, wet and shallow, show a characteristic shape and orientation and some have developed in Pleistocene dune fields. Others have developed in old river channels and from the deflation of lake floors. The pans are in a low-relief area developed on Palaeogene, Neogene and Quaternary beds and have been shaped by winds coming from the south west. They occur in an area which is predominantly steppe grassland. Comparisons can be made with other global pan areas in terms of their number, densities, areas, and depths and in terms of the materials on which they have developed, and the climatic conditions that occur here they are found.

Highlights

- One of the world's biggest, previously unstudied, areas of aeolian pans
- Data are presented on the main pan morphologies and their morphometry
- The pans have morphological similarities to those observed in areas like the High Plains of the USA, South Africa, the Pampas of Argentina and Australia

Keywords: Pans; Wind erosion; Kazakhstan steppes; West Siberian Plain

1. Introduction

Although the existence of pans in Kazakhstan and the West Siberian Plain within the Russian Federation has been known for some time, they have never been the subject of detailed study. 'Here we employ morphometric data collected from Landsat 7 imagery, with observations from Google Earth imagery and other datasets to explore the distribution, morphology, environmental relationships and origin of what appears to be one of the world's most important pan fields.

Pans (closed depressions) occur widely in the world's drylands (Figure 1; Table 1) notably in the Pampas (Fucks *et al*., 2012), Patagonia and Tierra del Fuego in Argentina and Chile, the Pantanal and upper Parana valley of Brazil (Stevaux, 2000; Soares *et al*., 2003), the Roraima/Guyana area (Latrubesse and Nelson, 2001), the High Plains and other parts of the USA and Canada (Sabin and Holliday, 1995; Holliday *et al*., 1996; Bowen et al., 2010), the north east of Spain (Gutiérrez et al., 2013), south west Mauritania (Mohamedou *et al*., 1999) the interior of Southern Africa (Goudie and Thomas, 1985; Holmes et al., 2008), extensive tracts of Australia (Boggs *et al*., 2006; Bourne and Twidale, 2010), and China (Goudie and Wells, 1995). They result from a variety of processes, of which aeolian excavation is probably the most important, and crescentic lunette dunes, composed of excavated material frequently (though not invariably) occur on their lee sides (Sabin and Holliday, 1995).

* Corresponding author. Tel.: +44 1865 512473,
Fax: +44 1865 512473.
E-mail address: andrew.goudie@stx.ox.ac.uk

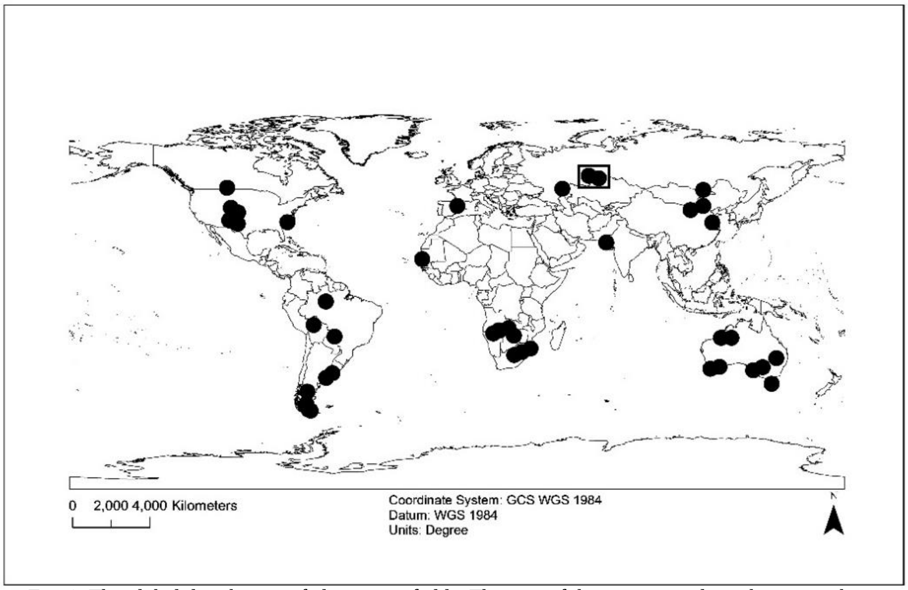

Fig. 1. The global distribution of classic pan fields. The area of the present study is shown as a box

