The provenance, variety, and deposition of sediment and the formation of dunes in the eastern Rub' al-Khali, southeast Arabia

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ABSTRACT

The enormous Rub' al-Khali desert in southern Arabia consists of a wide variety of different dune forms shaped by dominating northwestern and southwestern winds, particularly barchans, megabarchans, and star dunes. Surrounded by carbonate outcrops, the source of the desert's siliceous sediment is disputed among scientists, though most of it seems to have been eroded from the Zagros Mountains in Iran and the highlands in the Arabian Peninsula. The age of the Rub' al-Khali dunes is also disputed, though the enormity of the desert and the regional differences of sediment and dune type make acceptance or existence of a common dune age across the desert unlikely.

DEFINITION OF AREA

The Rub' al-Khali desert of southern Arabia spans 600,000 sq. km across Yemen, Oman, the United Arab Emirates (U.A.E.), and Saudi Arabia, making it the world's largest continuous sand desert or, as it is commonly referred as, a sand sea (Fig. 1). Its massive area, extreme aridity (potential evaporation exceeding precipitation by tenfold to thirtyfold), and intense temperatures (summers typically stay above 50 degrees Celsius) make it one of the most inhospitable places in the world, its name meaning "the Empty Quarter" (Garzanti et al., 2003). The desert occupies a broad depression extending southwest from the coast of the U.A.E. to the Asir highlands of eastern Arabia, containing large tracts of linear dunes (called 'uruq), with individual dunes up to 200 km long, as well as barchans, barchanoid ridges, and megabarchans (transverse dunes), some of which are 230 m high (Edgell, 2006). In addition to the large dunes, sand sheets cover

