ORAL ABSTRACTS
(In Programme Order)

Wednesday 23rd September - Session One: SALT TECTONICS RESEARCH AND CASE STUDIES

Paleogeography and tectono-stratigraphic evolution of the Aptian Ezanga-Loémé evaporites along the proximal domain of the south Gabon-Congo-Cabinda margin

Alexandre Pichat1*, Vincent Delhaye-Prat2, Michel Guiraud3, Laurent Gindre-Chanu4, Eric C. Gaucher5*
1 TotalEnergies / Univeristé de Pau et des Pays de l'Adour
2 TotalEnergies
3 Université de Bourgogne Franche-Comté
4 TERRA GEOSCIENCES
5 Lavoisier H2 Geoconsult

During the Early Cretaceous, massive evaporite accumulations formed in the opening South Atlantic. However, the evaporite depositional model is still poorly constrained at the scale of the West African margin. The present study focuses along the proximal domain of the south Gabon - Congo - Cabinda margin and is based on (i) log interpretations of 246 wells crossing undeformed to weakly deformed evaporite intervals and (ii) a structural characterization of the basement. The evaporites show eleven regional evaporite depositional cycles (CI to CXI) bounded by meter-thick shale beds. The cycles display alternating meter-scale carnallite-halite beds that can be correlated over several hundred kilometers, and CVI, CVII, CVIIIa and CX culminate in localized tachyhydrite accumulations. Cross section correlations and isopach maps help to understand the palaeogeographic evolution of each cycle and depositional environments that evolved from relatively deep at the base of cycles, to very shallow at their top. It highlights evaporite cycles for which the stratigraphic architecture of the salts was shaped by freshwater inflow sourced from the north and possible basement movements. Periods of increased confinement of the proximal domain from the distal one favored the development of depocenters with perennial subaqueous conditions and extreme salinities, in which more than 100 meters of tachyhydrite accumulation could locally be preserved. Marine influx increased starting from CX, allowing the deposition of sulphate beds. The salt section is capped by anhydrite deposits interbedded with clastic and dolomite, before the final marine invasion of the basin. For the first time, this study provides a large-scale depositional tectonostratigraphic setting of the Aptian salts in the proximal domain of the West African margin. The results are of interest for K-Mg salts exploration resources in the Aptian and pave the way for further investigation of the salt depositional environment in the distal domain.

Depositional models for giant salt deposits and their implications for the safety and stability of hydrogen storage caverns

Frank J Peel1, *Gillian M Apps1*
1The University of Texas at Austin

Solution-mined caverns in evaporite bodies are potential large-scale H2 storage sites. Evaporites consisting of pure halite could be perfect hosts, as it is non-reactive and homogenous. However, real-world evaporites commonly contain more problematic components that may cause problems including (i) differential solubility, leading to unpredictable and non-optimal original cavern shapes, and potential containment failure or pressure loss; (ii) mechanical instability, leading to post-solution deformation or failure of the cavern; (iii) physico-chemical reactivity between the host rock and the H2 or cushion fluid, leading to potential contamination of the stored hydrogen with undesirable or dangerous phases (eg H2S) or alteration of the cavern wall rock. Consequently, non-halite mineralogies within evaporites pose risks to H2 storage, whether these are high-solubility layers such as K-salts, low-solubility layers such as carbonates or CaSO4, or potentially reactive phases (sulphates, copper salts, etc). Therefore it is vital to predict the potential presence and thickness of problem layers; however they cannot be distinguished on seismic data, and published depositional models are not sufficiently predictive. We have developed new predictive models for the sequence and thicknesses of lithological layering in deep water salt giant deposits sourced from oceanic water, constrained by data from known salt basins (e.g. Gulf of Mexico, S Atlantic, Permian Basin of West Texas, Zechstein). The layering in our models is simplified into four groups (carbonate/CaSO4/NaCl/bitterns). We differentiate between basins subject to annual seasonal cyclicity (varving), creating a higher-frequency layering component, and those without seasonal varving. Model variants include cyclic draw-down, two-way reflux and one-way inflow. These models provide a template for the original compositional layering to be expected within giant evaporites. Deformation of the layer as it flows into salt domes or diapirs will change the layer thickness and complicate their geometry.

Basinwide development of km-scale gypsum networks: evidence for heterogeneity in evaporitic depositional systems

Jimmy Moneron1, *Joe Cartwright1, Dan Phillips1*
1University of Oxford

Evaporite depositional systems are often conceptualised as laterally extensive, layer cake alternations of the dominant evaporite facies arrayed cyclically according to an idealised evaporative sequence. A notable deviation from this model has been demonstrated by mapping the internal reflectivity of the Zechstein Evaporites of the Southern Permian Basin. The third, “Z3” cycle contains a prominent anhydrite layer, generally 30-50m thick, extending over the basinal palaeoenvironment. However, using regional merged 3D seismic surveys, we have been able to map a complex, branching network of anomalously thick zones (ATZ) first recognized from the Dutch Sector that extend over 1000 km from the UK into Germany, and possibly into Poland. We propose that these networks are depositional rather than diagenetic or deformational as suggested previously, and developed progressively by mound-like build-ups of thick gypsum reefs or shoals over a period of less than 105 years. This model, if correct, shows that the common assumption of lateral uniformity of evaporite facies may not always apply, particularly when regional subsidence maintains water depth over large areas for tens of thousands of years. This major cause of short-range heterogeneity has implications for seal integrity, storage, and more generally for drilling purposes such as through heterogeneous evaporite successions.

Salt Tectonics synchronous with salt deposition in the Santos Basin (Ariri formation, offshore Brazil)

Naïm Célini1, *Alexandre Pichat2, Jean-Claude Ringenbach2*
1Akkodis
2TotalEnergies

Halokinetic deformations synchronous with salt deposition are processes already suggested in several salt giants including the Lower Cretaceous salt deposits of the Santos Basin in Brazil. However, the dynamics of syn-depositional deformation has never been studied in a coherent depositional and structural framework. This study investigates well data and high-resolution 3D seismic images in the evaporitic Ariri Formation of the Santos Basin to understand the intra-salt deformations, estimate their timing and establish a link with the depositional setting of the evaporites. The seismic data shows numerous examples of intra-salt onlaps, erosive surfaces and sedimentary wedges highlighting the occurrence of deformations during salt deposition. Two dominant processes have initiated salt creep: the gravitational system promoted by the late-rift subsidence, and the density contrasts between a dense upper anhydrite-rich unit and a less dense lower halite-dominated unit. Updip, extension prevailed during salt deposition and favored a boudinage of the Ariri Formation. Downdip, early contraction favored the development of well-developed intra-salt minibasins. Deformation occurring during salt deposition and induced topographic relief likely influenced the hydrological conditions. It probably led to intra-salt dissolution/reprecipitation processes and hyper-saline conditions favoring the precipitation of tachyhydrite deposits in localized intra-salt depocenters. Eventually, post-salt minibasins systematically developed above syn-salt deposition depocenters, indicating that syn-salt deposition deformation had a strong impact on post-salt evolution. This new understanding of the intra-salt deformation in the Santos Basin paves the way for new interpretations of halokinetic deformations reported elsewhere in the South Atlantic or in other salt-giant provinces.

Geomechanical Insights into Salt-Bearing Rifted Margins: Numerical Modeling and Implications for Geological Storage

Mahdi Bakhtbidar1, *Jonas B. Ruh2, Oscar Gratacós1, Pablo Santolaria1, Pablo Granado1*
1Institut de Recerca UB-Geomodels, Dept. de Dinàmica de la Terra i de l'Oceà, Universitat de Barcelona (UB), C/Martí i Franquès s/n 08028 Barcelona, Spain
2Institute of Marine Sciences, CSIC, Barcelona, Spain

This study delves into the intricate dynamics of salt-bearing rifted margins (SBRMs), emphasizing the interplay between gravity-driven mechanisms and salt rheologies. Utilizing advanced two-dimensional finite-difference numerical modeling, we explore the formation and evolution of minibasins, salt walls, and diapirs within these structures. By integrating both linear and non-Newtonian rheological models, we aim to provide a comprehensive understanding of salt migration patterns and their impact on sediment trapping and subsidence. Our investigation focuses on two primary gravity-driven mechanisms: downbuilding and gliding. Downbuilding, driven by differential sediment loading, causes lateral salt flow and minibasin subsidence. In contrast, gliding involves the downslope movement of salt and overlying sediments, commonly observed at continental margins. Through simulations, we elucidate how various salt rheologies, from Newtonian to complex non-Newtonian behaviors, influence the structural evolution of SBRMs. Our findings reveal that non-Newtonian rheology, characterized by strain-rate weakening and stress-dependent viscosity, significantly alters deformation patterns within salt structures, impacting subsidence rates and the overall stratigraphic architecture of SBRMs. Additionally, our models highlight the competitive dynamics between minibasins, where varying subsidence rates and interactions with surrounding salt walls create intricate subsurface geometries. Understanding these processes is crucial for predicting the behavior of subsurface structures in SBRMs, which has significant implications for geological storage and resource exploration. Our study bridges the gap between simplified models and the complex reality of SBRMs, offering new insights into the geological processes shaping these environments. In conclusion, this study advances the understanding of salt-sediment interactions and their role in the evolution of rifted margins. By integrating sophisticated numerical modeling techniques, we provide a nuanced perspective on the geomechanical behavior of salt formations, paving the way for more accurate predictions and effective management of geological resources in these regions.

