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Salty Matters

John Warren - Friday, March 31, 2017

Salt, Oil, Gas and Metals: What drives the link?

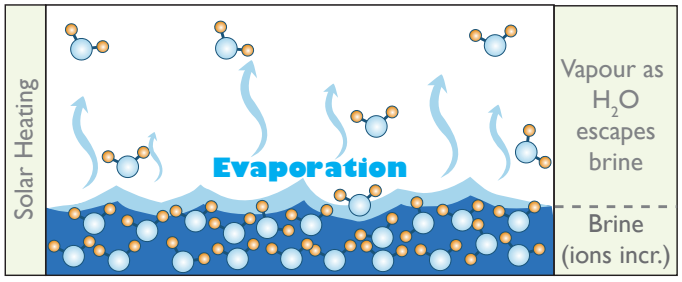

Figure 1. Brine formation by the loss of liquid water volume and can occur via solar heating at any liquid water surface, either at the surface of a standing water body or in a pore. A series of salts dropout from an increasingly saline brine.

Introduction

This article is based on a review written for CSPG Reservoirs and presented orally at the AAPG 2016 meeting in Calgary. It endeavors to give an up-to-date synopsis of how and why ancient salty basins tend to contain elevated levels of oil, gas and metals. It begins with an overview of hydrologies, then places ancient salt bodies in their climatic and tectonic context, and lastly looks at industrial associations and predictors. For brevity, details of many regions, deposits and references are summarised as tables (sans references), so feel free to contact me (jkwarren@saltworkconsultants.com or via www.saltworkconsultants.com) with requests for more comprehensive documentation of particular examples.

Evaporite styles reflect intrabasin brine hydrology

If we accept the definition of an evaporite as "A salt rock originally precipitated from a saturated surface or near surface brine in hydrologies driven by solar evaporation," then the greater volume of saline mineral salts in the earth's sedimentary realm are the product of solar heating of brine. There are other sets of mineral salts in the depositional and diagenetic realm with the same mineral composition as evaporite salts, but these salts result from cryogenic, hydrothermal or burial re-equilibration processes (Warren, 2016). For a water molecule to escape into the vapour phase in an evaporitic setting, and so increase the salinity of an enduring brine body or pore water in the capillary zone of a sabkha, the water molecule must; 1) absorb heat energy, 2) be located near the liquid surface, 3) be moving in the proper direction, 4) have sufficient energy to overcome liquid-phase intermolecular forces and, 5) pass through the surface tension interface (Figure 1).

Simple physics of molecular escape (rate and intensity) during solar evaporation essentially controls the potency of remaining brine. Bed textures and mineralogies entomb evidence of concentration levels in the brine and its hydrological setting/stability (Figures 2, 3). This makes evaporites excellent gauges of climate present and past. In combination, relative brine density and specific heat capacity of adjacent brine masses control density and thermal stratification in saline brine bodies located at or near the earth's surface (Figure 2). Subsequent burial

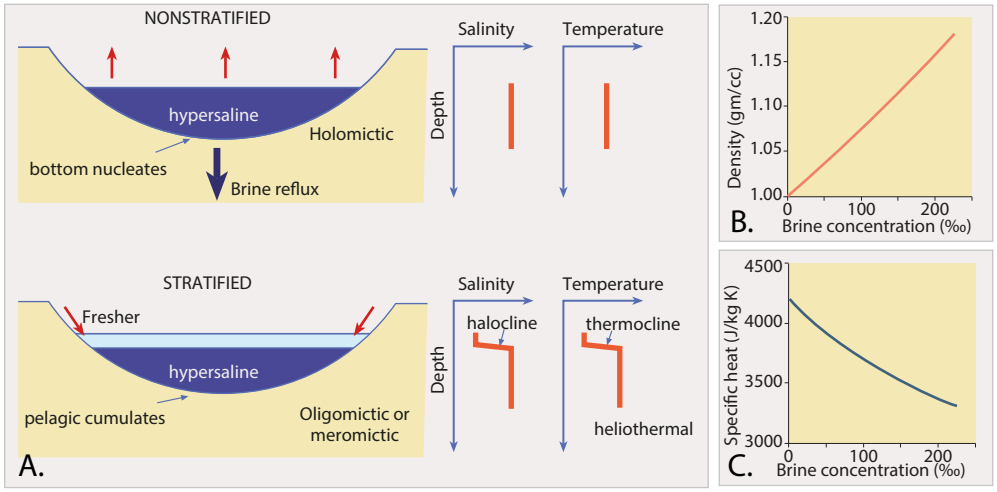

Figure 2. Brine stratification and its causes. A) Terminology and causes of water mass zonation in a perennial brine lake or seaway. B) Relationship between brine concentration and brine density; as concentration increases, density increases. C) Relationship between brine concentration and specific heat; as concentration increases, density increases specific heat decreases.

alteration controls later textural evolu-tion by interactions with regional shallow and deep phreatic crossflows (Warren, 2016).

Specific heat is the amount of heat needed to raise one gramme of a substance by 1 °C. For a given amount of heat in-put, a unit volume of hypersaline water will show a greater increase in temperature than a less salty water (Figure 2c). Given the same degree of insolation, this means density-stratified water bodies tend to be heliothermic, with the lower, denser bottom brine layer being warmer than the somewhat less saline, less dense, upper water layer (Figure 2a). The level in any water column where a marked change in temperature occurs is the thermocline, and in a density-stratified brine mass corresponds to the halocline, also termed a chemocline (Figure 3a). The combination of high temperature, high salinity and lower oxygen levels in the lower brine mass in a heliothermal brine system means only a specialised bio-ta can survive there, often with specialised bacterial populations living in waters just above a saline thermocline. A mod-ern example is the purple sulphur-oxidising community flourishing immediately above the halocline in Lake Mahoney, British Columbia. Fluctuating salinity and nutrient levels endemic to many evaporite depositing regions encourage preservation of elevated levels of organic matter in a variety of hypersaline settings past and present ("feast and famine" associations; Warren, 2011).

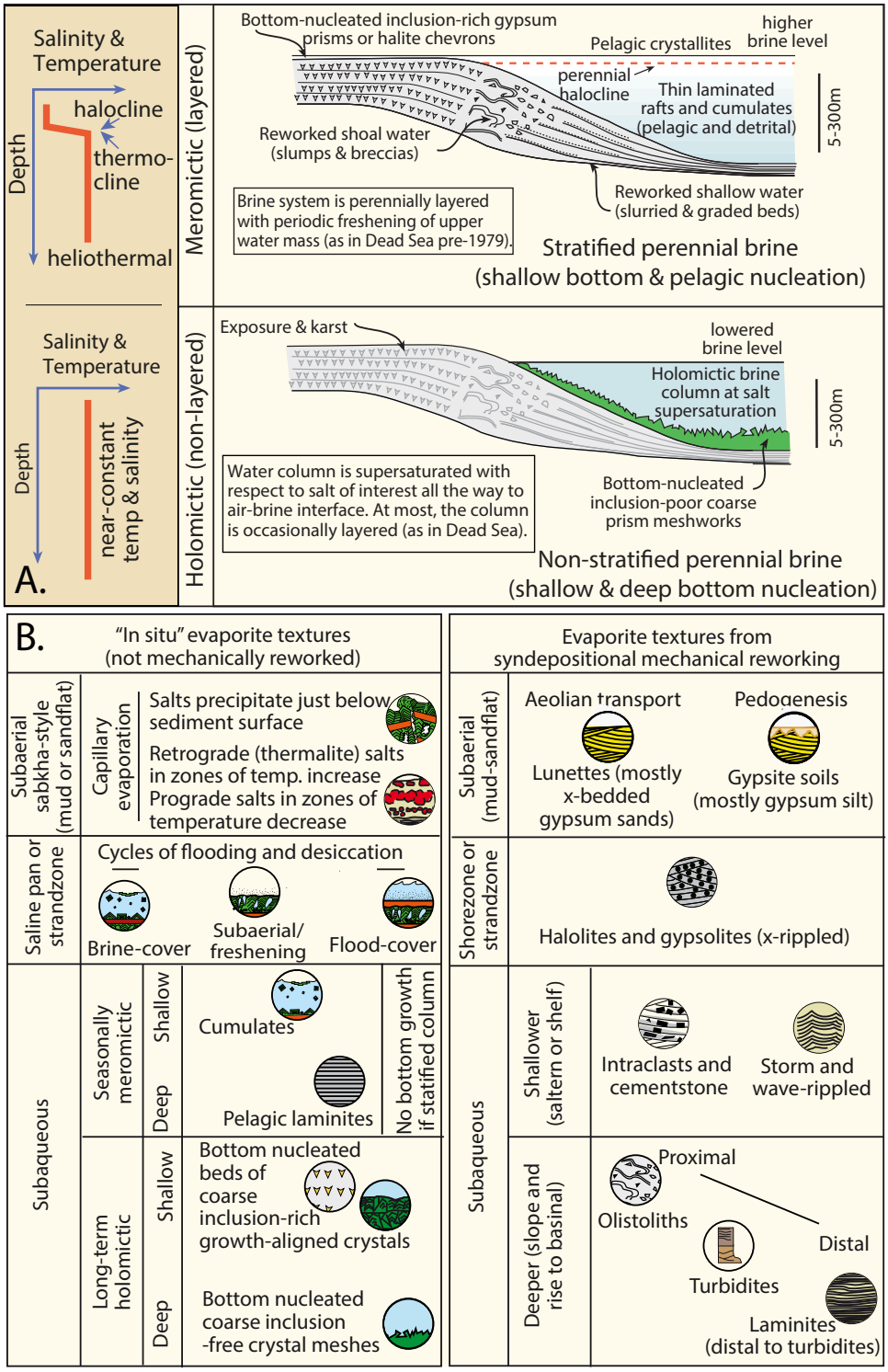

Figure 3. Inter-relationships between brine stratification, stability and depositional texture (After Warren, 2016). A) When stratified, bottom nucleation is restricted to shallower areas, when holomictic, bottom nucleated growth possible over whole basin floor. B) Significance of primary evaporite depositional textures as indicators of brine hydrology.