Table 1. Locations of some major classic panfields

Country	Latitude (º & ‘)	Longitude (º & ‘)
Angola	16 25S	19 47 E
Argentina	38 26S	60 54W
	44 46S	69 40W
	50 36S	70 03W
	53 42S	68 10W
Australia	35 00S	137 35E
	33 25S	141.56E
	29 15 S	140 21E
	33 18S	121 58E
	33 40S	118 36E
	34 13S	117 40E
	19 51S	122 35E
	19 53S	127 21E
	41 10S	146 10E
Bolivia	13 51S	66 45W
Brazil	3 01S	61 01W
	19 17S	56 59W
Canada	49 45N	106 52W
Chile	53 13S	68 58W
China	41 20N	114 23E
	39 28N	108 23E
Kazakhstan	54 09N	65 46E
	49 17N	48 47E
Mauritania	16 41N	16 15W
Mongolia	48 39N	114 22E
Mozambique	24 43S	34 06E
Namibia	23 41S	19 22E
	17 52S	16 52E
Pakistan	24 20N	69 19E
Russia	55 22N	61 11E
South Africa	26 20S	30 12E
	27 51S	26 29E
Spain	41 23N	0 10W
United States of America	33 02N	101 54W
	40 24N	105 05W
	38 17N	101 50W
	34 41N	105 54W
	33 48N	78 80W
Zambia	15 24S	23 51E
Zimbabwe	18 49S	26 21E

Regional descriptions of lunettes are provided for the High Plains of the USA by Holliday (1997), Tunisia by Perthuisot and Jauzein (1975), the Kalahari in Botswana by Lancaster (1978), South Africa by Goudie and Thomas, (1986), Mauritania by Mohamedou *et al*. (1999), the Pampas of Argentina by Fucks *et al*., (2012), south western Australia by Harper and Gilkes (2004) and Spain by Rebollal and Pérez-

González (2008). Stephens and Cocker (1946) and Campbell (1968) believed that deflation could account for many lunette features. As Campbell remarked (p. 104), “the close similarity between the composition of the lunette and its associated lake bed suggested that the two are causally related, i.e. that the material in the lunette was derived from the lake bed…”.

Desert closed depressions originate through four main types of process (Shaw and Thomas, 1997): structural controls (e.g. faulting and rifting, and downwarping); erosional controls (e.g. deflation, solution, animal scouring); ponding (e.g. in inter-dune troughs or ephemeral rivers) and dramatic (e.g. meteorite impacts, volcanic cratering). However, it is likely that many of the depressions, especially the smaller ones, have a partially or dominantly aeolian origin. That pans are at least in part of aeolian origin is indicated by their distinctive morphology (it has often been likened to a pork chop), their orientation with regard to prevailing wind directions (often with a crenulate windward side and a bulbous lee side), the presence of lunettes (composed in part of sediment deflated from pan floors) on their lee sides and observations on the ground and from space of dust plumes blowing from their surfaces.

Goudie (1999) developed a model of pan development which both recognized the variety of formative influences, and classified them into various categories. First of all, low precipitation is a *predisposing condition* which has various consequences: limited vegetation cover so that deflation can occur, animals concentrate at pans, (causing trampling and overgrazing which also promote deflation) and salt accumulation takes place (so that salt weathering can attack fine-grained bedrock, producing rock flour which can then be evacuated by the wind). These are *accentuating processes*, which serve to enlarge hollows, whether they are formed by other *initial formative processes* such as solution of carbonate and gypsum beds, or tectonics. Another predisposing condition is the presence of susceptible materials that can be eroded or deflated by wind. If pans are to develop it is necessary that the initial surface depression is not obliterated by the action of integrated or effective fluvial systems. *Non-restraining conditions* that limit fluvial activity are low angle slopes, limited relief, episodic desiccation, damming by dune encroachment, and tectonic disturbance. In addition pans should not lie in areas where sand actively fills in existing hollows, though they can and do develop in inter-dune depressions, particularly in linear and parabolic dune fields.

