Supplemental Information

Jurassic earthquake sequence recorded by multiple generations of sand blows, Zion National Park, Utah

Item DR1

The following text attempts to show that upward flow of groundwater under steady-state conditions *cannot* explain the sedimentary structures that we have described from the Navajo Sandstone at Zion National Park. The Nebraska Sand Hills are used here *not* because they are a good analog for the Navajo sands sea, but because they represent a “best-case” scenario for rapid, upward, steady-state flow of groundwater within an area of large, inland dunes.

1. Estimate of recharge at Jurassic (Utah) site

In the Nebraska Sand Hills, precipitation P is 400-600 mm/year, and recharge on average is 77 mm (Szilagyi et al., 2011). Prairie grasses and sparse shrubs currently stabilized Nebraska dunes. Hundreds of interdune lakes are present between dunes that reach heights of 130 m.

For the actively migrating Jurassic dunes (no vegetation), recharge was likely a higher fraction of precipitation (P) than in the NSH (which is 15%). At the same time, precipitation was likely lower, P=200 mm/year. By doubling the recharge fraction to 30%, one obtains a recharge value R=60 mm/year for the Jurassic dunes-- comparable to the Nebraska Sand Hills.

2. Dune size, water table, and horizontal groundwater velocity

For water table elevation under a dune with a half-width l_d=1000 m (perpendicular to elongation direction, and parallel to dominant wind), with the coordinate origin at x=0, it follows:

$$h(x) = \frac{R}{2T}(l_d^{\,2} - x^2), \qquad \text{(Bear, 1979)}$$

where $T = Kb$ is transmissivity of the unconfined aquifer. For typical aquifer thickness b=50m and hydraulic conductivity K=10 m/day under the dune, transmissivity is as follows

T=500 m^2/day

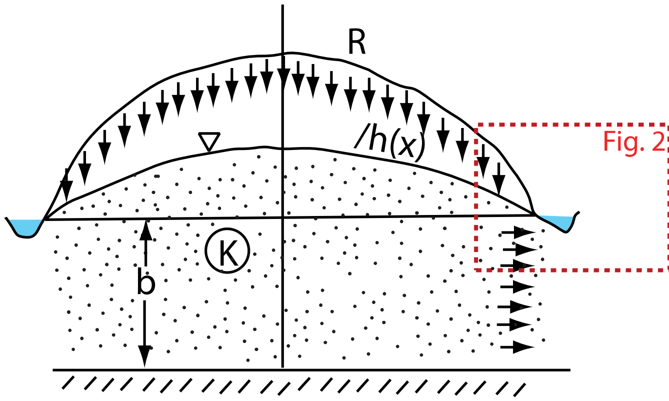


Figure DR1. Groundwater flow under dunes

The slope at the wetland-water table juncture is as follows:

$$\frac{dh(l_d)}{dx} = -\frac{R}{T} l_d = \tan\theta = -\frac{0.06/365}{500} 1000 \approx 10^{-4},$$

while <u>horizontal</u> groundwater velocity is

$$V_{hor}(l_d) = -K\frac{R}{T} l_d = -\frac{R}{b} l_d \approx 10^{-3} m/day = 10^{-5} mm/s$$

The slope and velocity in the aquifer generated by local recharge are small compared to the regional groundwater setting of the Great Plains (see below).

<u>3. Regional water table slope and horizontal groundwater velocity</u>

Large aquifers lacking topographic anomalies are also driven by groundwater recharge. For example, the water table map of NSH shows a head drop Δh =1m per distance L=1000 m. The horizontal head gradient is

$$\frac{dh}{dx} = \frac{\Delta h}{L} = \frac{1}{1000}$$

Again using K=10 m/day for sand, one obtains horizontal groundwater velocity:

$$V_{hor} = K\frac{dh}{dx} = 10\frac{1}{1000} = 0.01 m/day = 10^{-4} mm/s$$

This is the low-end groundwater velocity for the High Plains aquifer. In general, the horizontal head gradient and horizontal velocity may be an order of magnitude higher locally:

$\frac{dh}{dx} = \frac{1}{100} = 10^{-2}$, V_{hor}=0.1 m/day =10^{-3}mm/s.

