The Role of Salt Tectonics in the Energy Transition: An Overview and Future Challenges

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Running Title: Salt Tectonics and the Energy Transition

Keywords: salt tectonics; energy transition; hydrogen storage; salt caverns; CCUS; geothermal; oil and gas

Abstract

The fundamental properties of salt have long been exploited in the search for hydrocarbons, as they influence many of the hydrocarbon play elements. This industrial application has driven the pursuit of salt tectonic knowledge over the last century and led to major conceptual advances in the field. However, the current need, and social-political demand, to decarbonize suggests that the applicability of salt tectonic knowledge will expand to other aspects of the subsurface that are relevant to the energy transition. The pace of this change leaves the field of salt tectonics grappling with a fundamental question – what role does salt tectonics have as part of the energy transition? Here, we discuss the role salt tectonics can play in a number of key energy transition technologies, namely, energy storage as gas in salt caverns (e.g. hydrogen and compressed air), CO_2 storage, and geothermal energy. For each of these technologies we explore: i) fundamental concepts and driving forces; ii) how and why the properties of salt are of importance; and iii) the key salt-related technical challenges, potential future research directions, and technical approaches needed for large-scale development.

We highlight how salt basins offer vast potential for development throughout the energy transition including, but not limited to: i) the likely demand for thousands of new hydrogen storage caverns inside salt bodies by 2050; ii) a likely early focus for porous media CO_2 storage sites in basins strongly influenced by salt tectonics; and iii) enhanced geothermal energy potential in and around salt bodies. Effective exploitation of these resources will require a deeper understanding of the internal composition, geometry, and evolution of salt structures and their surrounding sediments, and potentially the development of more predictive models of salt tectonic behaviour. Critically, we see the need to integrate learnings of salt tectonics gained in the academic, mining, solution mining, and oil and gas communities, and apply a fresh perspective to answer research questions of relevance to the energy transition. Developing this new understanding will help optimise design, reduce geotechnical risk, and improve efficiency for energy transition technologies, thus indicating a strong future demand for salt tectonic research.

1. Introduction:

The properties of salt have long been exploited in the search for hydrocarbons, with its fundamental properties influencing all of the key petroleum play elements (e.g. Kirkland and Evans, 1981; Mello et al., 1995; Warren, 2006; Jackson and Hudec, 2017). For example, salt is i) thermally conductive, meaning it quickly removes heat from underlying source rocks and allow source rocks below the typical oil window to remain productive in very deep traps (e.g. Mello et al., 1995); ii) mobile, such that salt-related deformation generates a myriad of trapping locations and styles within salt basins, whereas the structural deformation modifies topography and bathymetry and therefore influences the distribution of syn-deformational reservoirs (e.g. Seni and Jackson, 1983; Hodgson et al., 1992; Rowan and Weimer, 1998; Gee et al., 2006; Winker and Booth, 2000; Cumberpatch et al., 2021); and iii) self-healing and crystalline meaning it is in most cases impermeable to pore water, hydrocarbons, and gases, and thus typically forms an ideal seal, to such an extent that 14 of the world's 25 largest oil fields are sealed by salt (Warren, 2006) (*Fig. 1*). The sealing behaviour of salt has also been exploited to store oil, gases, and wastes in underground salt caverns (e.g. Gillhaus and Horvath, 2008). These characteristics have driven the pursuit of salt tectonic knowledge over the past century, (e.g. see summaries in Jackson, 1997; Jackson and Hudec, 2017).

Current ambitions to decarbonize energy systems to reduce the harmful effects of anthropogenic global warming will require a combination of reducing fossil fuel consumption and carbon dioxide emissions, along with the ambitiously technological goal of capturing and sequestering as much atmospheric carbon dioxide from the air as possible (*Fig. 2*). Within this framework, a number of technologies have been proposed to help the transition to a stable, safe, low carbon energy economy, these include, but are not limited to: i) widespread use of carbon capture from industrial processes and subsequent sequestration within the subsurface; ii) upscaling of hydrogen production and usage requiring upscaling of subsurface hydrogen storage; and iii) wider use of geothermal energy (e.g. Ringrose and Meckel., 2019; Stephenson et al., 2019; Hashemi et al., 2021; Shuster et al., 2021; Tester et al., 2021; Crotogino, 2022; Lankof et al., 2022; Muhammed et al., 2022).

Critically, the properties of salt that make it such a valuable element in oil and gas exploration are also important to these energy transition technologies. For example, an understanding of salt properties and behaviour is critical for seasonal and/or strategic subsurface storage with high efficiency of recoverability (e.g. hydrogen, hydrocarbons and compressed air), and long-term sequestration where recoverability is not desired (CO_2 storage and waste disposal). Storage may be within the salt itself (e.g. salt caverns and intra-salt repositories for hydrogen or hydrocarbons) or within the sediments around the salt in traps generated by salt tectonics. Furthermore, understanding the thermal properties of salt and how the geometry of salt bodies may focus heat flow is important given that salt basins may be particularly prospective for geothermal energy (e.g. Tester et al., 2007; Moeck, 2014; Daniilidis and Herber, 2017; Raymond et al., 2022). In light of this, we explore the role salt tectonics can play in the energy transition. We specifically address the fundamental concepts and driving forces for aspects salt may influence in the energy transition including: storage inside salt domes, CO_2 storage in salt basins, and geothermal exploration. For each of these fields we outline our perspective on the key salt-related technical challenges, potential future research directions, and technical approaches needed. Overall, we find that if salt is to be fully exploited and to play a significant role in the energy transition, there will be strong future demand for salt tectonic research, albeit, with a shift in focus.

2. Storage in Salt Caverns

2.1. Salt Caverns Overview and Potential Future Demand

2.1.1 Salt Caverns Basics

Salt caverns are man-made voids in the subsurface created by the process of solution mining from domal or bedded salt deposits. In this process, low salinity water is pumped down a borehole that penetrates the salt, the water dissolves the salt, and the resulting brine is pumped to the surface, leaving a cavern (*Fig. 3a*). Salt caverns are typically developed at between 400 and 2000 m depth, with caverns in domal salt commonly 300-500 m tall, 50-100 m in diameter, and with a volume of 500,000 m^3 (e.g. Crotogino, 2016; Warren, 2016; Michalski, 2017; Muhammed et al, 2022). Caverns dissolved into bedded salts typically have lower heights and are smaller than those in domal salt (e.g. 100,000-300,000 m^3; Plaat, 2009; Matos et al., 2019), with heights restricted by the thickness of the soluble halite-rich units within lithologically heterogeneous bedded salt sequences (Foh et al., 1979; Bruno and Dusseault, 2002; Han et al., 2006) (*Fig. 3b*).

Caverns created by salt dissolution have commonly been created as an incidental byproduct of solution mining, where the salt content of the extracted brine is recovered by surface evaporation. Solution caverns have also been created intentionally for storage of hazardous waste, hydrocarbons, compressed air, or hydrogen (e.g. Wassman, 1983; Dusseault and Davidson, 1999; Gillhaus and Horvath, 2008; Warren, 2016 and 2017).

The primary function of solution caverns that are created as a byproduct of solution mining is to optimise salt recovery, so the resulting cavity may not have suitable geometry or stability for storage purposes. For example, they may be too large, or may extend to the edge of the salt and intersect the surrounding country rock. In contrast, solution caverns created for storage must be engineered for the purpose (e.g. Plaat, 2009; Cyran, 2020). This means maintaining a stable size and shape, not intersecting the boundaries of the salt body, and not prone to leak for appropriate timescales (*Fig. 3b*). Notably, the required timescales for safe containment vary markedly, being 30-50 yrs (for storing hydrogen and hydrocarbons) to ~1,000,000 years (for safe disposal of some nuclear wastes; Gibb, 1999; Warren, 2017).

A set of solution caverns within a single salt body is termed a cavern field, and as of 2008, >90% of known cavern fields in domal salt were located in the US Gulf Coast and the Southern Permian Basin (Central Poland, Netherlands, and North Germany) (Gillhaus and Horvath, 2008). Perhaps the best known storage caverns are those that comprise the Strategic Petroleum Reserve (SPR) along the Texas and Louisiana Gulf Coast, which were formed by the US Government in the 1970's to store oil in case of interrupted supply. Today, the SPR consists of 61 salt caverns at four locations, with a current authorised storage capacity of 714 million barrels (https://www.energy.gov/fecm/strategic-petroleum-reserve-9).

2.1.2 Salt Caverns and the Emerging Hydrogen Economy

Much attention is focused on balancing the need to transition to clean, renewable sources of energy with the need to meet global energy demand. Wind-sourced power varies with, and is limited by, seasonal and short-term weather; solar power is daylight-dependent so that it varies diurnally as well as seasonally. Neither source can be ramped up to match fluctuations in energy demand, so some means must be found to balance supply and demand (Heinemann et al., 2021). The issue of curtailment and intermittency of renewable energy is a costly one and a major obstacle to deploying renewable energy solutions at scale, in the United Kingdom alone wind energy intermittency cost the government £274 million in 2020 (Wallace et al., 2021). One solution is to find a way to store renewable-sourced power in the form of potential energy that can be released on demand.

Using hydrogen (H_2) to transport and store energy is a simple and technically feasible approach for balancing these intermittent supply and demand challenges at a large scale (e.g. Gahleitner, 2013; Crotogino, 2016; Tarkowski, 2019; Mouli-Castillo et al., 2021; Muhammed et al., 2022). During periods of higher than required output from wind or solar sources, the excess power can be used to electrolyze water and produce 'green' hydrogen (e.g. Crotogino, 2016). In addition, hydrogen can be produced either by steam methane reforming or autothermal reforming of natural gas, termed 'blue' hydrogen if coeval sequestration of carbon dioxide occurs, and 'grey' hydrogen if not. Hydrogen produced by any of these methods can be stored and used for energy generation later, or as chemical feedstock. However, the low density of hydrogen (0.089 kg/m^3 at standard temperature and pressure) and the significantly lower energy potential per unit volume of hydrogen when compared to natural gas (about one-third), means that to store energy at a scale sufficient to meet demands (terawatt-hour range) requires large volumes of hydrogen, and a vast upscaling of subsurface storage availability (e.g. Hashemi et al., 2021; Shuster et al., 2021; Crotogino, 2022; Lankof et al., 2022; Muhammed et al., 2022).

Potential sites proposed for large-scale hydrogen storage in the subsurface include salt caverns, depleted reservoirs, saline aquifers, or hard-rock lined caverns (e.g. Lord et al., 2014; Bunger et al., 2016; Tarkowski, 2019; Zivar et al., 2021; Crotogino, 2022; Muhammed et al., 2022). Of these, salt caverns are currently the only proven option, with caverns in three salt domes in the Texas Gulf Coast, and in the bedded salt at Teeside in the UK, proving salt caverns can safely store hydrogen for decades (e.g. Stone, 2009; Panfilov, 2016; Crotogino et al., 2018; Tarkowski, 2019). However, hydrogen storage in these facilities is mainly strategic to guarantee feed stock for refineries and fertiliser production, necessitating low frequency (monthly ? seasonal ?) injection and withdrawal cycles. Hydrogen storage, for the purposes of abating renewable energy intermittency for example, may require higher frequency injection and withdrawal cycles (aka. several cycles per year) and even though this is theoretically feasible there is limited operational data to inform us about the effects that these high rates of hydrogen injection and withdrawal cycles might have on the integrity of salt caverns and associated subsurface infrastructure.

Despite these data limitations, it is estimated that salt caverns might be ideal for hydrogen storage as: i) up to 10 cycles of injection and withdrawal per year might be possible at fast injection and withdrawal rates, meaning the approach is ideal for short- and medium-term storage (e.g. Tarkowski, 2019); ii) cavern shape and size can be customised, and can be stable for significant periods of time (Lord et al., 2014; Crotogino, 2022) iii) hydrogen loss by leakage is estimated to be minimal, due to the sealing nature of evaporites (low permeability to gas) even though this might be variable depending on specific characteristics of the salt formation (Crotogino et al., 2010; Lord et al., 2014; Warren, 2017; Matos et al., 2019); iv) the injection rate of hydrogen into salt caverns is not strongly dependent of complex multiphase flow phenomena (Wallace et al., 2021); v) salt is typically inert to hydrogen (although impurities in salt may not be and this aspect needs further research) and conversion of any water to brine reduces potential for bacterial activity (e.g. Bunger et al., 2016; Wallace et al., 2021; Crotogino, 2022); and vi) the proportion of cushion gas required is moderate compared to reservoir storage (Bunger et al., 2016). One of the main drawbacks to salt cavern storage is finding an economic and ecologically-friendly way to utilise or dispose of the brines extracted during leaching (e.g. Crotogino, 2022). Suggestions for brine uses include salt (NaCl) mining, geothermal and hydrocarbon operations along with lithium extraction, with the latter being intriguing given the demand for electric vehicle batteries (Kukla et al., 2019).

Although the technology needed for storage of hydrogen in salt caverns is proven at a small scale, implementation as the basis for energy transition will require vast upscaling. One estimate suggests that ~700 million metric tonnes of hydrogen could be used globally in 2050 if strong climate policies are enforced to limit global warming to 1.5° (BloombergNEF, 2020). To store 20% of this annual hydrogen demand would require 14,000 salt caverns to be developed, at a cost of $637 billion (BloombergNEF, 2020; ENTSOG, GIE and Hydrogen Europe, 2021). We now outline how salt tectonic research will be required for the safe and optimised development of salt caverns in a range of salt settings globally.

2.2. Role of Salt Tectonics in Large-Scale Development of Salt Cavern Hydrogen Storage

2.2.1 Overview of Heterogeneity in Salt Diapirs

Salt diapirs are rarely homogeneous bodies of halite, more typically they are heterogeneous bodies that may contain a range of evaporite minerals, other lithologies, internal structures, fluids and gases, colors, textures, that are influenced by the original paleoenvironment and complex internal salt flow patterns (e.g. Kupfer, 1976; Hofrichter, 1980; Talbot and Jackson, 1987; Jackson and Talbot, 1989; Kupfer, 1990; Koyi, 2001; Chemia et al., 2009; Looff et al., 2010a and b; Van Gent et al., 2011; Jackson et al., 2015; Rowan et al., 2019) (*Fig. 4*). We divide intra-diapir heterogeneities into two main types: *depositional heterogeneities*, those that developed as the evaporite sequence was deposited (halite, anhydrite, bittern salts, carbonates, clastics, ashes, and lavas) (*column 1 on Table 1*), and remaining *non-depositional heterogeneities* that are atypical of the salt mass (*columns 2-4 on Table 1*). Many of the intra-diapir heterogeneities in *Table 1* have previously been classified as *anomalous salt*, a term widely used in the salt mining and solution mining communities and which has no genetic connotation (e.g. Kupfer, 1976, 1990; Neal and Magorian, 1997; Looff et al., 2010a and b; Looff, 2017; Warren, 2017). However, we prefer not to use this terminology in this paper, for two reasons. First, many features termed *anomalous salt* are not actually composed of salt (e.g. igneous rocks, entrained country rock, encased minibasins, sutures etc). Second, the term *anomalous salt* was defined based on observations of US Gulf Coast salt diapirs, with the most prevalent usage of the term in the literature also referring this setting (e.g. Kupfer, 1976, 1990; Kupfer et al., 1998; Looff et al., 2010a and b; Looff, 2017). This can cause problems as features (particularly evaporite lithologies) that are anomalous on the US Gulf Coast may be perfectly normal inside salt domes in other basins. We therefore refrain from using *anomalous salt* and instead use our subdivision of intra-salt heterogeneities (*Table 1*).