The Birth, Evolution, and Death of Polygonal Diapir Arrays: Insights from the Norwegian Central North Sea

Mar Moragas1, *Oliver Duffy2, Tim Dooley3, Tarek Galhom4, Christopher A-L. Jackson5, Naiara Fernandez6, Gillian Apps3, Frank Peel3, Umut Isikalp3, Rob Gawthorpe4*
1 GEO3BCN-CSIC), Barcelona, Spain
2 Chevron, Houston, Texas, USA
3 Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas, USA
4 Department of Earth Science, University of Bergen, Bergen, Norway
5 Department of Earth Science and Engineering, Imperial College London, London, UK / Jacobs Engineering UK Ltd, Manchester, UK
6 GFZ German Research Centre for Geosciences, Potsdam, Germany

In sedimentary basins where salt mobilization forms diapirs, basin- or regional-scale diapir arrays often form one of two configurations, which may pass laterally into one another: linear-parallel and polygonal. Linear-parallel arrays are widely understood to form due to progradational loading or salt-detached extension, with wall long-axes trending normal to the loading or extension direction. In contrast, the origin of polygonal diapir arrays is more enigmatic. This study aims to explain the origin and demise of polygonal networks using salt-tectonic theory and observations from the Norwegian Central North Sea (NCNS). We propose that two processes likely contribute to the initiation of polygonal diapir arrays. First, if the salt is part of a purely viscous or mixed brittle-viscous system, then compositional or thermal variability can drive diapiric rise as polygonal arrays (all governed by fundamental physical principles). These are essentially internal processes. In contrast, polygonal arrays can also be formed due to external processes, such as multi-directional strain or salt flow above complex base-salt relief. The death or fading of polygonal diapir arrays can be caused by several factors, including one or a combination of exhaustion of salt supply; burial due to increase in sediment accumulation rate relative to salt rise rate; and lateral shortening of the salt basin. We can therefore consider which of those factors, if any, controlled the birth and death of polygons in the NCNS. Our mapping highlights how intrasalt lithological heterogeneities, early-formed diapirs, and the map-view geometries of walls and minibasins suggest density inversion as the driver for the birth of polygonal diapir arrays in the NCNS. In contrast, the death of the polygonal diapir array was controlled by a range of factors (e.g. salt thickness, sedimentation patterns and/or sediment accumulation rate, and mechanical properties of Zechstein Supergroup evaporites).

3D Geometry and Evolution of Salt Walls and Surrounding Minibasins: Contrasting Styles from the Norwegian Central North Sea

***Umut Isikalp1**, Oliver Duffy2, Mar Moragas3, Christopher A-L. Jackson4, Robert L. Gawthorpe1*
1University of Bergen
2Chevron
3Geosciences Barcelona,CSIC
4Imperial College of London

Salt wall geometries can vary widely due to the relative influence of factors including: i) local and regional stresses; ii) the composition, thickness, and 3-D flow of salt; and iii) the rate and style of sediment loading. Some salt walls are relatively simple, being linear to sub-linear in map-view, continuous along-strike, broadly symmetrical in cross-section, and with smooth gradations in width and height. In contrast, more complex walls may have more irregular, non-linear map-view geometries, composed of distinct segments with varying strikes, widths and heights. Whether simple or complex in geometry, the wall evolution influences, and is recorded by, stratal geometries in the flanking minibasins. Here we use borehole-constrained 3-D seismic reflection data from the Norwegian-Danish Basin, offshore Norway, to examine the 3-D geometry and evolution of two contrasting salt walls and the stratal geometries in their flanking minibasins. Wall 1 is relatively simple, being sub-linear, ~23 km long, with its main feature being a single stock located near its northern tip. Wall 2 is more complex with several key features including: i) a 26 km-long dogleg map-view geometry with marked variations in strike, width and height; ii) stocks located at changes in wall strike; iii) a salt sheet on its southwestern flank sheet capped by a perched minibasin. Both walls are flanked by minibasins displaying marked 3-D variability in stratal geometry and isopach thicknesses. The tectonostratigraphy of the minibasins reveals diachronous development of primary and secondary rim synclines, welds, and turtle anticlines both along- and across-strike of the wall. We demonstrate the importance of differential minibasin subsidence and 3D salt movement on the evolution and the final geometry of salt walls.

Fifth-order characterisation of sedimentology within halokinetic sequences

Kathryn Amos1, *Rachelle Kernen1, Jarred Lloyd1, Ingrid Anell2*
1The University of Adelaide
2the University of Oslo

Halokinetic sequences provide a very useful means of characterising the geometry of syn-tectonic deposits proximal (<1km) to a diapir; this framework is based on the interpretation of slump and debris flow deposits with an underlying erosion surface as the halokinetic sequence boundary. Most prior studies have focused on the structural evolution of halokinetic sequences through time, controlled by the relative rates of salt rise and sediment input. However, few studies have focused on the high-resolution (5th order) characterisation of sedimentology within halokinetic sequences. This combination of salt tectonic and process-sedimentologic interpretation of syn-tectonic deposits offers an opportunity to understand the sedimentary response to diapirism at a higher resolution, the potential for differentiation of diapiric and other triggers for sediment gravity flows, and improve the characterisation of lithofacies found in sub-aqueous strata proximal to diapirs. We present new outcrop observations from a geometrically complex diapir and adjacent minibasins in the Ikara-Flinders Ranges, South Australia. Observations were recorded through ~260m of strata within ~50m of the salt-sediment interface; dominated by mixed siliciclastic-carbonate sub-aqueous deposits. Clastic lithofacies range from boulder-sized clasts within a matrix-supported conglomerate to shale. Interpreted depositional processes include debris flow, slump and turbidity currents. Carbonate lithofacies range from stromatolitic boundstone to lime-mudstone. Minor aeolian siliciclastic sandstones are interpreted to interfinger with some of the stromatolitic boundstone units. Field observations are combined with petrographic analysis to enable a depositional environment and halokinetic sequence stratigraphic interpretation. Variations in lithofacies and the presence of meta-igneous diapir-derived-detritus in sediments provide insight into diapir movement history at a higher resolution than current halokinetic sequence stratigraphic models. Such studies will be useful for improved subsurface basin characterisation for geo-energy applications. Localised facies variations were observed, which could impact sealing competence if present in subsurface halokinetic strata targeted for gas storage.

Variable diapir origins and histories in the Basque Pyrenees: implications for intrasalt deformation

Mark G Rowan1, *Eduard Roca2**,** Josep Anton Muñoz2, Oriol Ferrer2, Rodolfo M. Uranga2, Iñaki Garcia3*
1Rowan Consulting Inc.
2Universitat de Barcelona
3Independant

Salt diapirs in the Basque Pyrenees contain halite and subordinate anhydrite, shale, carbonate, basalt, and Paleozoic metasediments. Because these diapirs are being considered for hydrogen storage but have different attributes, we examine several using surface and subsurface observations, along with conceptual models of intrasalt deformation, in order to predict some aspects of stringer distribution and geometry. The first difference is that whereas marginal diapirs (Bakio and Poza de la Sal) have only stringers of Keuper age, diapirs in the center of the basin (Villasana de Mena and Salinas de Rosío) have Muschelkalk and Rhaetian stringers due to inclusion of these stratigraphic levels in the evaporite sequence. Second, different diapirs have variable styles and histories. Bakio and Villasana de Mena diapirs had early extensional triggers and consequent boudinage of competent intrasalt layers; subsequent long-lived passive diapirism enhanced the boudinage and rotated the stringers to near-vertical orientations. In contrast, Salinas de Rosío and Poza de la Sal diapirs lacked extensional triggers. Salinas de Rosío originated as a salt pillow due to differential loading above a basement fault in postrift times, a pillow that was enhanced during the latest Cretaceous to Paleogene due to contractional buttressing against the fault. Salt broke through only during Miocene shortening, implying more continuous and folded stringers. Poza de la Sal originated as a contractional salt-cored anticline during synrift thin-skinned translation. Erosional removal of the roof in the Middle-Late Albian allowed salt to break through and begin passive diapirism. Finally, whereas three of the diapirs were squeezed during the Pyrenean Orogeny, thereby concentrating the stringers somewhat, Villasana de Mena was simply translated with minimal shortening. The key question is, having deciphered the variable origins and histories of these diapirs, can we use this to lower the risk of choosing the optimal diapirs and locations for salt caverns.

