Evidence of Rain Shadow in the Geologic Record: Repeated Evaporite Accumulation at Extensional and Compressional Plate Margins

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ABSTRACT: Arid climates have been common and effected water resources throughout Earth history. This climatic history provide a key to understanding current causes for desertification and a means to devise realistic strategies for coping with its effects. Desert climates are often indicated in the geologic record by thick sections of evaporites (anhydrite, gypsum and halite) that have accumulated in both lacustrian and marine settings either adjacent to margins of recently pulled apart continental plates, in compressional terrains of colliding margins, or in areas of local tectonic uplift or sediment accumulation that have isolated standing bodies of water from the sea.

These linear belts of evaporitic rocks can be directly related to rain shadow caused by:

1) The aerial extent of adjacent enveloping continental plates
2) The occurrence of uplifted crust marginal to linear belts of depressed crust
3) The occurrence of linear belts of depressed crust, with surfaces that are often below sea level
4) The occurrence of internal drainage and/or limited access to open ocean waters
5) The location within a climatic belt already characterized by low rainfall

Examples of evaporite generation in depressed extensional basins belong to the Mesozoic sedimentary section of the North and South Atlantic margins: the Mesozoic of the northern Gulf of Mexico; the Mesozoic of the Yemen rift belt; the Mesozoic and Tertiary of Eritrea; the East African Rift; the Dead Sea, and so on.

In contrast the current Arabian Gulf and its underlying Mesozoic to Tertiary rock section is a prime example of a linear intercontinental compressional zone that has a history punctuated by limited access to the sea and repeated desert climates. Other comparable examples include sections of the Silurian of the Michigan Basin and western New York State; the Devonian of western Canada and the Northwest USA; the Pennsylvanian of the Paradox Basin; the Permian of New Mexico and west Texas; the Permian of the Zechstein Basin; the Jurassic of the Neuquen Basin of Argentina; the Tertiary of the Mediterranean; and the Mesozoic and Tertiary of the final phases of the Tethys Sea (e.g., the Caspian and Aral Seas, etc.).

Examples of evaporite accumulation behind barriers developed by structure and sediment buildup include the Permian Khuff Formation and the upper Tuwaiq Mountain Group, both of which accumulated on the eastern margin of the Arabian Shield and were isolated from the Tethys Ocean.

The recognition of the strong tie between plate setting and climate can be used to predict the evolution of the climatic conditions within present day desert settings. The water resources in these areas of rain shadow and their proximity to the continental margins of lakes and narrow marine bodies match those of the past. These resources are often finite and need to be husbanded. Though some effects of deserts associated with rain shadow can be circumvented through river diversion and creation of artificially dammed water reservoirs, reverse osmosis etc., many other desert areas are subject to depletion of fossil water resources no matter the care taken to avoid this effect.

The geologic record of the earth has a strong message for us all, particularly hydrologists, suggesting that despite human intervention, the effects of desertification are difficult to contend with and often almost impossible to avoid. The overwhelming signal from Nature suggests that the solution to water resource problems is often a mix of better engineering of the current resources and thoughtful political decisions.

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INTRODUCTION

Examining plate reconstructions of continental positions through time immediately highlights the high frequency of desert climates through earth history (Golonka et al., 1994). For instance from geological record one can surmise that desert climates have existed from the Precambrian to the Recent, existing in the past as they do today on wide continental landmasses positioned in the arid subtropical belt straddling approximately 30 degrees of the equator, particularly when and where mountains surrounded these areas. In the examples that follow in the paper, we indicate that the coastal regions adjacent to terrestrial deserts have often been the sites of evaporite accumulation that can be used as evidence of desertification.