As any brine concentrates, its density increases (Figure 2b). The overlying water body must be holomictic for bottom-nucleated salts to accumulate across the subaqueous floor of a brine mass and for dense, saturated brine to sink into underlying sediments (Figure 3a). Holomixis means a near homogenous distribution of brine density, temperature, and salinity throughout the brine mass, with internal mixing being ongoing and mostly maintained by wind movement. In contrast, a meromictic brine body is internally stratified, with a lower more-saline, denser,

warmer water mass separated across a halocline from an upper, less saline, less-dense, cooler water mass. A longterm halocline hinders chemical or physical changes in the underlying denser waters, so shutting down bottom nucleation, as well as slowing and ultimate-ly stopping brine reflux. A permanently stratified system is ectogenic, while a brine column that is temporarily stratified is endogenic.

Over decades, saline water masses can change from ectogenic to endogenic. In February 1979, salinity equalisation drove the mixing of upper and lower water masses in the Dead Sea, resulting in a holomictic water body. Since then, aside from short episodes of storm-flood-driven freshening of the upper water mass in 1980 and 1994 (meromixis), the Dead Sea has been holomictic, and halite has been accumulating on the deep lake floor (Gertman and Hecht, 2002). Before 1979, the Dead Sea had been a stratified system for at least 400 years and only pelagic carbonate laminites with minor gypsum, not halite, accumulated on the deep lake floor, beneath a 370-380 m deep brine column.

Holomixis permits deposition of a coherent salt layer across the whole basin floor, beneath both shallow and deep brine columns. Density stratification allows evaporitic salts to crystallise only in the upper water mass or at the upper brine- lower brine interface, so bottom nucle-

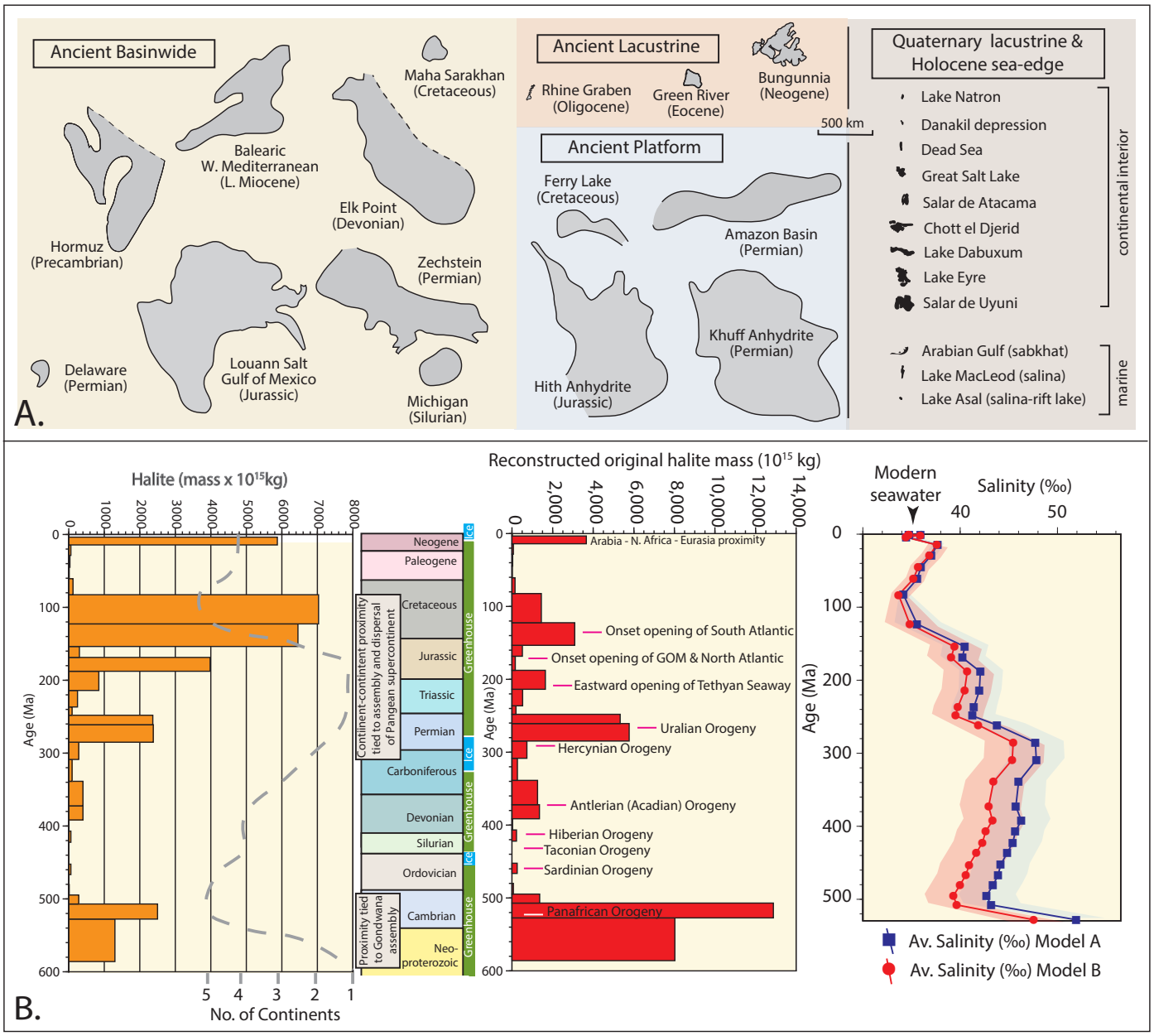

Figure 4. Ancient evaporites. A) Comparison in depositional extent of modern and ancient evaporites. B) Variable development of basinwide evaporites in time showing importance of proximity of tectonic plate edges (after Warren 2016). Also shows how deposition and dissolution of saline giant salt masses influence Phanerozoic ocean salinity (Hay et al., 2006).

ation tends to occur on the shallower lake floor, where it lies above the halocline (Figure 3a). That is, long-term (ectogenic) column stratification mean bottom nucleation of salts can only occur where the upper salt-saturated brine mass intersects the sediment bottom, with a pelagic settling of salts occurring deeper out in the depositional basin, as in the Dead Sea prior to February 1979 (Figure 3a). The bottom growth of crystals cannot occur on a deep bottom located beneath a density-stratified system, as there is no mechanism to drive ongoing supersatu-ra-tion in the lower water mass. For the same reason, constant brine reflux driving sinking of a dense brine into sediments beneath the floor of the evaporite basin can only proceed if significant regions of the overlying brine mass are holomictic. Deposition of capillary salts (sabkha deposits) occurs in subaerial settings, wherever the saline capillary zone inter-sects the land surface (Figure 3b).

When salts are accumulating beneath a holomictic brine mass, textures in bottom nucleates is controlled by the stability of the overlying brine column (Figure 3b). When the overlying column is deep (>30-100m) then, other than areas on the deep bottom of local phreatic spring-fed outflows, there is no general hydrochemical mechanism to drive fluctuations in bottom-brine chem-istry. The resulting deep bottom precipitates tend to be monomineralogic crystal clusters, possibly encased by re-transported material washed in from the shallower surrounds (Figure 3a, 3b). In contrast, when the overlying brine column is shallow (<30m and typically <5-10m) then the chemistry and stability of the brine varies on a shorter term (daily-weekly) basis, so more layered bi-mineralogic bottom-nucleates can accumulate as layered to laminated salt beds. In addition, all evaporite sediments can be re-worked by bottom currents, with similar textures to those that characterise siliciclastic and mechanically-modified carbonate sediments (Figure 3b).

"Now" versus "then" in evaporite deposition

Uniformitarianism is an essential tenet of geological understanding. Yet, when we look at evaporite volumes and depositional settings across deep time, we see that the diversity of modern evaporite analogues is con-strained by a deficit in two conditions, specifically; 1) the current lack of greenhouse eustasy; contemporaneous atmospheric conditions and sea levels are controlled by the earth's current icehouse climate mode and have been for the last 10-12 million years, and 2) the current lack at the plate-edge scale of marine seepage into large hydrographically-isolated oceanic sump basins (Warren, 2010). Both situations circumscribe different hydrologies and eustasies compared to continental-fed in-flows that typify the world's current larger evaporite basins. Today, and across the Quaternary, the largest and thickest salt stacks, with areal extents up to 10,000 km2 and thickness

Platform successions	*Age*	*Comments*
Rus Fm., Arabian Basin, Qatar, Saudi Arabia	Eocene, Lower	Has a total thickness of about 100 m, composed of limestones and dolomitic limestones (often argillaceous) passing upward into massive 10m thick saltern anhydrite
Ferry Lake Anhydrite, NE Gulf coast, USA	Cretaceous, Lower	Divided in 9 individual saltern anhydrites that are traceable from southern Mississippi to southern Florida and intercalated with normal marine bioclastic limestones
Smackover/Buckner Fm., N Gulf Coast, USA	Cretaceous, Lower	Buckner Anhydrite made up of intercalated 2-6m thick saltern anhydrites and marine limestones. It extends from Florida Panhandle to South Texas
Hith Anhydrite, Arabian Basin, Middle East	Jurassic, Upper	Hith anhydrite is a regional seal that extends across much of the Arabian Peninsula and locally reaches 170 m in thickness. It is composed of bluish-gray to alternating bands of blue and white anhydrite with two internal carbonates and separates marine carbonates of underlying Arab Fm from overlying Yamama (unconformable base).
Middle Anhydrite Marker, Khuff Fm., Middle East	Permian, Upper	Middle Anhydrite can be traced from eastern Saudi Arabia to offshore UAE, and reaches the onshore Fars Province of Iran. This anhydrite is some 12–17 m (20–39 ft) thick and consists of massive saltern anhydrite with minor thin interbeds of dolomite
San Andres Fm., Northern Dela-ware Basin margin, USA	Permian, Upper	Anhydrite occurs as widespread saltern units composed of massive nodular mosaic anhydrite beds up to 5m thick capping cyclic shoaling variably-dolomitised platform carbonates. Individual anhydrite beds (P1-P5) that can be traced from Palo Duro basin into shelf edge of the Slaughter-Levelland trend
Cadjebut Fm., Canning Basin margin, Australia	Devonian, Middle	Saltern anhydrites up to 5m thick extend across a Devonian platform embayment pass and pass laterally into the sulphide mineralised ore horizons of the Cadjebut Mine region. Saltern sulphates capped shoaling oncolitic and bioclastic muds that overlie normal marine grainstones and wackestones
Cool Creek Fm., Arbuckle platform, USA	Ordovician, Lower	At least three 1-2 m thick breccias, interpreted to be of solution collapse origin, are present in the Cool Creek and define the presence of former widespread saltern anhydrite units that capped restricted marine stromatolitic carbonate platform sediments
Red Heart Dolomite, Georgina Basin, Australia	Cambrian, Lower-Middle	Red Heart Dolomite which extends across much of Central Australia is a completely dolomitised 100m-thick platform carbon-ate deposited in an evaporitic shallow-water epeiric seaway It is characterized by at least four shallowing-upwards saltern anhydrite-capped cycles. Many of the surface and near-surface anhydrites caps are now leached and represented by collapse breccias
Intracratonic platform evaporite successions	Neoproterozoic to Eocene	North Sahara Basin, Africa; Canning Basin, Australia; Muschelkalk and Paris Basins, SW Germany and Spain; Amazonas Basin, South America; West Siberian Basin, Russia; Michigan Basin and Williston Basin, USA (see Table 2)