Given the need to vastly upscale the number of salt caverns that store hydrogen (or hydrogen as part of a mixture) globally, we see a fundamental need to better understand–even *predict*–the distribution of heterogeneities within salt diapirs, and the salt tectonic processes that control these heterogeneities, for four key reasons. First, improved predictability will be key for the development phase where well design will depend on prognosis of intra-salt heterogeneities that can impact well integrity and safety. Encountering unexpected heterogeneities during drilling can lead to dangerous pressures, washout and loss of circulation, and wells can be damaged by shearing or buckling if salt flow directions are incorrectly predicted (e.g. Looff, 2010a; Kukla et al., 2011; Weijermars et al., 2014; Strozyk, 2017; Warren, 2017) (*Fig. 5a*). Second, predicting the likely distribution of heterogeneities in salt stocks can help ensure the safe placement of salt caverns, which ideally will be located in relatively homogeneous halite, away from anomalous salt or permeable compositional layers, where properties and stresses are predictable, and where leakage is less likely (e.g. Koyi, 2001; Gillhaus and Horvath, 2008; Warren, 2016 and 2017; Pichat, 2022) (*Fig. 5b*). Third, to model the final geometries of leached caverns, and hence safely design cavern fields, requires an understanding of the likely distribution of intra-stock lithologies and other heterogeneities as cavern geometry is highly sensitive to spatial variations in solubility (e.g. Wilke et al., 2001; Cartwright and Ratigan, 2005; Rautman and Lord, 2007; Czapowski et al., 2009; Looff et al., 2010a and b; Warren, 2016; Cyran, 2020) (*Fig. 5c*). Fourth, maintaining the required purity of stored hydrogen requires an understanding of what lithologies and mineralogical alterations will outcrop on cavern walls since hydrogen can be highly reactive to some minerals such as anhydrite which may form contaminants such as H_2S that also pose a significant safety issue (e.g. Panfilov, 2016; Portarapillo and Di Benedetto, 2021).

2.2.2 The Origin, Nature and Distribution of Heterogeneities in Salt Diapirs

We now present an overview of the state of knowledge regarding the origin and distribution of different types of heterogeneities in salt diapirs outlined in *Table 1*.

2.2.2.1 Depositional Heterogeneities

A salt sequence accumulates through precipitation of salts from seawater, and a variety of evaporite lithologies are expected to develop (e.g. Usiglio, 1849). In sequence of precipitation, and in order of increasing solubility, these are most commonly carbonates, gypsum, halite, and bittern salts (potash), although the exact salts that precipitate are determined by local controls (e.g. Borchert and Muir, 1964; Kirkland and Evans, 1973; Schreiber, 1988; Warren, 2006; Babel and Schreiber, 2014; Jackson and Hudec, 2017). The salts, as well as any deposited clastics, develop compositional layering in an evaporite sequence that can contain weak (halite and bittern salts) and strong layers (anhydrites, carbonates, and clastics) and a range of viscosities (e.g. Rowan et al., 2019; Pichat, 2022) (*Fig. 6*). Some evaporite sequences, such as the Louann salt in the Gulf of Mexico, are almost entirely halite and thus contain minimal depositional compositional layering (e.g. Salvador, 1991; Rowan et al., 2019). For example, it is believed that onshore US Gulf Coast salt stocks are composed of ~92-99% halite and containing only minor anhydrite and sylvite (e.g. Lorenz et al., 1980; Kupfer, 1989, 1990). In contrast, many evaporite sequences are more heavily layered and compositionally heterogeneous, containing higher proportions of non-halite lithologies and termed layered evaporite sequences or ‘LES’, e.g. Zechstein Supergroup, Northwest Europe; Ariri Formation, Offshore Brazil; Ara Group, Oman; and the Kungurian salt of the Precaspian Basin, Kazakhstan, amongst others (e.g. Rowan et al., 2019) (*Fig. 6*). As salt begins to flow, stronger and weaker layers (if present) within the evaporite sequence can be deformed, entrained, and incorporated into salt diapirs (e.g. Escher and Kuenen, 1929; Talbot and Jackson, 1987; Koyi, 2001; Chemia et al., 2008; Van Gent et al., 2011; Rowan et al., 2019) (*Figs. 7 and 8*). An understanding of the mechanical properties and stratigraphy of the undeformed evaporite sequence is therefore critical before attempting to unravel the complex internal deformation within salt diapirs (*Fig. 8*).

There are a bewildering array of geometries inside salt diapirs – best exemplified by the mapped structures in the salt mines of Germany (e.g. Hofrichter, 1980; Richter-Bernburg, 1980; Mayrhofer, 1983; Schachl, 1987) (*Fig. 4a*). Thankfully, some fundamental principles of intra-diapir processes are well-understood, largely thanks to physical and numerical modeling studies (e.g. Escher and Kuenen, 1929; Talbot and Jackson, 1987; Koyi, 2001; Dooley et al., 2015), observations from well-exposed natural examples (e.g. Jackson et al., 1990; Burliga, 2014), and from 3-D seismic-based studies where intra-salt structure can be well-imaged (e.g. Van Gent et al., 2011; Fiduk and Rowan, 2012; Jackson et al., 2015). Escher and Kuenen (1929) demonstrated that, to the first order, any depositional heterogeneities (typically layering) inside diapirs can be broadly conformable with the salt-sediment interface, forming a high relief sheath anticline. This sheath and associated secondary folds develop in a manner akin to a horizontal tablecloth drawn upward through a horizontal napkin ring (e.g. Jackson and

Hudec, 2017; see also *Fig. 8*). Compositional layers become constricted as they enter the lower portion of the diapir, resulting in radial folds with upright axial traces that plunge steeply outwards, and as these structures rise in the narrow stock, they tighten and transition into more-or-less vertically plunging curtain folds (e.g. Stier, 1914; Richter-Bernburg, 1955; Talbot and Jackson, 1987; Jackson and Hudec, 2017) (*Fig. 7*). In nature however, this useful conceptual framework is complicated by the influence of: i) multiple generations of folds inside salt diapirs, some of which exist in the salt prior to entering the diapir, ii) progressive 3-D strain, and iii) vorticity and streams developed in the flowing salt (e.g. Talbot and Jackson, 1987; Jackson and Talbot, 1989; Talbot and Pohjola, 2009; Van Gent et al., 2011; Burliga, 2014; Fuchs et al., 2015; Jackson and Hudec, 2017). See section 8.3 in Jackson and Hudec (2017) for a review.

To shed light on, and ultimately *predict*, how any depositional heterogeneities deform and are distributed in salt diapirs, we should focus attention on the following research questions:

- Which evaporite sequences, or parts of evaporite sequences contain original and significant depositional heterogeneities, and which do not (e.g. Pichat, 2022)?
- How are different fold styles distributed inside salt diapirs (Richter-Bernburg, 1980; Jackson and Talbot, 1989; Callot et al., 2006; Van Gent et al., 2011; Burliga, 2014; Jackson et al., 2015)?
- How does the geometry and shape of a pillow or diapir influence the style and distribution of deformed depositional heterogeneities (Callot et al., 2006)? How does the mechanical stratigraphy (i.e. number, thickness, and

distribution of strong and weak layers) within the initial salt sequence influence the final distribution of deformed depositional heterogeneities (Koyi et al. 2001; Callot et al., 2006; Chemia et al., 2008; Dooley et al., 2015; Jackson et al., 2015; Rowan et al., 2019) (*Fig. 8*)?

- How do boundary conditions (e.g. sedimentation rates, erosion rates, and tectonic deformation), and location within the salt basin influence the style of deformation, and distribution of deformed depositional heterogeneities in salt diapirs (Chemia et al., 2008; Davison et al., 2017; Rowan et al., 2019)?
- How does late-stage tectonic shortening influence the structural style and distribution of depositional heterogeneities (Davison et al., 2017)?

Answering these types of questions will require access to good maps and digital datasets (e.g. LiDar and sonar) from salt mines and caverns, together with high-quality borehole-calibrated 3-D seismic data. Hypotheses derived from analyses of such datasets and placing them into a regional geological and salt tectonic context, should be tested in a new generation of physical and numerical models (e.g. *Fig 4b*). However, a combination of: i) the highly-contorted and sub-vertical nature of depositional heterogeneities (layering) inside diapirs; and ii) the fact that existing seismic surveys are not designed to image cap rock or the insides of salt diapirs but instead the stratigraphy surrounding the salt bodies for the purposes of oil and gas exploration, means that our capacity to visualise intra-salt deformation using conventional seismic methods is very limited. Advanced reprocessing techniques, such as reverse time migration have proven useful for imaging salt diapirs (in particular for a better delineation of the salt sediment interface)

(Thompson and Looff, 2021), however, these techniques are computational intensive, costly and time consuming. Ideally, new 3-D seismic surveys, both onshore and offshore, will be designed in the future with acquisition parameters to target shallow intra-salt features. Alternatively, vintage seismic could be revisited using unconventional reprocessing methods such as machine learning and artificial intelligence algorithms to try to improve intra-salt imaging but this is still an area where more fundamental research is needed. In addition, wider use of a fuller range of geophysical tools including but not limited to magnetotelluric, electromagnetic, borehole-based electrical resistivity tomography, radar and petrophysical tools such as triple-combo wireline logs and high-resolution image logs will likely play an important role in the characterization of intra-salt architectures (Thomson and Looff, 2021, 2022).

2.2.2.2 Non-depositional Heterogeneities

In this work, non-depositional heterogeneities comprise structures, inclusions, textures, and colours that are atypical of the salt mass, and that do not relate to the initial deposition of the salt sequence (e.g., modified from Kupfer, 1976, 1990; Looff et al., 2010a and b; Looff, 2017; Warren, 2017) (*Table 1; Fig. 9*). In broad terms, non-depositional heterogeneities are associated with lithologic impurities, shearing within the salt, fluid entry into the salt, or some combination of all (e.g. Looff et al., 2010a and b; Looff, 2017; Warren, 2017; Cyran, 2020). Furthermore, degradation of salt quality at or near non-depositional heterogeneities can allow fluids to leak into the diapir and is a major source of short- and long-term problems associated with man-made salt caverns (Warren, 2016, 2017). In general, non-depositional heterogeneities should be evaluated and avoided if deemed especially problematic during the solution mining or cavern storage operations.

Structures classified as non-depositional heterogeneities include joints, fractures, voids, faults, and shear zones (e.g. Kupfer, 1990). These form due to near surface strain and internal deformation of varying types in the diapir. Care must be taken to differentiate natural jointing, which is rare, and when present, continuous, from mining-induced joints, which are not classified as non-depositional heterogeneities and the locations are predictable (Kupfer, 1990)

Shear zones in particular have been recognized and interpreted inside salt diapirs, largely in US Gulf Coast diapirs (e.g. Balk, 1953; Muehlberger and Clabaugh, 1968; Kupfer 1974, 1976, 1990; Dooley et al., 2015; Jackson et al., 2015) (*Fig. 9*). It is widely accepted that some shear zones, termed external shear zones, form by differential salt movement near the edge of a diapir, and are expressed as a sheath of highly-strained salt along the diapir periphery (e.g. Balk, 1953; Kupfer, 1976;1990; Jackson et al., 1990; Looff, 2017) (*Fig. 9*). In contrast, the origin and distribution of shear zones located further into the body of a diapir are more controversial, as many heterogeneities previously termed 'shear zones' (*sensu* Kupfer, 1976) show no direct evidence of shear (Kupfer, 1990, 1998) but given that salt can be self-healing one must wonder if evidence of shearing might be elusive to find with time after deformation (*Fig. 9*). Interpretations of these features vary significantly, often depending on the salt basin being studied (e.g. U.S. Gulf Coast versus northwestern Europe), with schools of thought advocating that these "suspect intra-salt shear zones" represent; i) boundary shear zones (or internal shear zones), that form a network that bound salt 'spines' that move independently in an upward piston-like manner (e.g. Kupfer, 1976); ii) shear zones that occur around the edges of inclusions of any type within the diapir (Kupfer, 1990); iii) evidence of toroidal flow and folding within the diapir (Talbot and Jackson, 1987, 1989; Kupfer, 1990).

Inclusions classified as non-depositional heterogeneities can include: i) igneous rocks intruded into evaporite sequences and then subsequently incorporated into diapirs, or intruded directly into a pre-existing diapir (e.g. Schwerdtner and Clark, 1967; Davison et al., 2017; Martín-Martín et al., 2017; Magee et al., 2021); ii) rocks that were initially below, beside or above the diapir and which have been entrained into the diapir; and iii) any fluids and gases trapped during salt deposition, generated during burial, or which may have subsequently migrated into the diapir (Knauth et al., 1980; Jackson and Hudec, 2017).

Textures classified as non-depositional heterogeneities, include coarse-grained, extremely friable, extremely hard, and poikiloblastic salt (Kupfer, 1976; 1990; Looff, 2017; Warren, 2017). Notably, salt textures vary between different locations within salt diapirs (e.g. stem versus overhangs), so some spatial context is required when distinguishing ‘normal’ and ‘anomalous’ textures (e.g. Kupfer, 1990; Urai et al., 2008). A major source of the atypical textures is likely to be a result of dissolution and recrystallization of salt.

To deepen our understanding of the origin and distribution of non-depositional heterogeneities inside diapirs, we see a need for research addressing the following questions**:**

- How and why do shear zones form in salt diapirs and where might we expect them to occur (e.g. Kupfer, 1976; Rautman, 2010; Jackson et al., 2015; Looff, 2017; Duffy et al., 2022)?

- Do salt ‘spines’ exist as currently defined (Kupfer, 1976, 1989; Talbot and Jackson, 1987, 1989; Jackson and Hudec, 2017)?
- How and where do inclusions become incorporated into salt diapirs (e.g. Talbot and Jackson, 1987; Kupfer, 1989; Talbot and Jackson, 1989; Davison et al., 2017; Martín-Martín et al., 2017; Jackson and Hudec, 2017; Kernen, 2019)?
- How, why, where, and when do fluids enter salt diapirs (e.g. Knauth et al., 1980; Looff et al., 2010a and b; Looff, 2017; Warren, 2017)?
- How does late-stage tectonic deformation influence the nature and distribution of non-depositional heterogeneities (e.g. Davison et al., 2017)?
- Does the initial composition of the salt or tectonic setting influence the development and distribution of non-depositional heterogeneities?
- Can we reconcile differences in terminology used to describe non-depositional intra-salt heterogeneities, and interpretations of their origin, that differ between salt basins (e.g. US Gulf Coast versus northwestern Europe)?

Addressing these questions will require similar data and approaches as outlined in section *2.2.2.1*. However, in addition to study of borehole-calibrated seismic and other geophysical data, together with numerical and physical modelling to understand structural processes, we also envisage wider use of microstructural analysis to constrain the properties, deformation mechanisms, and likely recent boundary conditions experienced by diapiric salt (e.g. Urai et al.,1986; 2008; Carter et al., 1993; Looff, 2000; Mansouri et al., 2019; Cyran, 2021; Tămas et al., 2021). Furthermore, use of geochemical approaches applied to mine and well bore samples will help constrain the origin, composition, and potentially the age, of fluids and gases in salt domes, and how these relate to the distribution and nature of non-depositional heterogeneities (e.g. Knauth et al., 1980).

2.3. Salt Caverns: Research Outlook

Salt bodies have been used for several decades as repositories of a variety of fluids from hydrocarbons and hydrogen to waste disposal. Today, a pressing urgency associated with the need for rapid decarbonization of our energy systems clearly points to salt formations as a subsurface resource that will play an important role to develop a viable hydrogen economy. We can think of salt caverns storing hydrogen as subsurface mega-batteries that will play a crucial role as part of the new hydrogen ecosystem. The salt mining industry has accumulated decades of operational knowledge that coupled with modern salt tectonic concepts can help accelerate our capacity to predict intra-salt heterogeneities and better plan for the placing, design, construction and operation of salt caverns. Even though hydrogen storage is currently ongoing in some salt formations, research is still needed to fully understand the full complexity of salt body architecture and composition and their potential to interact with hydrogen.

3. Salt-Related CO_2 Storage in Salt Basins

3.1. Principles of CO_2 Storage and Relevance in Salt Basins

Anthropogenic CO_2 emissions are currently ~35 gigatons (Gt) per year (IPCC, 2021).