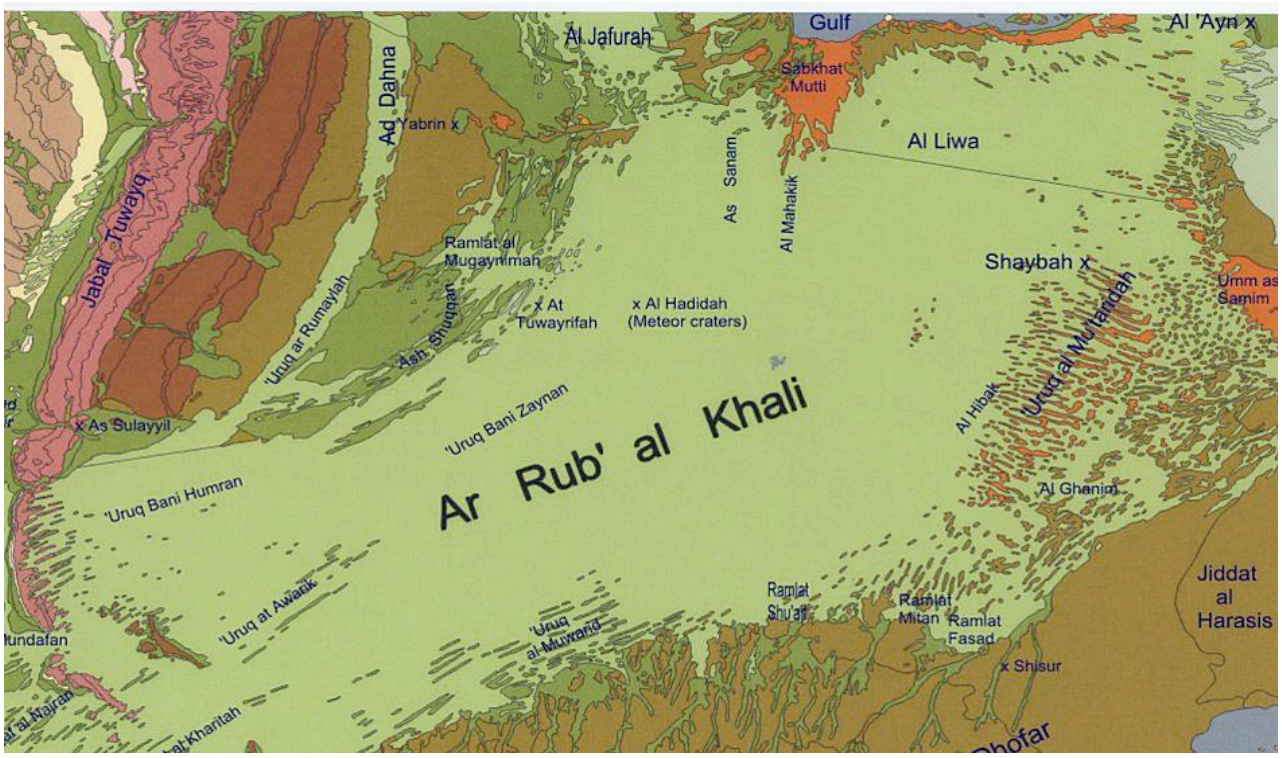

Figure 1 - Referential map for the Rub' al-Khali. Map from Edgell (2006, Fig. 7.3).

about 32% of the desert, figuring in the inter-dune areas of dune environments in which the interdune spaces are wider than the dunes (Edgell, 2006).

The scope of this paper cannot encompass the substantial entirety of the Rub' al-Khali, but will focus on that area in the east of the peninsula north-south from Al Liwa to Ramlat Mitan and west-east from Ar Sanam to Umm As Samim, roughly correlating to the extreme southeast of Saudi Arabia, northern Oman, and southern U.A.E. Though few outcrops of underlying strata dot the Rub' al-Khali (Stokes and Bray, 2005), enough appear in the east to determine that most of the area under study rests on either Miocene sediments or limestone of the Eocene Dammam Formation (Edgell, 2006). In addition, in U.A.E. and Oman, up to 80 km inland from the Persian Gulf, active dunes are underlain by carbonate-rich Pleistocene eolianite (Garzanti et al., 2003).

DUNE STRUCTURES

Power of the Wind

The great dune formations and accumulation of sediment are due to regularly occurring and powerful eolian systems on the Arabian steppe and in the Persian Gulf region (Fig. 2). They define the shape of dunes and manage the buildup of sands that has fed and continues to feed the growth of the Rub' al-Khali. Crescent-shaped barchans (and the larger transverse dunes) are usually attributed to a dominant wind direction with little vegetation to anchor the sediment, while linear dunes are many times caused by bidirectional wind patterns. Both dune types are very well represented in the eastern Rub' al-Khali, as are star (or pyramidal) dunes which are formed by multidirectional winds (Edgell, 2006).

By far the most important winds are the Shamal winds which, though occurring both in the summer and winter, are extremely persistent and powerful between late May and early July (Edgell, 2006). Traveling southeast along the Persian Gulf, the Shamal brings massive loads of dust and sand toward the U.A.E. where it suddenly changes directions toward a south-southwest orientation and goes across most of the Rub' al-Khali. Reaching its peak in the summer, with wind intensity reaching 50 km/hr in the east, the Shamal carries *millions* of tons of sediment into the Rub' al-Khali during each storm (Edgell, 2006). Another important wind is the Kharif which is a product of the South-West Monsoon, and extends to the southern edge of the Rub' al-Khali where it helps create a series of pyramidal and linear dunes (Edgell, 2006).

