Salt tectonics, sediments and prospectivity: an introduction

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Salt: an introduction

Salt is a crystalline aggregate of the mineral halite, which forms in restricted environments where the hydrodynamic balance is dominated by evaporation. The term is used non-descriptively to incorporate all evaporitic deposits that are mobile in the subsurface. It is the mobility of salt that makes it such an interesting and complex material to study. As a rock, salt is almost unique in that it can deform rapidly under geological conditions, reacting on slopes $\leq 0.5^\circ$ dip and behaving much like a viscous fluid. Salt has a negligible yield strength and so is easy to deform, principally by differential sedimentary or tectonic loading. Significant differences in rheology and behavioural characteristics exist between the individual evaporitic deposits. Wet salt deforms largely by diffusion creep, especially under low strain rates and when differential stresses are low. Basins that contain salt therefore evolve and deform more complexly than basins where salt is absent. The addition of halokinetic processes to the geodynamic history of a basin can lead to a plethora of architectures and geometries. The rich variety of resultant morphologies have considerable economic as well as academic interest.

Historically, salt has played an important role in petroleum exploration since the Spindletop Dome discovery in Beaumont, Texas in 1906. Today, much of the prime interest in salt tectonics still derives from the petroleum industry because many of the world's largest hydrocarbon provinces reside in salt-related sedimentary basins (e.g. Gulf of Mexico, North Sea, Campos Basin, Lower Congo Basin, Santos Basin and Zagros). An understanding of salt and how it influences tectonics and sedimentation is therefore critical to effective and efficient petroleum exploration. Within rift basins in particular, salt is seen to orchestrate the petroleum system. Through halokinesis it creates structural traps, counter-regional dips on continental margins, and it can carry or entrain adjacent lithologies via rafting. Salt influences syn- and post-kinematic sediment dispersal patterns and reservoir distribution and can therefore be important for the creation of stratigraphic traps. It can also form top and side seals to hydrocarbon accumulations and act as a seal to fluid migration and charge at a more regional scale. Salt may also dramatically affect the thermal evolution of sediments due to its high thermal conductivity. A thick layer of salt cools sediments that lie below it while heating sediments above it. This effect cannot be underestimated as it helps provide the favourable conditions for source rock maturation in the deepwater Gulf of Mexico and Santos basins, even though sedimentary overburden may be 5 km or more in thickness. Salt can also impact reservoir quality. The role of salt in the diagenetic history of reservoirs through its control on hydrothermal pore waters is a crucial element in the risking of the deepwater Palaeogene play of the Gulf of Mexico, for example. Salt continues to kinetically evolve through time, not only by the classical roller-diapir-pedestal-canopy/collapse progression but also with varying rates of deformation, in response to changing sedimentation rates and patterns. The relative timing of salt movement and its impact on source, reservoir, trap, seal and timing often governs the prospectivity in salt-related basins. Beyond the realm of petroleum, salt is also used as a resource for potash, gypsum and nitrates and has the potential to be employed as a repository for radioactive waste or a top seal to sequestered CO_2.

Salt tectonics, sediments and prospectivity: a conference summary

In January 2010, The Petroleum Group of the Geological Society in conjunction with the Society for Sedimentary Geology (SEPM), convened an international conference at Burlington House in London entitled Salt Tectonics, Sediments and

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Prospectivity. The aim was to bring together industrialists and academics to present a contemporary view of salt at a global scale and to examine its influence on syn-kinematic sedimentation, on basin evolution and ultimately on hydrocarbon prospectivity.

The conference was one of the best attended in recent years at the Geological Society and this volume incorporates 29 papers stemming from the conference. Salt tectonics obviously continues to be an important theme within both academic and industrial geoscience communities alike. This collection of papers creates a broad thematic set that encompasses much of the recent research into salt and sediment dynamics. It is hoped that this volume will act as a valuable modern reference and a springboard for future studies. This overview outlines the key findings and summarizes the key concepts that are presented more fully in the papers in the main body of this special publication. This is the first Geological Society Special Publication (GSSP) dedicated to salt tectonics and associated sedimentation since Alsop *et al.* (1996) more than 15 years ago; it therefore represents a timely addition to this expanding field.