2. The area

The area considered in this study is situated in the West Siberian Plain within Russia and Kazakhstan between c 48 and 58° N and c 60 and 80° E (Figure 2). It occurs at a low altitude (c 120-200m above sea level) and is a huge plain land with very limited relief. The main type of vegetation in the area is steppe (Rachkovskaya and Bragina, 2012). The climate is severe and highly continental in type. It is characterised by a relatively low mean annual rainfall of 150-400 mm, which increases from south to north. Dust storm activity is widespread (Sazhin, 1988). The area is covered by snow in the winter months. Soils are mostly chernozems, chestnut soils, and solonchaks (in depressions) (Nagumanova, 2007), and these are subject to varying degrees of deflation (Kliment’ev, and Pavleichik, 2013). Some of the depressions are important in terms of migratory birds and were designated by UNESCO as a World Heritage Site called ‘Saryarka – Steppe and Lakes of Northern Kazakhstan’ in 2008. However, some have been subjected to a range of human pressures, including Lake Karachay, which was employed as a site for disposal of Russian nuclear waste, while others have suffered from damming, impoundments, and water diversions ((Inyutina *et al*., 2009). There is a big range in the size of lakes in the area, with large examples such as Lake Chany (Shikano *et al*., 2006; Doi et al, 2004) and Lake Tengiz contrasting with the many smaller basins (Zhumangalieva, 2014). The former may at least in part have a structural origin. Some of the lakes are saline and have high pH values (see, for example, Yermolaeva, 2013).

The geology of the area consists largely of relatively unconsolidated sedimentary rocks (clays, marls, etc.) of marine and terrestrial origin dating back to the Palaeogene and the Neogene. These are mapped in Persits *et al* (1997) and details of stratigraphy are in Akhmetyev et al (2005). Marine conditions occurred in the Eocene and early Oligocene after which the sea began to retreat and the final emergence of a terrestrial environment occurred in the Miocene, during which a lacustrine-alluvial plainland developed (Zaklinskaya, 1962) There are also extensive areas of Quaternary superficial materials including aeolian sands (Volkov and Zykina, 1984). The area lay far to the south of the Quaternary ice caps, but water may have flowed down the Turgai Valley from mega-lakes in northern Siberia (Mangerud *et al*., 2001), creating drainage lines that are now relict.

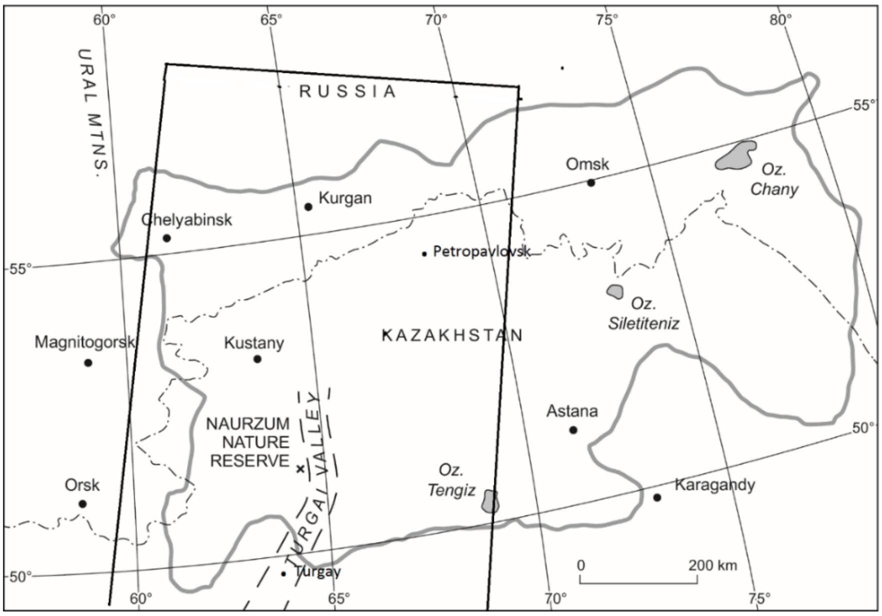

Fig. 2. The approximate extent of the panfield. The area covered by the Landsat study is shown by the boxed area