Dune Shapes

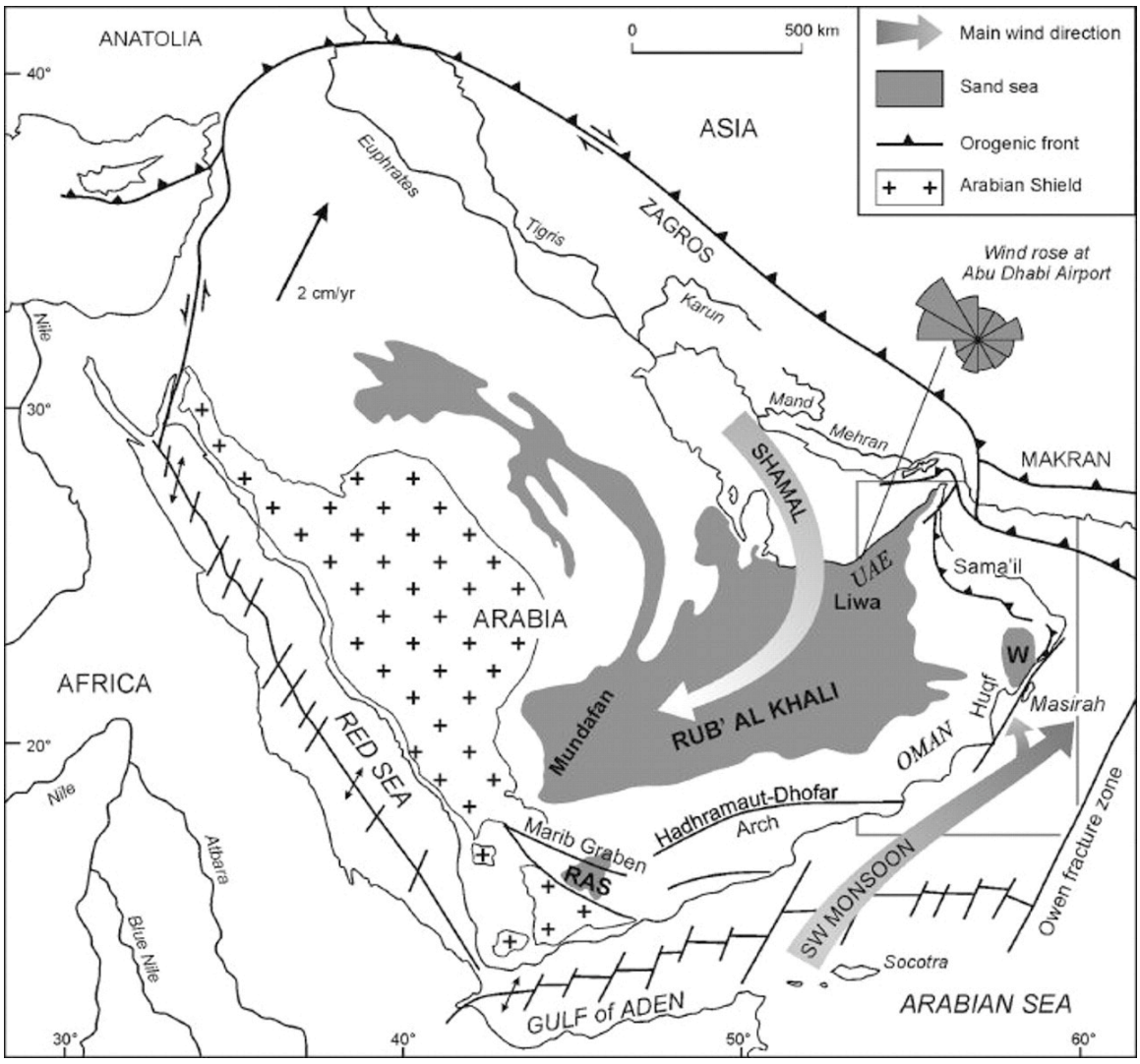

Figure 2 - Map showing dominant wind patterns shaping the Rub' al-Kahli. Map from Garzanti et al. (2003, Fig. 1).

Almost every dune shape is represented in the vast Rub' al-Khali. Even in the east only, there is a wide variety including barchans, megabarchans, pyramidal dunes, linear, sigmoidal complex, and hooked dunes. The 'uruq (linear) are the most frequently occurring dunes in the entire desert, covering about 28.8% of it, and their frequency transcribes to the eastern region as well (Edgell, 2006). Commonly occurring on the

‘uruq surfaces are smaller secondary dunes such as seif dunes, sigmoidal dunes, or barchans (Edgell, 2006).