The volume is separated into five main themes covering a variety of geographical and process-linked topics relating to salt tectonics, sediments and prospectivity. These include halokinetic-sequence stratigraphy, salt in passive margin settings, Central European salt basins, deformation within and adjacent to salt and salt in contractional settings and salt glaciers.

Halokinetic-sequence stratigraphy

Halokinetic-sequence stratigraphy involves the application of sequence stratigraphic principals directly to salt-influenced sedimentary strata. This section opens with a paper by **Giles & Rowan** that investigates concepts in halokinetic-sequence stratigraphy and deformation. Hook geometry halokinetic sequences are narrow unconformity-bounded zones of deformation with pronounced angular ($>70°$) discordances and abrupt facies changes. Wedge geometry halokinetic sequences display broader zones of folding, low-angle truncations and gradual facies changes. Composite halokinetic sequences may also form and reflect variations in the ratio of diapiric rise to sediment accumulation rates.

Rowan *et al.* describe the anatomy of an exposed vertical salt weld from the La Popa Basin of Northern Mexico. Halokinetic folding coupled with local unconformities suggest a precursor salt wall that was subsequently squeezed during regional contraction to form a vertical salt weld. The degree of deformation varies significantly along the length of the 24 km long weld and is thought to be controlled by the original thickness of the salt wall together with the amount and direction of subsequent shortening. Where contraction was normal to the salt wall, then the diapir was locally closed with little further deformation. However, where shortening was oblique to the wall then significant post-weld dextral shearing and fracturing took place, which may affect the sealing capacity of such welds.

Further detailed studies along the La Popa weld by **Andrie *et al.*** demonstrate that fluvial sedimentation in a shortening-induced salt-withdrawal basin displays distinct up-section changes in fluvial facies distribution and the geometry of halokinetic folding. Fluvial channels in the lower part of the sequence are typically thin, broad and display variable palaeocurrents, while the upper parts of the sequence are marked by thick, stacked channels with weld-parallel palaeocurrents. In addition, halokinetic folding of sediments also intensifies and becomes narrower up the sequence, reflecting reduction in sedimentation rates compared to salt rise rates.

Kernen *et al.* provide a stratigraphic analysis of Neoproterozoic sequences adjacent to an inferred allochthonous salt sheet in the Central Flinders Ranges of South Australia. Sediments adjacent to the salt represent a progradational sequence from wave-dominated shelf deposits through to coastal plain sediments. Halokinetic-sequence boundaries may be pronounced and marked by up to $50°$ of angular truncation.

Smith *et al.* consider the fracture-controlled palaeohydrology of a secondary salt weld in the La Popa Basin. Isotopic and fluid inclusion analyses suggest that veins were formed after salt was evacuated and are more abundant near a bend in the weld. In addition, such analyses also indicate that the weld acted as a vertical fluid conduit and a horizontal baffle. This has clear implications for hydrocarbon sealing potential, which may also be influenced by factors such as bends in welds and amounts of shortening across such structures.

Salt in passive margin settings

Mohriak *et al.* discuss salt structures in Brazil, ranging from intracratonic Palaeozoic basins to divergent margin basins formed during the Mesozoic break-up of Gondwana. Seismic reflection data together with magnetic and gravity data across Mesozoic rifts of the South Atlantic suggest a thick autochthonous salt layer that becomes pronounced above the transition from continental to oceanic crust. Recent discoveries suggest that pre-salt plays in deepwater settings will make an important contribution to future hydrocarbon production from the region.