The role of intra-salt stratigraphy and lithological variability on the internal and external geometry of salt bodies – a numerical modelling approach

Leonardo Pichel1, *Ritske Huismans1, Thomas Theunissen1, Rob Gawthorpe1, Jan Inge Faleide2, Sabine Delahaye3, Alexandre Pichat3, Manel Ramos4, Jean-Paul Callot4, Claude Gout4*
1Univeristy of Bergen
2University of Oslo
3TotalEnergies
4UPPA

Thick salt deposits occur in a wide range of sedimentary basins and are associated with large and geometrically complex structures owing to the inherent ability of salt to flow as a viscous fluid. Salt basins form major hydrocarbon provinces and are increasingly targeted for CO2/H2 storage, natural H2 exploration, and geothermal energy owing to the unique physical properties of salt. Despite considerable advances in understanding salt basins and salt tectonics, there is still a significant knowledge gap on the internal geometry of salt structures and the original (pre-deformed) salt stratigraphy. We apply a novel, high-resolution numerical modelling approach simulating salt tectonics for rift and rifted margin salt. We investigate the influence of layered salt with various i) viscosities (1016-1019 Pa s), ii) density, iii) thickness, and iv) stratigraphic arrangements on the kinematics and internal and external geometries of salt bodies for different basin geometries and base-salt relief. We include fully-scaled material properties to simulate halite, anhydrate and the very weak K-Mg salt layers which are critical for the use of salt caverns for H2/CH4 storage. Our results show that layered salt with variable viscosities produce significant intra-salt strain partition but also major variability on the basin-scale salt kinematics and external structure. Layered salt with both viscosity and density variations produce even further complexities in the internal diapir geometries with highly convoluted folding, horizontal and vertical shearing, and preferential flow of the weaker, less-dense salt into the core of diapirs. Moreover, the position and thickness of these layers also play a major role on the overall evolution and architecture of salt bodies. Our results can aid in the characterization of the internal structures of salt bodies and their relationship with their external geometry and basin-scale context, which are critical for the use of salt basins in the context of energy transition.

Architecture and controlling factors of intra-salt layers in diapiric structures: A numerical modelling approach

Manel Ramos1, *Ritske S. Huismans2, Leonardo M. Pichel2, Thomas Theunissen2, Jean-Paul Callot3, Alexandre Pichat4, Naim Célini5, Claude Gout3, Sabine Delahaye4*
1Université de Pau et des Pays de l'Adour / University of Bergen
2University of Bergen
3Université de Pau et des Pays de l'Adour
4TotalEnergies
5Akkodis / Total Energies

Understanding the structure of intra-salt layers within deformed salt bodies is crucial for effective CO_2 and H_2 storage in salt basins. This study employs high-resolution 2D finite element modelling to investigate how variations in salt stratigraphy and lithological variability and post-salt sedimentation patterns influence the deformation processes and the internal architecture of diapiric salt structures for different basin geometries. We test intra-salt lithological variability by varying the vertical arrangement, viscosity and density of salt layers as well as including non-viscous (frictional-plastic) layers simulating carbonates and/or siliciclastics embedded within the layered salt sequence. The models with alternated low (10^{18}) and high (10^{19} Pa s) viscosity salt layers show significant internal salt flow partition characterized by preferential flow of the weak salt layers into the core of diapirs, as the stronger layers remain at their flanks and/or underneath adjacent minibasins. The order of the strong and weak salt layers also has a significant impact on the overall external and internal style of salt deformation, with both the basal and top layer being the most significant. Increasing the density of strong salt layers produce even greater internal salt flow partition with pronounced intra-diapir complexity, convolute folding, repetition of intra-salt stratigraphy within diapirs and occasionally boudinage. Stronger and denser layers tend to get trapped at the base of diapirs and/or underneath diapirs while being folded and refolded by flow of the intervening weaker and less-dense layers. The basin geometry and the presence of base-salt relief also have a significant influence on the basin-scale style and magnitude of salt deformation. The results can help elucidate the basin-scale controls exerted on both internal and external diapir geometries for rift basins, which are directly applicable for various areas of the North Sea, a key location for utilization of salt structures for geo-storage.

Influence of intra-Zechstein Supergroup (ZSG) composition on internal deformation styles: Examples from the United Kingdom and Norwegian Continental Shelves

Harya Dwi Nugraha1*, Tarek Galhom2, Mar Moragas3, Oliver Duffy4, Rob Gawthorpe2, Christopher A-L. Jackson5*
1Department of Earth Sciences, University of Bergen, Norway; Center Sustainable Geoscience and Outreach (CSGO), Universitas Pertamina, Indonesia
2Department of Earth Sciences, University of Bergen, Norway
3Geosciences Barcelona (GEO3BCN-CSIC), Spain
4Chevron, USA;
5Department of Earth Science and Engineering, Imperial College London, UK; Jacobs, UK

Layered evaporite sequences (LES) can be highly heterogeneous, with variable intra-salt composition influencing patterns and magnitudes of salt flow and tectonic style. In the Zechstein Supergroup (ZSG) LES of NW Europe, four depositional zones (DZs) are identified, based on halite percentage: DZ 1 (0-10%), DZ 2 (10-50%), DZ 3 (50-80%), and DZ 4 (>80%). While it is commonly observed that diapirs are absent in DZ 1 and abundant in DZ 4, the variability of ZSG stratigraphy and its impact on salt tectonics within DZ 2 and 3 remains less understood, despite this being important for geostorage potential. This study utilises 3D seismic reflection and well data from the West Central Shelf, UK Continental Shelf (UKCS) and the Sele High, Norwegian Continental Shelf (NCS), to analyse the composition and geometry of salt structures within areas defined by known to be lithologically heterogeneous (spanning DZ 2 and 3). On the UKCS, co-linear, NW-trending salt walls (3.5-7 km-wide) dominate, whereas linear and polygonal salt walls (1-3 km wide) characterise the NCS. Structures in both areas exhibit complex intra-salt reflection geometries. For example, on the UKCS, internal unconformities and folds document the development of intra-ZSG minibasins and flanking diapirs, likely formed during salt deposition (Lopingian). Well data indicate the ZSG comprises, from bottom to top, carbonate, interbedded halite-potassic salt, and anhydrite. The NCS example documents the decoupling of intra-ZSG deformation styles, with diapir-bound minibasins in the upper part, and a more weakly deformed lower interval. Well data indicate this decoupling occurs along a carbonate layer (stringer) encased within an otherwise halite-dominated succession. Our findings demonstrate that, despite similar halite content and salt-tectonic styles, different stratigraphic sequences of competent and weak layers may result in markedly different intra-ZSG deformation. This study highlights the importance of understanding intra-salt deformation for assessing the halite potential for geostorage.

A semi-automated method to interpret layered evaporite sequence (LES) lithologies based on well-logs

Gabriela Salomao Martins1*, Christopher A.L. Jackson2*
1(Imperial College London (currently at AtkinsRéalis)
2(Imperial College London, currently at WSP)

Layered evaporite sequences (LES) are heterogeneous stratigraphic units comprising interbedded evaporitic and non-evaporitic rocks. Halite and other lithologies in an LES are commonly targeted as mineral resources. Halite is also frequently used as a geological storage unit for hydrogen, CO2, nuclear waste, and hydrocarbons. To assess the geological storage potential of an LES, it is essential to map its internal lithologic variability. Identifying insoluble and highly soluble layers interbedded with halite is important, given they may pose operational challenges and stability risks to salt caverns. Mapping the lithological variability of an LES is also key to understanding its mechanical stratigraphy, which can determine salt-related deformation styles. Here we use a large well-logs dataset supported by cores and seismic reflection data to develop a semi-automated and reproducible method that allows us to efficiently and accurately interpret intra-LES lithologies. We apply our interpretation method to The Zechstein Supergroup, a Late Permian LES present across NW Europe. By applying cut-offs based on typical petrophysical ranges of evaporitic and non-evaporitic lithologies, we automated the lithology identification of the purest (i.e., less mixed) intervals in the dataset. To interpret intervals outside of the typical petrophysical ranges, we first conducted a cross-plot-based analysis in a subset of wells. The results of the cross-plot-based interpretation were then used to calibrate a statistically robust lithological interpretation based on cluster analysis. We also integrated our lithology interpretation with seismic reflection data to understand the structural context of the wells. An advantage of our lithological interpretation method is that different levels of uncertainty can be flagged throughout the interpretation process. Intervals interpreted based on typical petrophysical ranges correspond to lower uncertainties. Whereas more mixed intervals interpreted in the subsequent phases carry higher levels of uncertainty.

Welding a layered evaporite sequence

Christopher A.L. Jackson1, *Gabriela Salomao Martins2, Vlad Mihalcea3*
1Imperial College London (currently at WSP)
2Imperial College, currently at AtkinsRéalis
3Imperial College London, currently at The University of Manchester

Welds are important because they can help reconstruct the evolution of salt-bearing sedimentary basins, impact hydrocarbon prospectivity and the sealing quality of sub-salt reservoirs used to store CO2. Cross-weld fluid flow is also crucial for hydrogen and nuclear waste storage in nearby diapirs. Despite its importance, few studies have explicitly focused on welds. There is still no systematic subsurface mapping of natural welds with enough well data to investigate the mechanisms involved in welding a layered evaporite sequence (LES) and the controlling factors of weld thickness and composition. To systematically document the expression of welds from the Zechstein Supergroup (ZSG) - a Permian LES in the Southern North Sea (SNS) and to understand the mechanisms involved in welding of an LES, we use 3D seismic reflection and a large well dataset. We show that mechanical segmentation is key for LES thinning and welding. We demonstrate that the ZSG is segmented into two units with contrasting mechanical behaviour: basal and upper units. The mechanically strong basal unit is near isopachous, solely composed of competent lithologies, and halite is absent. The basal unit is immobile and is not involved in salt flow. In contrast, the upper unit is dominantly composed of halite with interbedded competent layers, being thicker in thick salt domains and thinner in and around welds. The upper unit is mobile and flows away into flanking thicker structures as salt thins. As the basal unit is not involved in welding, we propose that the welding surface in the SNS sits at the interface between the basal and upper units as opposed to the ZSG stratigraphic base. Therefore, only remnant material from the upper unit accounts for weld thickness. We also recognise welding kinematics, mechanisms, and base-salt relief as additional controls of weld thickness and composition.