In order to limit climate change to 1.5°C, net emission needs to be reduced to zero (IPCC, 2022). While there is as yet no consensus on how this will be achieved, it is clear that it will require a combination of mitigation methods. Different analyses come up with different contributions from the various mitigation measures available, but commonly, they show about one third of the total reduction in CO_2 emissions coming from energy efficiency gains, another third from substituting non-carbon-emitting energy sources (e.g. wind and solar) for fossil energy sources, and the final third from everything else, including carbon capture and storage (CCS) (e.g. Pacala and Socolow, 2004; IPCC, 2014; International Energy Agency, Exploring Clean Energy Pathways, 2019) (*Fig. 2*). Without CCS, the possible paths to Net Zero shrink dramatically, the costs more than double and getting to Net Zero relies heavily on global behaviour change (IPCC, 2014). CCS is applicable across a broad spectrum of emissions sources, but it is most valuable where nothing else works well. Specifically, it can be used to mitigate the process emissions associated with production of cement, steel, petrochemicals, ethanol and hydrogen, among others. It can be applied to existing combustion-driven power plants to create low-carbon dispatchable power for those times when wind and solar sources are inadequate (e.g., calm nights). Added to Direct Air Capture or biofuel combustion, it can even remove existing atmospheric carbon (sometimes referred to as negative emissions). In short, CCS is the multi-tool of climate change mitigation—flexible, available immediately, proven and permanent.

At present, the global rate of CO_2 storage in CCS facilities is approximately 30 megatons (Mt) per year, i.e. about two orders of magnitude less than required for its projected role in climate change mitigation (Global CCS Institute, 2021). Estimates of total ultimate global storage capacity carry significant uncertainty but both global and regional assessments suggest that there is enough capacity for hundreds of years' worth of emissions (Halland et al., 2011; Bentham et al., 2014; IPCC, 2014; DOE NETL, 2015; Trevino and Meckel, 2017). The limitations are not technical or geological, but economic, regulatory and public acceptance.

At its most basic, CO_2 storage requires only a reservoir with sufficient injectivity and capacity to take the projected emissions stream, and a confining system capable of retaining the injected CO_2. Storage efficiency is maximised by storing CO_2 in a dense phase (either liquid or supercritical fluid), which requires a reservoir typically more than ~800m below the top of the water column (e.g. Ringrose, 2020) (e.g. *Fig. 10*). Similarly, the need for pressure space to accommodate injection suggests focusing on hydrostatic or under-pressured reservoirs (*Fig. 10*).

Unlike petroleum accumulating at equilibrium conditions on geologic time, CO_2 storage requires CO_2 injection at industrial rates. The result is that not all of the reservoir volume will be exploited (i.e. sweep efficiency is highly imperfect), pore water displacement is a concern, and pressure buildup tends to be the ultimate limit on injection (e.g. van der Meer and Yavuz, 2009; Ganjdanesh and Hosseini, 2018; Ringrose, 2020) (*Fig. 11*). The counterpoints are that: 1) injection volume is limited–unlike a good source rock that might generate sufficient petroleum to saturate all migration paths, injected CO_2 is unlikely to migrate far; and 2) the goal is sequestration and thus success does not require CO_2 to remain recoverable, concentrated or even mobile. Indeed, storage is most secure when the injected CO_2 is none of those. Dissolution, pore throat trapping, local capillary trapping and sub-economic buoyant traps along the CO_2 migration route are all viable storage, in addition to the large buoyant traps at the end of the migration path familiar to the petroleum industry (*Figs. 11 and 12*) (e.g. Nilsen et al., 2015; Sharma and

Van Gent, 2018; Singh et al., 2021; Ulfah et al., 2022). What is considered migration loss in petroleum is ultra-secure storage from the perspective of CO_2 storage. The same factors that hinder petroleum recovery serve to enhance storage security.

Deliberately seeking migration loss by injecting CO_2 downdip is a viable strategy that opens large volumes of the subsurface for CO_2 storage, not just the volumes within closure (e.g. Ulfah et al, 2022) (*Fig. 12*). Without restriction to buoyant traps, all of the storage window is potentially available for CO_2 injection and sequestration. That said, the details of the injection and confining intervals are critical to predicting the spread of the plume and de-risking containment. Ideally, injection would create a compact plume, offering cost-effective leasing and monitoring. Similarly, an ideal site would have low structural relief and a large aquifer connection, such that pressure would dissipate quickly post-injection and leave the CO_2 effectively immobile with minimal column height beneath a robust confining zone.

It is possible for some depleted oil and gas fields to be repurposed for CO_2 storage (e.g. Le Gallo et al., 2002; Agartan et al., 2018). However, suitable fields may not be available where storage is needed. Depleted fields have the advantage that the geological components of a CO_2 storage play (reservoir, trap, seal) are proven, subsurface control data already exist, and some existing infrastructure may be repurposable. However, existing wells within a depleted field constitute a potential risk to long-term storage, by leakage through faulty cement plugs to surface or to shallow aquifers. Depending on the number and condition of existing wells, the costs of review and remediation may far outweigh the advantages of historical reservoir performance data and potentially re-usable infrastructure.

Given this background, why are salt basins and salt tectonic research of value? The key here is that the economics of CO_2 storage are marginal, and most of the cost is in the capture and transport (Global CCS Institute, 2021). Minimising transport distance is highly desirable. Prime CO_2 storage sites must thus be close to major industrial CO_2 emissions areas, and where high quality data, infrastructure, proven reservoirs and seals (as constrained from prior hydrocarbon exploration activity), willing regulators, and public acceptance exist. Given these requirements, two of the most suitable basins for large scale CO_2 storage worldwide are the northwestern Gulf of Mexico and the North Sea, both of which are current focal points for CO_2 storage evaluation and development (e.g. Global CCS Institute, 2021). Critically, the geology of these settings is strongly influenced by salt - the Louann Salt in the US Gulf of Mexico, and the Zechstein Supergroup in the North Sea (*e.g. Fig. 10*). As petroleum geoscientists working these basins have already discovered, accurate predictions of reservoir architecture and potential seal risks depend on understanding the interactions of mobile salt with the depositional systems and subsequent structural deformation. This knowledge provides a sound basis which can now be applied to understand CO_2 storage sites in salt basins. As experience with CO_2 storage grows, other relationships may be discovered (e.g. Roelofse et al., 2019; Zhang et al., 2022) and as deployment grows and the CO_2 storage industry spreads (or transport costs fall), other salt basins may also become attractive storage targets.

A question relevant to the role of salt tectonics in CO_2 storage is: could CO_2 be stored widely in solution caverns at a large-scale as is proposed for H_2 storage? The simple answer here is no, for several reasons. First, the volumes of CO_2 that need to be sequestered to mitigate climate change are orders of magnitude greater than the total potential capacity in salt caverns (e.g. Bennaceur, 2014). Second, solution mining of caverns is expensive, especially compared to injection into naturally porous media such as a sandstone reservoir. Use of solution caverns is economically viable for energy gas storage (H_2 or CH_4) because the same cavern volume can be used repeatedly, and the cost of initial cavern creation is distributed across all the cycles of fulling and depletion, with new revenue generated by each cycle. In contrast, CO_2 is stored only once with no intention of future extraction, so all the development cost must be borne by one fill cycle, and there is no further revenue. Moreover, gas stored in salt remains entirely recoverable (or leakable, depending on perspective), an advantage for temporary storage and a liability for permanent sequestration. Third, the very factors that make salt caverns good for short-term gas storage, create unnecessary risks for long-term CO_2 sequestration. The ability of caverns to retain injected fluids in a mobile, highly pressured state means that they can be removed from the cavern rapidly and with very high recovery efficiency: this is ideal where storage is temporary and recovery is important, e.g. for energy gas (H_2 or CH_4). By contrast, it is potentially disastrous if the storage is meant to be permanent—in the event of containment breach, CO_2 stored in a cavern can leak rapidly and completely. Salt moves and on the millennial timescale required for CO_2 storage, that creates a serious liability. Overall, with possible exceptions where no other CO_2 storage options are available (e.g. AM da Costa et al., 2019; Goulart et al., 2020; PVM da Costa et al., 2020) it would seem preferable to reserve the caverns for short-term, limited volume gas storage (H_2, hydrocarbons etc) and focus CO_2 storage on the sediments between salt bodies.

3.2 Key Technical Challenges to CO_2 Storage in Porous Reservoirs in Salt Basins: Developing CO_2 Storage Plays

Fully exploiting the CO_2 storage potential in salt basins such as the Gulf of Mexico and North Sea will require a deeper understanding of the interactions between salt tectonics and CO_2 storage plays. There is a wealth of existing research on the influence salt has on the structural, stratigraphic and sedimentary evolution of basins. Many of the existing interpretation methods, data analyses, maps, and modelling approaches can be applied, adapted and developed further to meet the challenges associated with developing and monitoring CO_2 storage sites in salt basins. A key starting point will be to reframe the existing knowledge of how salt tectonics influences petroleum systems, and, where feasible, apply those to CO_2 storage systems. Play-Based Exploration is a widely used approach in the petroleum industry (e.g. Fraser, 2010; Hawie et al., 2016; Lockhart et al., 2018) and is now being adapted for CO_2 storage (Bump et al., 2021). We now present our view of the key technical challenges to be addressed within a play element framework as all petroleum play elements, with the exception of source rock quality, are applicable to CO_2 storage, providing proxies for injectivity, capacity, and containment potential (e.g. Bump et al., 2021).

3.2.1. Salt Tectonic Influence on Reservoir

CO_2 storage reservoirs must balance multiple requirements. On one hand, the need for injection at industrial rates favours thick, clean sands with well-connected pore space and large pressure compartments. On the other hand, CO_2 storage efficiency is closely related to sweep efficiency, and storage improves with the addition of reservoir heterogeneity, due to the development of microtraps along the migration pathway (e.g. Krishnamurthy et al., 2017; Trevisan et al., 2017). Reservoir heterogeneity, in the form of layered reservoir sequences with sharp permeability contrasts, can also contribute to confinement of CO_2 and displaced brines (Lindeberg, 1997; Oldenburg, 2008; Nordbotten et al., 2009; Sharma et al., 2017). Identifying prospective CO_2 storage reservoirs requires an understanding of reservoir deposition, which, in salt basins can be strongly controlled by salt tectonics (e.g. Hodgson et al., 1992; Rowan and Weimer, 1998; Winker and Booth, 2000; Mayall et al., 2010; Oluboyo et al., 2014; Doughty-Jones et al., 2017; Jackson et al., 2020; Howlett et al., 2021). Salt movement influences topography, the nature and distribution of depositional systems, and thus the distribution of facies and heterogeneities. Importantly, the distribution and quality of sands and depositional elements in different salt tectonic settings such as salt withdrawal synclines, isolated minibasins, expulsion rollovers, peripheral synclines around turtle structures, salt-detached ramp syncline basins, will vary throughout salt tectonic evolution and new research will be undertaken on the often complex relationship between sedimentary processes (sediment flux, deposition, erosion) and salt movement (uplift and subsidence patterns through time), with CO_2 storage in mind. In each salt tectonic setting, it will be important to constrain how the interactions have contributed to the reservoir architecture and heterogeneity, and thus the available pressure space for CO_2 (i.e. the connected reservoir volume available for dissipation of injection pressure). Research questions can be framed in the context of salt withdrawal synclines, a likely early focus for CO_2 storage, in part because they are located away from the more oil and gas prone structural highs (e.g. *Fig. 12*). A number of questions may be explored in such settings. First, how do depositional elements vary in salt-withdrawal synclines in different depositional environments, and how does salt movement influence this variability? As an example, shallow marine and deepwater systems respond differently to the presence of structural topography. A diapir crest in some shallow water settings may have very good, highly connected reservoirs across it, and between withdrawal synclines, as a result of wave action winnowing sediment over the elevated area. In deepwater however, where sand is carried in sediment gravity flows, those flows will travel preferentially in the topographic lows, leaving the salt diapir crest often devoid of sand.

Second, how can palaeo-topography be reconstructed in salt withdrawal basins? The evolution of palaeo-topography in a salt withdrawal basin is a function of the balance between subsidence and uplift and sediment flux to, and through, the basin (e.g. Prather et al., 2012; Christie et al, 2021). Successfully reconstructing palaeo-topography requires an understanding of where the salt has moved in three dimensions through time. In the case of minibasins, recent studies have shown how minibasins exhibit complex subsidence and rotation histories as a result of, amongst others: tectonic shortening, interactions with base-salt relief, translation down salt-detached slopes, and mechanical interactions with other minibasins (e.g. Fernandez et al., 2020; Jackson et al., 2020; Duffy et al. 2021). Such processes will have significant implications and thus should be constrained when reconstructing minibasin palaeo-topography. In general, reconstructing palaeo-topography is required to address exactly where reservoirs are deposited so as to: i) quantify and predict the larger connected pore volume in salt withdrawal synclines, so that pressure dissipation and injection capacity can be accurately predicted; and ii) predict permeability architecture in salt-withdrawal synclines, which impact migrations of CO_2 and displaced brines.

Third, where are stratal pinchouts located in salt withdrawal synclines? Where stratal dips are present, as in salt withdrawal synclines, significant CO_2 migration is possible, depending on the volume injected and the permeability architecture of the injection zone (e.g. *Fig. 12*). It may not be necessary to know the precise migration path, but it is important to assure that there will be no material impact (e.g., contamination of fresh water aquifers or producing hydrocarbon fields). Structural and stratigraphic traps up-dip of the injection point can be part of that assurance. Stratal pinchouts are common features in salt withdrawal settings, particularly in deepwater, and thus future work should aim to develop tectono-stratigraphic models that advance our understanding of their distribution in different salt withdrawal settings in space and through time, and hence predict their influence on CO_2 storage.

Overall, the focus of most recent literature on reservoir development in salt basins has been on deepwater clastic systems, driven by deepwater hydrocarbon exploration (e.g. Mayall et al., 2010; Giles and Rowan, 2012; Oluboyo et al., 2014; Cumberpatch et al., 2021). However, the economics of CO_2 storage favours short CO_2 transport distances, shifting the focus to present-day shallow water and onshore areas, where the reservoir targets for CO_2 storage may be shallow marine and continental rather than deep water deposits. Returning research attention to the influence of salt tectonic processes on reservoir development in these environments with the addition of modern seismic and well data, analysis and concepts, will yield new insight that may prove important for CO_2 storage. The same is true for carbonate reservoir systems, where the best reservoir permeabilities may developed over palaeo-highs, because of the original depositional setting (e.g. reefs) and post-depositional modification (eg. karst formation).

3.2.2. Influence of Salt Tectonics on Trap Formation, Migration Routes, and Seal Integrity

Salt tectonic processes generate complex structures with stratal dips that change rapidly through time and space, influencing migration routes and trap development. This salt-related structure can be a positive for CO_2 storage, mostly by helping to constrain the migration direction of the injected CO_2 and thus simplifying the monitoring process. However, there are also containment risks associated with these structures. For example in the deepwater Gulf of Mexico, where recent and Pleistocene deposition rates were extremely high (Galloway et al., 2011), shallow CO_2 storage traps associated with reservoirs in steeply-dipping strata that extend from shallow in the section down into the base of salt withdrawal basins require caution and should be carefully examined, if not avoided entirely (*Fig. 13*). In these shallow traps, a combination of tall column heights and overpressure caused by hydraulic connectivity to rapidly and deeply-buried sediments at the base of salt withdrawal synclines may mean the traps have already reached lithostatic pressures and failed, or be close to lithostatic pressures, and therefore likely fail with the addition of injected CO_2; a significant containment risk (*Fig. 13*).

In a similar line, halokinetic sequences (‘unconformity-bound packages of thinned and folded strata adjacent to passive diapirs’), as described in a range of depositional environments (Giles and Rowan, 2012; Hearon et al., 2014; Poprawski et al., 2016; Pichel and Jackson, 2020; Roca et al., 2021) may influence CO_2 migration routes and impact containment risk. These near diapir features are typically stacked into either tabular or tapered composite halokinetic sequences, with statal upturns that extend up the diapir flank, which are prone to fracturing, folding and faulting (e.g. Giles and Rowan, 2012; Hearon et al., 2014; Pichel and Jackson, 2020). Potential research questions related to these features include:

- Are halokinetic unconformity-bounded sequences and their associated deformation zones sites of potential leakage?
- Should CO_2 storage projects seek to avoid them, or can the risks be sufficiently mitigated to open that geology for CO_2 storage?
- Alternatively, can halokinetic sequences provide stacked stratigraphic trap opportunities?