The paper by **Davison *et al.*** considers salt deposition, loading and gravity-driven 'drainage' of salt in the Campos and Santos basins of southern Brazil. Evaporites, which are thought to have been rapidly deposited (<1 Ma) during the latter phase of extension, resulted in loading of the basin which thereby created further subsidence and consequent flow (or drainage) of mobile salt into these subsiding basins. Interpretation of seismic sections suggests that downslope flow of salt occurred before significant deposition of sediments, thereby resulting in the redistribution of salt load and probable reactivation of faults.

The role of halokinesis in controlling structural styles and sediment dispersal patterns in the Santos Basin is investigated by **Guerra & Underhill**. Deformation in the post-salt sequence is marked by gravitational gliding and spreading driven by halokinesis and sediment inflows. The Cabo Frio fault is a major landwards-dipping listric fault that controls major sediment depocentres upslope, accommodated downslope by shortening within salt-cored folds. Sediment supply from a variety of directions forms an interference pattern of folds and intervening minibasins. The post-salt sediments move basin-ward relative to the pre-salt sequence due to halokinesis, although restoration techniques allow key elements to be linked thereby improving petroleum system assessments.

Quirk *et al.* discuss salt tectonics on passive margins with examples from the Santos, Campos and Kwanza basins. Salt is considered to flow rapidly towards the ocean basin immediately after continental rifting due to thermal subsidence. Translation and extension of the salt overburden on both seaward- and landward-dipping normal faults mark the early history of inboard areas, whereas outboard areas are characterized by contractional structures. The processes of thermal subsidence and salt drainage are capable of moving sediment on passive margins tens of kilometres seaward in relatively short periods of time.

Quirk & Pilcher introduce the concept of flip-flop salt tectonics which relates to salt walls developed in extensional regimes. Within such settings salt walls may display strata truncated against both flanks, asymmetry related to normal fault growth patterns, and unconformities or onlap surfaces separating strata dipping in opposing directions. The structure is considered to develop by a normal fault detaching down one flank of a salt roller. Salt flows towards the crest in the low-stress area in the fault footwall, causing it to tilt backwards and become unstable. Growth then continues by switching to a new counter-dipping fault that detaches on the opposite margin of the salt body, leading to an unconformity and onlap surface. This process may repeat itself several times.

Fort & Brun discuss the kinematics of regional salt flow in the northern Gulf of Mexico. Contrary to previous interpretations that invoke sedimentary loading as the main driving force, they suggest that the primary control on salt tectonics in the northern Gulf of Mexico is gliding related to the overall dip of the margin.

Kane *et al.* document the halokinetic effects on submarine channel profiles from the Magnolia Field in the Gulf of Mexico. During the growth of salt structures, channels may become entrenched where their erosive potential is sufficient to outpace topographic growth. However, where flows are less frequent, topographic growth may form a barrier to successive flows, causing avulsion of the channel system. Large-scale sequences of salt growth and withdrawal may therefore result in a cyclic style of submarine channel evolution.

Albertz & Ings consider numerical models of mechanical stratification in basin-scale passive-margin salt tectonics. They present two-dimensional (2D) plane strain numerical experiments to illustrate the effects of variable evaporite viscosity and embedded sediment layers on the style of salt flow and associated overburden deformation. Low-viscosity salt may be almost completely expelled from beneath overlying basins while embedded sediment layers may partition salt flow, allowing contractional structures to develop during a seaward-directed salt squeeze. Density differences between embedded sediment layers and salt may result in fractionation, ultimately resulting in a thick zone of pure halite. Such a process of buoyancy fractionation may explain the occurrence of layered salt in autochthonous salt basins and pure halite in allochthonous salt sheets.

Adam & Krezsek analyse basin-scale salt tectonic processes in the Laurentian Basin offshore Atlantic Canada by integrating seismic interpretation with analogue experiments. More than 3 km of salt was deposited in a late Triassic age, 50–70 km wide basin structured by interconnected rift-related half-grabens. Subsequent sediment input mobilized salt into a series of domains dominated by salt welds and pillows, extensional diapirs and canopies, contractional diapirs and folds and allochthonous salt nappes. Secondary salt detachment levels display growth faulting together with mini-basin formation.

