SUPER-PERMEABILITY ZONES AND THE FORMATION OF OUTFLOW CHANNELS ON MARS.

S. C. Schon and J. W. Head, *Brown University, Department of Geological Sciences, Box 1846, Providence, RI 02912 USA; Samuel_Schon@Brown.edu.*

Introduction: Analysis of outflow channel formation on Mars has recognized permeability as an important constraint in the hydrologic system. Permeability is a particularly important parameter in assessments of groundwater release and regional aquifer recharge. Based on geomorphologic evidence, scenarios of massive water releases have been proposed, which seem to require paradoxically high matrix permeabilities. In this contribution we review the unique permeability features present in a terrestrial hydrocarbon reservoir and discuss the possibility of super-permeability zones in the Mars hydrologic system contributing to the high flux of outflow events.

Ghawar Oilfield, Saudi Arabia: Ghawar, the largest oilfield in the world, is a Jurassic-age carbonate reservoir (primarily the Arab-D Formation) with an anhydrite seal [1]. Located in eastern Saudi Arabia, the structure is a NNE-SSW trending anticline extending approximately 280 kilometers in length. However the field is not homogeneous and historically production has been focused in the northern sub-regions (Shedgum, Ain Dar, and North Uthmaniyah), which have high porosity and permeability, as well as thicker oil columns compared to the southern regions of Ghawar. The field has produced in excess of 55 billion barrels (~6.5B m^3) since production commenced in 1951, while some individual high-flow wells have the ability to produce up to 40,000 barrels/day by tapping zones of extremely high permeability. The field has had an active water-injection program since the 1960's to maintain reservoir pressure and facilitate recovery [2].

Super-*k* Zones: Permeability follows a log-normal distribution in typical reservoirs which implies that small amounts of a reservoir support a disproportionate fraction of total flow; super-k zones are an extreme exaggeration of this phenomenon. The term "super-*k*" originated in the 1970's to describe narrow layers of exceptional flow capacity defined by Saudi Aramco, which operates Ghawar, as zones that produce > 500 barrels per day per foot of thickness (BLPD/ft). Super-*k* zones can be identified by a loss of circulation while drilling, or from an analysis of cores (though super-*k* zones frequently exhibit poor core recovery), but the most conclusive identifications come from flow-meter surveys [3]. One super-*k* zone (typically between three and twelve feet thick) can routinely produce up to 80 percent of a high-productivity well's total flow and even higher percentages have been observed [4]. While this phenomenon facilitates extremely high levels of production in a dry area, it also provides a conductive pathway for water from the water flood front, which can lead a well to prematurely water out [2]. This decreases the horizontal sweep efficiency of the waterflood and can lead to stranded pay (economically producible hydrocarbons). This has led to extensive reservoir modeling efforts to understand how the waterflood interacts with super-*k* zones and how production should be structured to maximize total recovery and minimize the co-production of water. In essence, super-*k* zones can be thought of as large, naturally-occurring multilateral horizontal wellbores that are interconnected to other super-*k* zones by a network of faults and fractures. In this manner, super-*k* zones massively increase reservoir contact surface area and provide a natural means of channeling fluid flow.

While super-*k* zones have permeabilities several orders of magnitude greater than the surrounding reservoir rock, this does not entirely explain their unique hydrologic properties. For example, in a recent geostatistical modeling exercise undertaken by [5] it was found that a facies model alone was incapable of modeling super-*k* flow behavior. Only when a discrete fracture model was paired with the facies model were the results compatible with flow-meter data from the study area.

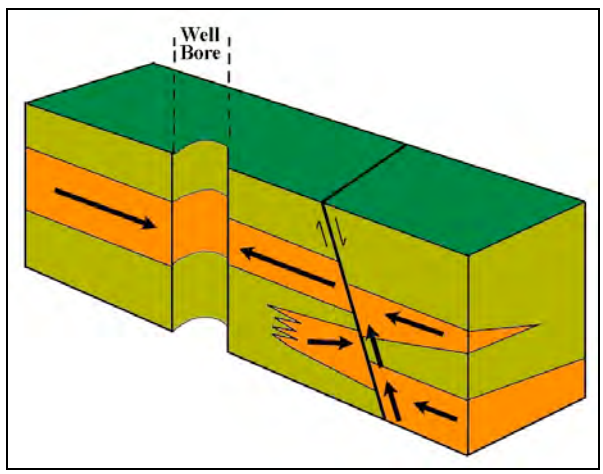

Figure 1: Super-*k* zone (orange) with flow direction indicated by arrows. Normal fault provides communication between stratiform layers.