4. “Shoreline Effect” at the juncture between a dune slope and a lake, or for the Jurassic site, at juncture of a dune slope and a flat land surface where water is evaporated from a shallow groundwater table

Pfannkuch and Winter (1984) investigated changes of groundwater flow direction and velocity near lake/wetland shorelines. The lake was presented as a horizontal plane of constant head. A shoreline (juncture between groundwater table and lake level) is a location where predominantly horizontal head gradient changes direction to predominantly vertical head gradient.

Simultaneously with the direction change, the magnitude of the gradient increases by an order of magnitude (factor of 10) in a very narrow zone parallel to the shoreline (or slope break), but decreases dramatically away from the shoreline towards the center of lake. This numerical result was obtained on a coarse grid, therefore the amplification of magnitude may exceed factor ~10 and induce even higher vertical velocity and gradient.

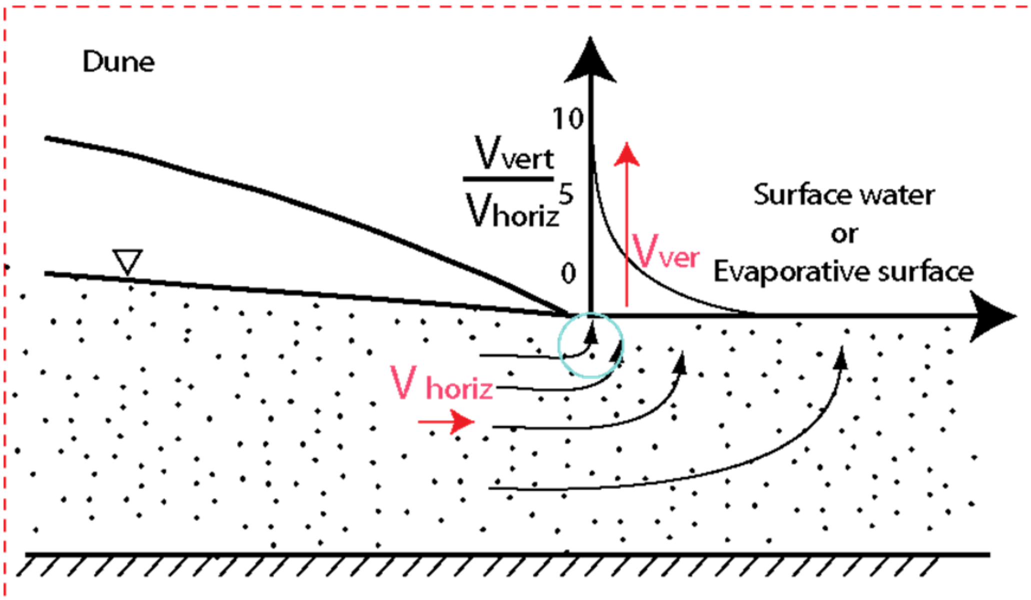


Figure 2. Illustration modified from Pfannkuch and Winter (1984), indicating 10-fold increase of velocity magnitude with the direction change

This can be written as

$$\left[\frac{dh}{dz}\right]_{shoreline} = 10\left[\frac{dh}{dx}\right]_{groundwater}, \quad V_{ver} = 10\ V_{hor}$$

Using $\frac{dh}{dx} = 10^{-2}$ and V_{hor}=0.1 m/day =10^{-3}mm/s, one obtains the magnitude of vertical gradient and vertical seepage velocity near the lake shoreline as follows:

$$\left[\frac{dh}{dz}\right]_{lake} = 0.1, \quad V_{ver} = 10\ V_{hor} = 1\ \text{m/day} = 10^{-2}\text{mm/s},$$

4. What gradient magnitude and vertical velocity is needed for fluidization of the sand?

deMarsily (1986, p.93) provided an estimate of the critical gradient that must be reached to fluidize sand:

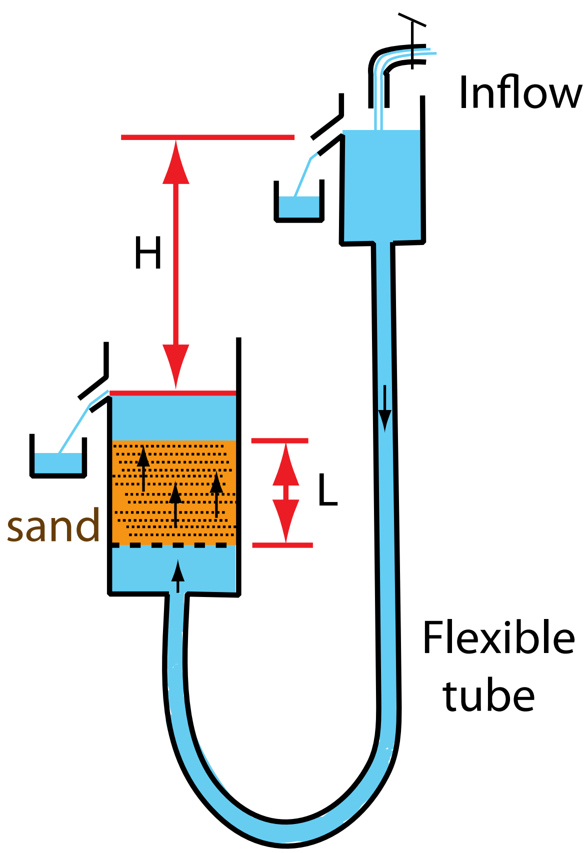
$$\left|\frac{dh}{dz}\right| = \frac{\rho_a}{\rho}$$

where

$$\rho_a = (1-n)(\rho_s - \rho),$$

ρ_s =2.65 g cm^{-3} is rock density, ρ =1.0 g cm^{-3} is water density, and n is porosity (~0.4 for eolian sand). Substituting values into equation for $\left|\frac{dh}{dz}\right|$ results in a criterion:

$$\left|\frac{dh}{dz}\right| = \frac{H}{L} \approx 1, \; V_{ver} = K\frac{dh}{dz} = 10*1 = 10\ \text{m/day} = 0.1\ \text{mm/s}$$



This means that vertical seepage velocity for fluidization should be ~ 0.1 mm/s.

5. Are the static head gradients at the toes of dunes sufficient to fluidize sand?

No. Our estimates show that vertical head gradients developed by several different mechanisms (dune-scale recharge, regional flow, and topographic differences) are on the order of 0.1, and the vertical flow velocities are on the order of .01 mm/sec.

Fluidization requires a vertical head gradient on the order of 1, and a vertical flow velocity of 0.1 mm/sec, as the theoretical approach by deMarsily (2009) shows.

Conclusions

The above analysis shows that, under static conditions, vertical head gradients at the toes of large dunes resting on near-horizontal terrain are lower by an order of magnitude than those needed to fluidize fine to medium sand.

The "boiling sand springs" on the floor of the deeply entrenched, steep-sided valley of the Dismal River (Nebraska Sand Hills; Guhman and Pederson, 1992) indicate that high head gradients in steady state conditions are possible, but extremely rare. Preservation of such a system in the stratigraphic record would likely require the presence of an erosional disconformity with high relief.

In transient conditions, however, pulses of seismic energy can rapidly increase head differences at sites far from epicenters (http://pubs.usgs.gov/fs/fs-096-03/). Such events could possibly trigger liquefaction and fluidization of water-saturated sediment, and if a seismic trigger is provided, the static groundwater conditions that are possible beneath the leeward toes of large dunes would make those sites especially susceptible to liquefaction and fluidization.

References

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Guhman, A.I, and Pederson, D.T., 1992, Boiling sand springs, Dismal River, Nebraska: agents for formation of vertical cylindrical structures and geomorphic change: Geology, v. 20, p. 8-10.