In all cases, the devil is in the detail of salt movement in three dimensions and through time, and a structural-stratigraphic approach undertaken using cross-discipline techniques of seismic interpretation and detailed log interpretation should yield predictive models for trapping and seal integrity questions.

3.2.3. Influence of Faulting and Fracturing Around Salt Structures and Implications for Trapping and Seal Risk

In some cases, the presence of reusable infrastructure or other surface constraints will favour CO_2 storage near salt. In such cases, long-reach wells may be used to inject the CO_2 down-dip, well away from the salt body so as to reduce the immediate containment risk posed by steep dips and potentially tall columns, near-diapir faults, fractures, and wells. However, injected CO_2 is likely to migrate back towards the diapir and eventually towards these sources of potential containment risk (e.g. *Fig. 12*). Therefore, for CO_2 storage using near-salt infrastructure to be feasible fundamental work must focus on constraining near salt leakage risk. To mitigate that risk, work must focus on constraining: i) the character and pressure characteristics of the down-dip reservoir; ii) the geometry, nature, extent, and distribution of near-salt faults and fractures; iii) the likely seal potential of near-salt faults, fractures, and even the salt-sediment interface; and iv) the distribution of stress and pore pressure variations (e.g. steep dips) around salt bodies. This opens a number of possible research questions to be addressed:

- Is there a difference in the containment risk between different salt-related fault families such as crestal faults, keystone faults, radial faults etc, and regional tectonic faults (e.g. Zhang et al., 2022)?
- Do the growth styles and the displacement histories of different salt-related fault types influence containment risk?
- Where are fracture systems most likely to develop around salt bodies and how might this impact potential CO_2 storage?

Notably, seismic imaging beside and above salt bodies is often poor and may complicate the task, thus improvements in seismic imaging in near salt settings is required. Developing the required datasets will require significant interpretation expertise, use of structural analogues and physical modelling to fill the gap. In the meantime, CCS is likely to simply avoid such geology.

3.2.4. CO_2 Storage Play Types in Salt Basins

Ultimately, a goal will be to reimagine petroleum play concepts and develop a range of new CO_2 storage play concepts. We envisage a systematic analysis of how common CO_2 play risk elements in salt basins vary in different salt basins (e.g. simple vs layered evaporite sequences); and how the development of salt tectonic structures, including turtles, megaflaps, salt withdrawal minibasins, salt sheets, welds, sutures, faults, halokinetic sequences, etcetera, impact CO_2 migration, container size and integrity. Ultimately, updated and targeted structural-stratigraphic models of salt movement through time in different settings will allow us to quantify risk (*Figs. 12-14*).

An example of a salt-related CO_2 storage play concept is one developed for salt withdrawal syncline settings (Ulfah et al., 2022) (*Fig. 12*). In petroleum systems, conventional, producible accumulations are found in buoyant traps, often located on structural highs. Clearly those same traps could work for CO_2 storage, but the goal of sequestration opens the door to other trapping mechanisms (dissolution, pore throat trapping, and local capillary trapping) and potentially injecting into synclines, seeking high-injectivity sands at the well location and migration loss as CO_2 moves up-dip (e.g., Ulfah et al., 2022). Petroleum exploration has catalogued a wide variety of salt-related plays and offers a valuable analog for CO_2 storage. However CO_2 storage differs from petroleum production, with different goals, boundary conditions and timescale and therefore different requirements for success. The era of CO_2 storage is only just beginning and new play concepts are inevitable. As ever though, accurate geologic prediction in salt basins will require understanding the salt and its influence on depositional systems and structural styles.

4. Potential for Geothermal Energy in Salt Basins

4.1. Fundamental Principles in Geothermal Energy

Exploration for geothermal energy has traditionally focused at or near plate tectonic margins (e.g. California, Pacific Ring of Fire, Iceland), above intra-plate thermal hotspots (e.g. Hawaii), or in intra-continental settings (e.g. East African Rift) (Moeck, 2014; Daniilidis and Herber, 2017). These are high-enthalpy, convection-dominated geothermal systems where heat is efficiently transported upwards by circulating fluids that migrate along permeable pathways (Moeck, 2014). In contrast, less attention has focused on sedimentary basins located away from plate margins, where neither asthenospheric anomalies or significant crustal extension occur. In these low-to-medium enthalpy settings, geothermal plays are controlled by conductive processes (e.g. Moeck, 2014; Sheck-Wenderoth et al, 2014; Daniilidis and Herber, 2017; Raymond et al., 2022).

The high costs associated with drilling and completion (e.g. Barbier, 2002; Johnston et al., 2011; Beckers et al., 2014) have proven a barrier to the exploitation of conduction-dominated geothermal energy. The low-to-medium enthalpy nature means deeper drilling is typically required to economically exploit resources than in tectonically-active systems. However, the social-political demand for renewable energy, plus technological advancements in three key areas has stimulated interest in exploiting geothermal resources from low-to-medium enthalpy settings (e.g. Tester et al, 2007; Moeck, 2014). First, advancements in drilling technology such as directional drilling, and a general trend towards more efficient drilling processes may reduce the costs associated with drilling significant distances. Second, Enhanced or Engineered Geothermal Systems (EGS) have been developed whereby fluid injection and hydraulic fracturing is used to increase the porosity and permeability of reservoirs, thus higher flow rates and greater thermal productivity from reservoirs. Third, Advanced Geothermal Systems (AGS) have been engineered with closed or semi-closed loop systems containing a working fluid (water, possibly supercritical CO_2) that is heated solely by conduction through the pipe (e.g. Holmes et al., 2021). AGS has the advantage of not requiring a porous and permeable reservoir near the heat source (e.g. Holmes et al., 2021). In addition, many of the sedimentary basins contain abundant subsurface data, knowledge, and existing infrastructure due to oil and gas activities (e.g., Gulf Coast, USA;, Zechstein-influenced portion of Northwest Europe). Utilising low-to-medium enthalpy geothermal systems can be used to electrify rigs, thereby, immediately reducing carbon footprint at wellsites as well as increase the asset life of the marginal fields.

Of particular interest here is that potential may exist where stratigraphic intervals with high thermal conductivity, such as salt, locally enhance heat flow at shallower depths, thereby reducing required drilling depths (e.g. Daniilidis and Herber, 2017) (*Figs 15 and 16*). Salt has a higher thermal conductivity (>6 W m^{-1} K^{-1} at 20℃; Lorenz et al., 1980) than the surrounding sediments (2-3 W m^{-1} K^{-1} at 20℃; Clauser, 2011), meaning heat is preferentially channeled through the salt, raising temperatures above the salt, and lowering them immediately below the salt, with implications for both geothermal resources and maturation of hydrocarbons (e.g. Selig and Wallick, 1966; O'Brien and Lerche, 1984; Kumar, 1989; Nagihara et al., 1992; Mello et al., 1995; Peterson and Lerche, 1995; Norden and Förster, 2006; Daniilidis and Herber, 2017) (*Figs 15 and 16*). Borehole-based measurements and predictions from numerical models have determined positive temperature anomalies at the top of salt structures that range between 15-35°C (e.g. Selig and Wallick, 1966; Geertsma, 1971; Vizgirda et al, 1985; Daniilidis and Herber, 2017). Importantly, the majority of this research was either focused largely on maturation of petroleum systems (e.g. Mello et al, 1995; Lerche and Petersen, 2017) or was conducted in the 1970's and 1980's when technological limitations meant low-to-medium enthalpy geothermal systems were not economically viable. In light of new technologies, recent attention has focused on the role of salt in the geothermal prospectivity of sedimentary basins, with temperatures >150°C suitable for conventional brine production-based geothermal exploration (e.g. Tester et al., 2007; Daniilidis and Herber, 2017; Raymond et al., 2022). Recent advances indicate the use of CO_2 as a working fluid or secondary fluid for geothermal heat production either in the subsurface or the heat exchange system on the surface can lower the required temperature down to 100°C or less, which can make such systems much more economically feasible in the long-term (e.g. Biagi et al., 2015). In terms of usage, geothermal plays above crests of shallow salt structures may be of sufficient temperatures for use in district heating networks (e.g. Norden and Förster, 2006; Noack et al., 2010; Daniilidis and Herber, 2017; Raymond et al., 2022). In contrast, deeper portions of salt basins (>3 km) may have higher temperatures and, particularly if stimulated by EGS, productivity rates sufficient for power production (e.g. Tester et al., 2007; Moeck. 2014).

4.2. Role of Salt Tectonics in Optimising Geothermal Energy in Salt Basins

Exploiting the geothermal potential in salt basins will require integration of salt tectonic understanding with geothermal modelling to constrain which parts of which salt basins are sweet spots for geothermal energy, and why. In our view, the key technical challenges regarding geothermal prospectivity in salt basins involve deepening our understanding of how and why heat flow distribution is influenced by: i) the 3D geometry of salt bodies and their salt tectonic context; ii) the potential for non-uniform transmission of heat through salt bodies; and iii) interaction of fluids with faults, fractures and permeable beds around salt bodies. We now identify our perspective on the key challenges to be addressed relating to each of these aspects in turn.

Many numerical geothermal models developed to examine the impact of salt on the distribution of heat in the subsurface often simplify salt bodies such that they are: i) abstract (i.e. removed from salt tectonic context); ii) composed purely of halite; iii) 2-D or have simple cylindrical shapes, and iv) have thermal conductivities that do not change with depth (e.g. O'Brien and Lerche, 1984; Mello et al., 1995; Cedeño et al., 2019) (e.g. Fig. 16). Studies with these simplifications provide a strong body of evidence, backed up by observations from natural salt basins, that temperatures generally increase above salt structures (e.g. Selig and Wallick, 1966; Geertsma, 1971; Vizgirda et al, 1985; Kumar, 1989; Mello et al., 1995; Peterson and Lerche, 1996; Daniilidis and Herber, 2017; Lerche and Petersen, 2017) (*Figs 15 and 16*). However, if we are to efficiently screen for the most prospective geothermal energy sites, we see the need to compare different salt basins and explore how a range of 3D salt geometries and salt tectonic scenarios as well as salt composition influence containment of heat and temperature distributions. For example:

- Are there differences in the geothermal energy potential around different styles of stocks, walls, and sheets (e.g. Mello et al., 1995; Peterson and Lerche, 1996; Lerche and Petersen, 2017)?
- Are diapirs that are directly sourced from mother salt more prospective than diapirs sourced from allochthonous sheets, if so why?
- How important is the depth to the source salt layer on temperature distributions?
- How and why do different types of welds influence temperature distributions?
- To what extent does the configuration, connectivity, and spacing of salt bodies influence temperature distributions (e.g. Cedeño et al., 2019)? Of interest here is the potential for surface-breaking diapirs to quickly leak heat out of a system, and the potential for mutual interference effects between salt structures within an array (e.g. Mello et al., 1995; Cedeño et al., 2019).

Kumar (1989) presents temperature distribution maps at different depths above Louisiana salt domes showing remarkably complex thermal patterns, typically superimposed on a general trend of increasing temperature towards the diapir (*Fig. 17*). These maps raise two fundamental questions: i) what is causing these complex second-order temperature anomalies above and around salt structures (see also Kumar, 1977)?; and ii) are these second-order temperature anomalies seen in different salt basins and above different types of salt structure?

A first hypothesis is that the second-order thermal anomalies are related to features and processes from outside of the diapirs. This line of enquiry opens up a further series of research questions.

- How does the presence, geometry, and distribution of permeable beds in the sediments vary around salt diapirs and how does this influence temperature distributions?
- How and why do overpressure and local hydrological processes vary around salt structures and how does this influence temperature distributions?
- How do different fault and fracture networks, that develop above and adjacent to salt for various reasons at different stages of salt rise and possible fall (e.g. radial faults, crestal faults, and faults related to regional tectonics), influence fluid flow and the distribution of heat around salt structures (e.g. Kumar, 1977; 1989; Lueck et al., 2022)?

Addressing the latter of these questions, along with developing a deep understanding of what can be notoriously complex in-situ stress fields around salt bodies (e.g. Fredrich et al., 2003; Dusseault et al., 2004; Luo et al., 2012; Nikolinakou et al., 2012) will be critical if EGS technology (hydraulic stimulation) is to be safely applied to geothermal reservoir sediments near salt structures. Understanding of fault and fracture origins and distributions, and in-situ stress fields will help estimate the potential for fault reactivation and minimise induced seismicity if we implement brine-based geothermal (Moeck et al., 2009; Moeck and Backers, 2011; Moeck, 2012; 2014).

A second hypothesis is that the patterns are the result of non-uniform transmission of heat through salt bodies. Entertaining this hypothesis opens up a range of research questions. For example, could the composition of the salt and the distribution of compositional variations in salt bodies significantly influence how heat is transmitted through salt (e.g. halite-dominated compositionally-homogeneous salt versus compositionally-heterogeneous salt)? Key to this question is the finding different evaporite minerals have different thermal conductivities at ambient conditions, with halite (5.80 W m^{-1} K^{-1} (±0.10)), anhydrite (5.39 W m^{-1} K^{-1} (±0.13)), and dolomite (4.92 W m^{-1} K^{-1} (±0.11)) having significantly higher thermal conductivities than gypsum (1.64 W m^{-1} K^{-1} (±0.24) (Pauselli et al., 2021) (*Fig. 15b*). Do the internal dynamics of salt flow or the presence of different types of heterogeneities within diapirs influence temperature distributions? Could fast-moving streams of salt identified in certain parts of domes (e.g. Dooley et al., 2009; Fernandez et al., 2020) influence temperature distributions? Intriguingly, Kumar (1989) noted a correlation between the spatial distribution of temperature anomalies above a salt diapir and the inferred location of salt ‘spines’ at the Jefferson Island salt dome. We believe this correlation merits further investigation, both at that location and in other salt bodies worldwide.

Addressing many of the questions outlined in this section will require a range of approaches and application of existing knowledge and concepts derived from hydrocarbon exploration and production. First, detailed mapping of the 3-D geometry of natural salt structures as well as the geometry and distribution of associated faults is needed. This work will require analysis of a range of subsurface data types (seismic, borehole geophysics, gravity, resistivity, electromagnetic). The resulting maps, when tied to regional geology and evaporite stratigraphy, will enhance understanding of the internal composition and kinematics of the salt structures, which may then be related to temperature distributions constrained from borehole bottom hole temperatures or heat flow measurements. Second, geomechanical modelling, coupled with detailed structural maps, will be required to predict the likely distribution and nature of faults, fractures, and in-situ stresses around salt bodies, and to reduce the risk of induced seismicity during well completion. Third, the derived maps and observations can then be integrated into numerical geothermal models to determine the degree of impact on temperature distributions. Allied to these approaches, there is need for fundamental research examining the thermal conductivities of different evaporite minerals under in situ conditions and ascertaining implications for geothermal exploration (e.g. Peterson and Lerche, 1996; Yang et al., 2020; Raymond et al., 2022).

5. Summary and Conclusions

We have outlined the importance of salt tectonics to a range of energy transition technologies and have highlighted some of the key technical challenges to their successful development at scale in salt basins. Any salt basin may potentially offer a combination of: i) storage sites inside the salt (e.g. hydrogen and compressed air in salt caverns); ii) storage sites in the porous media surrounding the salt (CO_2 storage, storage of waste brines); and iii) natural resources in the salt and surrounding sediments (geothermal energy, oil and gas, lithium potential) that are also likely to be required for exploitation, to varying degrees, throughout the energy transition (*Fig. 18*). These occur at a range of depths, with storage caverns between 400-2000 m, CO_2 storage between

~800 m and the top of overpressure, and hydrocarbons and geothermal resources at a range of depths (*Fig. 18*). Effectively exploiting these resources will require a deeper understanding of the composition, geometry, and evolution of salt structures and their surrounding sediments, as well as placing the areas of interest into basinal context (*Fig. 18*). We see potential for problem solving by reframing and applying knowledge and data gained from many decades of petroleum exploration and mining in salt basins to energy transition issues.