Ferrer *et al.* describe the evolution of salt structures during extension and inversion of the Parentis Basin in the eastern Bay of Biscay. Salt diapirs and walls began to grow during the Late Jurassic as the North Atlantic Ocean and Bay of Biscay opened. Many of the salt structures had stopped growing by the Mid-Cretaceous when their source layer had become depleted. However, during the Late Cretaceous–Cenozoic Pyrenean Orogeny, the basin was mildly inverted. Nearly all of this shortening was accommodated in the salt structures which were rejuvenated to form squeezed diapirs, possible vertical salt welds and salt glaciers.

Central European salt basins

This section opens with a paper by **Krzywiec** that provides an overview of the Mesozoic and Cenozoic evolution of salt structures within the Polish Basin. This Permian–Cretaceous basin forms part of a system of epicontinental depositional basins developed in western and central Europe that were filled with siliciclastics, carbonates and (Zechstein) evaporites. Salt-related structures that developed around the periphery of the basin (where salt was thinner) include grabens bounded by listric faults detaching on the salt and salt pillows. In the more central or axial part of the basin, where salt was thicker, mature salt diapirs developed. These structures were rejuvenated by Late Cretaceous inversion of the basin, and some were also reactivated during Oligocene or Miocene subsidence.

Burliga *et al.* use the analogue and numerical modelling of salt supply to the Klodawa diapiric structure rising above an active basement fault in central Poland. Experimentation shows that salt preferentially feeds from the footwall of the basement fault. Subsequent shortening of the model resulted in thinning and redistribution of material within the diapir, together with its stem shifting to the footwall. Numerical modelling suggests that the magnitude of the basement fault governs the amount of salt supply to a diapir across the fault and that there is a differential salt supply from the hanging walls and footwalls with time.

Maystrenko *et al.* discuss the regional role of Permian salt within the Central European Basin System. The Zechstein salt was mobilized in response to several post-Permian tectonic events, resulting in salt walls and diapirs reaching up to 9 km in thickness. Withdrawal of salt in to these structures has strongly influenced deposition and deformation of the Cenozoic sediments.

Brown *et al.* describe wedges and buffers with new structural observations from the Late Palaeozoic partially inverted Dnieper–Donets Basin of the Ukraine. This large intracratonic basin is characterized by late Devonian rifting when two evaporite sequences were deposited, followed by post-rift thermal sag in the Carboniferous that was associated in some areas with extension. It is proposed that basin margin extension may be linked to thick-skinned partial inversion of some basement rift faults. Inversion of basement faults induced monoclines that were possibly further exaggerated during later (pre-Alpine) tectonic phases. It is suggested that late Carboniferous to early Permian tectonics are marked by shortening rather than extension, which is contrary to many previous interpretations.

Deformation within and adjacent to salt

This section commences with a paper by **Cartwright *et al.*** concerning strain partitioning in gravity-driven shortening of a thick multilayered evaporate sequence from the Levant Basin in the eastern Mediterranean. Gravity spreading is driven by basin subsidence and tilting of the Levant margin and progradation of Nile sediments. Four separate major detachments within the Messinian evaporites are interpreted as halite-rich units, which partition flow within the evaporites. Shortening profiles suggest Poiseuille flow, with salt flowing downdip faster than intercalated sediment layers and also faster than overburden translation. This is the first published use of seismic data to demonstrate the flow regime within salt on a regional scale.

Fiduk & Rowan also analyse folding and deformation within layered evaporites. Investigation of the Santos Basin (offshore Brazil) reveals a thick sequence of evaporites comprising three relatively competent anhydrite 'beams' separated by three weaker (halite-rich) detachment layers. This mechanical stratigraphy responds in different ways to contractional deformation associated with convergent gravity gliding/spreading of the margin. Competent beams may become highly disrupted and curvilinear folds and sheath folds are also generated in association with the intense non-coaxial deformation that increases downwards due to strain partitioning across internal detachments within the evaporites.