Table 1. Selected platform evaporite examples (see Warren 2016; Chapter 5 for deposit details and listing of relevant citations)

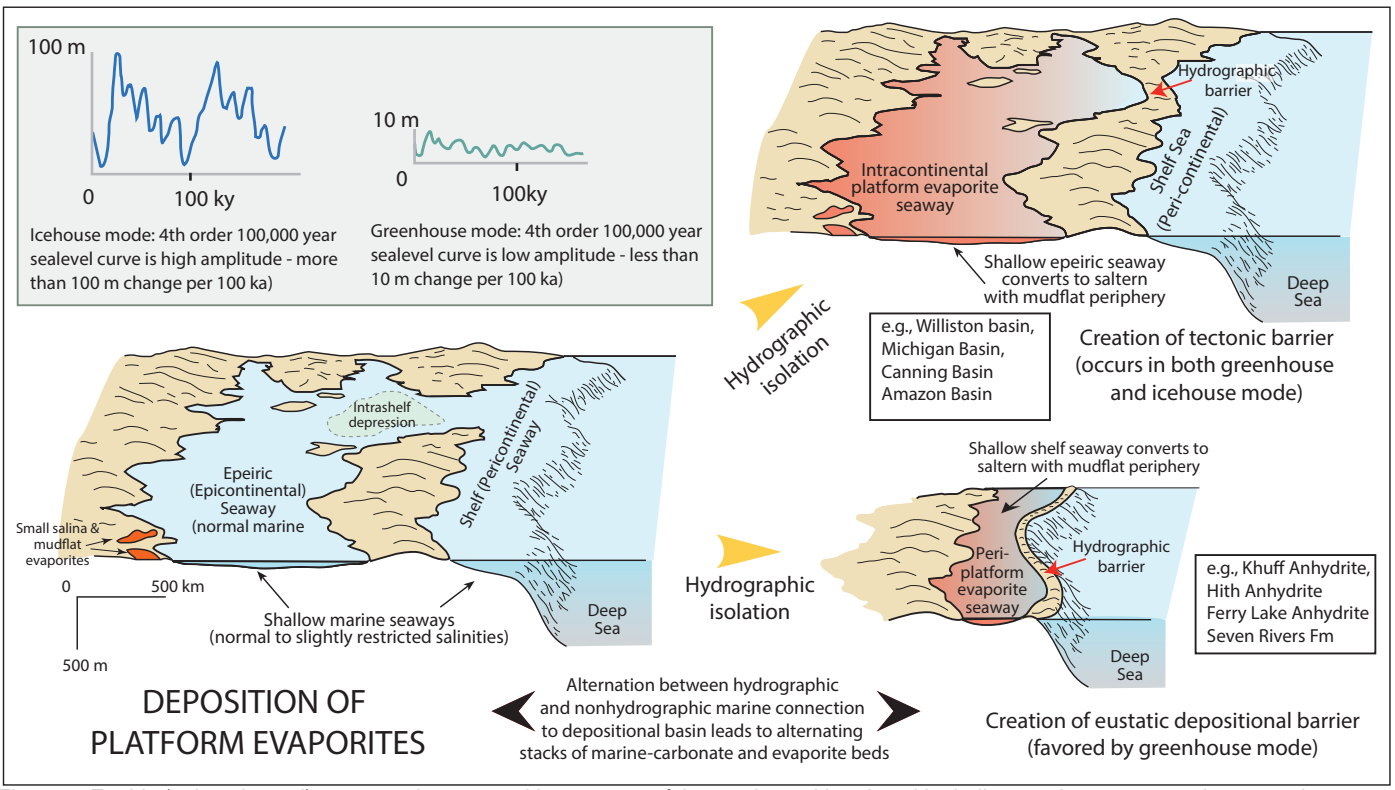

Figure 5. Epeiric (epicontinental) seaways that covered large areas of the continental interior with shallow marine waters are known as intracratonic basins, while epeiric seaways that formed as very wide shelf edges along the continental margin as known as pericontinental seaways. Waters were very shallow over areas that were hundreds to thousands of kilometres across. Neither setting has a modern counterpart; pericontinental seaways that evolve into salterns and or evaporitic mudflats are more typical of marine-margin eustatic styles on the earth in greenhouse climate mode, when the lack of permanent polar icecaps, especially coupled with higher rates of seafloor spreading, meant the continental freeboard was much larger than it is today (after Warren, 2010).

up to 900 m, tend to precipitate in the lower parts of suprasealevel intermontane lacustrine sumps located in tectonically active parts of continental interiors, such as Salar Atacama and Salar di Uyuni in the Andean Altiplano (Figure 4a). Most ancient evaporites are marine-fed and were deposited in huge hydrographically-isolated subsealevel marine-seepage sumps located in intracratonic basins or within rifts or compressional sutures. Often, the areal extents of these ancient systems were more than 250,000 km^2, this is more than two orders of magnitude larger than any Quaternary evaporite deposit. Bedded (pre-halokinetic) thicknesses could be more than a kilometre.

Ancient marine saline giants (megahalites and megasulphates) accrued in either of two plate-scale settings, which at times merged into one another, namely; 1) Platform evaporites (Figure 5) and, 2) Basinwide evaporites (Figure 6). The first major contrast with nonmarine continental dominance in Quaternary evaporite settings is the fact that platform evaporites require greenhouse eustasy, the second is that basinwide evaporites require tectonically- and hydrographically-isolated widespread subsealevel depressions, typically found along plate edges with continent-continent proximity (Figure 5).

Neither condition is present on the current earth surface. For basinwides, suitable hydrologic conditions were last present during the Messinian Salinity Crisis in the Mediterranean region, and platform evaporite settings were last present on earth across large parts of the Middle East carbonate platform during the Eocene (Tables 1, 2). There is a third group of ancient evaporite deposits; it encompasses all nonmarine lacustrine beds past and present (Table 3). This group has same-scale modern-ancient counterparts, unlike ancient marine platform and basinwide evaporites (Figure 4a; Warren, 2010, 2016).

Platform evaporites

Are made up of stratiform beds, usually <50 m thick and composed of stacked <1 to 5 m thick parasequences or evaporite cycles, with a variably-present restricted-marine carbonate unit at a cycle base (Table 1). Salts were deposited as mixed evaporitic mudflat and saltern evaporites, sometimes with local accumulations of bittern salts. Typically, platform salts were deposited in laterally extensive (>50-100 km wide), hydrographically-isolated, subsealevel marine-seepage lagoons (salterns) or evaporitic mudflats (sabkhas and salinas). These regions had no same-scale modern counterparts and extended as widespread dep-

ositional sheets across large portions of hydrographically isolated marine plat-form areas, which passed seaward across a subaerial seepage barrier into open marine sediments (Figure 5). In marine margin epeiric settings, such as the Jurassic Arab/Hith and Permian Khuff cycles of the Middle East or the Cretaceous Ferry Lake Anhydrite in the Gulf of Mexico, these platform evaporites are intercalated with shoalwater marine-influenced carbonate shelf/ramp sediments, which in turn pass basinward across a subaerial sill into open marine carbonates. Landward they pass into arid zone continental siliciclastics or carbonate mudflats.

Platform evaporite deposition occurred in both pericontinental and epicontinental settings, at times of low-amplitude 4th and 5th order sealevel changes, which typify greenhouse eustasy (Figure 5; Warren, 2010). Platform evaporites also typify the saline stages of some intracratonic basins. Platform evaporites cannot form in the high-amplitude, high-frequency sealevel changes of icehouse eustasy. The 100m+ amplitude oscillations of icehouse times mean sealevel falls off the shelf edge every 100,000 years, so any evaporite that had formed on the platform is subaerially exposed and leached. Fourth order high-amplitude icehouse eustatic cycles also tend to prevent laterally-continuous carbonate sediment barriers forming at the top of the shelf to slope break and so icehouse evaporite systems tend not to be hydrographically isolated (drawdown) at the platform scale. Rather icehouse eustasy favours nonmarine evaporites as the dominant style, along with small ephemeral marine-margin salt bodies, as seen today in the bedded Holocene halites and gypsums of Lake Macleod in coastal West Australia.

Ancient platform evaporite successions may contain halite beds, especially in intracratonic basinwide settings, but periplatform settings, outside of intracratonic basins, are typically dominated by 5–40 m thick Ca-sulphate beds intercalated with normal-marine platform carbonates (Table 1). The lateral extent of these epeiric platform sulphate bodies, like the Middle Anhydrite Member of the Permian Khuff Fm. of Saudi Arabia and the UAE, with a current area of more than 1,206,700 km^2, constitute some of the most aerially-extensive evaporite beds ever deposited.

Basinwide evaporites

Are made up of thick evaporite units >50–100 m thick made up of varying combinations of deepwater and shallow water evaporites (Table 2). They retain textural evidence of different but synchronous local depositional settings, including mudflat, saltern, slope and basin (Figures 6). When basinwide evaporite deposition occurs, the whole basin hydrology is evaporitic, holomictic, and typically saturated with the same mineral phase across vast areas of the basin floor, as in the Dead Sea basin today. The Dead Sea has a more limited lateral scale than ancient basinwides but currently has halite forming simultaneously as; 1) decimeter-thick chevron-dominated beds on the saline-pan floor of the shallow parts around the basin edge in waters typically less than 1-10 metres deep, and 2) as coarse inclusion-poor crystal meshworks of halite on the deep basin floor that sits below a halite-saturated brine column up to hundreds of metres deep (Figure 3a). Ancient basinwide successions are usually dominated by thick massive salt beds, generally more than 100-500 m thick. Deposits are made up of stacked thick halite beds, but can also contain substantial volumes of thick-bedded Ca-sulphate and evaporitic carbonate, as in the intracratonic basinwide accumulations of the Delaware and Otto Fiord Basins (Table 2).