When seeking to exploit the natural resources in salt basins and deploy energy transition technologies it is essential to consider the following core points. First, each salt basin is unique, they will vary according to factors including the tectonic boundary conditions, and the nature and thickness of the original evaporite stratigraphy. Second, salt diapirs are not simply cylindrical masses of homogeneous halite. In nature, diapirs are highly heterogeneous bodies that exhibit a wide range of internal compositions, geometries, behaviours (e.g. *Fig. 18*). Likewise, the stratal geometries observed in the sediments that surround salt diapirs are also highly variable (e.g. *Fig. 22*). Ultimately, each salt basin and each salt structure will have its own risk profile for the deployment of the different energy transition technologies based on its geological character. Salt tectonic understanding will help optimise design, reduce geotechnical risk, and improve efficiency for energy transition technologies.

Importantly, more than one energy transition technology may be viable for exploitation at a given salt diapir or within a salt basin, and thus there may be competition for resources (*Fig. 18*). It is important that subsurface and at-surface resources are utilised sustainably (e.g. Griffioen et al., 2014). As such, determining which resource is preferentially exploited in a given setting will require careful consideration of social, economic, and environmental implications at a range of scales (e.g. Griffioen et al., 2014). In addition, where multiple technologies exploit resources in close proximity to one another, there are also likely to be synergies between the industries that should be explored (e.g. sharing data, infrastructure and knowledge).

Overall, we emphasise that this overview is by no means an all-encompassing view. We hope this work will elicit conversation and insights from those with different perspectives on salt-related themes, particularly: geomechanics, rheology, microstructure, geochemistry, bedded salt geology, nuclear waste disposal, and the use of solution mining brines in lithium extraction processes (see also Kukla et al., 2019). Much research remains to be done.

6. Acknowledgements

We would like to thank the State of Texas Advanced Resource Recovery (STARR) at the Bureau of Economic Geology for funding this work. We thank Naiara Fernandez, Christopher A-L Jackson, Juan Soto, and Kurt Looff for constructive discussions, along with Nancy Cottington for figure drafting.

7. Figure Captions

Figure 1: Salt structures and their influence on petroleum system elements (Hudec and Jackson, 2017).

Figure 2: Projections of global emissions to 2050 and the projected role of varying technologies in reducing global emissions from Stated Policies Scenario down to Sustainable Development Scenario (National Petroleum Council Report, 2019; data from International Energy Agency, World Energy Outlook, 2019).

Figure 3: a) Examples of the solution mining process that creates salt caverns and influence on cavern geometry: (i) a broadly cylindrical cavern tends to develop when direct brine circulation is used. Low salinity water is injected through the tubing string deep into the cavern and brine is withdrawn through the annular space between the final casing and the tubing string; and (ii) a wide-topped cavern develops if reverse circulation is used. Low salinity water enters the cavity through the annulus near the cavern top and brine is withdrawn through the tubing string. in both direct and reverse circulation, a fluid blanket protects the cavern roof. b) Schematic (not to scale) sketches showing geotechnically favourable and less favourable settings for solution cavern development (after Gillhaus, 2010; Warren, 2016). Not to scale.

Figure 4: Cross-sections through natural salt diapirs showing heterogeneous nature. a) range of lithologies and flamelike folds in a German salt diapir (after Richter-Bernburg, 1970; Hofrichter, 1980; Jackson and Hudec, 2017). b) (i) Section through a time-migrated seismic cross-section across Liam diapir in the Santos Basin showing marked variations of seismic reflectivity within the salt sequence, the development of complex folding and flaps, and the intrusion of older salts into younger salt as a sheet. (ii) Physical model showing similar relationships as in (i) (Dooley et al., 2015).

Figure 5: Reasons why understanding origin and distribution of shear zones in salt diapirs is important. a) impacts of complex salt flow and shearing during drilling (modified from Looff et al., 2010a); b) preferential placement of salt caverns away from shear zones and intra-salt complexity

in the Benthe salt dome, Germany (Gillhaus and Horvath, 2008; original work by Richter-Bernburg, 1972); c) examples showing preferred planes of dissolution and anomalous cavern geometries in caverns on Barbers Hill salt dome, US Gulf Coast (from Looff, 2017 original images from Cartwright and Ratigan, 2005; Ratigan, 2009).

Figure 6: Simplified representative examples of stratigraphic columns from Layered Evaporite Sequences (LES's) worldwide: (a) Ariri Fm., offshore Santos Basin, Brazil (adapted from Gamboa et al., 2008); (b) Ara Gp., onshore Oman (adapted from Peters et al., 2003); (c) Zechstein Gp. from the Dutch portion of the Southern Permian Basin (adapted from Van Adrichem Boogaert and Kouwe, 1994); (d) Kungurian salt from the central region of the Precaspian Basin, Kazakhstan (adapted from Gralla and Marsky, 2000); (e) Messinian evaporites from the Levant Basin, eastern Mediterranean (adapted from Feng et al., 2016, and Alexandros Konstantinou, personal communication with authors of source article, 2019) (a) and (e) are constrained from wells, whereas the others are more schematic; ages spans and interval thicknesses are not equivalent in the different examples. Labels on the sides of panels (b), (c), and (e) refer to well-established intra-salt intervals defined in the literature. From Rowan et al. (2019) with only colours modified.

Figure 7: Salt flow (black arrows) and 3-D stresses (white arrows) associated with the evolution of a salt pillow containing a competent intrasalt unit (yellow). As salt flows into the pillow there is radial extension (boudinage) beneath the depocentres and radial contraction (folds) in the pillow core. In addition, tangential constrictional folding develops due to convergent flow into the pillow. From Rowan et al (2019) with only colours modified. Original sketch by Frank J. Peel.

Figure 8: Cross section through a physical model showing the deformation that occurs as minibasins sink into a 'Layered Evaporite Sequence'. The initial 'Layered Evaporite Sequence' is shown (top right) with halite equivalent in pink and interbedded sand equivalents shown as dark

blue, red, grey, and light blue. Minibasins simply subsided into the horizontally-bedded ‘Layered Evaporite Sequence’ resulting in intense deformation and folding as the layers within the sequence are incorporated into the diapir.

Figure 9: Structural map of the Belle Island Salt Mine. Shows two masses of salt separated by what were interpreted as boundary shear zones that are now incorporated in the salt. Regions of atypical ‘dark’ salt are associated with gas bursts, slabbing mine roof, leakage and relative instability. Note the internal complexity and heterogeneous nature of the salt (after Kupfer, 1974; Warren, 2017).

Figure 10: Geology of the northern Gulf of Mexico shown in line of section (location of section shown on inset map. The band of saturated colour is the pressure window within which supercritical CO2 can be stored. This interval is between ~800 m below top of the water table/sea surface (the minimum depth for supercritical CO2) and the top of geologic over-pressure as defined by Burke et al., 2012 (Figure modified from Bump et al., 2021).

Figure 11: Schematic diagram showing the distribution of CO_2 near an injection well and CO_2 trapping mechanisms. Low-permeability units prevent the upward migration of the supercritical CO_2 plume (*stratigraphic trapping*). *Residual trapping* occurs as some CO_2 is left behind as disconnected droplets at the trailing edge of the plume. As CO2 interacts with pore waters, some of it will dissolve (*solubility trapping*) and over longer timescales (e.g. 1000s of years) CO_2 may also react with the host rock, and precipitate as solid carbonate minerals (*mineral trapping*). Note that *structural trapping* can also occur as in oil and gas traps. The difference in this diagram is that structural trapping is intended as a backstop to retain any CO_2 that is not arrested in migration. Vertical exaggeration x50 (Bourg et al. 2015 - colours modified).

Figure 12: Example of salt-influenced CO_2 storage play concept in salt withdrawal synclines that may have high suitability for containment. CO_2 is injected at high rates into porous sands deposited near the syncline axis. In concept, connection to a large aquifer allows dissipation of injection pressure and therefore enables long-term injection. CO_2 migrates laterally (green plume), driven by injection pressure and buoyancy. As it migrates, CO_2 is arrested by capillary trapping, dissolution and baffling associated with any stratigraphic heterogeneities. The process is similar to migration loss in hydrocarbons and may be sufficient to arrest the entire plume, depending on injected volumes and stratigraphic architecture (see Ulfah et. al 2022).

Figure 13: Example of a salt-influenced CO_2 storage play concept that may pose a containment risk. Steeply-dipping strata on the right flank of the diapir is likely to be structurally and stratigraphically complicated and may be overpressured as a result of the connection to deeper aquifers (centroid effect). Low effective stress would make it not viable for injection and geologic complexity would render it unattractive to an operation that can choose where to inject.

Figure 14: Example of a salt-influenced CO_2 storage play concept that may pose a containment risk. Sands encased in shales within a turtle anticline geometry may be highly prospective for oil and gas, yet for CO_2 storage the pressurised sands may restrict CO_2 injection into the crest, and there may be difficulty in accessing pore space down-dip of the anticline crest.

Figure 15: a) Effect (schematic) of a 1-km-thick salt body in a shale interval on the geothermal gradient. The presence of the salt layer cools rocks below the salt and elevates the temperatures of rocks overlying the salt (modified and approximated after Mello et al. 1995). b) Thermal conductivity of rock salt compared to other lithologies (after Warren, 2016; 2017).

Figure 16: Effect of salt bodies of varying geometries on steady-stage temperature distributions. Salt bodies are encased in shale and have axisymmetric geometry. a) shows an example with no salt present. Temperatures above salt are typically elevated, temperatures below salt are depressed, and temperatures adjacent to salt are dependent on salt geometry (Mello et al., 1995).

Figure 17: Isotherm maps showing temperature distributions above Louisiana (US Gulf Coast) salt diapirs. Temperatures shown are in degrees Fahrenheit. Dashed lines indicate contours of the depth of the top salt surface (in ft). a) temperature distribution at the 10,000 ft level at the Plum Bob salt dome. b) temperature distribution at the 10,000 ft level at the Jefferson Island salt dome. c) temperature distribution at the 10,000 ft level at the Bayou des Allemands salt dome. In general temperatures increase over the diapirs. However, there is significant second-order variability in temperatures, the origins of which remain unclear and merit further research (Kumar, 1989 - colours modified).

Figure 18: Conceptual model illustrating the role of salt tectonics on the effective deployment of a range of energy transition technologies (energy storage in salt caverns, CO_2 storage, geothermal energy, oil and gas exploration). Note the influence of a wide range of salt diapir geometries and intra-salt heterogeneities. Diapir A is upward flaring and contains a boudinaged interval; Diapir B shows a salt sheet or wing developed and a complex configuration of 'slippery' and soluble bittern salts; Diapir C is a wide and faulted diapir with contorted anhydrite; Diapir D shows a teardrop geometry and is composed of relatively homogeneous halite; and Diapir E is deep-seated. The geometries and statal relationships in sediments surrounding the diapirs also vary significantly due to salt tectonic processes. Ultimately, each salt basin and each salt diapir is unique and understanding of salt tectonic processes is required to successfully deploy energy transition technologies.

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<table>
<tr><th>Depositional Heterogeneities</th><th colspan="3">Non-depositional Heterogeneities</th></tr>
<tr><th>Depositional Heterogeneities</th><th>Post-depositional Compositional Changes</th><th>Post depositional Physical Alteration</th><th>Anthropogenic Heterogeneities</th></tr>
<tr>
<td>Evaporite intervals
• evaporative carbonate
• gypsum/anhydrite
• halite
• bittern salts

Non-evaporite intervals
• sand
• shale
• biogenic carbonate

Syn-depositional igneous:
• lavas
• ashes</td>
<td>Inclusions:
• igneous intrusions
• entrained country rock (sutures, stoped sub-salt blocks, encased minibasins)

Chemical alteration:
• solution residue (e.g. caprocks)
• products of other chemical reactions (e.g. sulphate reduction by hydrocarbons)

Natural fluids:
• brines
• hydrocarbons</td>
<td>Deformation:
• faults
• shear zones
• fractures
• joints

Recrystallization (poikiloblastic? - course grains, friable)

Mylonitization (smaller grains)</td>
<td>Excavations and mines

Boreholes

Existing solution caverns

In-situ waste and storage:
• chemical waste
• radioactive waste
• munitions
• preserved valuable objects

Migrated anthropogenic fluids:
• brines
• hydrocarbons
• dissolved hazardous waste</td>
</tr>
</table>

Table 1: Classification of heterogeneities within salt bodies that may present challenges to engineering in salt.

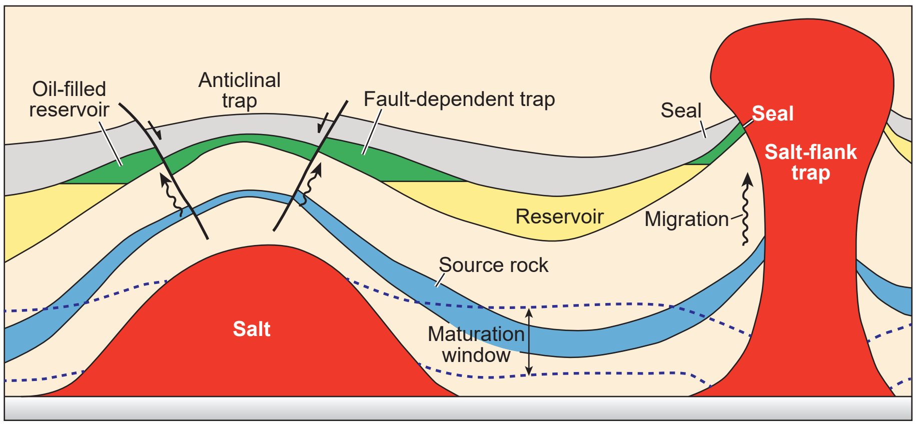


Figure 1: Petroleum system elements around salt structures (Hudec and Jackson, 2017)

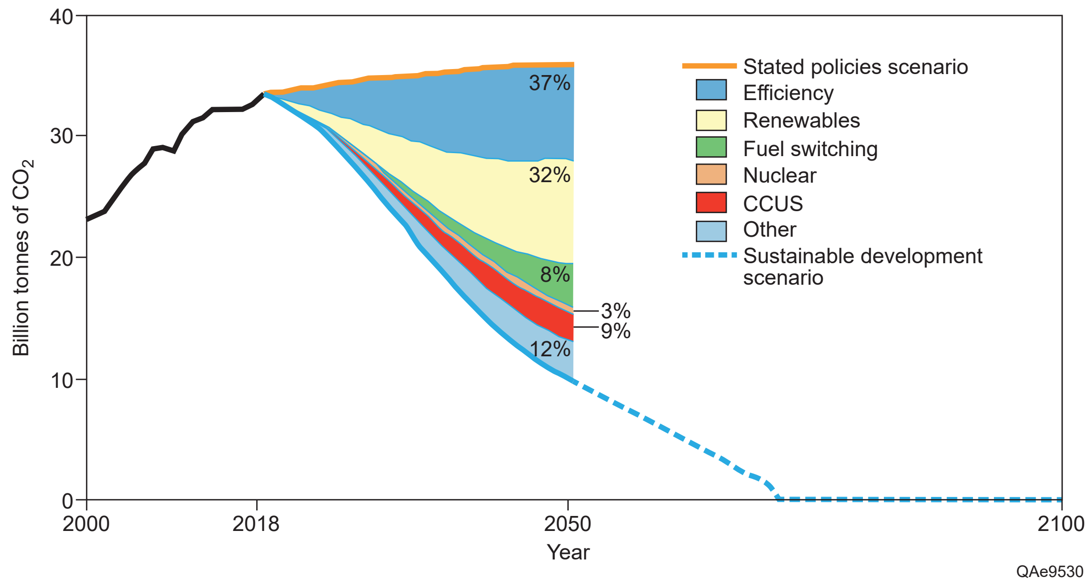


Figure 2: Projections of global emissions to 2050 and the projected role of varying technologies in reducing global emissions from Stated Policies Scenario down to Sustainable Development Scenario (National Petroleum Council Report, 2019; data from International Energy Agency, World Energy Outlook, 2019).