Strozyk *et al.* describe a 3D seismic study of complex intra-salt deformation from the Zechstein of the western Dutch offshore sector. They use 10 m thick anhydrite 'stringers' to study boudinage and constrictional folding within the evaporites, which is compared with observations from salt mines and numerical models. Such deformation is thought to reflect interaction of the layered salt rheologies, 3D salt flow and basement tectonics coupled with movement of the overburden.

Li *et al.* provide numerical models of displacement and deformation within 'stringers' embedded in down-built diapirs using a case study from the South Oman Salt Basin. They investigate via finite element models how differential displacement of the top salt surface induces salt flow and consequent folding and fracturing of large carbonate stringers that represent prospective hydrocarbon plays in the Oman salt diapirs. Models suggest that stringers may deform soon after the onset of salt tectonics, with extension leading to boudinage and fracturing, while shortening results in folding and thrusting of stringers.

Using an example from the Spanish Pyrenees, **Quinta *et al.*** use fracture pattern analysis as a means of constraining the interaction between regional and diapir-related stress fields. Joint and fault data collected from within the overburden adjacent to a diapir enables evolutionary models for stress fields around diapirs to be developed. Data suggest that stress fields evolve from being mostly related to regional tectonics to being dominated by local stresses associated with diapir kinematics.

The section closes with a thought-provoking paper by **Trude *et al.*** who describe potential salt-related structures from the Bristol Channel of southern England. Although previous interpretations of this well-studied area were linked to extension, inversion and strike-slip tectonics, this contribution challenges the established view. Aided by high-quality 3D seismic datasets from areas such as the Gulf of Mexico and Brazil, Trude *et al.* suggest that many of the well-known features in the Bristol Channel are actually better explained as collapse structures associated with salt withdrawal and diapirism in the Late Triassic and Early Jurassic.

Salt in contractional settings and salt glaciers

The Zagros Mountains provide perhaps one of the best places on earth to study the role of salt in a contractional setting, and this section opens with a paper by **Callot *et al.*** on pre-existing salt structures and folding in the Zagros. Using 4D analogue experiments imaged via X-ray tomography, these authors investigate the control exerted by pre-existing salt structures during subsequent compressive deformation. They suggest that initial diapir shape may control subsequent geometries with vertical pipe-like diapirs being shortened and localizing sharp overturned folds, while pillow-like diapirs may act to preferentially orientate ramps. Linear salt ridges also have a strong effect on the lateral extent and orientation of folds and typically form a disconnect for structures on either side.

Baikpour & Talbot study allochthonous Tertiary salt nappes in northern Iran via Advanced Synthetic Aperture Radar (SAR) images. They use SAR images to show that regional folds and faults are active south of the Alborz Mountain front, but are 'dampened' by the presence of allochthonous salt. A linked seismic reflection study shows that faults are longer than anticipated for earthquakes with magnitudes <3.5, suggesting that regional strains are more aseismic than previously realized.

Masrouhi & Koyi continue the analysis of lateral salt flow by investigating a Tunisian example of a submarine salt glacier formed in the Cretaceous passive margin of North Africa. The Triassic salt appears interstratified between two Cretaceous units that display normal stratigraphic younging. The salt is considered to have been emplaced as a bedding-parallel extrusion along the sediment–water interface during the Cretaceous. Such salt glaciers are typically marked by extensional faulting associated with the presence of a slope and basinward flow of salt, and characterize allochthonous salt sheets in a number of passive margin settings.

The final contribution by **Graham *et al.*** considers allochthonous salt in the sub-Alpine fold–thrust belt of SE France. Although the geology is well known, aspects of its structure remain enigmatic and may best be explained by invoking salt tectonics whereby an inverted Jurassic sequence represents an overturned flap created when salt was emplaced at higher levels along the sea floor. This allochthonous extrusion or salt glacier, which may have been similar to those in the Gulf of Mexico, was subsequently exploited by regional contractional thrusting during the Alpine Orogeny to generate the observed complexity.