Owing to inherent purity and thickness of the deposited halite, many halite-dominant basinwide beds are also remobilized, via loading or tectonics, into various halokinetic geometries (Hudec and Jackson, 2007). Some basinwide systems (mostly marine-fed intracratonic settings) entrain significant accumulations of marine-fed potash salts, as in the Devoni-an Prairie Evaporite of western Canada. In contrast, all Quaternary examples of commercial potash deposits are accumulating in continental lacustrine systems (Warren 2016; Chapter 11).

Basinwide evaporite deposits are the result of a combination of tectonic and hydrological circumstances that are not currently active on the world's surface (Figure 4b). They were last active in the Late Miocene (Messinian), in association with soft-suture collision basins tied to the Alpine-Himalaya orogenic belt, and in Middle Miocene (Badenian) basins developed in the early rift stages of the Red Sea. Basinwide systems will be active again in the future at sites and times of appropriate plate-plate interaction, when two continental plate edges are nearby, and the intervening seafloor is in or near a plate-edge rift or suture and is both subsealevel and hydrographically isolated (Figure 6).

Lacustrine (nonmarine) evaporites

Quaternary continental playa/lacustrine are constructed of stratiform salt units, with the greater volume of saline sediment accumulating in lower, more-saline portions of the lacustrine landscape. Beds are usually dominated by nodular gypsum and displacive halite, deposited in extensive evaporitic mudflats and saltpans with textures heavily overprinted by capillary wicking, rather than as bedded bottom-nucleated layers on the subaqueous floors of perennial brine lakes (Figure 3b; Ruch et al., 2012). In ancient counterparts, the total saline lacustrine thickness ranged from meters to hundreds of meters, with lateral extents measured in tens to hundreds of kilometres (Table 3; Figure 4a). Lacustrine salt beds are separated vertically, and usually surrounded by, deposits of lacustrine muds, alluvial fans, ephemeral streams, sheet floods, eolian sands, and redbeds. As today, ancient lacustrine salts accumulated in endorheic or highly restricted discharge basins, with perennial saline water masses tending to occur in the drainage sumps of steep-sided drainage basins (Warren, 2010, 2016). Saline lake basins accumulating gypsum, or more saline salts like halite or glauberite, typically have a shallow water table in peripheral saline mudflat areas and so are dominated by continental sabkha textures. Nearby is the lowermost part of the lacustrine depression or sump where deposition is

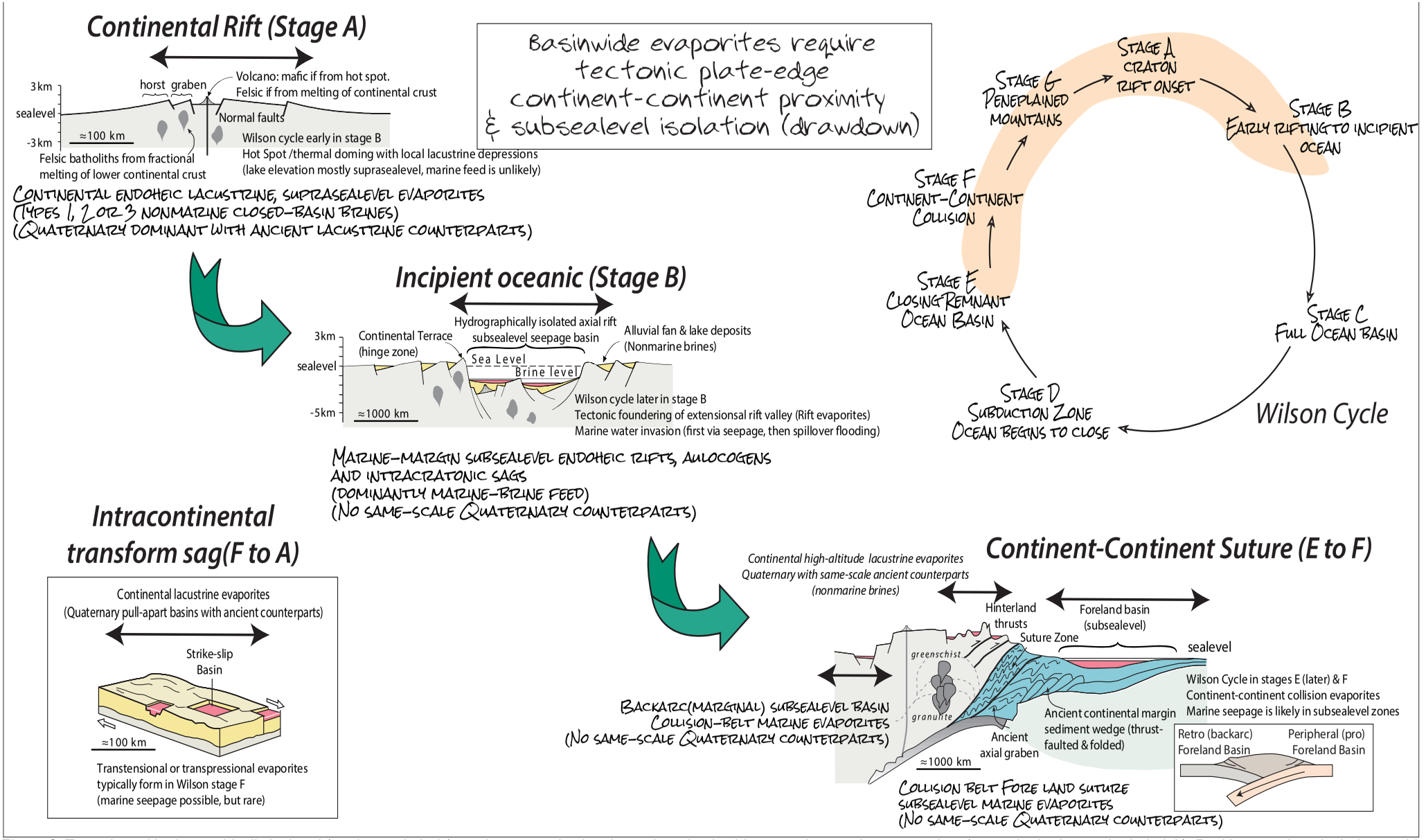

Figure 6. Tectonic and hydrographically isolated (marine endorheic) continent-margin situations where basinwide evaporites tend to accumulate (evaporite beds are shaded pink). Positions are largely tied to world-scale times of continent-continent proximity and so can be tied to the various stages of the Wilson Cycle (After Warren, 2010)

Sequence of interest	*Basin/setting and Location*	*Age*	*Basin style*	*Tectonic event*
Messinian Evaporites	Lago-Mare ("lake sea"), Mediterranean	Miocene, Upper	Flexure	Convergent foreland, Alpine orogeny
Belayim and Gharib formations	Gulf of Suez - Red Sea, Middle East	Miocene, Middle - Upper	Extension	Red Sea Breakup and the formation of the Red Sea/ Suez Rift
Gachsaran Formation	Mesopotamian Basin, Middle East	Miocene, Middle	Flexure	Convergent foreland Zagros-Taurus
Maha Sarakham Formation	Khorat Basin, Thailand	Cretaceous, Upper	Flexure	Convergent foreland Cretaceous inversion and thrust loading
Todilto Formation	Todilto Basin, New Mexico, USA	Jurassic, Middle	Flexure	Convergent foreland Ancestral Rockies
Louann Salt	Gulf of Mexico Basin, Gulf Coast	Jurassic, Middle	Extension	Incipient Gulf of Mexico- Atlantic rift
Argo Formation & Osprey Evaporites	Scotian Basin, and Grand Banks, Canada	Upper Triassic-Lower Jurassic	Extension	Incipient Atlantic rifting
Northwich Halite	Cheshire Basin, United Kingdom	Triassic	Extension	Incipient Atlantic rifting
Halite (S1-S4, Las and Dogger Anhydrite units)	Oued Mya Basin, Algeria, Northern Sahara	Upper Triassic-Lower Jurassic (Liassic)	Extension	Intraplate sag basin atop grabens created by incipient Atlantic and Tethyan rifting
Saliferous units	Ghadames (Berkine) Basin, Algeria	Triassic, Upper Jurassic, Lower	Extension	Intraplate sag basin atop grabens created by incipient Atlantic and Tethyan rifting
Argiles d'Argana	Essaouria Basin, Morocco	Triassic, Upper	Flexure	Intraplate sag basin atop grabens created by incipient Atlantic and Tethyan rifting
Formation Salifere	Saharan Atlas, Algeria	Triassic, Upper	Flexure	Intraplate sag basin; incipient Atlantic and Tethyan rifting
Salina d'Ourgla	Northern Sahara Salt Basin, Algeria	Triassic, Upper	Flexure	Intraplate sag basin; incipient Atlantic and Tethyan rifting
Nikitov, Slavyan, and Kramatov Formations	Dnieper-Donets Basin, Ukraine and Russia	Permian, Lower (Kungurian salt)	Flexure	Post-rift sag reactivated by Uralian Orogeny (Hercynian)
Rotliegende Group	Dniepr-Donets Basin, Eastern Europe	Permian, Lower	Flexure	Foreland Variscan Orogeny
Zechstein Basin, NW Europe	NW European Basin, NW Europe	Permian, Upper	Flexure	Post Variscan Orogeny collapse
Castile Formation	Delaware Basin, West Texas	Permian, Upper	Flexure	Marathon-Ouchita
Iren Horizon Kungurian evaporites	North Caspian Basin (aka Pri- or Peri-Caspian), Khazakhstan and Russia	Permian, Lower	Flexure	Foreland, Uralian Orogeny. Collision of Russian Platform with the Siberia/Kazakhstan block
Otto Fiord Formation	Sverdrup Basin, Canadian Arctic Islands	Carboniferous	Extension	Synrift stage of post-Caledonian intracontinental rifting
Paradox Formation	Paradox Basin, Colorado-Utah USA	Carboniferous, Upper	Flexure	Ancestral Rockies
Caurauri Formation	Amazonas Basin, South America	Carboniferous, Upper	Flexure	Distal effect of Marathon-Ouchita orogeny
Windsor Group	Magdalen Basin, Eastern Canada	Carboniferous, Lower	Extension	Cabot fault-Belle Isle transtensional system
Liven Horizon	Dniepr-donets Basin, Ukraine and Russia	Devonian, Upper Frasnian and Famennian	Extension	Synrift via crustal stretching (passive margin)
Prairie Evaporite	Elk Point Basin, Western Canada Plains	Devonian, Middle	Flexure	Intracratonic sag; a distal effect of thrust-loaded compression of the western Laurasian plate
Salina Group	Michigan Basin, USA	Silurian, Middle-Upper	Flexure	Intracratonic sag during Taconian thrust loading, sits atop Mesoproterozoic Midcontinent rift basin
Mallowa Salt (Carribuddy Formation)	Canning Basin, Northwest Australia	Ord. -Silurian	Extension	Pre-rift to Synrift stage of intracratonic sag
Chandler Formation	Amadeus Basin, Central Australia	Cambrian, Lower	Flexure	Petermann Range Orogeny - Gondwana Accretion
Lower and upper Usolye Group	Turukhan - Irkutsk - Olekmin salt basin, SE Siberian Craton	Late Neoproterozoic (Vendian)-early Cambrian	Flexure	Intracratonic Sag- Gondwana assembly
Hormuz Formation	Arabian Basin, Middle East	Late Neoproterozoic- early Cambrian (550 Ma)	Compression	Collision flexure - Pan African Orogeny; Gondwana Accretion
Ara Salt, Oman	Fahud, Gaba and South Oman Salt Basins, Oman	Late Neoproterozoic- early Cambrian (550 Ma)	Compression	Collision flexure - Pan African Orogeny; Gondwana Accretion
Bitter Springs Formation	Amadeus Basin, Central Australia	Early Neoproterozoic (≈ 800 Ma)	Extension- intracratonic sag	Rift - Rodinia breakup
Callana Formation	Adelaide Geosyncline, South Australia	Early Neoproterozoic (≈ 800 Ma)	Extension- intracratonic sag	Rift - Rodinia breakup
Browne Fm	Officer Basin, West Australia	Early Neoproterozoic (≈ 800 Ma)	Extension- intracratonic sag	Rift - Rodinia breakup