Reproducing deformation of complex salt stratigraphies using analogue modelling: new insights in the frame of the energy transition

Célini Naïm1, *Alexandre Pichat2,Sylvie Schueller-Messie3, Jean-Marie Mengues3, Claude Gout4, Sabine Delahaye2, Jean-Paul Callot4*
1Akkodis
2TotalEnergies
3IFPEN
4University of Pau

Since the 1990's, analogue modelling has been extensively employed to reproduce halokinetic deformation. Most of studies used this approach to elucidate the controlling parameters of salt tectonics and the interrelationship between these parameters and the subsequent geometries in the post-salt sediments. Several studies focused on the impact of brittle layers in the modelled salt stratigraphy, whereas the influence of low viscosity K-Mg salts has been less investigated in analogue modelling. Nowadays, there is a need for a more detailed characterisation of the internal structure of salt bodies in order to predict the optimal location for the development of salt caverns for hydrogen storage in the context of the energy transition. Salt cavern must be developed in salt units as halite pure as possible. Thus, predicting where and why various salts are distributed in diapiric bodies becomes of primary importance. The DEEP IN SALT project includes a facet led by the University of Pau, TotalEnergies and IFPEN, dedicated to analogue modelling of diapiric structures containing halite, brittle (anhydrite, carbonate) and low viscosity (K-Mg salts) layers. The main challenge of this study was to develop a material that can represent low viscosity K-Mg salts in sandbox models. In this presentation, we introduce the chosen material, its properties, and the sandbox models that we produced containing the new material interlayered with silicone and sand. We discuss the reliability of the material, its representativeness in relation to natural cases and the way the models can increase the understanding of intra-salt deformation.

Diversity of turtle anticlines: from seismic examples to field observations

María Carrión-Jiménez1, *Mar Moragas2, Antonio Teixell1, Oliver Duffy3, Naiara Fernandez4*
1Universitat Autònoma de Barcelona, Bellaterra, Spain
2 Geosciences Barcelona (GEO3BCN-CSIC), Spain
3 Chevron, Houston, Texas, USA
4 GFZ German Research Centre for Geosciences, Potsdam, Germany)

Turtle-back anticlines are defined as mounded strata between salt diapirs, with a thick sedimentary sequence in the core that thins laterally. Turtle structures form between diapirs whose flanks subside, and record the history of salt flow and diapir narrowing through time. They are key to track the complex 3D evolution of salt wall-minibasin systems. In this work we analyse seismic and field examples to identify types of turtle structures and how they record complex salt migration. The Central North Sea (CNS) is a natural laboratory for salt tectonics that provides valuable examples related with the mobilization of the Zechstein supergroup (Late Permian) and the development of minibasins enclosed by salt walls during the Triassic. We examine the morphology and geometry of a ca. 31 km-long zig-zag shaped salt wall and its flanking minibasins which contain different types of turtle structures. In addition to classic turtle anticlines with anticline axial plane parallel to the salt wall strike, two across-strike turtle axes have been identified. Based on the observations from well-constrained seismic data we have interpreted that those turtles are associated to the migration of salt towards transverse salt bodies or spurs splaying from the main sinuous salt wall. We compare these examples with a well-exposed across-strike turtle structure in the Central High Atlas salt province of Morocco. This Jurassic antiformal structure records the past existence of transverse spurs (now only partially preserved) from the NE-SW oriented Aberdouz salt wall that collapsed early in the extensional evolution of the Atlas basin. The high-quality examples from the North Sea and the Atlas illustrate how the distribution and type of turtle anticlines are controlled by the 3D geometric pattern of salt migration and associated salt-sediment interaction.

Revisiting the structural evolution model of the Gina Krog Field: Implications for near-field exploration in a mature field amidst for the energy transition

Asdrúbal Bernal1, *Annika Ulfsdotter1*
1Equinor ASA

The Gina Krog field, located on the Utsira High in the central North Sea, exemplifies Equinor's commitment to the energy transition, boasting a low CO_2 footprint and reliable energy provision. Discovered in 1978, with production commencing in 2017, the field has transitioned from gas injection to pressure depletion methods and achieved full electrification in September 2023. This field's structural complexity is driven by salt tectonics, with only one well penetrating the top salt. This poses significant interpretative challenges for the salt's geometry and the Hugin Formation reservoir, which is not imaged in seismic data. The reservoir's presence is inferred from coal markers at the base of the Hugin Formation. A comprehensive review of the structural and stratigraphic models was undertaken in 2018 to enhance injection well drilling, fault-seal modelling, and near-field exploration. This presentation will outline the revised models and their contribution to exploration efforts. The integration of structural and isopach maps, growth strata analysis, and kinematic modelling facilitated an updated structural model for the Gina Krog Field. The revision suggest that the Hugin Formation's deposition was synchronous with salt movement in certain areas, while in others, it either preceded or followed salt tectonic events. The southwestern structures are characterized by salt-cored anticlines and domes with crestal normal faulting, exhibiting episodic growth from the Triassic to the Cretaceous, influenced by the Brae Fault system and a Miocene contractional phase. The central field area features syncline-anticline-syncline structures formed by extension and inclined shear along a northeast-southwest striking listric fault. The revised model underscored the Dougal structure as a promising target, with the primary uncertainty being reservoir presence, as demonstrated by the syn-tectonic nature of reservoirs in other field structures. Drilling in November 2023 confirmed a gas accumulation within a reservoir analogous to those in adjacent structures, validating the model's predictive capability.

Thursday 24th September - Session Two: SALT IMAGING, PLAYS AND STORAGE

Internal Deformation of a thin Layered Evaporite Sequence: Implications for hydrogen storage (Neuquén Basin, Argentina)

Rodolfo Uranga1, *Joaquín Cardozo2, Oriol Ferrer1*
1Universitat de Barcelona
2YPF

The transition to renewable energy sources requires efficient, widespread storage systems, with hydrogen emerging as a promising carrier. Salt caverns offer a viable solution for large-scale hydrogen storage due to the geomechanical properties and sealing capacity of salt. The construction of salt caverns for hydrogen storage requires halite-rich intervals with minimal insoluble content, adequate depth, and sufficient thickness. These requirements are especially important in bedded salt formations, where the risk of not meeting these criteria is higher. This study integrates seismic and well data to examine the internal deformation of the Upper Troncoso Member's thin layered evaporite sequence (LES) in the Neuquén Basin, Argentina, assessing the potential of using salt caverns for hydrogen storage. The LES is characterized by strong rheological contrasts between halite, sylvite, and interbedded anhydrite. Regionally, 2D seismic data illustrates how tectonic shortening related to the Andean orogeny caused thick-skinned deformation in the internal parts of the orogen and thin-skinned deformation in the external ones where the shortening is distributed across multiple detachments, with the Upper Troncoso Mb being the uppermost one. Shortening in the fold and thrust belt's frontal sector is mainly accommodated by the internal deformation of the LES, evidenced by symmetrical folding/buckling of ductile layers and minor faulting of the brittle components. Locally, the Paso Bardas Norte 3D seismic interpretation reveals lateral salt migration due to regional shortening, creating areas with varying halite thickness. By adopting a minimum halite threshold thickness of 200 meters, it was possible to map the optimal zones for salt cavern construction. Overall, this study provides a framework for assessing geological risks and initial volumetric estimations for hydrogen storage, applicable to other areas in the Neuquén Basin and similar salt-bearing foreland basins worldwide.

A lifecycle approach to hydrogen storage cavern design and execution – examples from Project HyStock in The Netherlands

Allard Van der Molen1, *Marinus den Hartogh1, Patrick Roordink2, Jeroen Dirven2*
1Nobian
2Gasunie

The HyStock project involves the construction of three new caverns (of 1 million m2) for the storage of hydrogen in Zuidwending, the Netherlands. The caverns will be leached by Nobian to extend the existing EnergyStock natural gas storage operated by Gasunie, who will also operate the hydrogen storage facility. The project is located in a Zechstein salt dome from which solution mining has taken place since the 1960s. The dome is about 2.5 km in height and 2 km wide at the HyStock location and is expected to consist mainly of Z2 and Z3 evaporites at this location. Gasunie and Nobian use standardised cavern integrity management systems as guidelines for all activities during the entire lifecycle of a (storage) cavern, from exploration of a new site to the aftercare of abandoned caverns. In this presentation, we will provide several examples of this lifecycle approach in the design, execution and operation of the HyStock hydrogen storage caverns. The data gathering program of the HyStock wells is designed to reduce subsurface uncertainty and to make informed operational decisions throughout the cavern lifecycle. The cavern design follows that of existing natural gas storage caverns and ensures efficient storage cycles while keeping convergence to a minimum. During leaching, sonar measurements ensure the cavern shape and size stays within designed limits. Subsidence modelling for this project incorporates insights from the recently completed Cavern Closure Consortium. This ensures cavern safety, not only during leaching and storage operations, but also in the decades after abandonment. A seismic monitoring network has been in operation in the area for four years and has shown the seismic risk to be small and without risk to existing buildings. This network will be expanded to monitor for induced seismicity during leaching and storage operation of hydrogen.