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Item DR2

Figure 4 with and without annotation

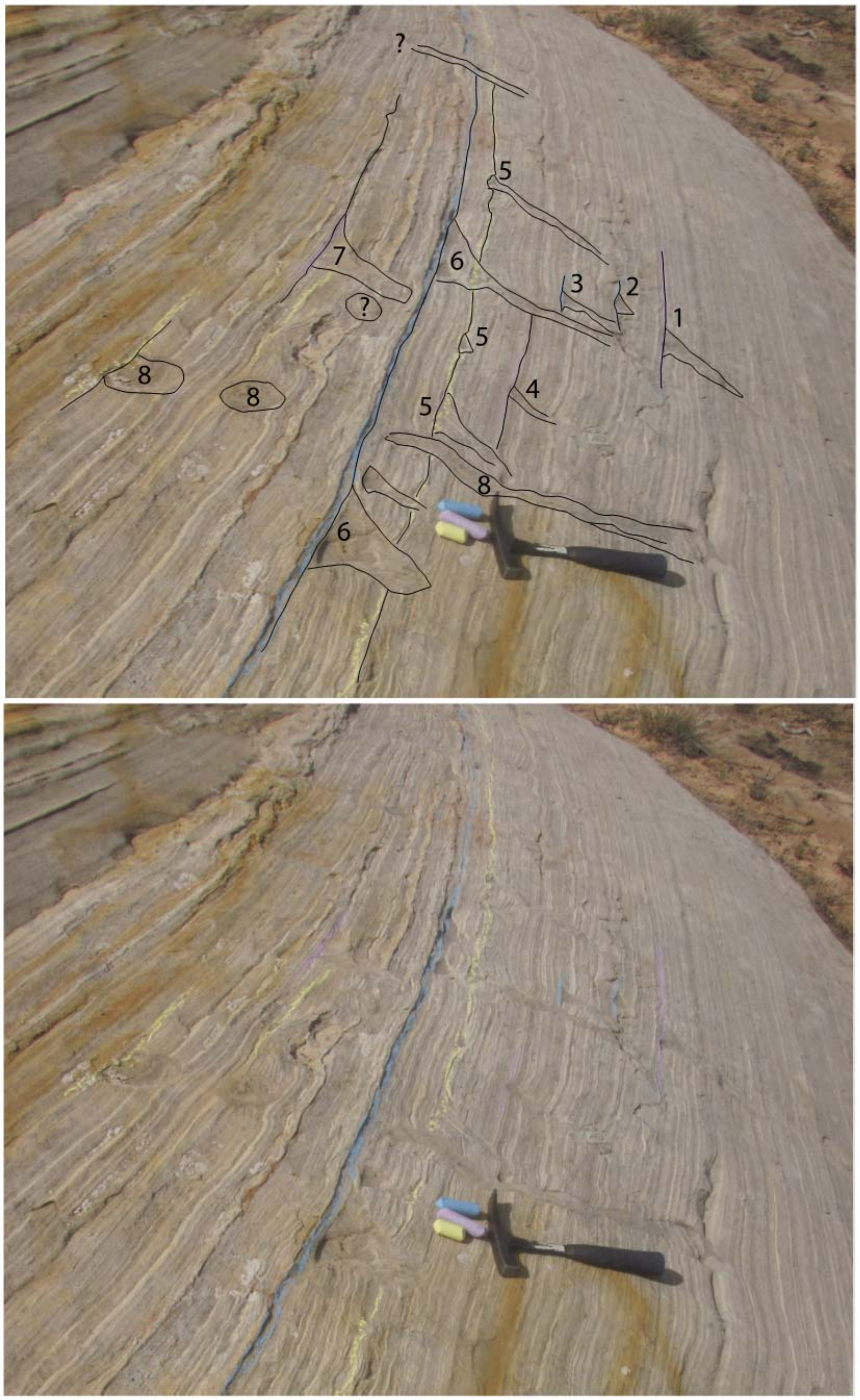

Figure 4 with and without annotation.