Table 2. Selected basinwide evaporite examples classified by age and tectonic setting (see Warren 2016; Chapter 5 for deposit details and listing of relevant citations)

Sequence of interest	*Basin/setting*	*Locality*	*Age*
Beds of displacive borates	Bigadic, Emet and Kirka basins	Turkey	Neogene
Gypsiferous Blanchetown Formation	Palaeolake Bungunnia	Murray Basin, Australia	Neogene
Massive halite of Salar Grande	Cordillera de la Costa forearc	Central Andes, Chile	Neogene
Bed I and Bed II	Olduvai Gorge, East African Rift	Tanzania	Pliocene
Furnace Creek Fm. (borate beds)	Extensional half-graben	Death Valley, USA	Pliocene-Miocene
Gypsum as beds and fracture-fills	Sivrihisar/Sultancayir/ Cankiri basins	Anatolia, Turkey	Miocene
Lacustrine carbonates	Ries-impact-crater	Southern Germany	Miocene
Lacustrine halite, 2.5 km thick	Hualapai basin	NW Arizona	Miocene
Kirmir Fm.	Beypazari Basin	NW Turkey	Miocene, Middle - Upper
Juncalito Fm.	Puna Plateau - intra-arc basin	NW Argentina	Miocene, Middle -Upper
Bedded and nodular gypsum (glauberite)	Calatayud Basin	Spain	Miocene, Lower
Bedded and nodular gypsum (glauberite)	Ebro Basin - foreland basin	Spain	Miocene, Lower
Creede Fm.	Ancient Lake Creede	Colorado, USA	Oligocene, Upper
Potash beds of Couche Inferieure	Mulhouse Basin	Rhine Graben, Europe	Oligocene, Lower
Green River Fm.	Uinta and Piceance basins	Utah and Colorado	Eocene
Bembridge Limestone Fm.	Isle of Wight	Southern England	Eocene, Upper
Taleh Fm.	Somalia	El Bur Plateau	Eocene, Lower -Middle
La Tinaja del Oso (colemanite)	Magdalena extension basin	Mexico	Mid-Tertiary
Uhangri Fm.	Yucheon Group	SW Korea	Cretaceous
Mmashoro Fm.	Basal Kalahari Group	Botswana	Cretaceous, Upper
El Molino Fm.	Potosi Basin	Bolivia	Cretaceous, Upper - Tertiary, Lower
Lagoa Feia Fm.	Campos Basin	Brazil	Cretaceous, Lower
Codocedo Limestone Member	Atacama region	Northern Chile	Jurassic, Upper - Cretaceous, Lower
Drakensberg Group	Intercalated in Karoo basalts	Southern Namibia	Jurassic, Lower
Kalkrand Fm.	Karoo flood basalt province	Namibia	Jurassic, Lower
Mercia Mudstone Group	North Atlantic rift basins	Southern Britain	Triassic, Upper
Passaic and Lockatong Fms.	Newark Basin	Eastern North America	Triassic, Upper
Blomiden redbeds	Fundy Basin	Nova Scotia	Triassic, Upper
Buntsandstein	Helgoland Basin	East Greenland	Triassic, Middle
Pingdiquan Fm.	Junggar Basin	NW China	Permian, Upper
Groden Fm.	Intermontane basins, Alps	Tyrol, Austria	Permian, Upper
Opeche Shale	Williston Basin	North Dakota, USA	Permian, Middle
Nippewalla Group	Continental interior sag basins	Kansas, USA	Permian, Middle
Rotliegende sediments	Muhlhausen and Ilfeld basins	Germany	Late Carboniferous-Permian
Old Red Sandstone (middle)	Orcadian Basin	Scotland	Devonian, Lower
Parakeelya Alkali Member	Officer Basin	Australia	Cambrian

Table 3. Selected pre-Quaternary lacustrine evaporite examples classified by age and tectonic setting (see Warren 2016; Chapter 5 for deposit details and listing of relevant citations)

typified by ephemeral ponded brine pan deposits, rather than permanent saline waters.

Saline lacustrine mineralogies depend on compositions of inflowing waters, so depositional sumps in regions with non-marine ionic proportions in the feeder inflow, accumulate thick sequences of nonmarine bedded salts dominated by trona, glauberite, and thenardite. In contrast, nonmarine areas with thalassic (seawater-like) inflows tend to accumulate more typical sequences of halite, gypsum, and anhydrite.

Across the Quaternary, less-saline perennial saline-lake beds tend to occur during more humid climate periods in the same continental-lacustrine depressions where saline-pan beds form (e.g., Lake Magadi, Great Salt Lake, Lake Urmia). On a smaller scale, in some modern saline lake basins, parts of the lake floor can be permanently located below the water surface (Northern Basin in the Dead Sea or Lake Asal). In some modern saline sumps dominated by mudflats, a perennial saline lake water mass is located toward the edge of a more central salt-flat zone, forming a perennial water filled “moat” facies surrounding a seasonally desiccated saline pan (as in Salar, de Atacama, Salar de Uyuni, Lake Magadi, Lake Natron). These permanent to near-permanent saline water “moat” regions are typically created where fresher inflows encounter saltier beds of the lake centre, dissolve them, and so form water-filled peripheral depressions. Bottom sediment in the moats tend to be mesohaline carbonate laminites, which can contain TOC levels as high as 12%.

High-water stage perennial saline lacustrine sediments tend to be

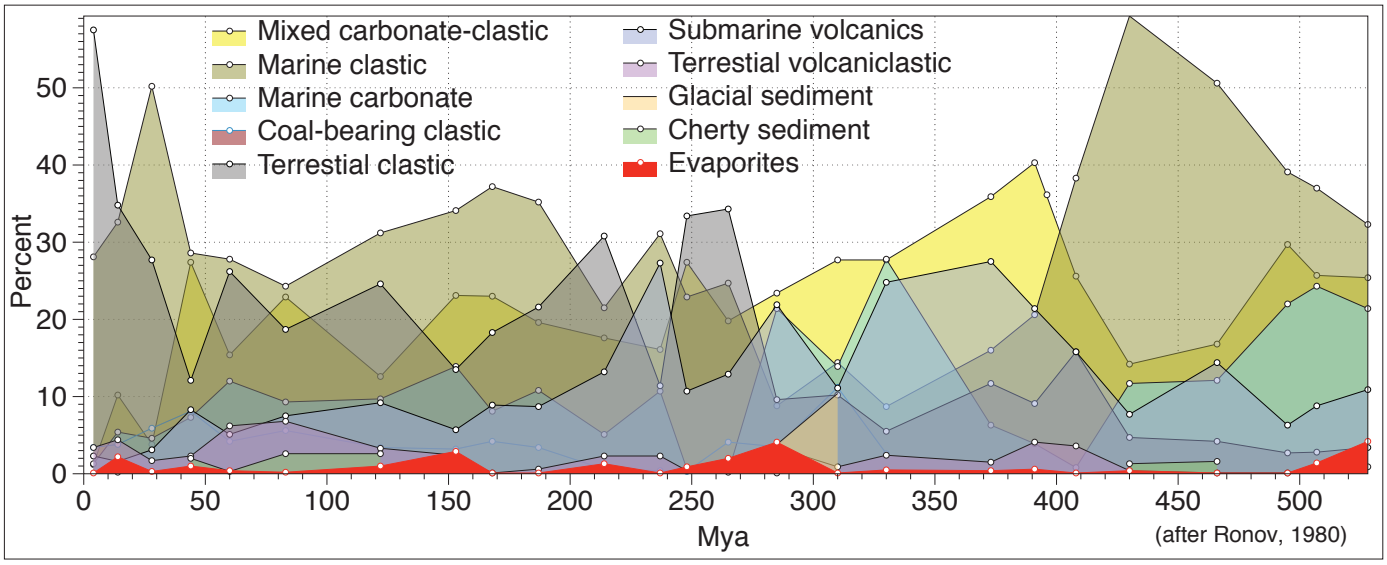

Figure 7. Relative proportion of Phanerozoic sediments (replotted from tables in Ronov, 1980)

carbonate-rich or silica-rich (diatomaceous) laminites. Ancient examples of large saline lacustrine deposits made up of alternating humid and desiccated lacustrine units include the Eocene Green River Formation of Wyoming and the Permian Pingdiquan Formation of the Junggar Basin, Chi-na (Table 4). Evaporites deposited in a suprase-alevel lacustrine basin (especially Neogene deposits) have numerous same-scale Quaternary analogues, unlike the more voluminous ancient marine platform and basinwide evaporites (Figure 4a).