As with the deserts of the present day, deserts of the past were by definition closely linked to a lack of water resources. The sedimentary record shows that unchanging and repeated desertification caused the water table to decline and become saline, as it did in the rain-shadowed deep intermountain basins of the western USA, British Columbia, the Andes, and the Tibetan Plateau with the precipitation of evaporite minerals (Kendall, 1992). Natural vegetation would have declined, as it clearly has done through the last 3000 to 4000 years in the Rub al Khali (Glennie, 1997) and in the Tigris/Euphrates valleys (Thomas and Middleton, 1994). Erosion of sediments would have been common (Thomas and Middleton, 1994) and aeolian sediments tended to accumulate, as they did to form sandstones of the Navajo Formation (Kocurek, 1991) and the Rotliegendes Formation (Glennie, 1997; and Howell and Mountney, 1997).

Geological data suggest that repeated occurrences of desert climate and their common origins were and are unavoidable. Nevertheless though desertification is imposed by geography and physiographic position, one can argue that the effects of deserts can be ameliorated by transporting water through the diversion of current drainage (Thomas and Middleton, 1994) and by reverse osmosis of seawater and subsurface brine, as can be seen at various locations in Saudi Arabia, Kuwait and the United Arab Emirates (Morton et al., 1996; Al-Mutaz, 2001; Gotor et al., 2001; Harusi et al., 2001; Martin-Lagardette, 2001; Shaposhnik et al., 2001; Wilf and Schierach, 2001; and Zilouchian and Jafar, 2001). In contrast Bourouni et al. (2001) suggest that a process of humidification-dehumidification (HD) is a technique that can be adapted for water desalination when the demand is decentralized.

Similarly judicious use of fossil water (Leake et al., 2000 and Alliey et al., 1999) suggests that it is possible to develop, manage, and protect groundwater resources in a sustainable manner. The same thing can be said of judicious catchment of existing runoff (Guymon and Hromadka, 1985). In light of this argument we suggest that the earth's history can be used to better understand the broader causes of current desertification and develop realistic strategies for coping with its effects.

THE STRATIGRAPHIC SIGNAL OF DESERT CLIMATES

Desert climates are indicated by the presence of aeolian sediments, as for example the Jurassic Navajo sandstones of the Western USA (Prothero and Schwab, 1996) and the Rotliegendes sandstones of the Permian of the Zechstein Basin in Western Europe (Glennie, 1997; Howell and Mountney, 1997). They may also signal themselves with the focus of this paper, evaporites. These evaporite indicators can be continental salt flat and playa evaporites like those of Death Valley (Spencer and Roberts, 1998; Roberts and Spencer, 1998), or the Wilkins Peake Member of the Green River Formation (Kendall, 1992); arid coastline evaporites like those of the Permian backreef section of the Guadalupe Mountains of west Texas (Ward et al., 1986), or the easternmost of the Hith Anhydrite of the Central offshore UAE (Alsharhan and Kendall, 1994); or they may occur as isolated marine and lacustrian evaporite basins such as that of the current Caspian Sea (Dzens-Litovskiy and Vasil'yev, 1973) or the Aral Sea (Rubanov and Bogdanova, 1987) representing the last dying gasp of the Tethys Sea, or as the product of isolation related to breakup as in the Gabon Basin in the South Atlantic, (Trayner et al., 1992) or the initiation of the Gulf of Mexico (Cheong et al., 1992) or the North Atlantic (Carswell et al., 1990; Tanner, 1995; El-Tabakh et al., 1997; Koning 1998).

When and where do evaporites associated with desert climates occur?

The literature cited above suggests that deserts and evaporites are associated but it remains to be established when thick sections of evaporites (anhydrite, gypsum, and halite) accumulate. They are found in both lacustrian and marine settings (Kendall, 1992) either:

1) Adjacent to margins of recently pulled-apart continental plates (Figure 1).
2) In compressional terrains of colliding margins (Figure 2).
3) Behind structural and depositional barriers (Figure 3). If these various linear tectonic belts

are in rain shadow there is a consequent accumulation of evaporite sediments. This rain shadow might be caused by