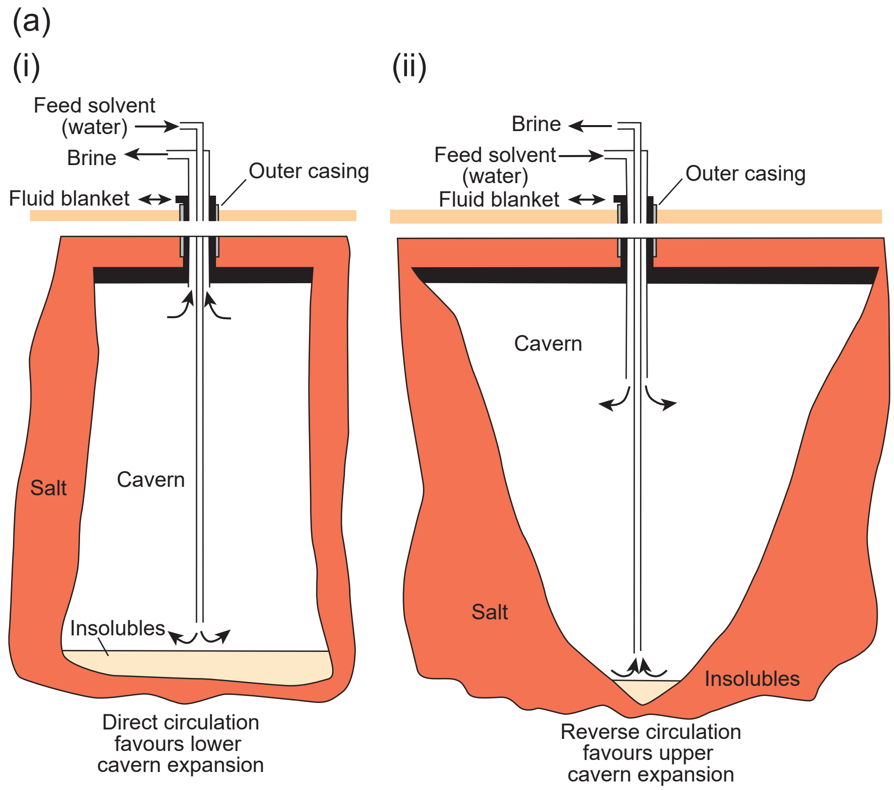


Figure 3: a) Examples of the solution mining process that creates salt caverns and influence on cavern geometry: (i) a broadly cylindrical cavern tends to develop when direct brine circulation i s used. Low salinity water is injected through the tubing string deep into the cavern and brine is withdrawn through the annular space between the final casing and the tubing string; and (ii) a wide-topped cavern develops if reverse circulation is used. Low salinity water enters the cavity t hrough the annulus near the cavern top and brine is withdrawn through the tubing string. in both direct and reverse circulation, a fluid blanket protects the cavern roof. b) Schematic (not to scale) s ketches showing geotechnically favourable and less favourable settings for solution cavern development (after Gillhaus, 2010; Warren, 2016). Figure is not to scale.

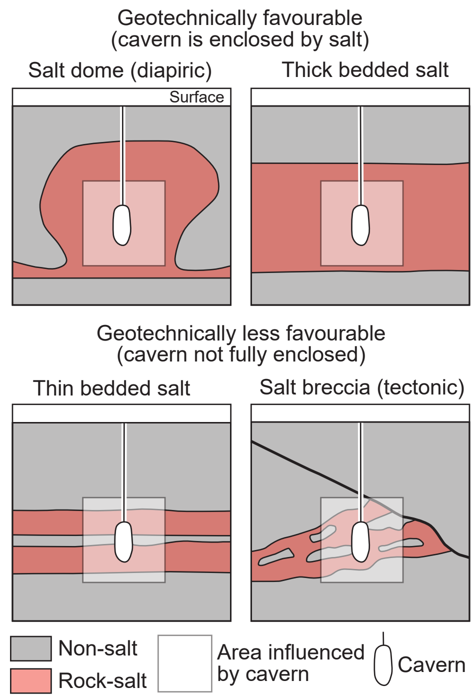


Figure 3 b) Schematic (not to scale) sketches showing geotechnically favourable and less favourable settings for solution cavern development (after Gillhaus, 2010; Warren, 2016). Figure is not to scale.

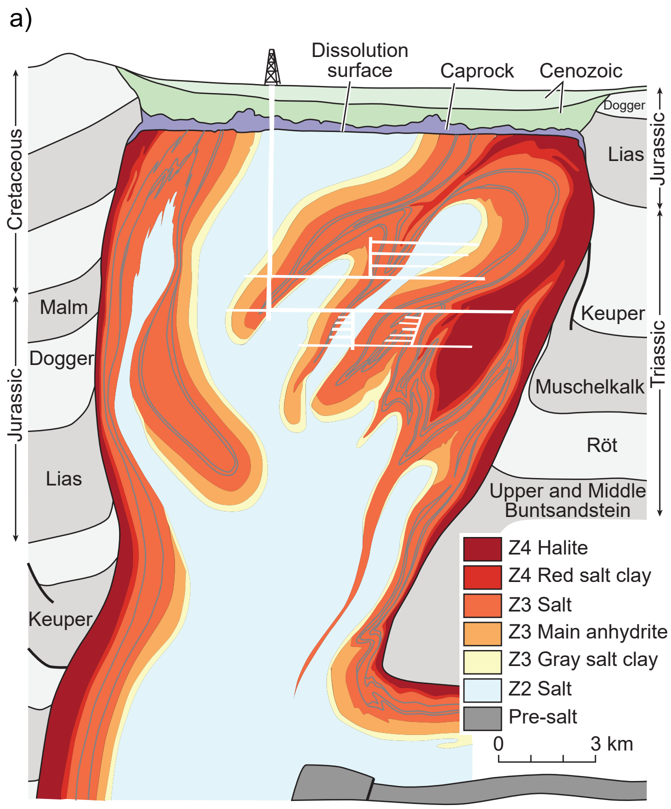


Figure 4: Cross-sections through natural salt diapirs showing heterogeneous nature. a) range of lithologies and flamelike folds in a German salt diapir (after Richter-Bernburg, 1970; Hofrichter, 1980; Jackson and Hudec, 2017).

b)

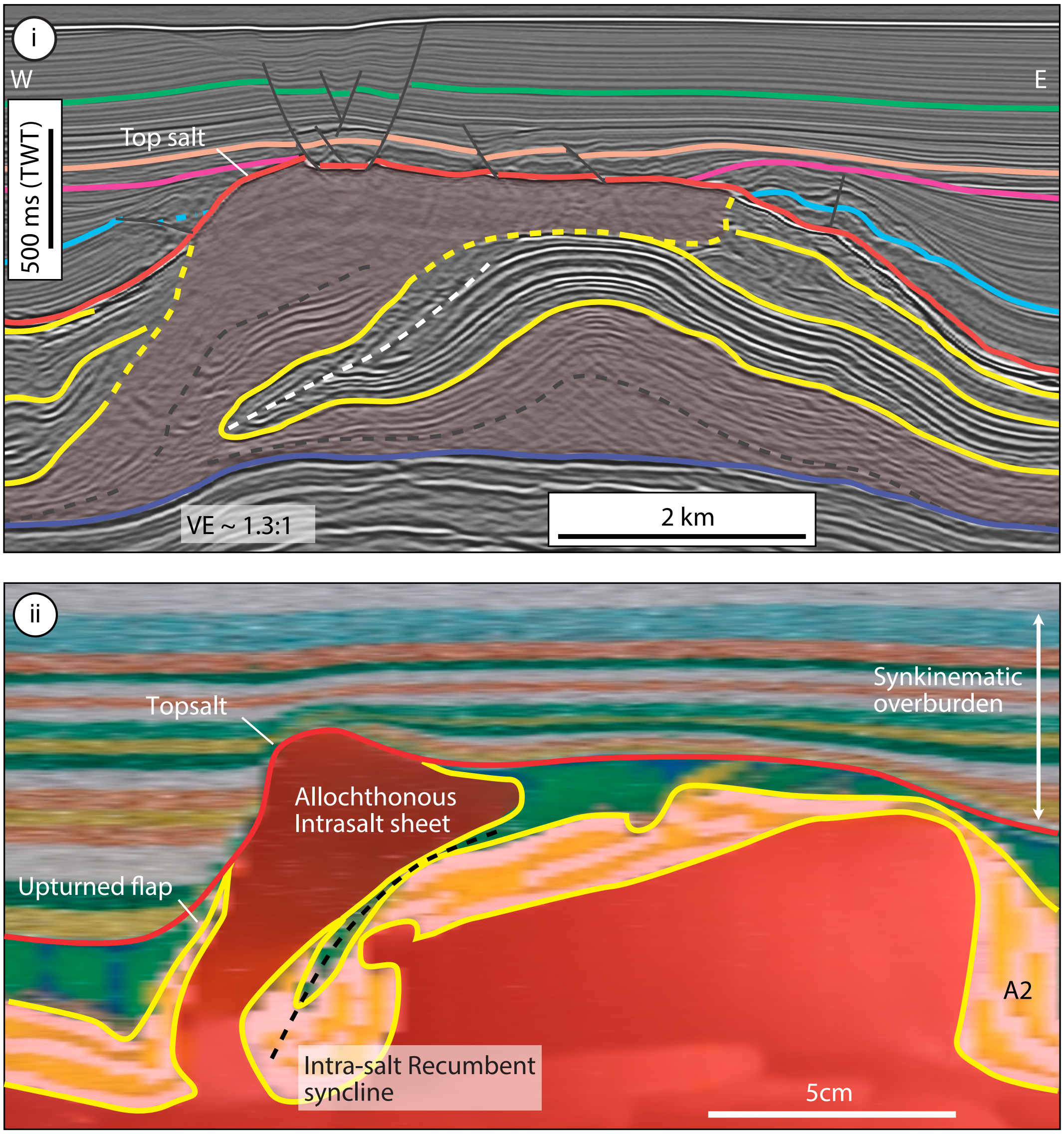


Figure 4: (b) i) Section through a time-migrated seismic cross-section across Liam diapir in the Santos Basin showing marked variations of seismic reflectivity within the salt sequence, the development of complex folding and flaps, and the intrusion of older salts into younger salt as a sheet. ii) Physical model showing similar relationships (both Dooley et al., 2015)

a)

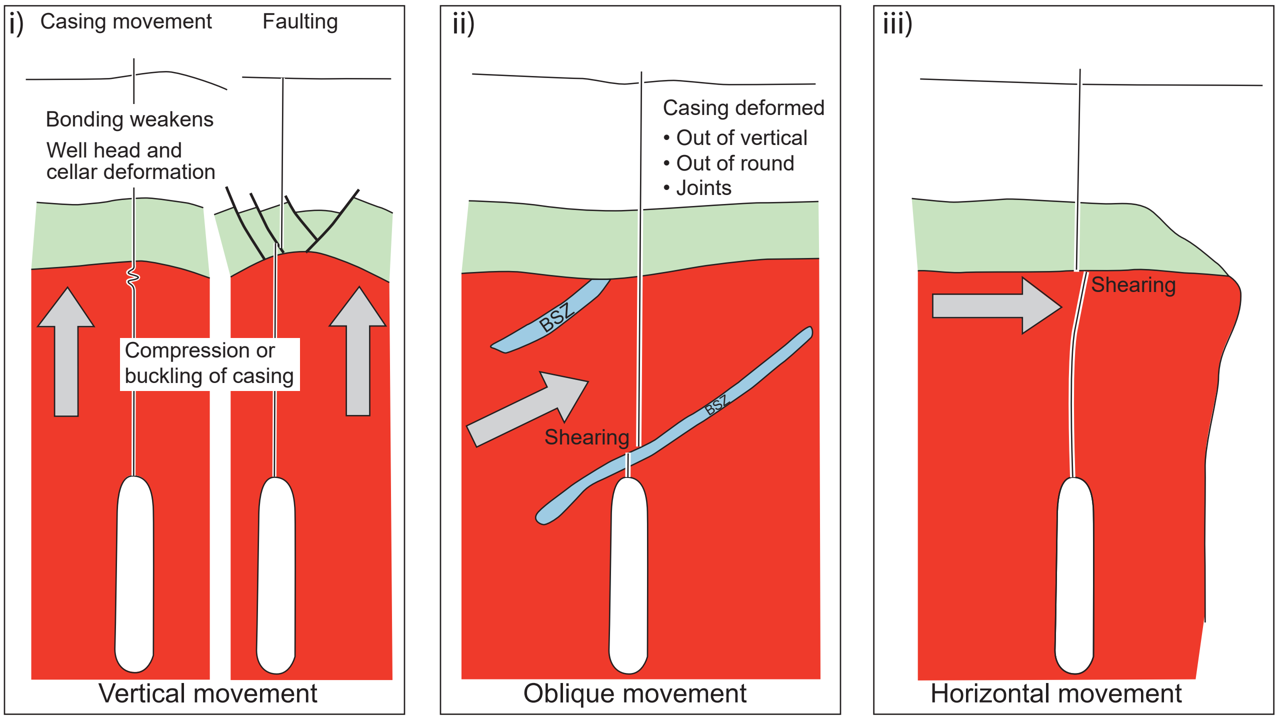


Figure 5: Reasons why understanding origin and distribution of shear zones in salt diapirs is important. a) impacts of complex salt flow and shearing during drilling (Looff et al., 2010b);

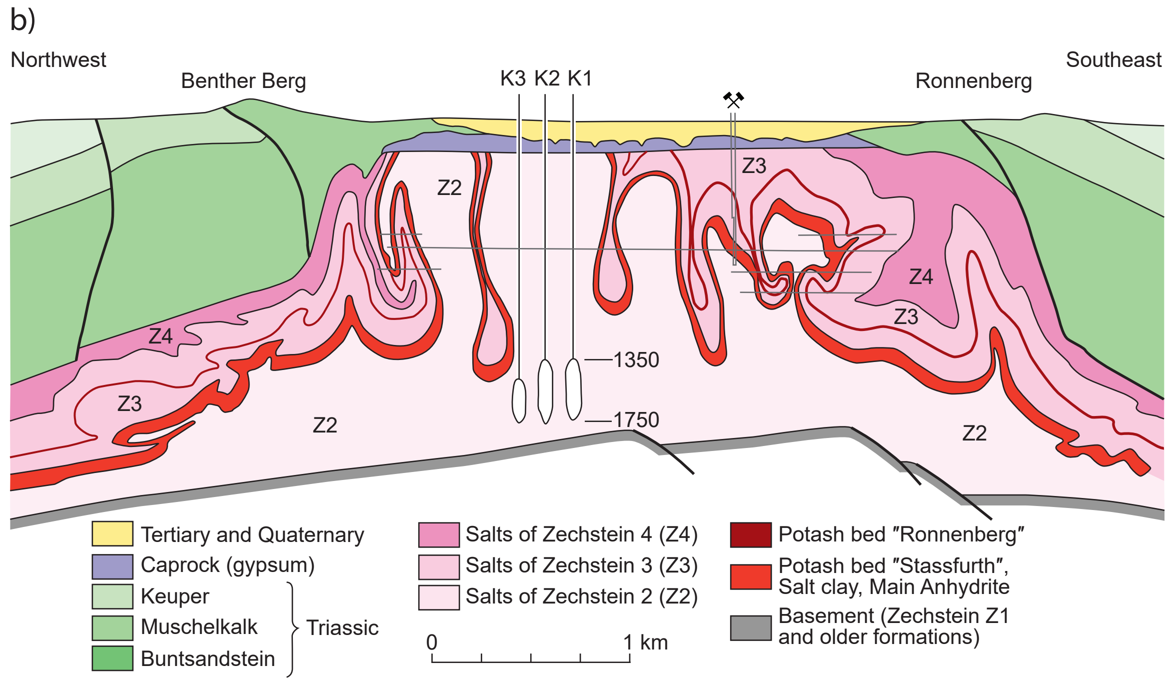


Figure 5: Reasons why understanding origin and distribution of shear zones in salt diapirs is important. b) preferential placement of salt caverns away from shear zones and intra-salt complexity in the Benthe salt dome, Germany (Gillhaus and Horvath, 2008; original work by Richter-Bernburg, 1972);

