
John K. Warren

Evaporites

A Geological Compendium

Second Edition

 Springer

Contents

1	Interpreting Evaporite Textures	1
	What is an Evaporite?	1
	Solar-Heated Brine Concentration	1
	Cryogenic and Other Non-solar Saline Mechanisms	2
	Burial and Hydrothermal Salts	5
	So, What Exactly Is an Evaporite?	8
	Primary Evaporitic Carbonates	12
	Carbonate Laminites (Subaqueous?)	13
	Strandzone Associations: Microbialites, Pisolites and Tepees	14
	Vadose Pisolites, Ooids and Coated Grains	32
	Tepees	35
	Carbonates: Present and Past	37
	Primary Evaporite Salts	39
	Gypsum Beds	39
	Halite Beds (Chevrons and Crusts)	44
	Pedogenic and Wind Reworked Salts	48
	Laminites from Settling of Pelagic Salts	54
	Salt Reefs, Are They Real?	58
	Secondary (Diagenetic) Evaporites	60
	Intrasediment Salts	60
	Syndepositional Karst in Crusts	62
	Shallow Mineralogic Re-equilibration	65
	Burial of Sulphate Evaporites	69
	Evaporites as Uplift Indicators (Tertiary Evaporites)	74
	Fibrous Gypsum and Halite (Satinspar)	76
	Anhydrite Rehydration at the Microscale	79
	Saline Clay Authigenesis	80
	Textural Synthesis	83
2	Depositional Chemistry and Hydrology	85
	Quaternary Deserts and Evaporite Assumptions	85
	Quaternary Evaporites in a Köppen Climatic Framework	92
	Local Variations in Climate	98
	Chemical Evolution of Surface and Nearsurface Brines	103
	Marine Brines	103
	Nonmarine Brines	112
	Separating Marine from Nonmarine	120
	Back Reactions	121
	Marine Aerosols and Continental Gypsum	123
	Acid Groundwater in Continental Saline Systems	127

Indicators of Brine Parenthood	132
Bromine Profiles – Parentage or Stability?	132
Sulphur and Oxygen Isotopes	135
Boron Isotopes	138
Chlorine Isotopes	140
Fluid Inclusions and Brine Temperatures	144
Seawater Evolution	147
A Phanerozoic Dilemma: Marine Versus Nonmarine Potash?	147
Precambrian Oceanic Chemistry	153
Precambrian-Cambrian Transition	159
Hydrology Is Depositional Style	162
Active Phreatic/Vadose Regime	162
Hydrologies in Saline Basins	163
Mudflat Aggradation Mirrors Watertable Change	168
Indicators of Fluctuating Watertables	169
Degrading Hydrology and Playa Capture	175
Remote Sensing of Saline Hydrologies	177
Salinity Stratification Controls Texture	185
Brine Stability and Evaporite Textures	188
Brine Reflux Drives Substrate Alteration	190
Can Reflux Really Work?	196
Importance of Hydrographic Isolation	198
Extraterrestrial Hydrologies, “Freeze-Dried” Salts, and the Meaning of Life	201
3 Sabkhas, Saline Mudflats and Pans	207
Introduction	207
What Is a Sabkha?	210
Marine Coastal Sabkhas	211
Carbonate-Hosted Coastal Sabkhas in the Southern Arabian Gulf	212
Siliciclastic-Hosted Coastal Sabkhas, Western and Northern Arabian Gulf	231
Other Coastal Sabkhas	240
Interpretive Limitations of Holocene Sabkha Models	249
Lacustrine Sabkhas and Pans	251
Depositional Characteristics	251
Styles of Continental Sabkhas	256
Salt-Pans (Marshes) and Diapirs	299
Why and Where of Sabkhas & Pans?	301
4 Subaqueous Salts: Salinas and Perennial Lakes	303
Introduction	303
Sea-Margin Subaqueous Salts	305
Coastal Salinas of Australia	305
Coastal Salinas of the Middle East	316
South American Salinas and Dolomite	321
Continental Subaqueous Basins	324
Perennial Saline Lakes	324
Lake Asal, Republic of Djibouti	372
Are Modern Saline Lakes all Shallow?	374
5 Ancient Basins and Stratigraphic Evolution	381
Introduction	381
Linking Present to Past Aridity	382
Varying Extent of Ancient Evaporites	388
Building Blocks of Ancient Salt Beds	393
Evaporites: Broad-Scale Depositional Models	398