- The aerial extent of adjacent enveloping continental plates. In fact current deserts are often related to rain shadow caused by wide continental plates as can be seen in the Sahara (Benazzouz, 1993), and the Empty Quarter or Rub al Khali of Arabia (Glennie, 1997; Howell and Mountney, 1997) and central Australia (Woods et al., 1990; Nanson and Price, 1998).
- The occurrence of uplifted crust marginal to linear belts of depressed crust forming intermountain basins like that of Clinton Lake, British Columbia, (Renaut, 1994); the Salar Grande in the Altiplano "Puna" Plateau of the northern Chilean Andes (Alonso et al., 1991); Eastern Californian Death Valley (Spencer and Roberts, 1998; Roberts and Spencer, 1998); Mongolia (Owen et al., 1997); Xinjiang (Jiang et al., 1991)
- The occurrence of depressed-crust in linear belts with surfaces that are often below sea level such as the current Dead Sea (Neev and Emery, 1967; Kendall and Harwood, 1996; and Csato et al., 1997); the Mediterranean during the Messinean, (Schreiber, 1975); the Red Sea (El-Anbaawy et al., 1992) and the Gulf of Suez; Aral Sea (Rubanov and Bogdanova, 1987); and the Caspian Sea (Dzens-Litovskiy and Vasil'yev, 1973).
- The occurrence of internal drainage and/or limited access to open ocean waters as can be seen in the Aral Sea (Rubanov and Bogdanova, 1987); Caspian Sea (Dzens-Litovskiy and Vasil'yev, 1973); the early South (Trayner et al., 1992) and North Atlantic (Carswell et al., 1990; Tanner, 1995; El-Tabakh et al., 1997; and Koning, 1998), Late Triassic and Early Jurassic of Gulf of Mexico (Cheong et al., 1992).

Evaporite generation during breakup of continental plates

The Mesozoic sediments of the northern Atlantic (Carswell et al., 1990; Tanner, 1995; El-Tabakh et al., 1997; Koning, 1998) exhibit the presence of an isolated linear belt of interior drainage with a limited or restricted entrance to the sea (Figure 1). Regional drainage tended to flow away from breakup margins and the air system was that of the arid tropics. There was a wide envelope of surrounding continents. Other similar extensional evaporite basins include the Mesozoic of the northern Gulf of Mexico (Cheong et al., 1992); the Mesozoic of the South Atlantic margins (Trayner et al., 1992); the Mesozoic of the Yemen rift belt (Youssef, 1998; Csato, 1998; Csato and Kendall, 1997); the Mesozoic and Tertiary of Eritrea; the East African Rift; the Dead Sea (Neeve and Emery, 1967; Kendall and Harwood, 1996; Csato et al., 1997), and so on.

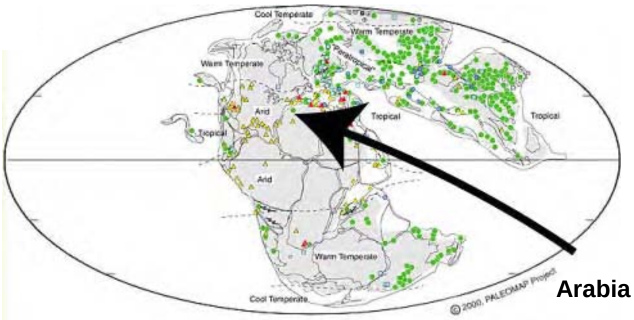

Figure 1. The geography of the Lower Jurassic arm of the northern Atlantic exhibit the presence of an isolated linear belt of interior drainage with a limited or restricted entrance to the sea (Scotese and Sager 1988; and Golonka et al 1994). Regional drainage tended to flow away from breakup margins and the air system was that of the arid tropics. There was a wide envelope of surrounding continents.