The highest dunes in the Rub’ al-Khali are the megabarchans which can rise up to 230 m above interdune corridors. These megabarchans occupy about 38,000 sq. km or 6% of the desert, but a significantly higher proportion in the east. There, they can especially be found concentrated around the ‘Uruq al-Mu’taridah and ‘Uruq ash-Shaybah areas (Fig. 1) (Edgell, 2006). They take the form of giant crescents with huge slip faces on their south or southeastern sides and are commonly between two and four km in length. Like ‘uruq, many secondary dunes form on the stoss sides of megabarchans like smaller barchans or sigmoidal dunes (Fig. 3).

Barchans and megabarchans can laterally link together to form barchanoid dune ridges. These are especially prevalent in the al-Liwa region in southern U.A.E. where there are at least 70 dune ridges and are encroaching upon older megabarchans (Edgell, 2006).

In addition, one of the most interesting dune formations are those of star dunes which may rise up to 180 m high and can be up to 2 m in diameter. Particularly widespread in the al-Ghanim region, these large solitary dunes form by the convergence of several dune ridges where winds beat about the compass until the dune becomes relatively stable (Edgell, 2006).

VARIETY OF SEDIMENT

Throughout most of the Rub’ al-Khali, the sediment is predominantly siliceous, with up to 90% of it being quartz and the rest mainly feldspar (Edgell, 2006). In the east, however, there is less a disparity with monocrystalline quartz accounting for about 71-

Figure 3 - Aerial view of megabarchan with smaller secondary barchans on stoss side. Picture from Edgell (2006, fig. 9.30).

76%, feldspar 14-16%, and the rest being carbonate, chert, and metamorphic grains (Garzanti et al., 2003). The sediment is light yellow to reddish yellow, being redder in the east where we're focusing due to a light coating of ferric oxide on grain surfaces. Those dunes in the north and east within about 100 km of the Persian Gulf are much more calcareous, but the carbonates remain at secondary amounts, either as dolomite or calcite (Goudie et al., 2000). Even in the extreme northeast of the desert, the sediment is still quartzitic, with curiously deeper shades of red.

PROVENANCE

The fundamental question regarding the sediment of the Rub' al-Khali considers why there is such a large amount of siliceous sand in the desert when almost all surrounding outcrops are carbonates. Different hypotheses have been conjured in order to

explain the provenance of sediment in which only the extreme eastern and northeastern areas have any significant amount of carbonate material. Elsewhere is predominantly quartz and feldspar, but these lead to the discovery of the original sources of the sediment. As Garzanti et al. (2003, p. 572) put it, "Relating the sediment of modern sands to the geologic evolution of wide and complex source areas… sheds light on sediment production and transport pathways, and helps in making predictions on detrital-mode trends in time and space".

One theory which has stood the test of time fairly successfully posits that upwind highlands, undergoing heavy erosion before and during the Pleistocene, are the source of the Rub' al-Khali sediment. This sediment would be deposited in the Gulf, but would become available during glacial periods when sea level was much lower and more land and loose sediment was available for eolian transportation (Holm, 1960). However, this theory did not specify any location and could not account for all sedimentation. Some speculated that eastern sediment was derived from the nearby Oman Mountains or from local Tertiary sandstones (Besler, 1982; Edgell, 2006).

These theories betray the groundless supposition that Arabia has been in isolation, ignoring the fact that high, greatly eroded mountains with calcareous *and* quartzose formations are right across the Gulf in the Zagros Range of Iran (Fig. 4). This most compelling theory offers the most logical and comprehensive guide to Rub' al-Khali sediment provenance. Indeed, mineralogical studies of Quaternary sand dunes in the U.A.E. confirm that the source of sand was most likely the Tertiary fold belt of the Zagros and the Oman Mountains (Ahmed et al., 1998). It seems most definite that at

Figure 4 - Mountain in the Zagros Range in Iran. These mountains are thought to be the origin of most of the sediment in the Rub' al-Khali. Picture from http://www.livius.org/a/iran/zagros/zagros-2.jpg.

times of greater precipitation, the Zagros Mountains and other highlands of the Iranian plateau were heavily eroded and sediment carried by the Tigris, Karun, and other rivers into the Gulf. The dunes of the Rub' al-Khali, especially in the north and northeast, would then be formed mainly during intervals of low sea level when sediment from the dry Persian Gulf would easily be carried by winds greater than today's (Edgell, 2006).