3. Data Sources

Maps of the distribution and form of pans were obtained from various types of remote sensing imagery, including that available through Google Earth. However, a detailed Landsat-based morphometric survey was also made for part of the pan area (Kent, 2006). The Landsat 7 data for this study were obtained from the Global Land Cover Facility (University of Maryland). The precise study area was defined by the Landsat path and row images, corresponding to Landsat rows 020-026 and paths 158-163. For each image, each of the eight bands was separately downloaded and decompressed. Bands one to seven were overlaid using ER Mapper 6.1, and saved as a Raster dataset. This produced a seven layer image which could then be used for the analysis. Digital Elevation Models (DEMs) were also downloaded for this area. These data were collected by the Space Shuttle radar, and give a spatial resolution of 90m (3 arcseconds).

Both the Landsat Imagery and DEMs were analysed using ER Mapper 6.1. This allows the analysis of images in Red, Green and Blue (RGB) and Pseudocolour. DEM data were displayed in Pseudocolour, and an appropriate colour ramp was used to assign colours to cell values.

4. Methods: Landsat Data Collection

Data collection in this study was undertaken on two groups of samples. The first involved measurement of all the pans identified in the study area demarcated by the box in figure 2 (8927 pans), whilst the second measured variables for two transects within this boxed area (196 pans).

4.1. Sample one – all pans

The distribution of pans was mapped by displaying images in colour bands which best display both wet and dry pans. RGB 7,4,2 was of most use in this respect, and formed the back drop to the majority of our data collection. The pan area was recorded for each pan using the Map Composition Extents window in ER Mapper. It was also recorded whether each pan was wet or dry. To do this, the Landsat image was displayed in band combination RGB 7, 5, 4. This makes the presence of water clear, as there is complete absorption and no reflectance at these wavelengths. Where pans were present that had some water but were not full, the pan was recorded as being wet.

4.2. Sample two: transects

The samples taken were along two transects, in which any pan touching the line was measured and recorded: one transect running North-South and one running East-West. The North-South transect was defined by Easting 65°E and the East-West transect along Northing 55°N. These were chosen after the distribution of pans had been mapped, and were designed to coincide broadly with the largest pan fields in this area.

The first feature to be measured among the transect samples was pan depth. As the seven layer raster dataset does not contain height data, a height raster layer was added to the image. These are available as 30 arcsecond (90m), latitude/longitude tiled DEMs from the Global Land Cover Facility. To measure the pan depth, a cross section of the pan was constructed using ER Mapper's Traverse function. From this, the maximum height above sea level (a.s.l) at the edge of the pan was recorded, along with the minimum height. The difference gives the maximum pan depth. The traverses were constructed for an area larger than the pan itself, and this was used to indicate whether lunette dunes were present on the lee side of the pan. Data for the major and minor axis lengths of the pan sample were also collected.

5. Pan types

The pans straddle the border between Russia and Kazakhstan and occur in the lee of the Urals. Many pans within this area, especially the smaller ones, have a circular plan-form, and this is the dominant type (Figure 3).

Fig. 3. Google Earth image of small round pans. Scale bar is 5 km. ©Google Image Landsat 2014

However, many larger pans have a classic shape with a bulbous lee side that lies transverse to the dominant wind directions (Figure 4) and a crenulated windward side.

These classic pans have a fairly consistent morphology as can be seen where they occur in groups, as near Chelyabinsk (Figure 5). Such groupings of large pans in the lee of the Urals appear to be analogous to the situation in the lee of the Rocky Mountains in the USA near Fort Collins in Colorado.

