Preamble and summary

Thick sections of evaporites (anhydrite, gypsum and halite) in the geologic record usually have accumulated adjacent to margins of recently pulled apart continental plates or in compressional terrains of colliding margins. They occur in both ancient lacustrian and marine settings where desert climates prevailed. 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

The current Arabian Gulf and the underlying Mesozoic to Tertiary rock section commonly contains evaporites and is a prime example of a linearly depressed intercontinental compressional zone that has a history punctuated by limited access to the sea and repeated desert climates. Other comparable examples with thick evaporite sections include sections of: the Silurian of the Michigan Basin and Western New York State; the Devonian of Western Canada and the NW 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., in the Caspian and Aral Seas, etc. etc.

Extensional evaporite basins include: the Mesozoic of the northern Gulf of Mexico; the Mesozoic of the North and South Atlantic margins; the Mesozoic of the Yemen rift belt; the Mesozoic and Tertiary of Eritrea; the east African Rift; and the Dead Sea, etc., etc.

The recognition of this strong tie between plate setting and climate can be used to predict the climatic conditions of ancient desert settings and associated thick evaporites. This rule of thumb is base on the fact that modern areas of evaporite accumulation match areas with rain shadow and a proximity to the continental margins where lakes and narrow marine bodies match similar evaporite settings of the past.

The section that follows below is based on a paper by Kendall et al (2002) that describes the evidence of rain shadow in the geologic record and how it produced repeated evaporite accumulation at extensional and compressional plate margins.
For instance from the character of the sedimentary record, particularly the presence of evaporites and associated subaerial dune sands, one can surmise that desert climates have existed from the Precambrian to the Recent. Their setting in the past matches that of today; in other words on wide continental landmasses positioned in the arid subtropical belt that straddles a belt approximately 30 degrees from the equator, particularly when and where mountains surrounded these areas. The examples listed below indicate that the coastal regions adjacent to terrestrial deserts have often been the sites of desertification and have been associated with evaporite accumulation.

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 Rhub 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 (Kucurek 1991) and the Rotliegendes Formation (Glennie 1997; and Howell and Mountney 1997). The geological data suggest that repeated occurrences of desert climate and their common origins were imposed by geography and physiographic position. The Stratigraphic Signal of Desert Climates

Desert climates of the past are best indicated by the presence of evaporites. These evaporite indicators can be continental salt flat and playa evaporites like those of Death Valley (Spencer and Roberts 1998, and 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, and Koning 1998).

Other indicators of desert climates are 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).

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:
2) In compressional terrains of colliding margins:

(Figure 2) 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 desert shadow formed by the
surrounding subcontinents of Arabia and Asia Minor. (Photo by NASA).

3) **Behind structural and depositional barriers:**

(Figure 3) Setting of the Late Paleozoic Khuff Formation of Saudi 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.

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 Rhub al Khali of Arabia (Glennie 1997; Howell, and Mountney 1997) and central Australia (Woods et al. 1990, and 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; and Roberts and Spencer 1998); Mongolia (David and Nicholas 1994); and Xinjiang (Jiang 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; and 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. Evaporite generation during collision of continental plates

The current Arabian Gulf and the underlying Late Mesozoic to Tertiary of the area (Murriss 1980), the Fars of Iran (Buchbinder 1995; Aqrawi 1993; and 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; and 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 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; and Al-Aswad 1997) and the UAE and Oman (Murriss 1980) (Figure 3) and early Mesozoic Arab D and Hith Anhydrite Formations of Saudi Arabia, southern Kuwait, and western Iran (Murriss 1980; Alsharhan and Magara 1994; and De Matos 1994) (Figure 4).
In both these cases the sedimentary sections of the Arabian Gulf 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. 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 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.

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 predict the occurrence of evaporites in 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 and lead to the accumulation of evaporites. Here the earth's geologic record provides a strong message that the effects of desertification suggest that evaporites occur in settings associated with the initial phases of continental break up and continental collision.

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