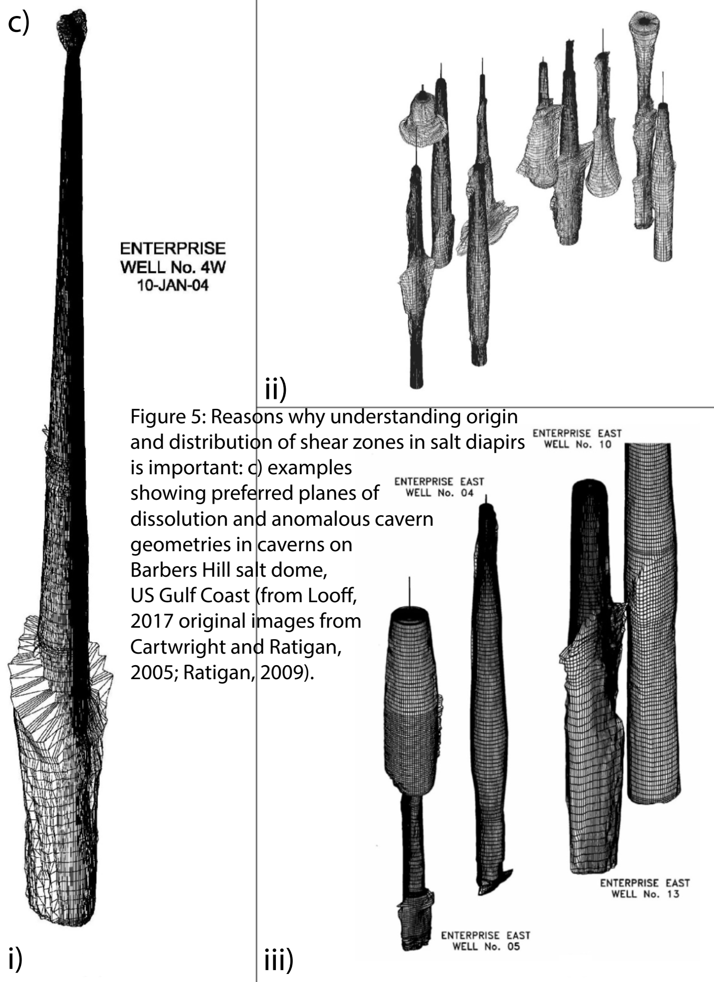


Figure 5: Reasons why understanding origin and distribution of shear zones in salt diapirs is important: c) examples showing preferred planes of dissolution and anomalous cavern geometries in caverns on Barbers Hill salt dome, US Gulf Coast (from Looff, 2017 original images from Cartwright and Ratigan, 2005; Ratigan, 2009).

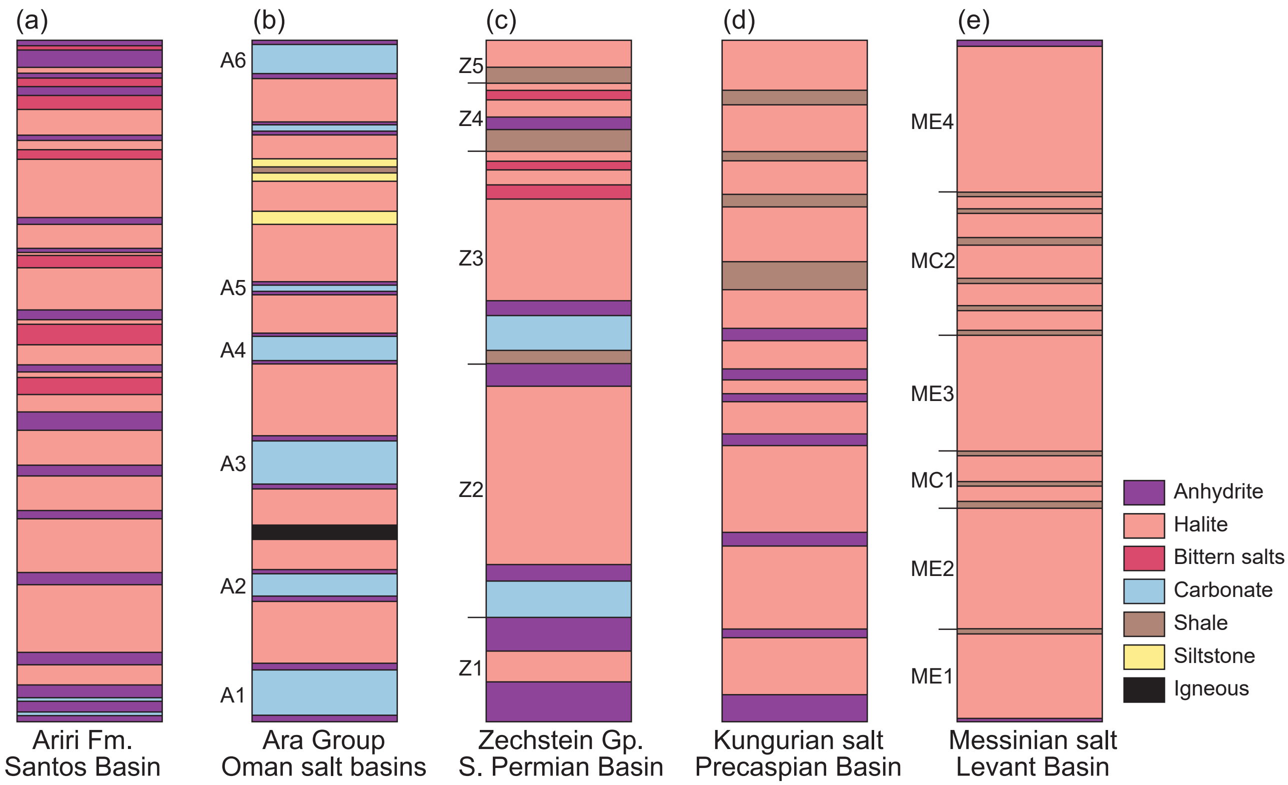


Figure 6: Simplified representative examples of stratigraphic columns from Layered Evaporite Sequences (LES's) worldwide: (a) Ariri Fm., offshore Santos Basin, Brazil (adapted from Gamboa et al., 2008); (b) Ara Gp., onshore Oman (adapted from Peters et al., 2003); (c) Zechstein Gp. from the Dutch portion of the Southern Permian Basin (adapted from Van Adrichem Boogaert and Kouwe, 1994); (d) Kungurian salt from the central region of the Precaspian Basin, Kazakhstan (adapted from Gralla and Marsky, 2000); (e) Messinian evaporites from the Levant Basin, eastern Mediterranean (adapted from Feng et al., 2016, and Alexandros Konstantinou, personal communication, 2019) (a) and (e) are constrained from wells, whereas the others are more schematic; ages spans and interval thicknesses are not equivalent in the different examples. Labels on the sides of panels (b), (c), and (e) refer to well-established intra-salt intervals defined in the literature. From Rowan et al. (2019) with only colours modified.

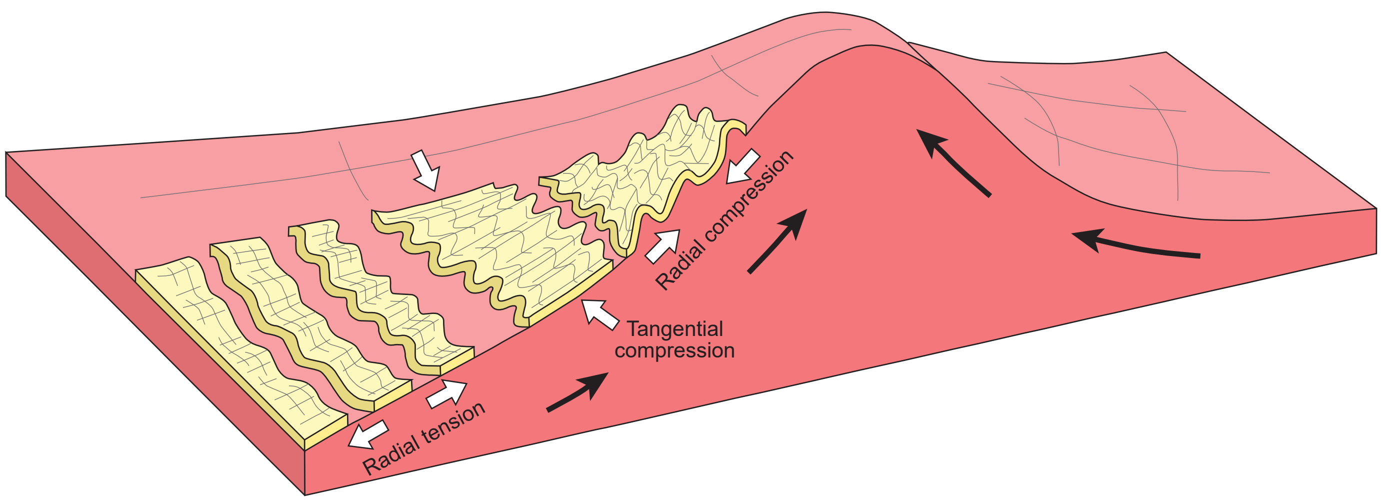


Figure 7: Salt flow (black arrows) and 3-D stresses (white arrows) associated with the evolution of a salt pillow containing a competent intrasalt unit (yellow). As salt flows into the pillow there is radial extension (boudinage) beneath the depocentres and radial contraction (folds) in the pillow core. In addition, tangential constrictional folding develops due to convergent flow into the pillow. From Rowan et al (2019) with only colours modified. Original sketch by Frank J. Peel.

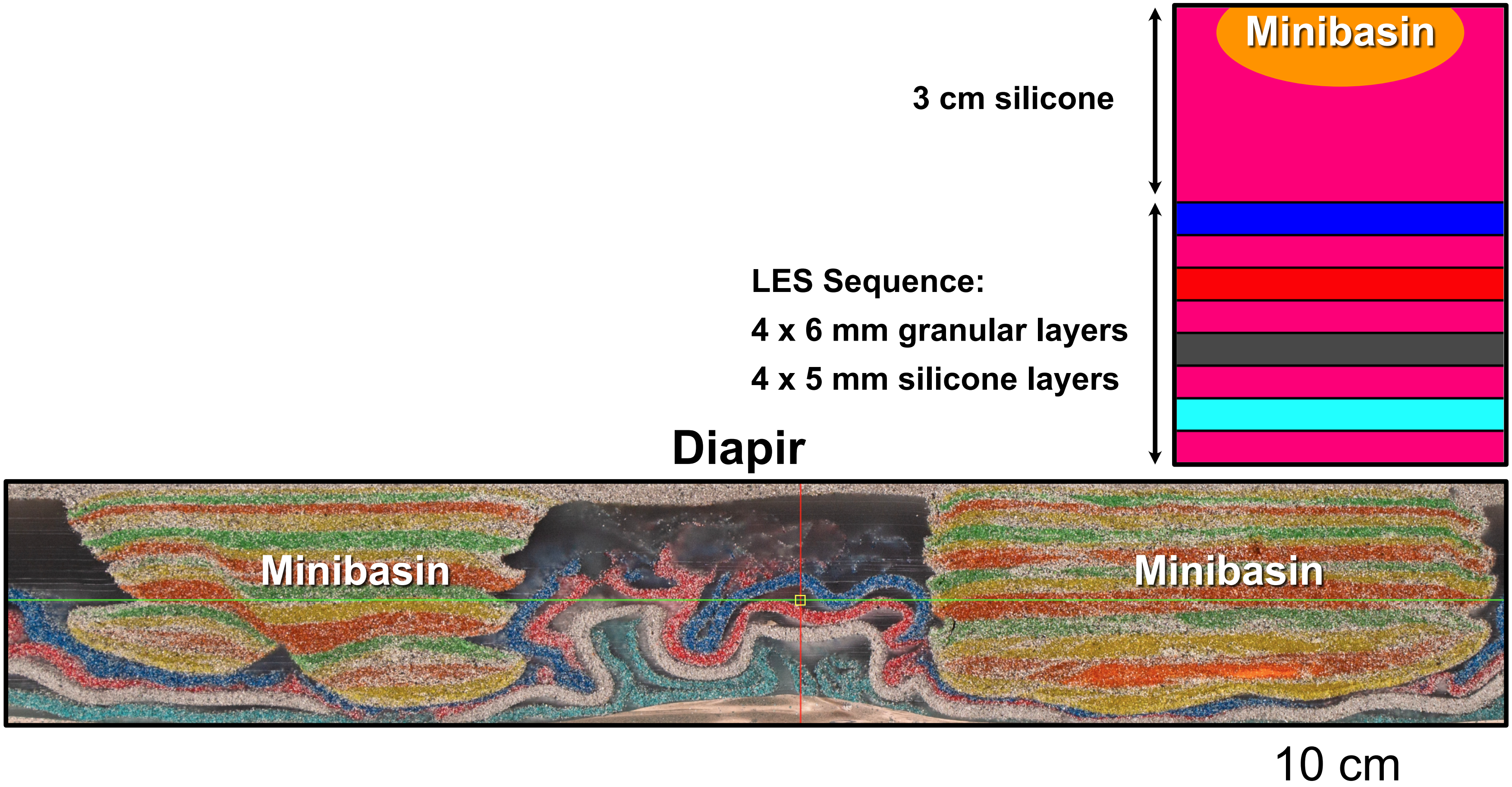


Figure 8: Cross section through a physical model showing the deformation that occurs as minibasins sink into a 'Layered Evaporite Sequence'. The initial 'Layered Evaporite Sequence' is shown (top right) with halite equivalent in pink and interbedded sand equivalents shown as dark blue, red, grey, and light blue. Minibasins simply subsided into the horizontally-bedded 'Layered Evaporite Sequence' resulting in intense deformation and folding as the layers within the sequence are incorporated into the diapir.

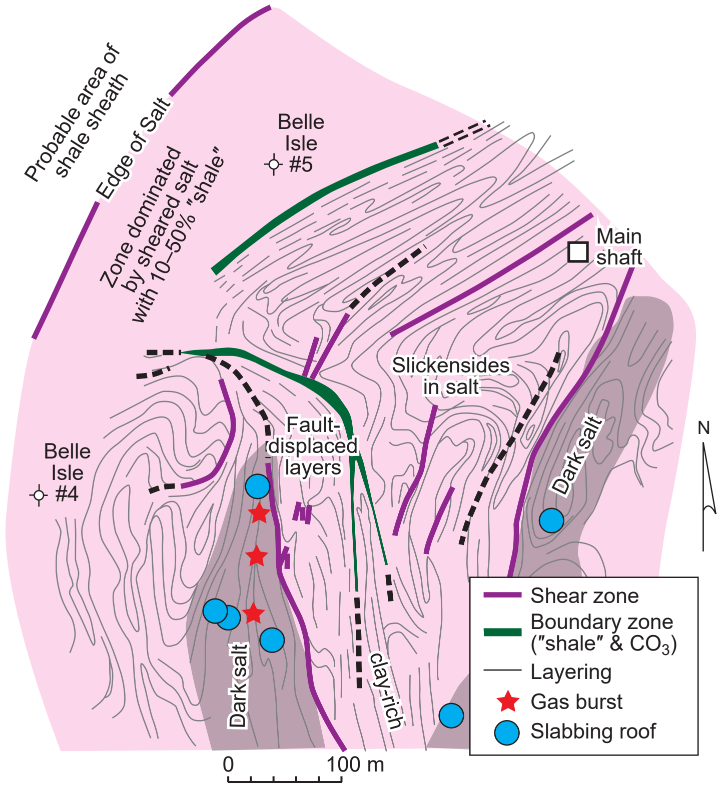


Figure 9: Structural map of the Belle Island Salt Mine. Shows two masses of salt separated by what were interpreted as boundary shear zones (green) that are now incorporated in the salt. Regions of atypical 'dark' salt are associated with gas bursts, slabbing mine roof, leakage and relative instability. Note the internal complexity and heterogeneous nature of the salt (after Kupfer, 1974; Warren, 2017).