Subsurface Energy Storage Potential in Salt Structures in the UK and Dutch Sectors of the Southern North Sea

Sjastri Hansen1, *Jürgen Adam1*
1Royal Holloway, University of London

Energy security within the transition to a low carbon economy will require, in part, divesting from fossil fuels but also increased investment in and deployment of renewable energy resources. The policies adopted by the UK and the EU suggests that the renewable energy deployment forecast for the North Sea region will rely strongly on increased windfarm installations. Wind power tends to be intermittent and variable, necessitating the development of gigawatt (GW) scale energy storage solutions. The characteristics of salt formations make them ideal for the development of salt caverns for subsurface energy storage in the form of compressed air (CAES) and hydrogen (HES). The study area is in the Southern North Sea basin (SNS). The SNS is characterised by the accumulation of massive cyclical Permian Zechstein evaporitic sequences, extensively deformed by post-Permian salt movement, resulting in thicknesses ranging from less than 50m to greater than 2500m. As a mature hydrocarbon basin, the SNS has undergone years of extensive exploration and as such, has substantial geological and geophysical data available for projects focusing on energy storage. In this study, a regional 3D time-migrated seismic mega-merge and 46 correlated wells were used to conduct an adapted Play-Fairway Analysis, to identify potential exploration targets on a regional scale. This approach involves generating risk maps assessing the presence and efficiency of a source, migration pathway, a reservoir and a seal, which form the critical elements of a working hydrocarbon system. The key outcomes indicate that: i) Prospective salt structures are located mainly offshore UK. There are ten main areas of interest where the salt structure depth and thickness are within the required depth ranges for safe CAES operation and ii) in just one of the leads identified there is potential to develop 365 caverns, with a total effective cavern volume of 229 million cubic metres and a total of 214GWh of potential energy storage. These findings suggest that the SNS UK offshore sector has huge potential to develop salt caverns for energy storage. CAES and HES in the SNS can be viable additions to the UK/EU energy mix.

The Seismic Imageability of Internal Salt Architectures and Inclusions

Chris Willacy1, *Tim Dooley2*
1Shell Research Limited
2Applied Geodynamics Lab, Bureau of Economic Geology, University of Texas

Hydrogen storage in salt caverns is seen by many as an important solution for the Energy Transition, enabling both short and long-term storage of renewable energy sources, via transformation to and reuse of hydrogen as an energy carrier. Whilst storage in salt caverns has been demonstrated, the upscaling required to meet the energy demands of society are significant and this must be achieved in a safe and sustainable way. The internal architecture of salt can be highly complex, with varying lithology, sutures, shear zones, geobody entrapment and the presence of inclusions (gases and fluids), all of which pose a risk for the construction, storage, and abandonment of salt caverns. Imaging features within salt bodies can be particularly challenging onshore where the seismic signal with respect to noise of seismic data is typically low and legacy surveys have not been designed for inclusion imaging. Advances in geophysics can provide much needed solutions to this problem, however, the cost of new acquisition is high and land access prohibitive. To quantify our ability to image features within salt bodies we present a novel workflow which combines physical (sandbox) models with wave equation modelling and imaging. The rich detail provided by physical models, which incorporate inclusions, has been captured via the construction of an earth perturbation model. Interfaces, faults, and small-scale scatterers are modelled using elastic wave equation forward modelling. This synthetic data is then imaged with reverse time migration. Noise levels constrained from field data are added to produce realistic synthetic seismic datasets. Into this background framework salt caverns are added, from actual field examples using cavern sonar profiles. Hydrogen leakage scenarios are assessed and the 4D seismic detectability quantified, therefore allowing for robust measurement, monitoring, and verification plans to be established for safe cavern storage.

On the role of thermal stresses in salt caverns for fast cyclic hydrogen storage

Herminio Tasinafo Honorio1, *Hadi Hajibeygi1*
1TU Delft

The use of solution-mined salt caverns for storage purposes is a proven technology that has been used for many decades, initially for crude oil and other hydrocarbon derivatives, and later for natural gas (main application nowadays). More recently, in the context of energy transition, salt caverns are considered the most viable option for compressed air (CAES) and hydrogen storage. In addition to salt formations being available worldwide, salt rocks present favorable mechanical properties and extremely low permeability, which is particularly important for hydrogen storage. As the energy transition progresses and the need for storage systems increases, the use of salt caverns is expected to expand, thus requiring careful design to ensure mechanical performance and mitigate risks. One of the aspects to be considered is the temperature variations of the gas inside the cavern. Due to the fast injection/production cycles, less time is available for heat exchange with the surrounding rocks, which produce thermal amplitudes up to around 40°C. Consequently, thermal stresses are induced on the cavern walls, which can impact mechanical stability. Additionally, the creep behavior of salt rock is highly affected by temperature and it can affect the expected cavern volumetric convergence. In this work, we investigate the effect of temperature variations on the mechanical behavior of salt caverns for fast cyclic storage of hydrogen. For this purpose, a three-dimensional finite element simulator is developed to perform the numerical analyses. The simulator considers a one-way coupling between the energy conservation equation (heat diffusion) and linear momentum balance equation with thermal stresses included. The results help to understand the role of thermal stresses and temperature changes on the mechanical stability of salt caverns for fast cyclic loading conditions.

Potential and challenges of offshore salt caverns for energy storage in the southern North Sea

David Waltham1, *Juergen Adam1, Sjastri Hansen1*
1Royal Holloway, University of London

The extensive Zechstein megahalite of the southern North Sea (SNS) contains abundant salt anticlines and diapirs suitable for salt cavern construction. These structures are close to existing and planned wind farms suggesting that caverns might be useful for grid-scale energy storage using a number of different possible technologies (compressed air, hydrogen, pumped-hydro, thermal energy storage, flow batteries and hybrid systems). However, whilst onshore salt caverns have been extensively used for gas storage, no offshore caverns have been constructed anywhere in the world. Consequently, there are significant uncertainties concerning the viability of offshore energy storage in salt caverns. A new assessment of the salt cavern potential in the offshore UK and Dutch sectors of the SNS, based on the interpretation of a regional 3D seismic mega-merge survey and well correlation (Hansen & Adam, 2024: this conference), has identified prospective salt structures located close to offshore windfarms with energy storage capacities in the range of 50-250 GWh per structure. We then used a finite difference model to show that using sea water instead of fresh water increases salt cavern excavation time by around 12%. This model also predicts the salinity of the resulting brines to inform decisions on brine disposal. We find that output salinity reaches around 8-times normal sea-water salinity towards the end of excavation. This presents challenges for environmentally safe brine disposal when excavating caverns in shallow marine settings. Finally, we assess the cost, energy density, roundtrip efficiency, environmental safety and technology readiness level (TRL) of energy storage technologies to indicate which are most promising in the SNS setting. All technologies have technical drawbacks ranging from low-round trip efficiency of hydrogen storage to low energy density for pumped-hydro and low TRL of flow batteries. However, this is offset by the promise of large storage capacities close to electricity generators and consumers.

The energy potential in salt

Jørgen Clausen1, *Jesper Culmsee1, Lars Storm Pedersen1*
1SaltPower

"Salt domes: is there more energy available from their salt than from their oil?". The question was posed in 1978 by Wick and Isaacs1, based on the idea of using the osmotic pressure in hypersaline brines to produce energy. The osmotic pressure of saturated brine is 400 bars and offers a huge potential for power production. The technology to be used is Pressure Retarded Osmosis (PRO) and since 2015 SaltPower has developed the process to commercial readiness. The process requires a constant stream of brine and low salinity water, separated by a semipermeable membrane. High pressure is applied to the brine whereas the low salinity water is at a pressure of a few bars. Due to the osmotic pressure of the saturated brine, water will naturally migrate from the low-pressure, low salinity side to the high-pressure brine side through the semipermeable membrane, increasing the brine volume and dilute the brine in the process. The increase in the diluted high pressure brine volume is utilized to produce electrical power in a turbine or used as hydraulic pumping power. The first osmotic power plant from SaltPower is now in operation at a salt manufacturer in Denmark and the technology is ready to be applied in MW scale. Compared to other renewable energy forms, PRO produces baseload power. Around the world, the potential for osmotic energy is huge with salt domes located near low salinity water sources. With further development of the technology, osmotic power plants can be placed off shore on top of salt domes. To further add to the green transition, the PRO technology can be used to create large underground hydrogen storage in salt caverns needed for a hydrogen-based economy.
1 Gerald L. Wick, John D. Isaacs, Science, New Series, Vol. 199, No. 4336 (Mar. 31, 1978)