Current and future directions of salt research

The broad panoply of papers presented here offer insight into the general status of research into salt tectonics. This current body of research has built on the many decades of work that has improved our understanding of salt both from a deformation perspective (e.g. establishing flow laws for salt movement) and also how it influences structural and stratigraphic architectures.

Certain avenues of research (both geographic and thematic) are clearly more in vogue than others at this moment. For example, key regions are currently Brazil, Gulf of Mexico and Central Europe and research themes include the regional scale behaviour of salt and its internal mechanical stratigraphy. Much of this research has been driven by, and significant insights gained from, analogue modelling. This continues to be a focus area as it offers a relatively inexpensive means of creating scaled models of salt structures. Often the aim is to understand kinematics and to model progressive episodes of deformation. While these models are becoming increasingly sophisticated, incorporating digital photogrammetry such as Particle Image Velocimetry (PIV) analysis and Computed Axial Tomography (CAT) scanning, discrete and finite element modelling offer additional insights into tectonic processes. Here computer power is key to developing large-scale sophisticated continuum models for sedimentary basins that contain salt.

This avenue of research will continue to develop and may help characterize strain rates and how specific basin geometries and subsidence patterns influence salt tectonics. This has particular application to solving the conundrum: does salt glide or spread under a differential sediment load?

A further avenue for modelling research that has become increasingly of interest to the petroleum industry is in understanding the geomechanics of salt. Because salt behaves over long time periods as a fluid, it cannot support a shear stress. The stress tensor within a salt body is simultaneously both hydrostatic and lithostatic. One consequence of this stress system is that it perturbs the regional stress state and results in complex interactions between the salt and the visco-elastic wall rocks. This has important consequences for drilling close to salt diapirs and through salt sheets, and for understanding the containment potential of salt as a side seal to petroleum traps. Recent finite element modelling illustrates the effects of the presence of salt on regional stress tensors. More advanced models using more realistic rock properties and variable mechanical stratigraphy will further advance our knowledge of salt geomechanics and hopefully contribute to a fuller understanding of how salt promotes wall rock deformation and influences hydrocarbon sealing, trapping and pore pressure development.

Improvements in seismic reflection, acquisition and processing techniques have led to vast advances in our understanding of salt and sediment interactions both along the flanks of vertical or overturned salt margins and in sub-salt plays such as Tupi offshore Brazil. In addition, seismic resolution has now been refined to such a level that internal structures within salt sheets and salt diapirs are now being imaged, providing a huge opportunity to consider the variability within 'salt' and to link this directly with resulting structures. The recognition of partitioned flow within salt bodies may become increasingly significant in determining the behaviour of salt and its interaction with sediment.

The improved imaging of salt bodies using seismic reflection data now offered by enhanced processing techniques opens up new avenues for salt-sediment research. In the past, the geometry of salt bodies often had to be inferred. Now that clear images of salt sidewalls and bases are available, it is possible to revisit models for balancing and restoring cross-sections through salt both in 2D and, more importantly, in 3D. This enables a better understanding of the geodynamic evolution of salt within a sedimentary basin and how the surrounding rocks have deformed to accommodate this flow. Additional trap potential may be identified or weak points in structures and pore pressure cells recognized that delimit or condemn exploration targets. These new data, when made available, will enhance the continued study of salt tectonics and how salt both positively and negatively impacts the exploration for hydrocarbons in salt-related basins.

Other improved techniques for the remote analysis of salt flows include Interferometric Synthetic Aperture Radar (InSAR) that continues to develop and will provide information on surficial salt flows over periods of weeks if not days. Similar resolution may also be provided by microseismic analysis with implications for toxic waste and CO_2 storage within salt. Finally, remote analysis via InSAR, microseismicity and even widely available Earth imaging tools can now be used to focus fieldwork and outcrop studies better. This fundamental ground truthing will continue to provide the scientific reassurance that is required to test and further constrain models of salt tectonics and their associated sediment interactions.

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