Salt punches above its weight, but why? (facilitator for economic accumulations of oil, gas and metals)

In terms of total mass in sedimentary basins, the proportion of evaporite across the world's Phanerozoic basins is rarely more than 2% (Figure 7; Ronov, 1980). Today we have comprehensive documentation that salt horizons, their brines, associated dissolution and alteration conduits control significant economic associations of oil, gas and metals (Warren, 2016):

- 50% of world's carbonate reservoirs (seals, traps and source rocks)
- All the world's supergiant oil and gas fields in thrusts (seals and structural traps).
- All supergiant sedimentary copper deposits (halokinetic brine focus)
- 50% of world's giant SedEx deposits (halokinetic brine focus).
- 80% of giant MVT deposits (sulphate-fixer & brine interface)
- World's largest Phanerozoic Ni deposit (meta-igneous – Noril'sk).
- Many larger IOCG deposits (meta-evaporite, brine and hydrothermal).

This enrichment runs counter to a proportion of 2% of the world's Phanerozoic sediments. The exact why or how of these associations is still not well understood. Most geologists working with oil, gas or metal buildups in a salt-rich basin will come to have a suspicion, and for some, the conviction, that salt or its subsurface alteration plays a role in defining the position or enrichment level of the commodity of interest. Evaporite masses in the subsurface, especially if halite-dominant, enable both physical and chemical alterations, which tend to improve economic prospectivity. The unique properties of salt in the diagenetic realm tend to facilitate, focus and stabilise processes that lead to elevated levels of accumulations of

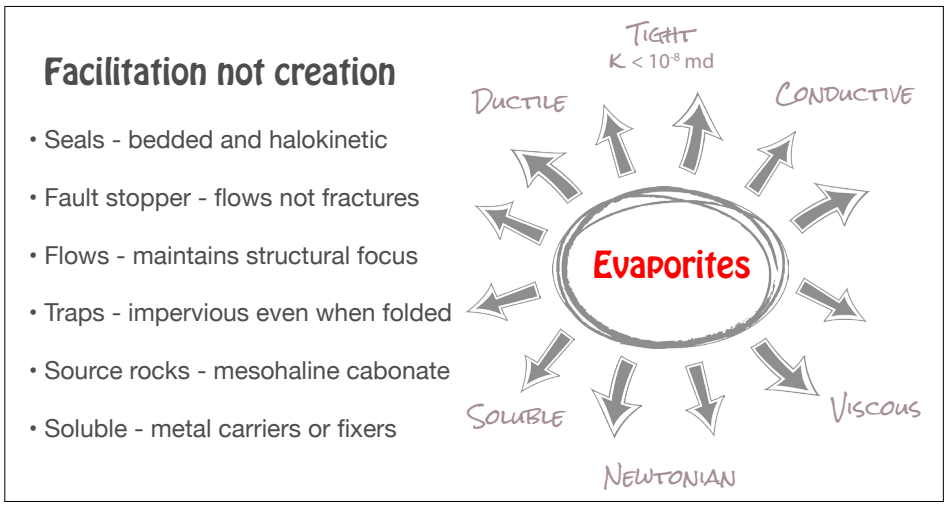

Figure 8. Subsurface evaporites (especially if halite-dominant) possess a set of unusual physical and chemical properties, compared to siliciclastics and carbonate sediments, these unusual properties facilitate economic accumulations of oil, gas and metals.

various commodities (Figure 8). That is, evaporites in a basin tend to enhance the volume of oil, gas or metals in an accumulation, but are not necessarily the direct cause of the accumulation/precipitation.

Hydrocarbon–evaporite association

When the reservoired hydrocarbon below a salt seal is oil, little or no leakage can take place through a laterally continuous evaporite. Even when the reservoired hydrocarbon is methane, little or no loss occurs, even by diffusion (Ehgartner et al., 1998). The much greater efficiency of evaporite seals, compared to shales, is clearly seen in the total hydrocarbon volumes held back by the two lithologies. Total worldwide shale sediment volume in the Earth's sedimentary crust is more that an order of magnitude greater than that of evaporites, yet the split between reservoired hydrocarbons below a shale or an evaporite seal is roughly 50:50 (Grunau, 1987). Likewise, typical volumes of salt-sealed giant fields dis-covered in the last decade are much grander than that held in mudrock-sealed systems (Bai and Yu, 2014).

Of the 120 giant oil and gas fields discovered in the period 2000- 2012 some 54.6 % are hosted in marine carbonates and 12% in lacustrine carbonates, meaning less than a third of new giant discoveries are in siliciclastic reservoirs (Figure 9a). Some 56% of these oil and gas giants have an evaporite seal, with 82% of the marine carbonates having an evaporite seal and 91% of the lacustrine carbonates having an evaporite seal (Figure 9b, c). Clearly, carbonate reservoirs with evaporite seals constitute most of the giant oil and gas discoveries across the period 2000-2012, and the proportions of this association are likely to increase in conventional discoveries across the next decades (Bai and Yu, 2014).

Of these 120 oil and gas giants, one is a megagiant field with a recoverable reserve of 50 Bboe (Billion barrels oil equivalent) or more, and 6 are supergiant fields with recoverable reserves of 5 Bboe or more. The seven largest fields are: Galkynysh (aka Yolotan or Osman) gas field in the Ama-Darya Basin of Turkmenistan with an original 2P reserve of 67.1 Bboe, making it likely the second largest known gas field in the world; Kashagan oil field (18.1 Bboe) in the North Caspian basin; Kish 2 gas field in the Arabian Basin (Iran): Lula (previously known as Tupi), Franco and Libra oil fields in the Santos Basin of offshore Brazil; and Sulige gas field (5.7 Bboe) in the Ordos Basin, China. In this listing, the geology of Galkynysh is not yet reliably published, but of the remaining 6, only Sulige does not have an evaporite association.

Typical bedded evaporite seals, especially beds composed of monomineralogic assemblages such as massive nodular anhydrite or massive halite and have measured entry pressures more than 3000 psi. Most impure evaporite

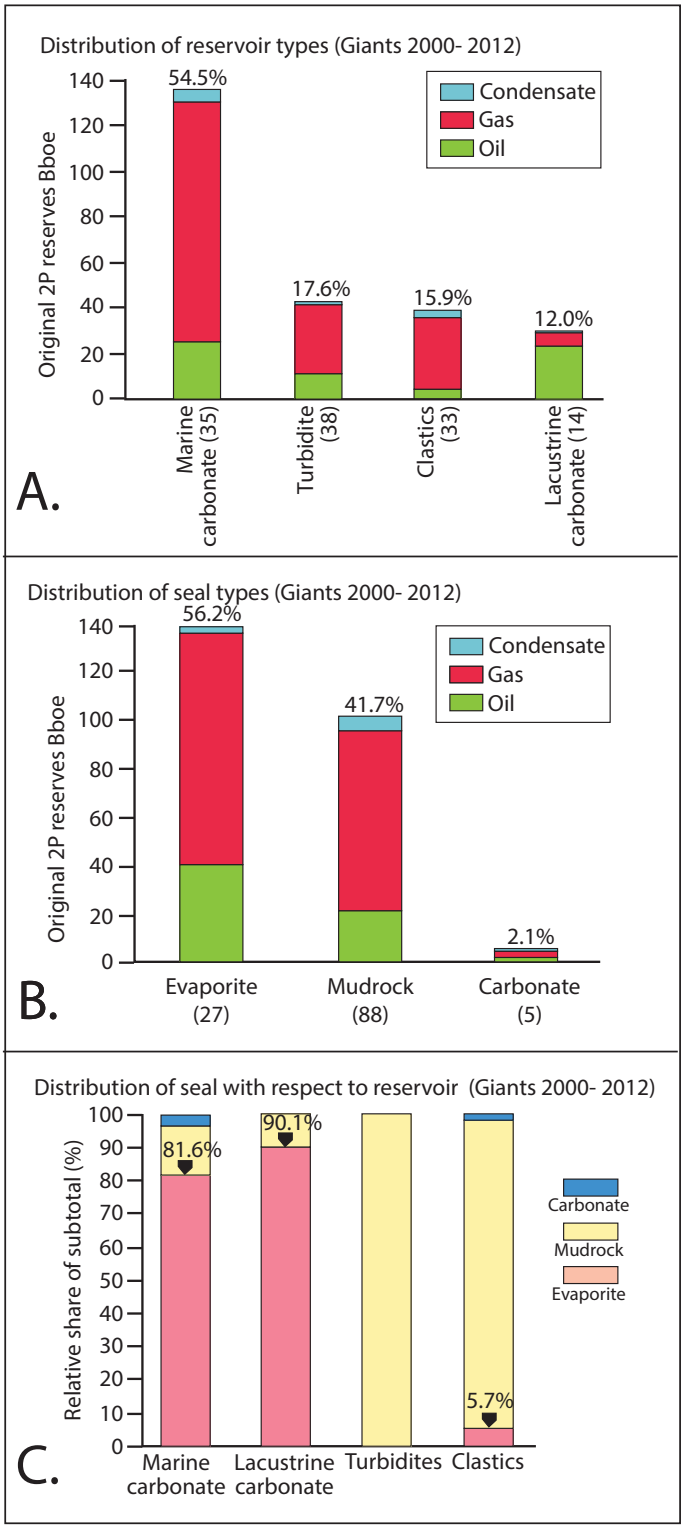

Figure 9. Evaporite seals to giant fields discovered in the period 2000-2012. A) Dominant reservoirs for oil and hydrocarbon type. B) Seal mineralogy. C) Relations of reservoir to seal mineralogy (after Bai and Yu, 2014)

beds have entry pressures greater than 1000 psi, as do many evaporite-plugged reflux dolomites. Contrast this with most shales, which tend to be water-bearing (mostly bound and structural water), with typical entry pressures between 900 and 1500 psi (Sneider et al., 1997). Al-