Underground Hydrogen Storage in salt– views and lessons from a mining authority

Elisenda Bakker1, *Heijn van Gent1, Gerco Hoedeman1*
1State Supervision of Mines

In the Netherlands Underground Hydrogen Storage (UHS) in salt caverns is considered a prime candidate for large scale energy storage. The use of salt caverns for UHS would be an application of existing and proven technologies for a new energy storage medium for which the safety standards are not well-know yet. SSM is both an advisor on permitting, and a regulator on safety and the environment. This puts us in a unique position to influence safety performance during the full life cycle of a cavern field. We use our experiences from past operations, recent research, and ongoing pilots to initiate discussions and research to improve the general knowledge about solution mining and cavern abandonment, with the aim to let operators adjust mining strategies for UHS. Traditionally, solution mining follows the same sequence of steps; design, development and abandonment. For UHS a phase of storage is added, which may have great consequences for the development of UHS projects. What is often overlooked is the abandonment and post-mining phase of a cavern field. During this phase salt creep could lead to ongoing subsidence for many decades, all the while the cavern stability and integrity needs to be maintained. During storage, processes like these might already start and affect operations. Additionally, prior to abandonment operators need to think about the need to re-brine and the effects that may have on the stability and integrity of a cavern. Moreover, we know that storage caverns are operated under relatively fast cycles. How does that effect the overall stability and integrity of a cavern field? On top of that, storage caverns that are operated under relatively fast cycles show high creep rates, which may lead to more subsidence. Better understanding of all these topics may help determine standards to which storage caverns may be safely operated.

3D Geological Modelling of the Internal Structure of the Asse Salt Diapir, Germany

York Fischer1
1Federal Institute for Geosciences and Natural Resources (BGR)

The use of the deeper underground for disposal of industrial waste or the storage of hydrocarbons or hydrogen increases continuously and is essential for a progressive energy transition. For example, salt structures are suitable for geological storage but require a thorough understanding of its complex internal topology and strong deformation. By integrating and interpreting all available data, a detailed 3D geological model often represents the base for further planning purposes. As part of the retrieval planning of radioactive waste from the Asse II salt mine in Northern Germany, a 3D model of the Asse salt diapir was commissioned. In this case, it will help to determine a feasible location for the construction of a retrieval mine. The modelled intra-salt stratigraphic sequence includes Zechstein layers from the Stassfurt (z2) to the Aller (z4) formation. Input data comprise well data, GPR signals, geologic mappings and more. Modelling the lithologically different ductile salt layers of the Asse diapir presents a challenging task because they are strongly folded, partially overturned, frequently intertwined and often taper out. In contrast, competent layers such as anhydrite tend to fracture in brittle manner and can form massive boudinaged blocks floating within the viscous salt matrix. The visualization of such complex structures cannot be implemented satisfactorily using conventional 3D modelling software that utilizes fixed interpolation algorithms. Therefore, we use OpenGeo7, an in-house software that allows comprehensive manual input and a tight control of the topology yielding a high structure resolution. Here, we present the model of the region around the Asse II salt mine and the modelling process itself. Future modelling efforts will focus on zones of major interest with regard to the planned retrieval mine and will provide additional model horizons.

Salt as a Host Rock for Caverns and Radioactive Waste Storage: Multiscale Challenges and Insights from Coupled Numerical Modeling

Tobias S. Baumann1, *Maximilian Kottwitz1, Anton Popov1, Joyce Schmatz2, Benoit Brouard*
1 smartTectonics GmbH, Mainz, Germany
2 Microstructures And Pores GmbH, Aachen Germany
3Brouard Consulting, Paris, France

Salt structures are known to be ductile and impermeable, they serve as host rocks for the disposal of high-level radioactive waste, salt solution mining, and storage caverns. Energy storage in salt caverns (compressed air and hydrogen) is an essential part of the energy transition. Despite their significance, our understanding of the deformation and transport processes within salt rocks remains incomplete, posing challenges in the efficiency and safety of industrial applications. In industrial contexts such as solution mining and energy storage, accurate descriptions of thermomechanical loads and induced stresses in salt and adjacent sedimentary rocks are critical. For the storage of radioactive waste in salt domes, we also need to consider long-term deformation mechanisms under extreme conditions, such as potential future glaciation events. To make reliable predictions using coupled 3D numerical thermo-hydro-mechanical (THM) models, it is essential to have accurate and well-constrained creep properties. These models must integrate site-specific material properties since inherent heterogeneities within salt, such as megacrystals and second-phase impurities, significantly influence creep behavior at the micro- and laboratory scales. In addition, constraints derived from cavern operations and geological observations help ensure reliable upscaling and verification of laboratory-determined creep properties. Furthermore, heterogeneities at the scale of caverns and domes, such as anhydrite stringers, or mechanically distinct adjacent salt units, significantly influence the dynamics and the stress state of the salt dome and locally affect the operation and abandonment of caverns and waste repositories. In our contribution, we will showcase numerical modelling examples from past and ongoing projects on waste disposal, cavern abandonment and storage in salt domes. We will highlight how our work integrates into a collaborative multi-scale approach with external partners, demonstrating how the combination of microstructural insights, geological observations and operational data enhances the predictive capabilities and safety of salt-based storage systems.

Salt-embedded basins as geothermal reservoirs: a petrological and thermophysical study of the sedimentary succession of the Estopanyà and Boix synclines (South-Central Pyrenees, NE Spain)

Pedro Ramirez-Perez1, *Gabriel Cofrade1**,** David Cruset2, Juan Diego Martín-Martín1, Jean-Pierre Sizun3, Ernest Onetti1, Irene Cantarero1, Anna Travé1*
1 SGR Geologia Sedimentària/IR Geomodels, Universitat de Barcelona (UB)
2 Group of Dynamics of the Lithosphere,GEO3BCN-CSIC
3 Chrono-Environnement, UMR CNRS 6249, Université de Franche-Comté

The Estopanyà and Boix synclines are two salt-embedded structures in the South-Central Pyrenees within the Serres Marginals thrust sheet (NE Spain). From the Upper Cretaceous to the Oligocene, the Alpine orogeny produced the nucleation, inflation, extrusion, and welding of two salt walls adjacent to these synclines modifying their sedimentary dynamics. In this contribution, we present the thermophysical properties of the synorogenic sedimentary succession of the Estopanyà and Boix synclines to discuss which factors primarily affect reservoir properties and the potential of these structures as geothermal reservoir analogues. 106 rock samples were collected and classified in three lithological groups and eight rock types according to thin-section description: 1) carbonates include lacustrine mudstones-wackestones, marine and palustral packstones-grainstones, breccias, and edaphic limestones; 2) arenites include fluvial hybrid sandstones and deltaic calcarenites; and 3) altered rocks include chalks and calcitized dolomites. The petrophysical and petrothermal data was acquired from 77 rock cubes (39 samples) and 107 rock slices (57 samples). Petrophysical results reveal well-clustered mineral densities (2.64-2.72 gcm-3), whilst variable connected porosity (0.50-17.63 %), permeability (0.001-15.30 mD), and seismic velocity values (1777-6560 ms-1 for dry and 2701–6344 ms-1 for water-saturated values). The highest porosities belong to chalks followed by sandstones and carbonates. Permeability values show that sandstones are more permeable than carbonates and chalks. Conversely, P-wave velocities are faster for carbonates than for the other lithological groups. The thermal conductivity (2.059-4.685 Wm-1K-1) of the studied succession is independent of petrophysical properties or facies. Porosity plays a key role in the observed petrophysical variation. Rock texture and alteration strongly influenced the pore-space distribution and its connectivity. In this sense, calcification and brecciation are predominantly observed affecting the diapir margin sedimentary succession in Estopanyà and progressively decreases away from the diapir, underlying the importance of sedimentology and diagenesis on the reservoir quality of salt-embedded basins.

Understanding the riddles of energy and CO2 geostorage in and around salt structures from field examples in Portugal.

Pedro Barreto1
1Geo Logica XYZ

The ongoing energy transition process brought back the importance of salt structures for underground storage of other gases such as hydrogen, carbon dioxide, compressed air, as well as for geothermal energy projects. As usual, new applications bring new concepts, new challenges and new players into the geostorage arena. Nonetheless, new players are often not fully familiarised with the geotechnicalities involved in these projects, and consequently are unaware of the problematics associated. Several examples worldwide (Lake Peigneur, Avery Island, Súria, Maceió) came to reinforce the idea that careful planning and detailed geological characterisation of salt structures is paramount during the development of underground storage projects in and around salt structures. If once the internal composition of salt structures was a domain better understood by mining experts and the surrounding structure by the oil and gas industry, to strive today in geostorage arena, players will need an holistic approach that combines up-to-date pragmatic knowledge from both industries, i.e. understanding of the geological properties from the core to the surroundings of salt structures. This study reviews main geological concepts, uncertainties and potential geohazards that need to be considered when planning a geostorage facility inside or adjacent to salt structures. It presents real examples from outcrops, mines and quarries in Portugal combined with seismic and well data. Although Portugal is not an hydrocarbon producer, the country produced asphalt and bitumen from the flank of a salt diapir in the XIX century and for the past two decades has been storing gas in underground storage facilities inside a salt diapir. Adding to outcropping salt structures with world class exposures, it makes the country an ideal field laboratory to understand the variability and complexity of salt structures. The goal is to provide geoscientists and engineers involved in geostorage projects with real field examples of the main geological technicalities and issues behind underground storage in salt structures, in order to optimize projects and reduce associated risks, from project area screening to project completion as well as during the exploitation of geostorage infrastructures.