Clearly, super-*k* zones exhibit behaviors of both stratigraphic and structural origin. This was also confirmed by the modeling work of [6] which employed over sixty years of production history data and found super-*k* zone permeabilities to be tens of Darcy in magnitude. Stratigraphically super-*k* zones are charac-

terized by stromatoporoids (especially *Cladocoropsis*) and partial dolomitization. Swart et al. [4] proposed a formation process in which "early partial dolomitization" was followed by diagenetic fluids that dissolved non-dolomitized material based upon stable isotope data suggesting multiple diagenetic events. Meyer [7] reports evidence of stratiform units with facies properties similar to super-*k* zones, which do not always exhibit super-*k* like flow behavior. This illustrates the uncertainties that still surround super-*k* flow and reservoir communication, but it also clearly points to the importance (and perhaps dominance) of fractures and faults in producing, and more importantly, sustaining super-*k* flow rates.

It is clear that in order to sustain the flow rates characteristic of super-*k*, zones must be aerially extensive and/or be in communication with other portions of the reservoir through fault/fracture structures. During basin formation and tectonic modification, fracturing occurred that preferentially affected the already-cemented, *proto*-super-*k* zone dolomites [4]. Furthermore, it is widely recognized from seismic surveys that the Ghawar field is heavily faulted. Therefore, most current efforts at modeling the reservoir utilize dual-porosity, dual-permeability methods to capture super-*k* features and flow effects [8, 9, 10, 11].

Parameter	Arab-D Formation, Ghawar Field, Saudi Arabia				
Region	Ain Dar	Shedgum	Uthmaniyah	Hawihay	Haradh
Av. Porosity of Reservoir [2]	0.19	0.19	0.18	0.17	0.14
Av. Permeability of Reservoir, Darcy [2]	0.617	0.639	0.220	0.680	0.520
	Super-*k* Zones				
Permeability, Darcy	1-5	"tens of Darcies"	25-55	530	1-6
Source	[10]	[6]	[11]	[8]	[8]

Table 1: Permeability data for matrix rock and super-*k* zones of the Ghawar oilfield, Saudi Arabia.

Discussion: While there has been speculation about the possibility of large carbonate assemblages on Mars, recent data do not support this proposition [12, 13]. Therefore, if the super-*k* flow phenomenon has relevance for Mars hydrologic system, it is necessary to consider other substrates and formative mechanisms for the development of high permeability zones. A significant portion of Mars southern highlands rocks is composed of lava flows and igneous materials. Interpreted to be similar to unfractured terrestrial basalts, Mars average surface permeability is thought to be ~1 Darcy [14, 15].

To first order, Mars has processes potentially amenable to the formation of super-permeability zones akin to terrestrial super-*k* zones – perhaps with even greater discharge potential. Stratiform zones of high permeability and connective structures are speculated to have significantly different morphology and provenance on Mars. Among the broad mechanisms are: (1) zones of aeolian material deposited between periods of volcanic flows, (2) pyroclastic deposits emplaced by volcanic eruption interbedded with basaltic lava flows [e.g., 16, 17], (3) permeable stratiform zones interconnected by structural features such as faults and dikes [e.g, 18, 19, 20], (4) localized zones of highly fractured basalt or other layers, (5) megaregolith or crater ejecta layers [e.g., 15], and (6) dikes as important communicative structures between stratiform layers as well as initiators of outflow events [e.g., 20, 21].

Preliminary Conclusions: The Ghawar oilfield is an illustrative example of the importance of communicative zones of extremely high permeability in understanding the dynamics of complex reservoirs and hydrologic systems. Such features are useful in considering the drainage of large reservoir complexes under the Martian cryosphere to form outflow channels. However, even the extreme super-*k* permeabilities shown in Table 1 fall several orders of magnitude short of the permeabilities (>100,000 Darcies) proposed by others for the formation of outflow channels [21, 22]. Therefore, other factors, such as those listed above, are also required. For example, zones of high permeability could function to expedite drainage of distal reservoir sectors and channel fluid movement into a structural network. Flow in the structural network could be further enhanced by the overpressure of the hydrologic system induced by the cryosphere [23, 24].

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