Problems in Correlation <i>Sans</i> Hydrology	437
Dolomite Aprons in a Drawdown Basin	440
Sequence Stratigraphy in Evaporite Basins?	443
Does Sealevel Control Salt Sequence Boundaries?	446
Icehouse and Greenhouse Eustasy	447
Basinwide Evaporites	451
Basinwide Examples	454
Summary	490
6 Flowing Salt: Halokinesis	491
Introduction	491
Physics of Salt Systems	494
Density, Viscosity, Strength & Buoyancy	494
Thermal Effects	503
Flow Textures and Rates	504
Triggers, Drivers and Outcomes of Salt Flow	510
Diapirs and Extension	512
Diapirism and Differential Loading	514
Sedimentation Rate Controls Diapir Shape	516
Extension, Falling Diapirs and Turtles	518
Falling Diapirs Drive Raft Tectonics	519
Salt as Sheets, Allochthons and Breakouts	521
Inflation, Deflation, Welds and Basal (Subsalt) Shear Zones	524
Near-Diapir Suprasalt Shear (Drag Zones)	534
Welds, Loading Detachments and Growth Faults	536
Fault Families in Allochthons	545
Linking Allochthons at the Basin Scale	548
Compressional Salt Tectonics	551
Shortening with Gravity Gliding	552
Thin-Skinned Fold and Thrust Belts	558
Inverted Salt Basins	563
Mild Shortening in Tectonically Confined Basins	564
Salt Extruding Today?	571
Browne Formation Oldest Known Salt	580
Sediments and Flowing Salt	583
Sedimentation and Evolving Salt Structures	585
Sediments Tied to Salt Basin Evolution	593
Subsalt Sections	600
Caprock Formation (Diagenesis of Salt)	600
Complications of Shale Diapirism	605
Summary	612
7 Salt Dissolution and Pointers to Vanished Evaporites:	
Karst, Breccia, Nodules and Cement	613
Introduction	613
Evaporite Landforms	618
Local Scale Karst	618
Regional-Scale Karst	624
Salt Dissolution: Solution Breccias and Residues	639
Defining Evaporite Dissolution Breccia	639
Bedded Solution-Collapse Breccias	641
Breccia Extent	645
Diapiric Solution Breccias	650
Diapiric Versus Salt Ablation (Retreat) Breccias	654
Salt-Cored Thrust and Fold Breccias, Rauhewacke and Orogeny	656

Partial Salt Dissolution: Residues of Less-Soluble Salts	665
Focused Rapid Dissolution – Evaporite Clasts	666
Diffuse Dissolution -Markers and Residue Beds	667
Basal Anhydrite, Thailand	672
Caves in Evaporite Karst	674
Gypsum Caves.	675
Halite Caves	685
Evaporite Speleothems in Non-evaporite Karstified Host	691
Hazards Tied to Evaporite Karst	692
Problems in the Ripon Area, UK	694
Problems with Miocene gypsum, Spain	697
Gypsum Karst in Mosul, Iraq	699
Coping: Man-made Structures Atop Salts.	699
Solving the Problem?	703
Sulphuric Acid Speleogenesis	704
Mineralised Hypogene Breccias	712
Filled Vugs and Nodules	715
Silicified Evaporites	716
Calcitisation and Dedolomitisation	724
Celestite as an Evaporite Indicator?	735
Fluorite as an Indicator?	743
Baryte as an Indicator?	747
Authigenic Anhydrite as a Burial Salt	753
Enigmatic Outlines in Pseudomorphs	758
Summary	760
8 Hypersaline Fluid Evolution During Burial and Uplift	763
Basin-Scale Burial Hydrology	763
Fluids in Subsiding Basins.	769
Compactional Fluids	769
Thermobaric-Thermohaline Fluids	770
Deep Flow in Pull-Apart Basins	774
Flow in and Adjacent to Collision Belts	775
Flow in Post-Orogenic Hydrologically-Mature Basins.	780
Alteration, Pressure Cells and Salinity-Driven Convection.	786
Haloes, Convection and Saltout	786
Evaporites as Pressure Seals	789
Salt-Maintained Overpressure.	792
Controlling Unpredicted Pressure Changes	802
Drilling Mud Chemistry in Salt Systems	804
Salt-Generated Underpressure	805
Temperature Anomalies and Brine Flow	806
Fluid Flow in Halokinetic Basins.	809
Suprasalt Fluid Flow and Alteration	809
Burial Dewatering of Hydrated Salts.	814
Brine-Rock Burial Evolution	818
Brine Chemistry at Depth	819
Effects and Indications of Water-Salt Interactions.	824
Crustal Cycling of Brines?.	826
9 Halotolerant Life in Feast or Famine: Organic Sources of Hydrocarbons and Fixers of Metals.	833
Introduction	833
Evaporitic Source Rocks	837