Tectono-Stratigraphy Of The Norwegian-Danish Basin: Halokinetic Control On The Plays For CO2 Storage

Simon Blondel1, *Evans Sian1, Hansen Torsten1, Rikke Bruhn2, Braathen Alvar1*
1University of Oslo
2Equinor

The Norwegian-Danish Basin (NDB) holds an optimal position for Carbon Capture and Storage (CCS) activities in northern Europe. The Norwegian part of the NDB remains poorly explored, but it has the potential to store significant amounts of CO_2. The stratigraphic architecture of the potential storage units and the formation of structural closures in the NDB was strongly controlled by salt tectonics of the Zechstein evaporite sequence. We map the main lithostratigraphic groups of the Norwegian sector of the NDB. The results allow us to divide the study area into eleven structural domains recording the multi-stage deformation of the NDB. Thin-skinned salt tectonics during the Triassic recorded salt flowing from the basin highs (Stavanger Platform to the North and Vinding structural domain to the south) toward the deepest part of the basin (the Åsta graben domain and the later uplifted Jurassic highs). This resulted in the formation of NW-SE trending discontinuous salt walls from the Egersund Basin to the Flekkefjord high, which strongly influenced the Mesozoic evolution of the study area. The Late Jurassic-Early Cretaceous rifting initiated the subsidence of the Egersund Basin and the Central Graben rift basins to the south. In the western part of the study area, due to the restricted salt supply and the welding beneath inverted Triassic minibasins, salt walls collapse and Mid Jurassic-Early Cretaceous secondary mini-basins subside into their crests. In the eastern part of the study area, diapirs do not show evidence of collapse. After a period of quiescence, late Cretaceous to Palaeocene inversion results in the uplift of the Stavanger Platform and the Lista blocks, destabilizing the Chalk above reactivated salt structures and locally folding the overburden. In the eastern part of the study area, the tectonic loading is accommodated by active diapirism with arching of the post-salt strata above rejuvenated salt diapirs.

Salt diapirs and minibasins of the Hummer Fault Zone, offshore Southern Norway – structural evolution and CO2-storage perspectives

Torsten Hundebøl Hansen1, *Simon Blondel1 Sian Evans1, Rikke Bruhn2, Alvar Braathen1*
1University of Oslo
2Equinor ASA / University of Oslo

The Norwegian-Danish Basin (NDB) stretched from what is now offshore Southern Norway to Eastern Denmark. While hydrocarbon exploration has seen little success here, several Mesozoic to Paleogene sandstone units provide ideal reservoirs for CO2 storage, onshore and offshore. Zechstein salt structures are prominent and salt tectonism strongly influenced depositional patterns through much of the basin's history. Over the past few decades, our understanding of salt tectonics has seen major advancements. A modern take on the structural development of the NDB is therefore critical for recognising opportunities (e.g. traps) and risks (e.g. compromised seals) for CO2 storage. Here, we bring preliminary findings from our work on the western part of the NDB, offshore Southern Norway. In this study, we apply 3D seismic and well data to investigate the development of salt walls, stocks, and minibasins along the Hummer Fault Zone. Here, a basement-fault trend appears to have influenced the local development of salt stocks and rotated minibasins in the post-Permian deposits above – this in spite of being deeply buried since the Triassic. We seek to answer: 1; To what extent did sub-salt movement along the Hummer Fault Zone control salt-tectonic development above it, and when were sub-salt faults active? 2; How did salt tectonism respond to changes in the regional tectonic and depositional regimes? 3; Do indications of seal bypass and vertical fluid escape occur in relation to salt structures? 4; What risks and opportunities for CO2 storage occur at different structural levels, and are they generally applicable?

Catastrophic leakage through thick evaporite seals

Joe Cartwright1
1University of Oxford

Evaporites are often assumed to be the ideal seal rock, imbued with durable, low permeability from an early stage of burial and the ability to self-seal fractures by virtue of its rheology and ability to flow on short time scales. Coupled with the typically large lateral extents, stratigraphic continuity and thickness, it is no surprise to see that evaporites have successfully sealed many billions of barrels of oil for millions of years. As we contemplate more diverse roles for evaporite deposits and evaluate their sealing potential, it is perhaps worthwhile to consider cases where even thick evaporite deposits have failed as seals, and catastrophic leakage of fluids has occurred as a result. By understanding past failures, we can fine tune our measures of risk for the range of uses for which salt seals are an integral component. A number of examples of highly focused fluid venting through thick evaporite deposits are presented, and the conditions under which this seal failure occurred are analysed. Failure is exclusively driven by high fluid overpressures, and is often episodic with a surprisingly comparable periodicity, irrespective of location and geological context. In addition to the evidence for repeated seal breaching, these case studies capture some of the flow behaviour of evaporites, and the venting structures act as rare natural constraints against which rheological models can be tested.

POSTER ABSTRACTS

High-resolution structure and salt-sediment interaction around an exposed salt sheet

Antonio Teixell1, *Naiara Fernandez2, Pierre Labaume3, Idoia Rosales4, Antonio Barnolas1, María-Luisa Arboleya1*
1 Departament de Geologia, Universitat Autonoma de Barcelona, Spain
2 GFZ German Research Centre for Geosciences, Potsdam, Germany
3 Université de Montpellier, France
4 Instituto Geológico y Minero de España, Madrid, Spain

We report detailed geometries of subsalt and suprasalt sedimentary bodies at the Idalioun Keuper sheet of the High Atlas basin. The Atlas orogen uplifted a former Jurassic rift basin filled with marine carbonates, turbidites and shales affected by salt tectonics of the Triassic (Keuper) evaporites. The Idalioun is a good field analogue providing clues to the emplacement mechanisms and evolution of salt sheets. Exceptional outcrop of a complete profile of the 2-km-long allochtonous Keuper body from feeder to front records ca. 20 my of diapir flaring in deep-marine environment. Subsalt features: despite the current flat-lying disposition (likely a secondary feature caused by layer rotation as the underlying km-scale minibasin subsided), the sheet cuts upsection across an inclined, thick subsalt stratigraphy of turbidites and shales with a regional ramp angle of 30-40°. However, at the dm-scale, the sheet overlies a strikingly continuous recumbent syncline. Despite diapir-edge folding, sequence punctuation by halokinetic unconformities is not observed, indicating fast salt advance such that overturned layers were not truncated by unconformable strata but were rapidly covered by the sheet. The salt sheet front: the quenching of the sheet is recorded by multiple burial sedimentary wedges, bounded by salt spines extruded above a pinned front before the sheet was definitively arrested. Suprasalt features: a thin carapace of condensed carbonates, topped by a ferruginous hardground, is disaggregated but covers much of the sheet rear suggesting open-toe advance during part of the history. The carapace and the exposed sheet were subsequently buried by a thick carbonate and shale succession onlapping towards the feeder, which deflated the salt body imparting the observed tabular (sheet) shape. The Idalioun field case illustrates the subtle distinction between flaring (overhanging) diapirs and salt sheets, and brings insights on the decoupling between subsalt and suprasalt sections experiencing different sorts of minibasin stratal rotation.

Hydrogen storage in salt caverns: a first screening of the potential in the Southern Norwegian North Sea

Daniele Blancone1, *RUIZ MARAGGI, LEOPOLDO MATIAS2 , CARDOZO, NESTOR1 MOSCARDELLI, LORENA2, ESCALONA, ALEJANDRO1*
1 Department of Energy Resources, University of Stavanger, Norway
2 Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin

H2 storage in man-made underground salt caverns is one of the best options to mitigate the challenges related to intermittent availability of renewable resources. This is due to the properties of halite, which has low permeability and low reactivity, and to the large availability of salt structures in several basins. Offshore salt caverns are frontier exploration. In the Norwegian North Sea (NNS), there are many structures in the Upper Permian Zechstein salt, which could potentially host caverns. Evaluating the storage potential of this area however is difficult because limited seismic imaging and well control inside the salt structures. This study presents an assessment of the H2 storage potential of salt structures in the southern NNS (area = 48,000 km2). Seismic and well data were used to map the salt structures, construct a depth map of the top salt, and isolate potential salt structures (depth < 1 800 m). Then, the GeoH2 App was used to estimate the potential number of salt structures, caverns, and H2 volume and energy stored per license block. Maximum potential is towards the SE shallow areas (Egersund Basin), and the total H2 energy that could be stored is 900 TWh, which by far exceeds Norway's yearly electricity consumption (220 TWh in 2022).
References Maraggi, L. M. R., Moscardelli, L. G., [2023]. Modelling hydrogen storage capacities, injection and withdrawal cycles in salt caverns: Introducing the GeoH2 salt storage and cycling app. International Journal of Hydrogen Energy, 48(6), 26921-26936.
Marín, D., Cardozo, N., Escalona, A., [2023]. Compositional variation of the Zechstein Group in the Norwegian North Sea: implications for underground storage in salt caverns. Basin Research, 35(4), 1460-1485.