Fig. 4. Google Earth image of a classic pan. Scale bar is 2 km. © 2014 Google, ©Cnes Spot Image

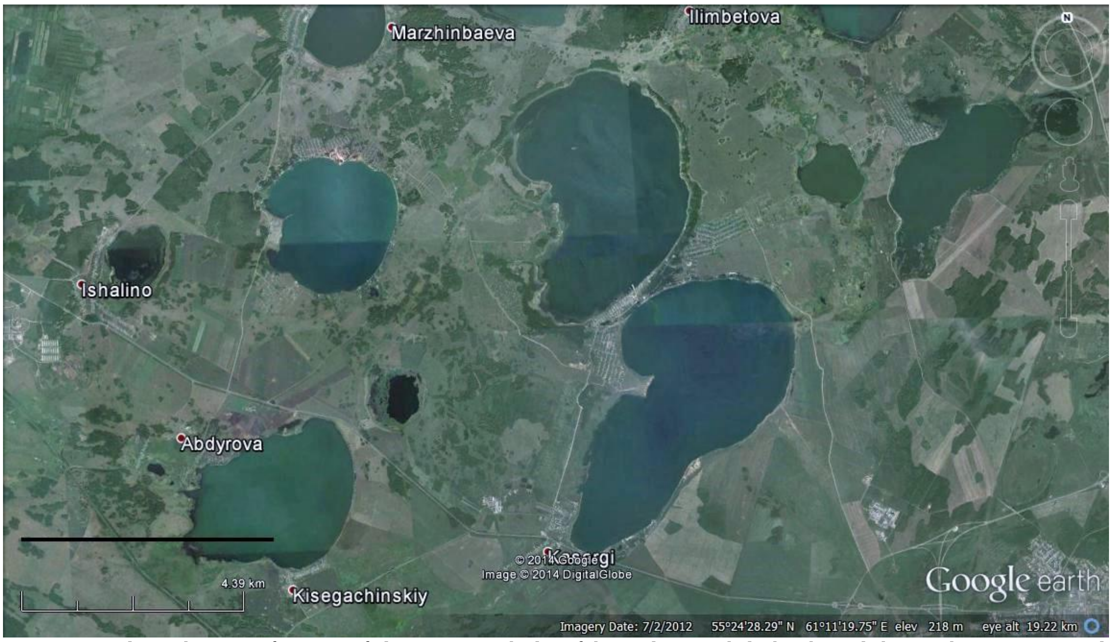

Fig. 5. Google Earth Image of a group of classic pans in the lee of the Urals near Chelyabinsk. Scale bar is 5 km. ©2014 Google, ©Digital Globe

The classic forms may display a lunette or lunettes on their lee sides (Figure 6), though this is by no means universal. Of the 196 pans in the sampled transects, however, 140 pans (71.4%) had lunettes. The lunettes, where present, tend to be 5-10 m high.

Another characteristic form, here called 'foetal', may be created by the merger of two or more pans, or the division of one pan on its windward side by encroaching linear dunes or a stream delta (Figure 7). This type also has a bulbous lee side and a crenulated windward side. Comparable forms are represented by the Lake Chrissie Pans of eastern South Africa.

Other pans have a tear-shaped form, and these are a particular feature of those areas where there are linear dunes (Figure 8).

Fig. 6. Google Earth image of Lazurny Pan with two lunettes on the lee side.©2014 Digital Globe, ©CNES/Astrium. Transect position shown by white line (11.8 km long)

Fig. 7. Google Earth image of foetal pan. Scale bar is 2 km. ©2014 Digital Globe, ©2014 Google

Fig. 8. Google Earth image of tear-shaped pans. Scale bar is 1 km. ©2014 Digital Globe, ©2014 Google

Indeed, particularly in the north east of the panfield, the pans are plainly developed in inter-dunal swales and have a morphology that reflects this (Figure 9). Similar inter-dunal pans occur in Argentina (Fucks et al., 2012), the High Plains of America, the western Thar desert of Pakistan, and the deserts of south eastern Australia (Goudie and Wells, 1995).

Fig. 9. Google Earth image of pans developed in the swales of linear dunes that run from WSW to ENE. Scale bar is 10 km. ©2014 Digital Globe, ©2014 Google. ©Cnes/Spot Image

There are two other environments where distinctive pans occur. One is where they have developed along relict stream channels. These are linear features that occur in strings (Figure 10). These forms appear to be broadly comparable to the palaeo-channel pans of Western Australia (Bourne and Twidale, 2010) or of the High Plains of the USA (Goudie and Wells, 1995).

Fig. 10. Google Earth image of pan complex developed along a drainage line. Scale bar is 5 km. © 2014 Cnes Spot Image

Finally, where a large lake basin has become desiccated, a series of pans may be created on the lake floor (Figure 11), rather as with the case of Estancia Lake in New Mexico, USA.