Halobiota: Adaptations and Bio Markers	853
Metabolic Pathways in Producers and Consumers	854
Light Dwellers and Pigmentation	856
Non-photosynthesizers and Layering	860
Salinity Tolerance	864
Primary Producers (Photosynthesizers)	864
Halobiotal Heterotrophs (Consumers)	873
Cellular Adaptations to Hypersalinity	884
Life in a Layered Microbial Mat?	888
Biomarkers and Microbial Responses to Changing Salinities	890
Do Biomarkers Indicate Hypersalinity?	893
Organic Enrichment	898
Biological Responses to Variably Layered Brines: Cycles of “Feast or Famine”	900
The Where and When of Productivity	912
Life, Brine Seeps and Dissolving Salts	919
Geological and Hydrological Features	919
Life, Fe and Sulphur in Seafloor Brine Lakes	923
Rim Life, CH ₄ and H ₂ S in Seafloor Brine Lakes	930
Hardgrounds, Settings and Stable Isotopes	933
Ancient Saline Seeps	935
Life in the Saline Subsurface	939
Bacterial Sulphate Reduction (BSR)	940
Thermochemical Sulphate Reduction (TSR)	945
H ₂ S, Natural Gas and Metallogeny	949
Hydrothermal Cracking in Saline Rift Lakes	952
Summary	955
10 Hydrocarbons and Evaporites	959
Introduction	959
Seal Capacity of Evaporites	965
So Why Do Evaporites Seal?	965
Environments Favouring Seal Continuity	968
Reservoirs and Traps	971
Bedded Salt Seals	971
Exploration Paradigms in the Bedded Evaporite Hydrocarbon Association	1025
Halokinetic Salt Traps	1031
Supradiapiric Traps	1032
Tiered Allochthon Plays in the Deepwater Realm	1038
Minibasin Plays	1047
Intrasalt Halokinetic Plays	1049
Subsalt Reservoirs in Compressional Evaporite Provinces	1063
Evaporite Dissolution	1073
Athabasca Tar Sands, Western Canada	1077
11 Potash Resources: Occurrences and Controls	1081
Introduction	1081
Production and Consumption	1085
Ore Extraction Technologies	1088
Conventional Mining	1088
Solution Mining of Potash	1095
Lake Brine Processing and Solution Chemistry	1096
Ore Beneficiation	1096

Quaternary Potash	1100
Playas of the Qaidam Basin	1100
Danakil Depression, Ethiopia	1109
Inland Chotts and Coastal Sabkhas in North Africa	1119
Potash from Brine	1124
Ancient (Pre-Quaternary) Potash	1136
Upper Rhine Graben, France	1136
Khorat Plateau, Thailand	1139
Cretaceous Trans-Atlantic Potash	1145
Moroccan Meseta (Late Triassic)	1148
Permian Potash	1149
German Potash (Z1, Z2 and Z3 Potash)	1149
Z3 – Boulby Potash, UK	1150
New Mexico Potash, USA	1154
Upper Kama Potash Region, Cis-Urals Russia	1156
Canadian Maritimes (Mississippian of Nova Scotia and New Brunswick)	1160
West Canadian Potash (Devonian)	1163
Pripyat Basin (Devonian) Belarus	1168
Other Significant Deposits	1170
So, How Does Mineable Potash Form?	1172
Controls on Potash Quality: Anomalies, Leaching and Problematic Mine Waters	1174
Potash Occurrence and Quality at the Worldscales	1181
12 Non-Potash Salts: Borates, Na-Sulphates, Na-Carbonate, Lithium Salts, Gypsum, Halite and Zolites	1187
Introduction	1187
Borate Salts (Tincals)	1187
Character, History and Processing	1187
Geology of Borates	1192
Evaporitic Borates and the Evolution of Life	1209
Sodium Sulphate Salts (Salt Cake)	1209
Character and History	1209
Canadian Brine Extraction	1216
Karabogazgol Brines, Turkmenistan	1220
Laguna Del Ray Brines, Mexico	1224
Spanish Glauberite Mines	1226
Turkish Deposits	1228
Other Sodium Sulphate Deposits	1231
Sodium Carbonate Salts (Soda ash)	1233
Character and Extraction History	1233
Trona in North America	1238
Natural Soda Ash in China	1242
Trona in the African Rift	1244
CaSO ₄ and NaCl	1246
Calcium Sulphate (Gypsum)	1246
Rock and Pan Salt (Halite)	1249
Lithium and CaCl ₂ Brines, Iodine and Bromine	1256
Lithium Brines	1256
CaCl ₂ Brines and Minerals	1268
Iodine	1273
Bromine	1277
Nitrate Salts (Nitratite and Saltpetre)	1278