Zechstein halites as a potential hydrogen storage solution – Interim Results

Emma Bedda1, *Tom Randles1, Harry Morris1, Ed Hough1*
1British Geological Society

Energy Storage is a key component in the UK's strategy for decarbonising the economy by 2050; hydrogen and compressed-air energy storage (CAES) are both core elements required to integrate renewable energy technologies into electricity grids and domestic heating networks. Bulk energy storage technologies are required to accommodate the UK's fluctuating daily and seasonal energy supply requirements. To support the development of low carbon solutions for net zero the UK's underground storage capacity must therefore be increased. Subsurface salt caverns and depleted oil and gas fields have been identified as potential sites for CAES or hydrogen storage, with hydrogen storage in porous rocks at early stages of commercial consideration. This study seeks to understand the potential capacity for hydrogen salt cavern storage in the Southern North Sea (SNS) with particular focus on Permian halite deposits. We present interim results of a study investigating the distribution and thickness of halite units within the Zechstein Group of the SNS. 3D seismic interpretation and seismic attribute analysis (e.g. Pseudorelief) is used to identify key evaporite-carbonate cycles and to derive maps of halite distribution and thickness, which are then calibrated to available well data. In conjunction with log response data, this stratigraphic geometry is used to identify areas with halite deposits that are potentially suitable for salt cavern storage and provides a dataset with which to assess potential storage capacity. We will highlight some of the challenges associated with mapping halite deposits from seismic data, and discuss the workflows used to produce robust depth and thickness maps for individual halite intervals. This work is part of a multi-centre NERC-funded project in collaboration with the National Oceanography Centre (NOC) and Plymouth Marine Laboratory (PML).

Reproducing deformation of complex salt stratigraphies using analogue modelling: new insights in the frame of the energy transition

Naïm Célini1, *Alexandre Pichat2, Sylvie Schueller-Messie3, Jean-Marie Mengues3, Claude Gout4, Sabine Delahaye2, Jean-Paul Callot4*
1Akkodis
2 TotalEnergies
3 IFPEN
4University of Pau

Since the 1990's, analogue modelling has been extensively employed to reproduce halokinetic deformation. Most of studies used this approach to elucidate the controlling parameters of salt tectonics and the interrelationship between these parameters and the subsequent geometries in the post-salt sediments. Several studies focused on the impact of brittle layers in the modelled salt stratigraphy, whereas the influence of low viscosity K-Mg salts has been less investigated in analogue modelling. Nowadays, there is a need for a more detailed characterisation of the internal structure of salt bodies in order to predict the optimal location for the development of salt caverns for hydrogen storage in the context of the energy transition. Salt cavern must be developed in salt units as halite pure as possible. Thus, predicting where and why various salts are distributed in diapiric bodies becomes of primary importance. The DEEP IN SALT project includes a facet led by the University of Pau, TotalEnergies and IFPEN, dedicated to analogue modelling of diapiric structures containing halite, brittle (anhydrite, carbonate) and low viscosity (K-Mg salts) layers. The main challenge of this study was to develop a material that can represent low viscosity K-Mg salts in sandbox models. In this presentation, we introduce the chosen material, its properties, and the sandbox models that we produced containing the new material interlayered with silicone and sand. We discuss the reliability of the material, its representativeness in relation to natural cases and the way the models can increase the understanding of intra-salt deformation.

Quantification of the probability of induced seismicity associated with large-scale underground hydrogen storage in Dutch salt formations

Naomi Van Den Ameele1,*Hadi Hajibeygi1, Heijn van Gent2, Annemarie Muntendam-Bos1,2*
1Delft University of Technology,
2Dutch State Supervision of Mines

Construction and cyclic operation of multi-cavern systems within salt pillars presents notable geomechanical challenges, including subsidence due to cavern convergence, pressure interactions between caverns, leakage and induced seismicity. Monitoring stations in the northeast of the Netherlands have consistently reported small seismic events (local magnitudes ≥ -2), the underlying physics of which are poorly understood. As the operational activity in the salt domes is expected to scale up due to the prospects of underground hydrogen storage (UHS) in salt caverns, it is crucial to investigate the mechanisms underlying the observed seismic events. More importantly, it is essential to quantify the probability of increased seismic events, as the result of the increase in the UHS projects. This study aims to assess the probability for induced seismicity associated with the prospect of large-scale hydrogen storage (UHS) plans. To this end, it is crucial to understand, analyse, and quantify the mechanisms behind induced seismicity observed due to the salt cavern leaching and cyclic storage operations within the Dutch salt domes. As a necessary bench-mark step for our study, it is essential to explain the occurrence of small-scale events for the existing caverns. We commence by constructing simplified yet meaningful simulation models, which include the basic characteristics of the salt formation, salt cavern, operational conditions, and the presence of structural features in the salt formation as well as in the over- and side-burden. Subsequently, the deformation evolution of the system is quantified and the impact of uncertainties on stress and deformation assessed. The simulation model will be coupled to a seismogenic source model to compute the spatio-temporal development of the seismic activity in the model due to the deformation evolution.

Discovery of Palaeogene Halokinesis in the North Sea Basin

Prosper Ingram Deitch1, *Harry Doust2, John Verbeek2, Anouk Beniest2*
1 Vrije Universiteit Amsterdam currently working for the Dutch State Supervision of Mines
2 Vrije Universiteit Amsterdam

The subsurface of the North Sea Basin houses an abundance of deformed Late Permian Zechstein salt. These salt structures may play a crucial part in the energy transition in the form of sealing formations or even gas storage capacity in salt caverns. We studied the North Sea Basin area just north of the Frisian Islands of Terschelling and Ameland, using analysis of 3D seismic data and publicly available thickness maps, in order to increase our understanding of (1) the structural salt province of the southern North Sea Basin and (2) the timing of halokinesis. Thickening up to 400 m of the silicilastic North Sea Groups was observed in the newly discovered Oosterend, Nes and Schiermonnikoog-Lauwerszee minibasins, in the area between the Terschelling Basin and the Lauwerszee Trough (Dutch offshore). We show for the first time that these minibasins were actively subsiding during the Palaeogene. Analysis of the underlying units showed no such thickening, indicating that the subsidence of these minibasins did not occur before the Palaeogene. As such, we are the first to posit a Palaeogene phase of halokinesis that affected the southern North Sea Basin.

A drill down into the Zechstein: learnings from legacy hydrocarbon wells to understand drilling and salt cavern placement hazards.

Rachel E. Brackenridge1, *Houghton Thomas1*
1Univerisity of Aberdeen

The evaporite sequences of the UKCS have the potential to facilitate the energy transition as a critical intermittent energy store or as a top seal for subsurface sequestration in pre-salt sediments. However, drilling operations through evaporite sequences can be hazardous and unpredictable and salt cavern stability can be compromised due to heterogeneities in evaporite facies. Using legacy hydrocarbon well reports and petrophysical data, this research takes learnings from previous operations across the UKCS to assess the key drilling risks within different evaporite formations. Principle identified drilling hazards are: (1) overpressure zones; (2) mobile K-Mg salts (or 'squeezing salts') resulting in washout zones or causing drill pipes to become stuck; and (3) brine pockets. Encountered drilling hazards are controlled both geographically and stratigraphically where bedded sequences are found as these hazards are controlled by the palaeoceanographic history of each basin and the degree of subsequent halokinesis. Hazards are common, but less predictable within salt structures. Case studies are presented to highlight characteristic drilling hazards within the evaporite sequences of different basins across the UKCS. A robust understanding of the predicted facies and associated drilling hazards aids operations; could avoid unnecessary delays; and allows for improved integrity of well completions and salt caverns.

Simulating long-term CO_2 geological storage in depleted reservoirs and aquifers

***Sophie Godefroy**[1], Alireza Emadi[1]*
1.SLB

Carbon capture and storage (CCS) is recognized as a solution for reducing the greenhouse gases (GHG) from the atmosphere. CO_2 emissions from manufacturing industries and power plants are collected and injected into storage formations. Possible geological storage formations are aquifers and depleted reservoirs, including near salt formations. A crucial requirement is the long-term integrity of the seal for the physical trapping of the gas. Therefore, an accurate simulation of the short- to long-term behavior of CO_2 within the formation and possible geomechanic effects is needed to ensure secured storage of the CO_2 in the geological formation. In this paper, we will present the tools at our disposal to simulate a CCS process in underground reservoirs. We will show an integrated workflow that can be used to model CO_2 injection and retention in any type of geological reservoir. A commercial subsurface software platform will be used to create the geological model and a high-resolution reservoir simulator will be used to model the dynamic process of fluid flow and retention of CO_2 in the reservoir. We present how different features in the reservoir simulator enable realistic modelling of CO_2 partitioning between water and hydrocarbon phases and how different modelling methods enable realistic modelling of aqueous phase properties (density, viscosity and enthalpy) once CO_2 gets dissolved in the water. Accurate modelling of CO_2 properties and possible effects of pressure and temperature changes is essential for long-term CO_2 storage projects. The workflow can be combined with geomechanics evaluations to study the integrity of the geological system. We will illustrate the subject with integrated studies in synthetic reservoirs and show how the injected CO_2 will behave over time in these geological formations.