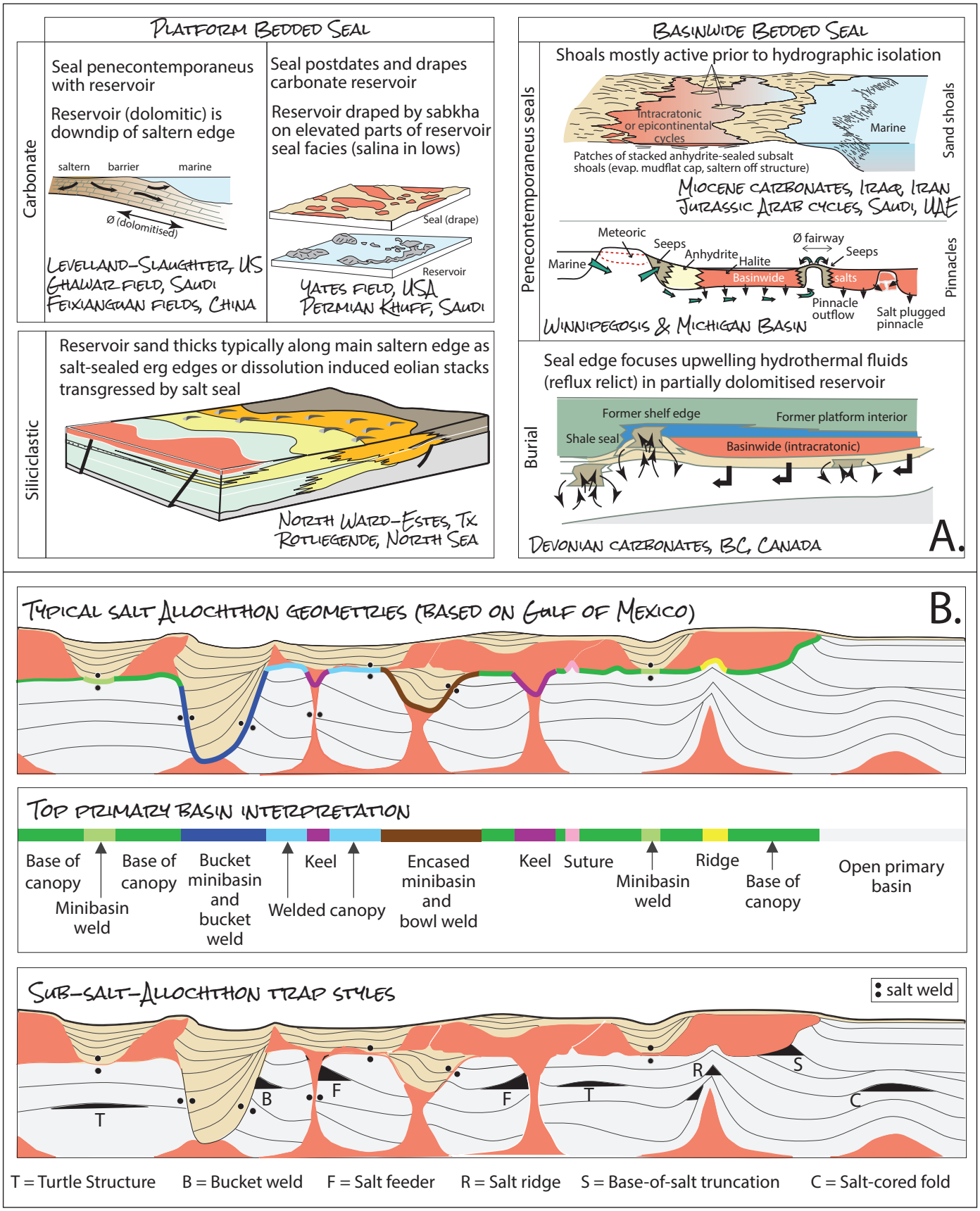

Figure 10. Examples of salt-hydrocarbon associations. A) Summary of the various ancient platform and basinwide bedded evaporite settings where a combination of evaporite sealing, dolomitisation (both early and late) and focused evaporite-related fluid flow creates a variety of hydrocarbon traps (after Warren, 2016; Chapter 10). B) Halokinetic structuration and sealing based on sub-allochthon traps in the Gulf of Mexico (after Pilcher et al., 2011).

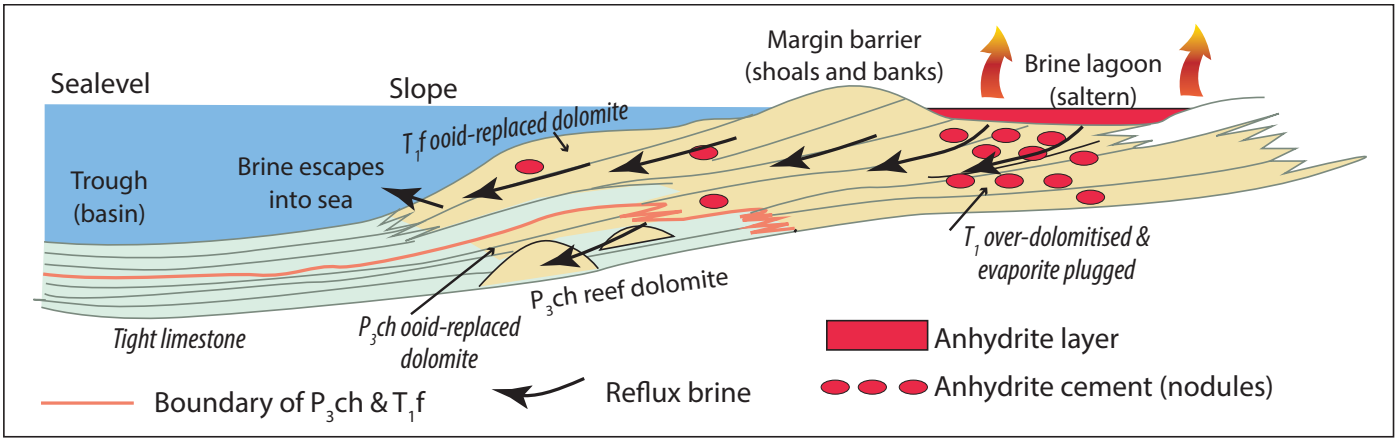

Figure 11. Model of reservoir creation via saltern brine reflux, based on dolomite distribution in the Upper Permian Changxing Formation (P_3ch) and the Lower Triassic Feixianguan Formation (T_1f), NE Sichuan Basin, China (after Jiang et al., 2013).

though such shales are respectable seals, over time shale allows substantial diffusive leakage of methane and even liquid hydrocarbons via inherent microporosity, less so if the shales are organic-rich. Even ignoring halite's ability to reanneal and flow under stress, any evaporite seal has much lower intrinsic permeability than shale, and this helps maintain its seal integrity. With permeabilities of 10^{-7} md, a hydraulic gradient of 0.01, and a porosity less than 0.01, a brine would take somewhere between 3 and 30 million years to flow 1 metre into an unfractured halite seal. For anhydrite, which has permeability some 100 times higher than halite, a brine would take between 30,000 and 300,000 years to flow 1 metre into the seal (Beauheim and Roberts, 2002).

Evaporites are excellent longterm seals to substantial hydrocarbon columns. This applies to any siliciclastic or carbonate reservoir adjacent to bedded or halokinetic salty seals (Figure 10). The exemplary ability of bedded evaporites to act as seals holding back massive hydrocarbon columns is clearly seen in the Middle East, where Ghawar, the world's largest oil field, is sealed by bedded anhydrites of the Jurassic Arab D Formation and the overlying Hith Anhydrite seal. This evaporite seal association in Ghawar holds back an estimated remaining reserve of more than 100-200 billion barrels. Bedded platform anhydrites also seal Safaniya, the world's largest offshore field, also in Saudi Arabia, with estimated reserves of more than 25-30 billion barrels of oil and 5 billion cubic feet of natural gas. Likewise, Permian platform anhydrites are the regional seal to North Field in offshore Qatar, the world's largest single gas field (non-associated gas) with more than 500 tcf of reserves (Alsharhan and Nairn, 1997). This gas is reservoired and sealed in the evaporitic dolomites of the Permian Khuff Formation and recent announcements by the Qatari Government have postulated more than 900 tcf of certified non-associated gas sealed in the North Field structure.

In terms of physical processes, buried near-pure halite beds and masses (rock salt) in the sedimentary realm are rheologically unusual compared to other nearby sediments, in that at geological time scales rock salt can set up deformation responses that mimic Newtonian fluid responses. At the same time, intercrystalline textures in the flowing salt mass maintain seal integrity, even as local crystals dissolve and reprecipitate. That is, down to depths of 6-8 km rock salt flows and maintains seal integrity, while adjacent non-salt sediments tend to fault and fracture. The ability of bedded salt to seal (Figure 10a) and of flowing salt to create and seal supra-, intra- and sub-salt reservoirs is well documented (Figure 10b).

Dense evaporitic brines can pass through adjacent or underlying sediments both at the time the bedded salts are accumulating, or later as a subsurface salt mass dissolves. For example, chemical responses, created within the set-up hydrology of widespread salt deposition and early burial, drive brine reflux, moving magnesium-rich modified seawater brines into and through the underlying carbonate sediments. This hydrology crafts broad reflux dolomite haloes, with local burial anhydrite patches and overall improves intercrystalline connectivity, at least until the dolomite reservoir becomes overdolomitised (Figure 11). Once this happens, all effective polyhedral porosity is lost in the dolomite and the reservoir potential is destroyed. Later dissolution brines can create hydrothermal waters capable of leaching and burial dolomitization, as in the burial-dolomite reservoirs of the Western Canada Sedimentary Basin (Davies and Smith, 2006).

Organic–hydrocarbon association

As long ago as the middle of last century, Weeks (1961) emphasised the importance of evaporites as seals to many of the world's major hydrocarbon accumulations. He also pointed out that many of the cycles of deposition that involve organic-rich carbonate marls or muds also end with evaporites. Clearly, in evaporitic settings, there is