Magnesite and Magnesia Salts	1282
Sulphur Salts (Brimstone)	1287
Usage History and Industry Trends	1287
Types of Natural Sulphur Deposits	1289
Biology of Native Sulphur	1290
Occurrences and Textures	1290
Zeolites – Molecular Sieves	1292
Usage and Production	1293
Geological Controls on Saline Zeolitisation	1294
Summary	1300
13 Solution Mining and Salt Cavern Usage	1303
Introduction	1303
The Solution Mining Process	1304
History of Salt Solution Wells	1304
Well and Cavern Design	1306
Solution Well Styles	1309
Techniques in Potash Operations	1310
Lithology Effects Shape	1312
Well Pad Design	1314
Blinding and Phase Chemistry	1316
Phase Chemistry – Trona Solution Mining	1316
Use of Salt Caverns	1318
Energy Liquids & Compressed Air Storage	1318
Waste Disposal	1323
Problems in Salt Solution Mines, Conventional Mines, Well-Bores and Storage Facilities	1325
Case Histories: Caving Brinefields	1326
Case Histories: Caving and Leaking Wells	1343
Case Histories: Storage Cavern Problems	1357
Gas Escape, Explosions and Fires from Cavern Leaks	1359
Recognising and Preventing Potential Cavern Problems	1366
Salt Creep	1366
Salt Falls Versus Roof Collapses	1368
Ground Subsidence	1369
Surface Indicators of Breached Caverns	1370
Monitoring and Minimizing Collapse	1371
Natural or Anthropogenic Subsidence?	1371
So How Stable is a Storage Cavern?	1372
Cavern Plugging	1372
Summary	1374
14 Meta-evaporites	1375
Introduction	1375
World-Scale Tectonism	1379
Many Meta-evaporites are Pre-Neoproterozoic	1381
Protoliths Across the First 2 Billion Years	1384
Metamorphism: Onset and Evolution	1387
Thrust Belts; Dynamic or Regional Metamorphism	1387
Meta-evaporite Mineral Associations	1394
Scapolite and Scapolitization	1394
Albitites and Albitization	1401
Tourmaline and Tourmalinisation	1405
Sodian Phyllosilicates and Talc	1414
Precious Stones as Meta-evaporites	1417
Elevated Magnesium Levels in Metasediments	1428

Meta-evaporite Examples	1430
Examples in the Greenschist Realm	1430
Examples in the Amphibolite/Granulite Realm	1438
Implications	1468
15 Lower Temperature Metals in an Evaporitic Framework	1469
Introduction	1469
A Little Classification/Exploration Philosophy	1473
Evaporite-Related Metalliferous Brines?	1474
Modern Basin Brines: Composition	1476
Basinal Brines: Metal Carrying Capacity	1480
Low Temperature Sediment-Hosted Ore Deposits (Evaporite-Related)	1490
Red Sea – Modern Metalliferous Brine Lake Laminite Beds	1491
Stratiform Copper Deposits (Salt-Related)	1498
Stratiform Cu Halokinetic-Salt Associations	1500
Sediment-Hosted Cu in Bedded Evaporite Context	1516
Stratiform Sediment Hosted Pb-Zn Deposits (Salt-Related)	1524
Evaporite Associated MVT Deposits	1525
Evaporite-Associated SedEx Deposits	1563
Arid-Zone Diagenetic Uranium and Copper Associations	1584
Duricrusts: Yilgarn Australia and Namibe, Africa	1584
Porphyry Copper, Supergene Enrichment and Aridity	1586
Base Metals, Evaporites and Diagenetic Accumulations: A Summary	1588
16 Magma-Evaporite-Hydrothermal Metal Associations	1591
Introduction	1591
Metal Transport in the High Temperature Saline Realm	1593
Regional Orthomagmatic- Evaporite Interactions	1595
Orthomagmatic Ni-Cu Associations with Evaporites as a Sulphur Source	1596
Paramagmatic Interactions	1602
Cooking the Salt: Dykes and Sills in Salt	1602
Molten Salts: Natrocarbonatite and Brine	1606
Phreatomagmatic Iron-Rich Associations	1609
Korshunovsky (Korshunovskoye) Iron Ore Deposits, Siberia	1609
Paramagmatic Saline Haloes	1610
Iron-Oxide Copper Gold (IOCG) Deposits	1616
IOCG in an Evaporite/Basinal Brine Milieu	1620
So What Is a IOCG Deposit and Is Mineralisation Evaporite/Brine Related?	1640
Hydrothermal (Non-evaporitic) Salts and Metalliferous VHMS Deposits	1643
VHMS Deposits in Subduction-Related Island-Arc Settings: Kuroko-Style Deposits	1646
VHMS Deposits with Thermal Anhydrites at mid Ocean and Back-Arc Spreading Centres	1650
VHMS Deposits with Hydrothermal Anhydrite at Sediment-Covered Spreading Centres: Besshi-Style and the Guaymas Basin	1654
Evaporites and Metalliferous Deposits	1656
References	1659
Index	1783