Different formations in the Zagros confirm the likely probability of that range being the chief source of Empty Quarter sediment. The Agha Jari Formation, which is widely exposed throughout southern Iran, consists largely of predominantly quartz sandstone. Likewise, the Bakhtiari Conglomerate has a thick matrix of quartz sand, while carbonates are also prevalent in the Zagros, Garzanti et al. (2003) confirming that most

northern dunes in the U.A.E. and Oman, where carbonate material is more widespread, were derived from the Zagros and transported to the Rub' al-Khali region by the Shamal winds.

AGE OF ACCUMULATION

There is much uncertainty and dispute among scientists attempting to determine when the Rub' al-Khali dunes were constructed. Most scientists place the creation of the sand seas in the Pleistocene - it's just a matter of when in the epoch, variations ranging in the hundreds-of-thousands of years (Goudie et al., 2000). The periodization is additionally challenged by the sheer scale of the Rub' al-Khali and the regional differences discovered in dune age. Goudie et al. (2000) placed the sands of the extreme northeast of the desert in the latest Pleistocene and earliest Holocene and said that it happened during a single, rapid accretionary phase. Thus, in one region, 17 m of sand was deposited in just a few thousand years. Also, new dune accumulation may be attributed to vegetation destabilization loosening sediment (Goudie et al., 2000).

However, other reliable evidence places dune construction much earlier. Lake bed deposits and fauna remains found in between 'uruq show that lakes and swamps had existed between some of the great linear dunes in a Late Pleistocene wet interval from around 32 ka to 21 ka and again in an Early Holocene wet phase between 9.6 ka and 5.9 ka. Thus the giant dunes were established by the Late Pleistocene and probably earlier. There is even some evidence of dunes in the western U.A.E. up to 800 ka, though most accumulation seems to have occurred within the last 100,000 years (Edgell, 2006).

CONCLUSION

Despite its name as the Empty Quarter of Arabia, the Rub' al-Khali desert of southern Arabia is rich in its diversity of desert forms. The Shamal and, to a lesser extent, the Kharif, winds clash with smaller wind systems to form massive 'uruq, barchans, megabarchans, and star dunes. The quartzitic and carbonate sediment of the desert was most probably derived from highlands in the Iranian plateau and transported to the peninsula during times of low sea level, but unknown exactly when.

REFERENCES CITED

Ahmed, E.A., Soliman, M.A., Alsharhan, A.S., and Tamer, S., 1998, Mineralogical characteristics of the Quaternary sand dunes in the eastern province of Abu Dhabi, United Arab Emirates, *in* Alsharhan, A.S., Glennie, K.W., Whittle, G.L., and Kendall, C.G., eds., Quaternary Deserts and Climatic Change: Rotterdam, The Netherlands, Balkema, p. 85-90.

Besler, H., 1982, The north-eastern Rub' al Khali within the borders of the United Arab Emirates: Zeitschrift für Geomorphologie, v. 26, p. 495-504.

Edgell, H. S., 2006, Arabian deserts: nature, origin, and evolution: Dordrecht, The Netherlands, Springer, 592 p.

Garzanti. E., Ando, S., Vezzoli, G., and Dell'era, D., 2003, From rifted margins to foreland basins: investigating provenance and sediment dispersal across Desert Arabia (Oman, U.A.E.): Journal of Sedimentary Research, v. 73, p. 572-588.

Goudie, A.S., Colls, A., Stokes, S., Parker, A., White, K., and Al-Farraj, A., 2000, Latest Pleistocene and Holocene dune construction at the north-eastern edge of the Rub Al Khali, United Arab Emirates: Sedimentology, v. 47, p. 1011-1021.

Holm, D.A., 1960, Desert geomorphology of the Arabian Peninsula: Science, v. 132, p. 1369-1379.

Stokes, S., and Bray, H.E., 2005, Late Pleistocene eolian history of the Liwa region, Arabian Peninsula: GSA Bulletin, v. 117, p. 1466-1480.