6. Size, depth and wetness of pans

Some of the data from the Landsat analysis are shown in Table 2.

Figure 11. Google Earth image of Tengiz palaeolake. Scale bar is 10 km. © 2014 Google, © 2014 Cnes Spot Image.

Table 2. Summary of the key morphometric data from the analysis of Landsat imagery

Feature	Sample size	Mean	Max	Range	Other notes
Ratio of major to minor axes	196	1.45	5.55	4.82	
Pan Area (km^2)	8927	1.39	190.3	189.99	
Pan Depth (m)	196	4.99	25	24.7	
Pan Circumference (km)	196	3.79	17.97	17.79	
Lunette presence	196	N/A	N/A	N/A	140/196 (71.4%)
Wet/dry pans	8927	N/A	N/A	N/A	Wet = 7686/8927 (86.1%)

The mean area of a pan over the 8927 pans studied was 1.39 km². Pans showed high variability in area, with a range of 190 km², and a standard deviation of 4.44 km^2. The histogram in figure 12 shows the distribution of pan area. From this it can be seen that there is a highly skewed distribution and that there are many pans with areas less than 2 km², and then a lower frequency for areas above 2 km² up to the maximum value of 190.3 km². The circumference of pans was recorded for the transect samples. The mean circumference was 3.79 km, with a standard deviation of 2.97.

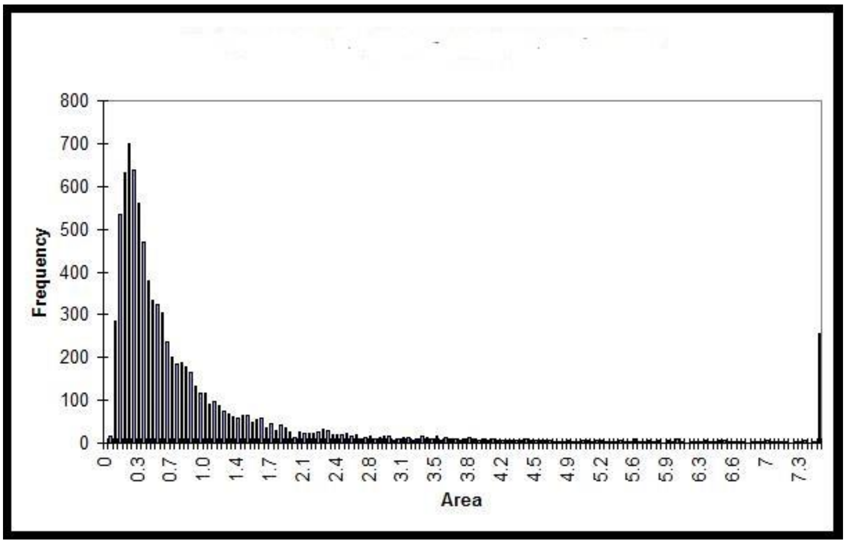

Fig. 12. Frequency distribution of pan areas (km)

The depth of pans was recorded for the transect samples. The mean depth was 4.99 m, with a range from 0.3 m to 25 m. Variation in pan depth is small, with the majority of pans less than ten metres deep. These are therefore essentially shallow features.

Many of the pans identified were lakes, with 86.1% containing water at time of the Landsat image. This might suggest that a landform assumed to be created by aeolian deflation is relict, and formational processes are no longer active. However, at certain times of the year and during extended droughts, it is probable that pans could dry out (Vasilev *et al*, 2006). Furthermore, the presence of stabilised linear dunes, and the analysis of pan sediments, indicate that climatic conditions may have been drier both in the Late Pleistocene (Volkov and Zykina, 1984) and during certain parts of the Holocene (Zakh *et al*., 2010). Basins initiated by deflation in dry phases may be enlarged and shaped by wave action in subsequent moister phases, as has been proposed for the oriented basins in the Llanos de Moxos in Bolivia (Lombardo and Veit, 2014).

7. Climatic environment

The mean annual precipitation for selected stations in the area is shown in Table 3. The data are derived from Weatherbase.com. Values range between c 156 and 429 mm. These values are comparable to those found in most of the other major world panfields, though less than those for some areas.