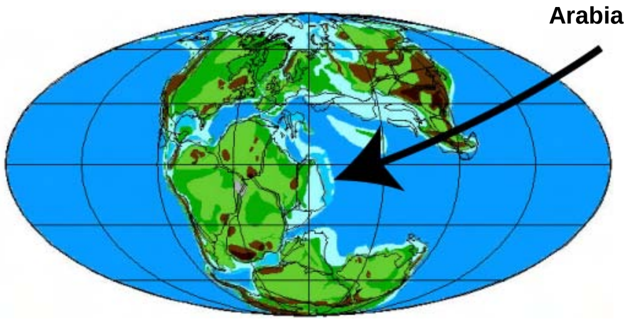

Figure 2. Setting of the Late Paleozoic Khuff Formation of Arabia (Golonka et al 1994) which contains evaporites formed when barriers were formed by the movement of what was an original Hercynian horst and block terrain adjacent to the southern shore of the Tethys Ocean. These barriers limited access to the sea punctuating the geological record with evaporites when there was an associated occurrence of repeated desert climates. These bodies of the seawater occurred as isolated linear belts of interior drainage with restricted entrance to the open Tethys Ocean. Regional drainage probably tended to flow into this basin, and the air system was that of the arid tropics. There was a wide envelope formed by the surrounding subcontinents of Arabia and Africa.

Evaporite generation during collision of continental plates

The current Arabian Gulf and the underlying Late Mesozoic to Tertiary of the area (Murris, 1980; Buchbinder, 1995; Aqrawi, 1993; Kashfi, 1980) are stratigraphic sections that represent prime examples of a linearly depressed intercontinental compressional zone that has a history punctuated by limited access to the sea and repeated desert climates (Figure 2). This sea represents an isolated linear belt of interior drainage with a restricted entrance to the open ocean. Regional drainage tends to flow into the Arabian Gulf and the air system is that of the arid tropics. There is a wide envelope formed by the surrounding subcontinents of Arabia and Asia Minor.

Other comparable examples from collision margins include sections of the Silurian of the Michigan Basin, which is situated on the cratonic interior landward of the Appalachian Foreland basin (Briggs and Lucas, 1954; Briggs and Briggs, 1974; Nurmi and Friedman, 1974; Gill et al., 1978; Shaver, 1991); the Devonian of Western Canada and the Northwest USA where the sediments collected in the cratonic interior landward of the Cordilleran Foreland basin (Whittaker and Mountjoy, 1996; Kendall, 1978; Wardlaw and Reinson, 1971; Klingspor, 1969); the Pennsylvanian of the Paradox Basin which is located in the cratonic interior landward of the Cordilleran Foreland basin (Kendall, 1988; Williams-Stroud, 1994); the Permian of New Mexico and west Texas, which is located in the

Figure 3. The current Arabian Gulf represents prime example of a linearly depressed intercontinental compressional zone that has a history punctuated by limited access to the sea and repeated desert climates. This sea represents an isolated linear belt of interior drainage with a restricted entrance to the open ocean. Regional drainage tends to flow into the Arabian Gulf and the air system is that of the arid tropics. There is a wide envelope of dsesert shadow formed by the surrounding subcontinents of Arabia and Asia Minor. (Photo by NASA).

cratonic interior landward of the Marathon Foreland basin (Ward et al., 1986); the Permian of the Zechstein Basin which is located in the cratonic interior landward of the Alpine Foreland basin (Strohmenger et al., 1996; Smith, 1980; Wagner et al., 1981; Goodall et al., 1991); the Jurassic of the Neuquen Basin of Argentina located in the cratonic interior landward of the Andean Foreland basin (Barrio, 1990); the Tertiary of the Mediterranean, which is a basin trapped when oceanic crust was caught between Africa and the Alpine chain (Schreiber, 1975); and the Mesozoic and Tertiary of the final phases of the Tethys Sea where the cratonic interior lies landward of the Alpine/Himalayan Foreland basin in the Caspian Sea (Dzens-Litovskiy and Vasil'yev, 1973) and Aral Sea (Rubanov and Bogdanova, 1987).

Evaporite generation behind structural and sediment-generated barriers.