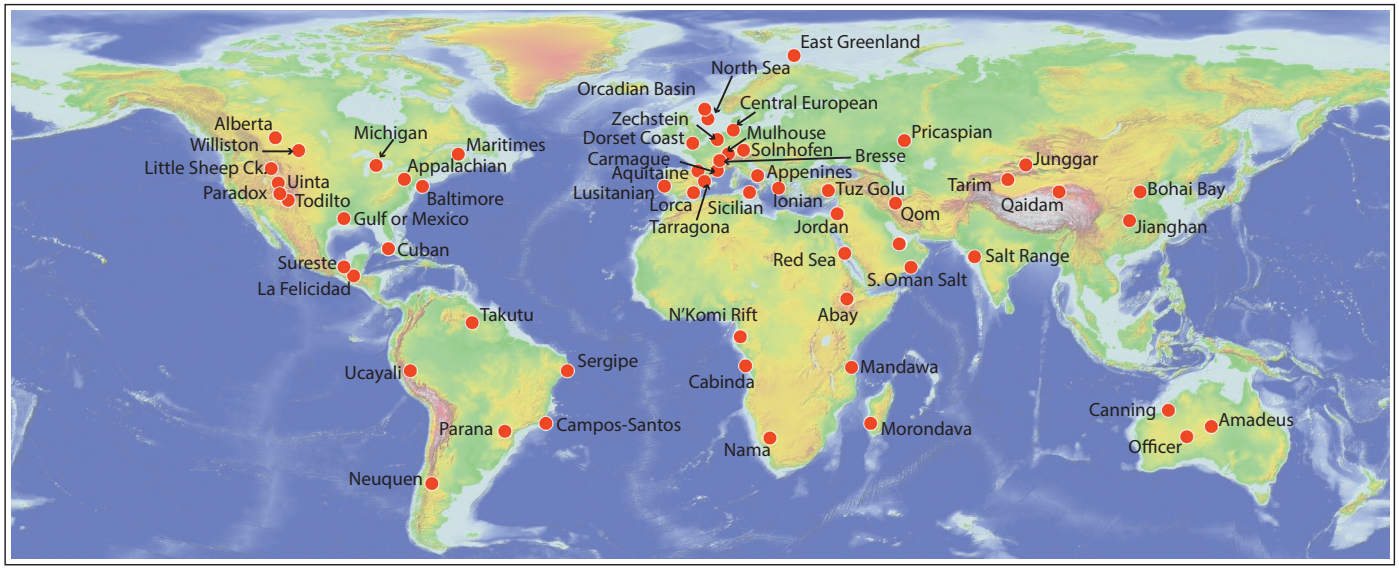

Figure 12. Worldwide distribution of evaporite-related source rocks named with respect to hosting basins (replotted from SaltWork GIS database version 1.7).

an association with Type I-II hydrogen-prone kerogens in mesohaline source rocks, and this is related to the ability of halotolerant photosynthetic algae and cyanobacteria to flourish in periodically mesohaline waters. Such kerogens tend to be oil-prone rather than gas prone and typified by long-chain hydrocarbons (Warren, 2011).

Much of the mesohaline organic matter preserved in evaporitic carbonates, and the resulting source rocks, originated as planktonic blooms (pelagic "rain from heaven") or from the benthic biomass ("in situ" accumulations). Such organics typically settled out as seriate pulses of organic matter (often pelleted and laminated) that sank to the bottom of a layered brine column. Each pulse was tied to a short period when surface brines were diluted and halotolerant producers (mostly cyanobacteria and algae) flourished in the freshened lit zone. That is, laminated mesohaline mudstones that constitute most evaporitic source rocks reflect biological responses to conditions of "feast or famine" in vacillatingly-layered brine bodies (Figure 12; Warren, 1986, 2011).

Worldwide, studies of schizohaline evaporitic basins have shown that organic-rich mesohaline sediments can accumulate beneath ephemeral surface brines in salterns, or in basin and slope settings in both marine and continental settings (Figure 12; Kirkland and Evans, 1981; Oehler, 1984; Warren, 1986, 2011; Rouchy, 1988; Busson, 1992). The most prolific accumulations of organics in ancient evaporitic settings tend to be laminated micritic carbonates deposited be-neath intermittently stratified moderately-saline (mesohaline) anoxic water columns of varying brine depth.

There are three, possibly four, major mesohaline density-stratified settings where organic-rich laminites (source rocks) accumulate in saline environments that are also associated with, or evolve into, evaporite deposits (Warren, 2011):

1) Basin-centre lows in marine-fed evaporitic drawdown basins (basinwide salts).

2) Mesohaline intrashelf lows atop epeiric evaporitic platforms.

3) Saline-bottomed lows in perennial underfilled saline lacustrine basins.

4) Closed seafloor depressions in halokinetic deepwater marine slope and rise terrains.

The metal–evaporite association

In addition to the evaporite hydrocarbon association, there is an association of evaporite settings with the larger of the known MVT, Sedex, Stratiform Sedimentary Copper and some IOCG associations (Figure 13; see Warren 2016, Chapter 15 and 16 for detailed case histories and models). The role of evaporites in focusing metalliferous ore accumulations is two-fold; 1) In solution (halite-dominant precursor) they can act as chloride-rich metal carriers and 2) Locally, as beds or masses (especially of $CaSO_4$), their dissolution products, especially if trapped, can supply sulphur (mostly as bacteriogenic or thermogenic H2S) and also set up chemical interfaces that act as foci in the setup of brine mixing conditions suitable for precipitation of metal sulphides or native elements. Hence, most evaporite-associated ore systems tend to be epigenetic, rather than syngenetic. Subsurface salt beds and masses are merely the solid part of a large ionic recycling system; dissolved metals are another part, and zones of mixing between the two are typically sites

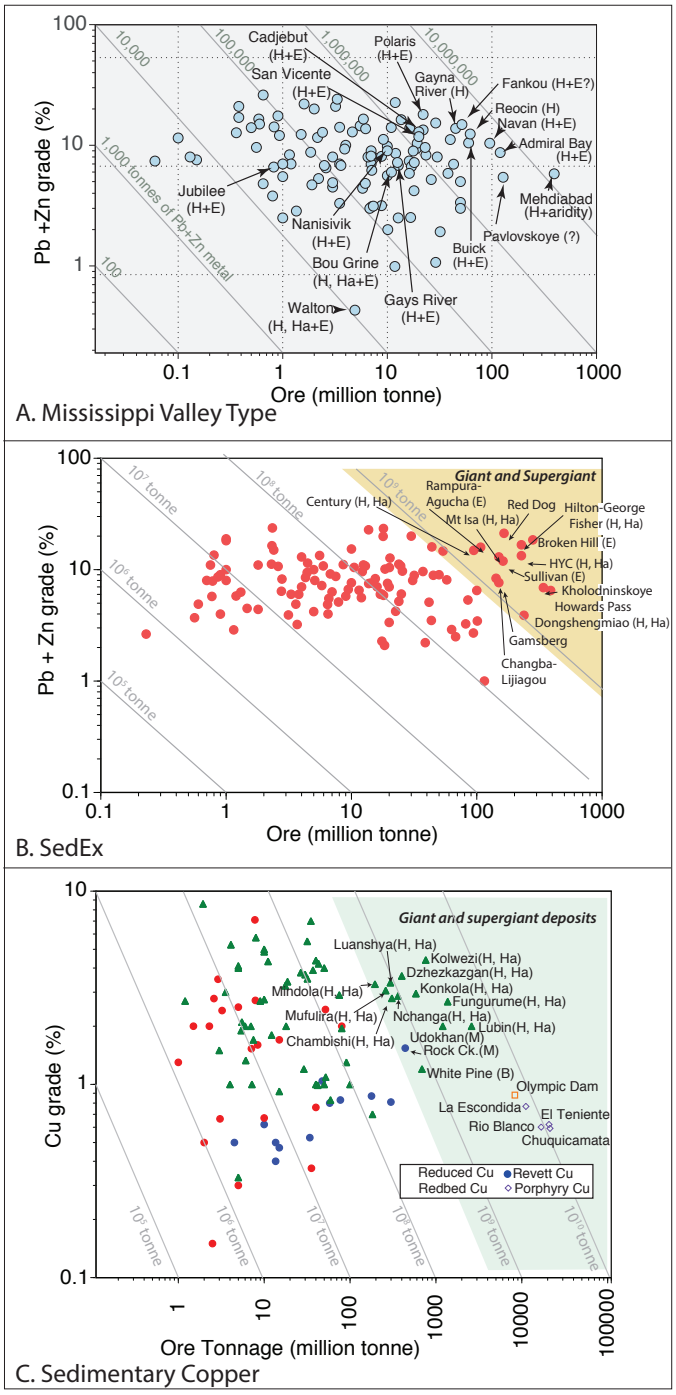

Figure 13. Resource plots for various metal accumulations showing those with evaporite associations. H indicates hypersaline ore fluids, E indicates evaporites or indications of its former presence, Ha= halokinetic, B = bedded, M = meta-evaporite (ireplotted from SaltWork GIS database version 1.7).

where ores tend to accumulate. Halokinesis steadies the position of a redox interface, tied to a salt dissolution brine halo, and enables an extended phase of focus to a metal precipitative (redox) interface at a stable location in subsurface earth-space (War-ren, 2016).

At the world-scale, evaporite-associated metalliferous systems are driven by plate tectonics. Halite-dominated sequences, deposited in the drawdown basin centres, tend to dissolve in burial, and so supply chloride ions to the brine system. Salt beds that are thick enough tend to flow and so focus the upward, and centripetal passage of basinal and hydrothermal fluid flows. Dissolving gypsum or anhydrite beds, typically deposited higher on the basin platform or diagenetically accumulated along salt dissolution edges and touchdowns can supply sulphur, via bacterial or thermochemical sulphate reduction, while simultaneously focusing metalliferous brine flows into the precipitation interface.

When the chemistries of the dissolving salt beds and the metal carriers interact so that redox fronts, salinity contrasts, and other precipitative interfaces are set up, an ore deposit can form. Thus, in base and precious metal exploration within evaporitic terranes, we are ultimately searching for those parts of a subsurface ionic cycling system where the salt dissolution, salt beds and metal systems have interacted to create economic levels of metalliferous precipitates.

If salt is more than a seal, then.....

From a time in the 1950's and 1960's when evaporites were mostly seen as seals, knowledge systems developed over the next five decades now allow us to do much more with respect to predictive industrial geology, centred on the following evaporite facts:

1) The distribution of evaporite depositional textures maps paleotopography across the underlying carbonates and si-liciclastics. So, depositional signatures preserved in the seal can be used to map reservoir quality trends in terms of reflux dolomite intensity, anhydrite cement-patch distributions and zones of subaerial diagenesis

2) Thick beds of halite tend to accumulate in particular plate tectonic settings. Beds deposited in plate-edge saline sumps tend to flow via sediment loading and extension, without later superimposed tectonic stresses. In contrast, bed deposited in intracratonic settings tend to require later externally-imposed tectonic stress in order to flow. Hydrocarbon trapping geometries are tied to particular styles of salt tectonics

3) Mesohaline source rock distribution is related to evaporite basin architecture and likely fluid escape pathways, which in turn are related to seal type and timing of salt dissolution or halokinetic withdrawal.

4) Potash ore quality controls are related to the timing of various brine crossflows generated during deposition, mesogenesis and telogenesis.

5) Positions of likely base metal and copper accumulations relate to set-ups of dissolution-related of redox interfaces, mesogenetic cross-flows, and in some cases, halokinetic geometries. At the plate tectonic scale, these accumulations occur at particular hydrological interfaces within the basin architecture.

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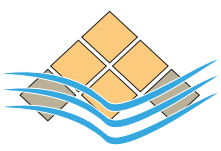

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