The area appears to be one with substantial aeolian activity. Larionov *et al*. (1999) presented evidence suggesting wind deflation is an important factor in sediment removal for this area. They calculated the wind erosion index across the Former USSR and this showed that the area of study has some of the highest wind erosion index values for the whole of the Former USSR. It is also an area with a relatively high incidence of dust storms. Sazhin (1988) suggested that in general they occurred on 15-20 days in the year in West Siberia and Northern Kazakhstan. Data were also presented by Zhirkov (1964), who reported that the average annual number of dust storms was 12 in Kustany, 22 in Pavlodar, 21 in Astana, 19 in Karaganda and 21 in Turgay. In some years the number of dust storms can be higher than this, and in 1955 there were 49 dust storms in Astana. Similar values for dust storm incidence are shown in the recent studies by Indoitu *et al*. (2012) and Orlovsky *et al*. (2013). The dust storm season starts in April, after the snow cover has melted, and continues through to October and November, with the maximum number occurring in May and June. Some satellite images show dust being blown off pan floors (Figure 13).

Table 3 Annual precipitation totals (mm) for major pan areas

Kazakhstan and West Siberia	
Arqalyk, Kazakhstan	243
Chelyabinsk, Russia	429
Kurgan, Russia	383
Kustany, Kazakhstan	336
Omsk, Russia	330
Petropavlosk, Kazakhstan	353
Turgay, Kazakhstan	156
Other areas	
Bahia Blanca, Argentina	550
Boa Vista, Brazil	1710
Carolina, South Africa	752
Dodge City, Kansas, USA	549
Duolan, Inner Mongolia, China	389
Gravelbourg, Canada	390
Gurvandzagal, Mongolia	255
Hwange, Zimbabwe	560
Katanning, W. Australia	480
Keetmanshoop, Namibia	143
Kimberley, South Africa	420
Llanos de Moxos, Bolivia	>1600
Lubbock, Texas, USA	450
Mavinga, Angola	813
Maxixe, Mozambique	943
Mildura, Victoria, Australia	260
Mongu, Zambia	960
Ordos, China	394
Rio Grande, Tierra del Fuego, Argentina	330
Urucum, Brazil	1038
Zaragoza, Spain	330

Fig. 13. A dust plume blowing off Lake Siletiteniz (from AQUA, April 21st, 2012) (Courtesy of NASA)

The wind direction frequency in dust storms in Omsk is clearly from a south westerly direction (7% from SSW, 22% from SW, 13% from WSW, and 15% from W) (Sazhin, 1988). This ties in with the orientation of the pans. Winds in general also tend to be from this quarter, as illustrated by the data shown in figure 14.

