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REPLY: GEOPHYSICAL STUDIES AT KARTCHNER CAVERNS STATE PARK, ARIZONA

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In his discussion, Dale Green raises some very cogent questions concerning the mechanisms responsible for natural-potential (NP) anomalies over caves. Space limitations prevented my elaborating on those mechanisms in the paper (Lange 1999), so I take this opportunity to do so here.

Downward filtration in the vadose zone is a function of the vertical hydraulic conductivity of the system, enhanced by the presence of a tension dome over an air-filled cave, particularly above its walls. According to Ford & Williams (1992: 313), infiltrating waters drain preferentially towards the domes and, if chemically aggressive, can result in stoping. Thus, preferential infiltration over the cave leads to a localized enhancement of the streaming potential within and around the cave roof.

Even if the hydraulic conductivity of the cave roof is equivalent to that of the surrounding country rock, water discharging from the cave ceiling enjoys a free fall to the floor, whereas water within the rock walls is confined to its resistive fracture pathway to the depth of the cave floor (Fig. 1a,b). In the analogous electric circuit connected to a battery, current flow through a resistor of a particular value (cave roof) in series with a straight wire (the void) will be nearly twice that of two such resistors in series (country rock lacking voids). The effect of enhanced roof-rock permeability is particularly evident in the NP lows associated with subsidence fractures over mapped galleries of West Virginia coal mines.

Dale Green makes a good point about the paucity of vegetation over Kartchner Caverns and its effect on evapotranspiration. The known cave occurs beneath limestone outcrop having little or no soil cover; hence, only a sparse desert flora grows on the surface. But though the transpiration component of upward water movement may be minimal, the evaporative component in summer is amplified by the "...profusion of fractures and faults crossing cave passages..." (Graf 1999: 63). Due to the high permeability of the cavern roofs, I would expect the top of the vadose water column to reside deeper over the voids than over the less fractured rock separating the galleries. The expected result is a more positive electric response over the wall rock than over the roof rock during the dry seasons. The above arguments assume vertical water movement. However, if most of the flow follows the dipping bedding planes (See Graf 1999: Fig. 2 or Jagnow 1999: Fig. 4), the NP anomalies at the surface could be displaced relative to their corresponding subterranean structures. A more substantive interpretation of the caverns' electrical expression at the surface requires additional NP measurements during different seasons.

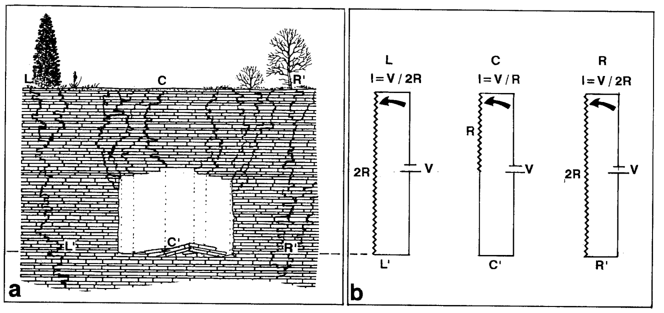

Figure 1:

a) Two fracture pathways for downward percolating water in the country rock around an air-filled cave are designated L-L' (left) and R-R' (right). A similar pathway via the cave roof and void space is designated C-C' (center).
b) Electrical equivalents for the three hydraulic flow paths, where the electric variables are V, battery voltage; R, path resistance; and I, current. The much larger current flowing in the center circuit simulates the greater hydraulic flux along path C-C'. This increased filtration velocity results in a magnified streaming potential over the cave, which is further enhanced by the higher incidence of fractures within the cave roof.

The telluric response, measured by the *gradient method*[*] , over a resistant cylinder (void), is a sombrero-type anomaly, predominantly positive, as depicted in Keller & Frischknecht (1970: Figure 170). Green implies that the gradient method was employed over his desert lava tube. Using the *long-line method*, however, as applied at Kartchner Caverns, the corresponding telluric response (current normal to the cylinder) would have the form of the single cycle of a sloping sine wave, as illustrated in Lange & Kilty (1991: Fig. 3). This is the integral of the gradient anomaly. While telluric "noise" was recognized in the meter readings during the NP survey at Kartchner Caverns, it is unlikely that the alternating and erratic long-period telluric signals would be confused with the relatively systematic dc voltage response between one observation point and the next. Considering that in summer 1989 the apparent resistivity of the Escabrosa Limestone exceeded 1000 ohmmeters—beyond the resolving capability of the Geonics

[*] In gradient mode, two closely-spaced electrodes are moved successively across the ground surface; in long-line mode, one electrode remains fixed while the other steps out to an ever-increasing distance of separation.

EM-34® instrument—telluric responses over Kartchner Caverns probably would be small. In a more conductive environment, large voids near the surface would more likely be detected by the telluric method, as demonstrated theoretically by Keller & Frischknecht (1970).

Natural-potential anomalies are frequently compounded from several mechanisms acting in different directions; for example, downward percolation over a lateral cave stream, tapped by a metal-cased well. Once the individual components are delineated, however, these components can be modeled by one or another method, such as that conceived by Sill (1983). Experimental work above and within an air-filled cavity has been performed by Quarto & Schiavone (1996). As a result of these measurements and observations over other cave sites, they concluded that air-filled cavities in sedimentary rocks give rise to NP anomalies. In their words: "...the anomalies have an electrokinetic origin generated by the percolation of the meteoric waters toward the cavity. The sign of the anomalies depends on the main water flow direction and is dictated by the geological environmen." (Quarto & Schiavone 1996: 429).

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