In contrast to the above examples are the Late Paleozoic Khuff Formation of Saudi Arabia (Charara et al., 1991; Al-Jallal, 1991, Stump and van der Eem, 1994; Al-Aswad, 1997) and the UAE and Oman (Murris, 1980) (Figure 3) and early Mesozoic Arab D and Hith Anhydrite Formations of Saudi Arabia, southern Kuwait, and western Iran (Murris, 1980; Alsharhan and Magara, 1994; De Matos, 1994) (Figure 4). In both these cases the sedimentary sections of the Arabian Gulf contain

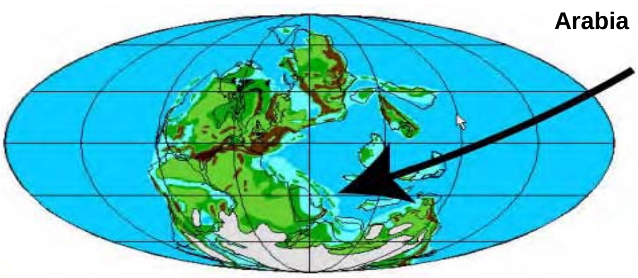

Figure 4. Setting of the Late Jurassic Arab D and Hith Anhydrite Formations of Arabia (Golonka et al., 1994) which contain evaporites formed when barriers were formed by the movement of what was an original Hercynian horst and block terrain adjacent to the southern shore of the Tethys Ocean and the accumulation of sediment over them. These barriers limited access to the sea punctuating the geological record with evaporites when there was an associated occurrence of repeated desert climates. These bodies of the seawater occurred as isolated linear belts of interior drainage with restricted entrance to the open Tethys Ocean. Regional drainage probably tended to flow into this basin, and the air system was that of the arid tropics. There was a wide envelope formed by the surrounding subcontinents of Arabia and Africa.

evaporites formed when barriers were formed by the movement of what was an original Hercynian horst and block terrain adjacent to the southern shore of the Tethys Ocean. These barriers accumulated sediment over them and limited access to the sea. This lead to the punctuation of the geological record with evaporites when there was an associated occurrence of repeated desertclimates. These bodies of the seawater occurred as isolated linear belts of interior drainage with restricted entrance to the open Tethys Ocean. Regional drainage probably tended to flow into this basin, and the air system was that of the arid tropics. There was a wide envelope formed by the surrounding subcontinents of Arabia and Africa.

Another comparable feature is that of the Lower Cretaceous Ferry Lake Anhydrite of Alabama and Florida (Raymond, 1995), which formed behind a carbonate barrier with limited access to the Gulf of Mexico.

CONCLUSIONS

The recognition of the strong tie between plate setting and climate can be used to understand the unforgiving evolution of the climatic conditions within present day desert settings. The water resources in these areas of rain shadow and their proximity to the continental margins of lakes and narrow marine bodies match those of the past. Current resources are often finite and need to be husbanded. Though some effects of deserts associated with rain shadow can be circumvented through river diversion and creation of artificially dammed water reservoirs, many other desert areas are subject to depletion of fossil water resources no matter the care taken to avoid this effect.

Certainly the earth's geologic record of has a strong message for us all, particularly the hydrologists among us. Despite human intervention, the effects of desertification are difficult to contend with and often almost impossible to avoid. The overwhelming signal from Nature suggests that the solution to water resource problems is often a mix of better engineering of the current resources and thoughtful politics motivated by an understanding of the natural systems involved. It would appear that reverse osmosis could best take advantage of the secondary and tertiary use of wastewater (Al-Mutaz, 2001; Gotor et al., 2001; Harusi et al., 2001; Martin-Lagardette, 2001; Shaposhnik et al., 2001; Wilf and Schierach, 2001; and Zilouchian, 2001). In contrast, Bourouni et al. (2001) suggest that a process of humidification-dehumidification (HD) is a technique that can be adapted for water desalination when the demand is decentralized.

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