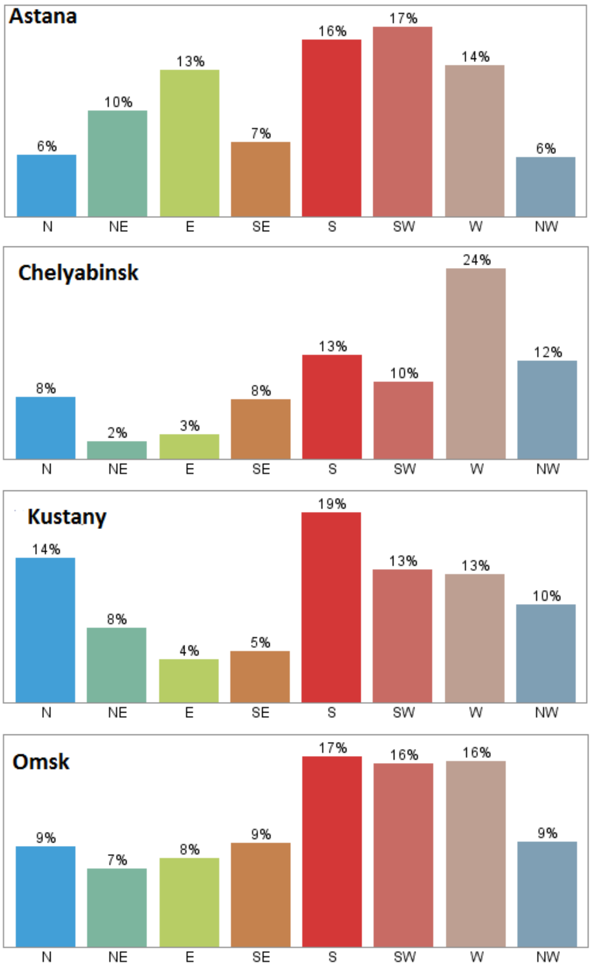

Fig. 14. Percentage time of wind from different directions for selected stations (derived from data in WeatherSpark) (http://weatherspark.com/averages) (accessed June 20th, 2014)

The orientation of the linear dunes in the area is also indicative of the importance of winds from the south west.

8. Discussion and Conclusions

The West Siberian plain is one of the world's great pan fields as evidenced by the data presented here. The pans have many similarities with those from other low to mid-latitude grassland areas and some thousands have been identified and mapped within the study area. This makes it comparable to other parts of the world. Boggs et al. (2006) for example, measured 4500 pans in their study area in Western Australia and Holliday *et al* (1996) mapped 25,000 pans in the southern High Pains of the USA, whilst Bowen et al (2010) mapped 22045 pans in Kansas alone. The overall density of pans in our area is around 6.4 per 100 km^2, though locally values are higher than that. However, the mean density value is similar to that found by Goudie and Wells (1995, Table 1) for Hwange, Zimbabwe (14.9), the USA High Plains (4.1-33.3) and for Argentina (5.9-89.6), and to the mean value for Kansas (21) (Bowen, 2011). Most of the pans measured in this study are modest in size, with a mean area of 1.39 km^2 and a mean circumference of 3.79 km. These sizes appear to be slightly greater than those in the southern High Plains of the USA where they range in size from 80 m^2 to 4.8 km^2, and where most are smaller than 1.5 km^2 (Sabin and Holliday, 1995). In South Africa, the mean pan size for 5040 pans was 0.20 km^2 (Goudie and Thomas, 1985). In Patagonia, the modal size of pans was 0.1- 0.25 km^2 (Mazzoni, 2001).

Some of the larger pans appear to result from pan amalgamation, producing a foetal shape, while others have a tear shape. The depths of the pans range from 0.3 to 25 m. This appears to be comparable to the playas of the USA High Plains, where the mean depths ranged from 3.07 m for those without lunettes, to 17.75 m for those with lunettes (Sabin and Holliday, 1995).

In common with other pan fields, the pans are concentrated in an area of semi-aridity, where the mean annual rainfall averages 150-450 mm. This is comparable to values obtained for most other major pan areas in the world, though there are some panfields where higher mean annual rainfall occur. Many of the pans (86.1%) contain water at the present time, which suggests that they could be out of equilibrium with the present climate. This is something that has been suggested for pans in areas like the Pantanal and Roraima areas of Brazil (Latrubesse and Nelson, 2001; Soares *et al*., 2003), where relict dunes also occur.

The area is also one that is characterised by high wind erosion potential and dust storm activity. The pans are concentrated on Tertiary sedimentary rocks and on Quaternary sediments and this is comparable to the situation in other of the world's pan fields, where the presence of susceptible materials, especially unconsolidated sands and clays, is a major control of occurrence. In common with all the other major pan fields it is an area of very low relief. Although most of the pans occur in herb and grass dominated areas (steppe), as is also the case for the Argentinian Pampas, the High Plains of the USA, and the veld of South Africa, some occur in areas of pine forest and bogs, which also suggests they may be out of equilibrium with the present climate. However, steppe was more widespread in portions of the Holocene (Kremenetski et al., 1997; Sorrel *et al*., 2007; Zakh *et al*., 2010), suggesting that the climate was more arid than today. Moreover, an aeolian origin for the pans is suggested by the presence of lunettes on their lee sides and by the preferred orientations of pan long axes, which corresponds with that of dune orientations in the area. The formative winds come predominantly from the south west. Westerly winds are also the formative ones in other mid-latitude pan areas, including the High Plains of the USA the Pampas of Argentina, and the Lake Chrissie Pans of South Africa (Wellington, 1943).

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