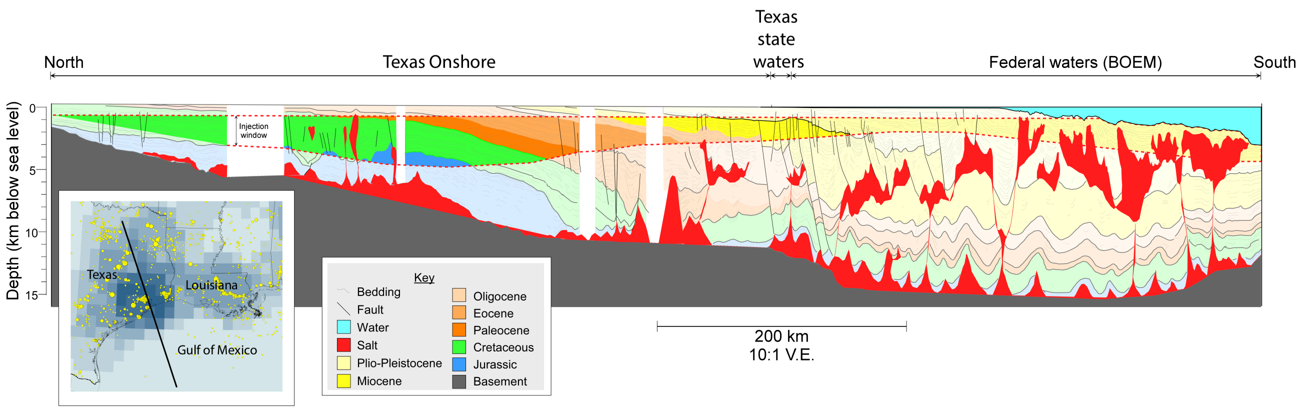


Figure 10: Geology of the northern Gulf of Mexico shown in line of section (location of section shown on inset map). The band of saturated colour is the pressure window within which supercritical CO2 can be stored. This interval is between ~800 m depth and the top of geologic over-pressure as defined by Burke et al., 2012 (Figure modified from Bump et al., 2021).

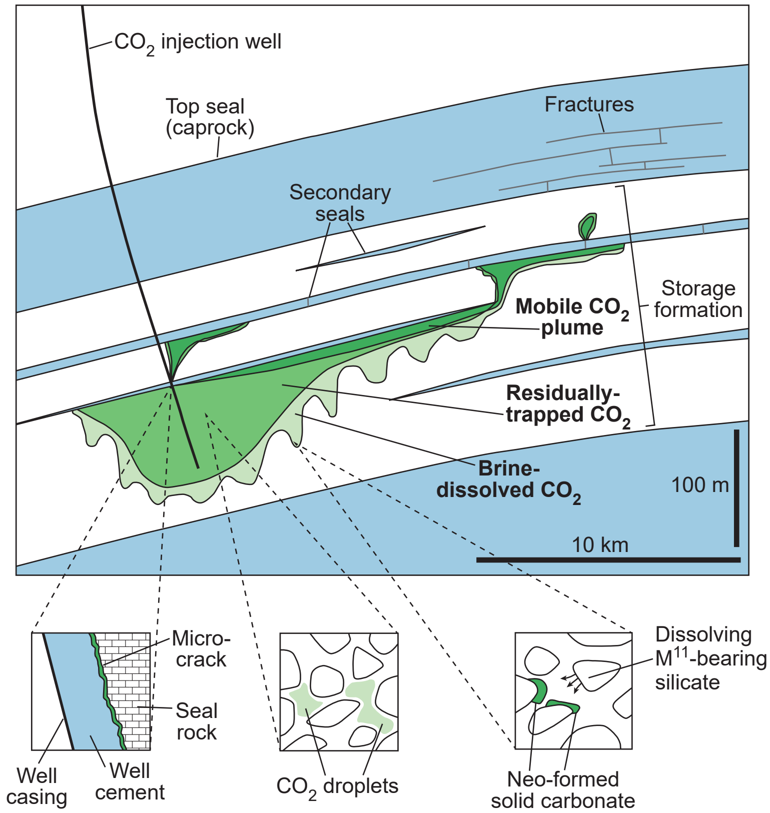


Figure 11: Schematic diagram showing the distribution of CO2 near an injection well and CO2 trapping mechanisms. Low-permeability units prevent the upward migration of the supercritical CO2 plume (stratigraphic trapping). Residual trapping occurs as some CO2 is left behind as disconnected droplets at the trailing edge of the plume. As CO2 interacts with pore waters, some of it will dissolve (solubility trapping) and over longer timescales (e.g. 1000s of years) CO2 may also react with the host rock, and precipitate as solid carbonate minerals (mineral trapping). Note that structural trapping can also occur as in oil and gas traps. The difference in this diagram is that structural trapping is intended as a backstop to retain any CO2 that is not arrested in migration. Vertical exaggeration x50 (Bourg et al. 2015 - colours modified)

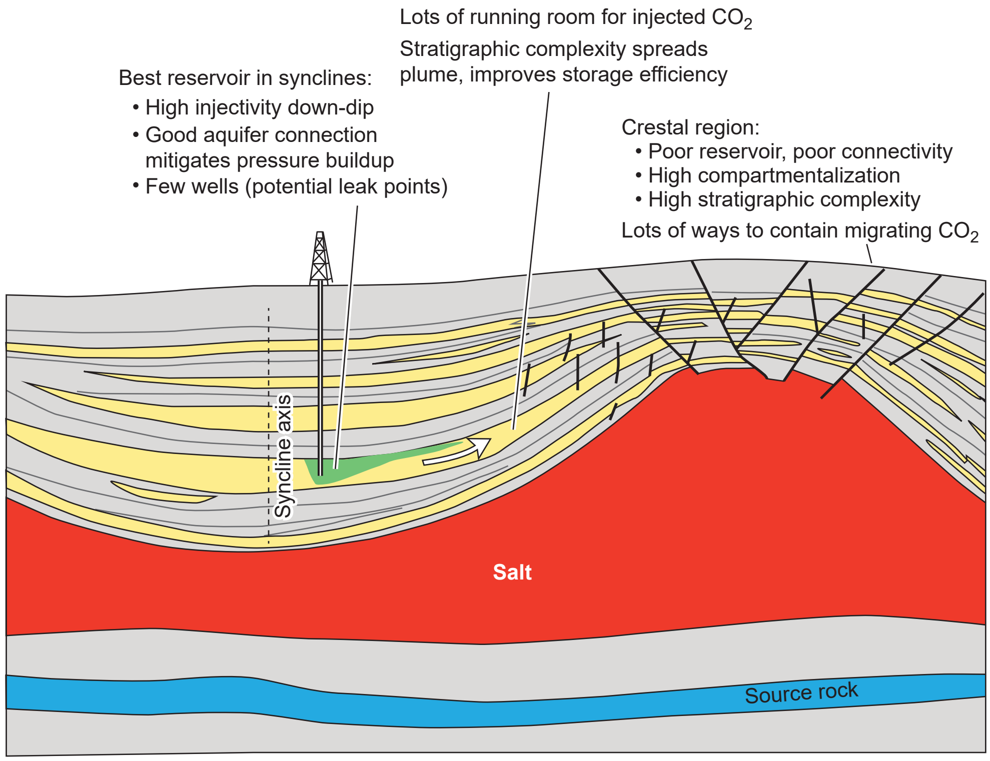


Figure 12: Example of salt-influenced CO2 storage play concept in salt withdrawal synclines that may have high suitability for containment. CO2 is injected at high rates into porous sands deposited near (not at) the syncline axis. In concept, connection to a large aquifer allows dissipation of injection pressure and therefore enables long-term injection. CO2 migrates laterally (green plume), driven by injection pressure and buoyancy. As it migrates, CO2 is arrested by capillary trapping, dissolution and baffling associated with any stratigraphic heterogeneities. The process is similar to migration loss in hydrocarbons and may be sufficient to arrest the entire plume, depending on injected volumes and stratigraphic architecture (see Ulfah et. al 2022).

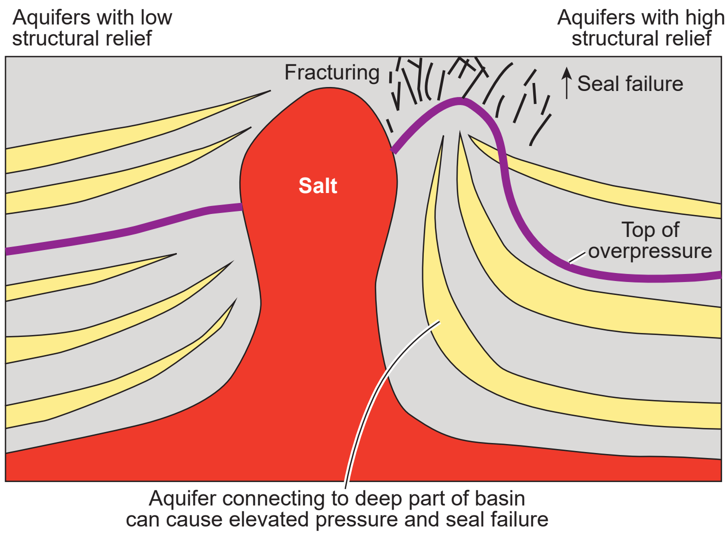


Fig. 13: Example of a salt-influenced CO2 storage play concept that may pose a containment risk. Steeply-dipping strata on the right flank of the diapir is likely to be structurally and stratigraphically complicated and may be overpressured as a result of the connection to deeper aquifers (centroid effect). Low effective stress would make it not viable for injection and geologic complexity would render it unattractive to an operation that can choose where to inject.

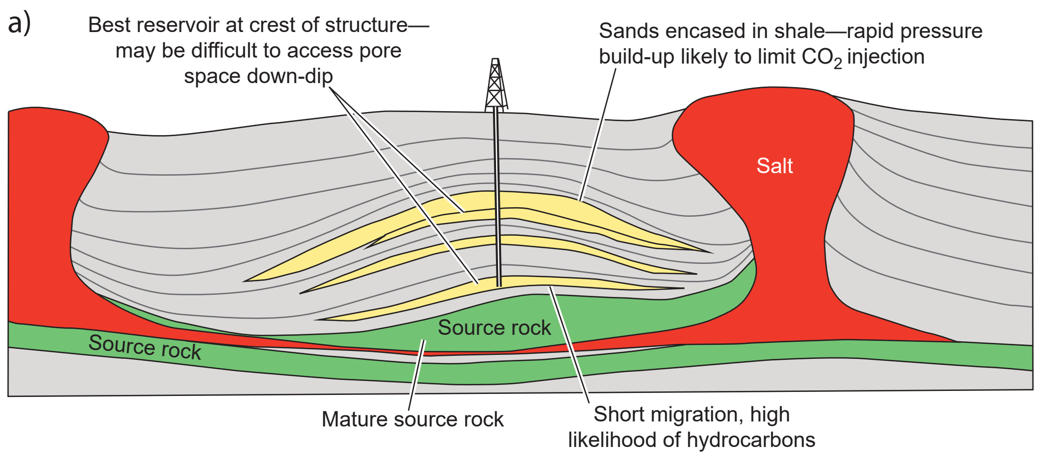


Fig. 14: Example of a salt-influenced CO2 storage play concept that may have pose containment risk. Sands encased in shales within a turtle anticline geometry may be highly prospective for oil and gas, yet for CO2 storage the pressurized sands may restrict CO2 injection into the crest, and there may be difficulty in accessing pore space down-dip of the anticline crest.

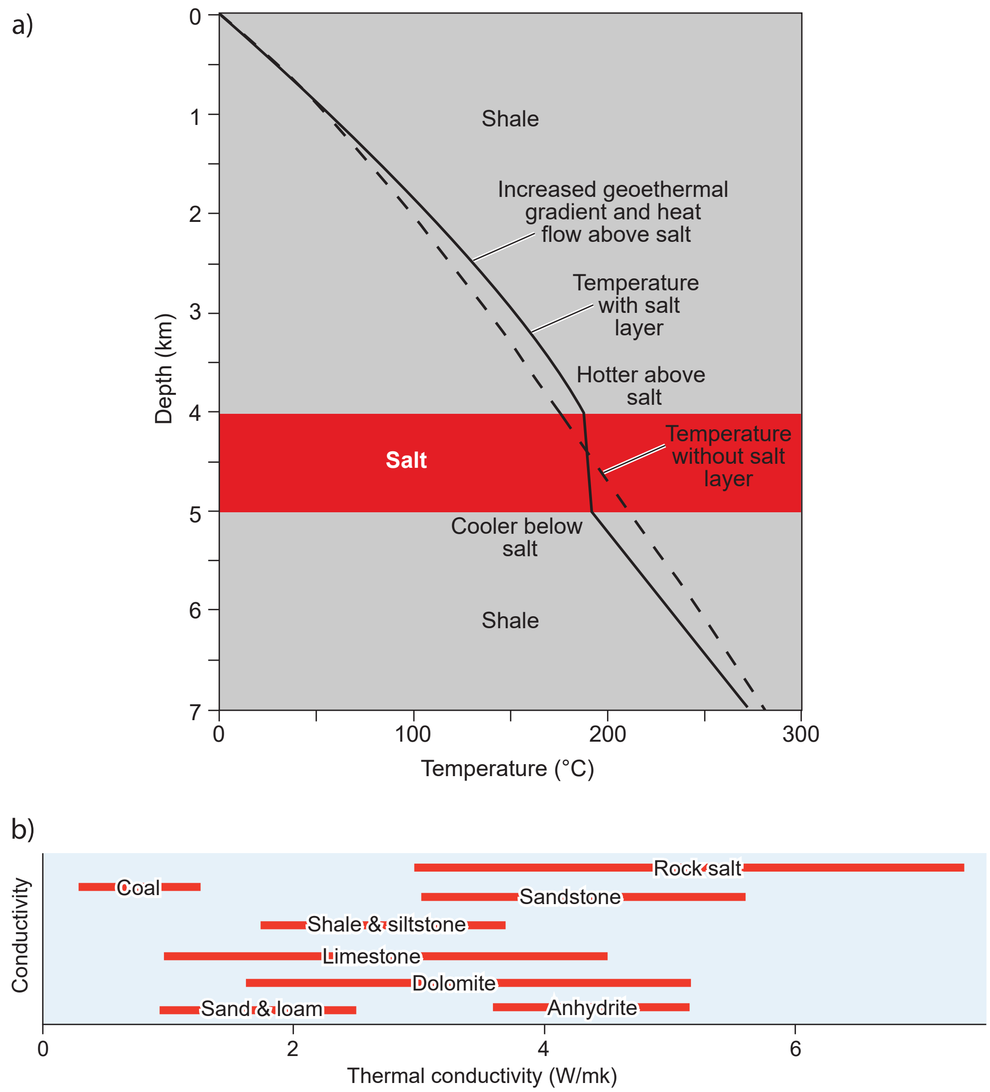


Figure 15: a) Effect (schematic) of a 1-km-thick salt body in a shale interval on the geothermal gradient. The presence of the salt layer cools rocks below the salt and elevates the temperatures of rocks overlying the salt (modified and approximated after Mello et al. 1995). b) Thermal conductivity of rock salt compared to other lithologies (after Warren, 2016; 2017).

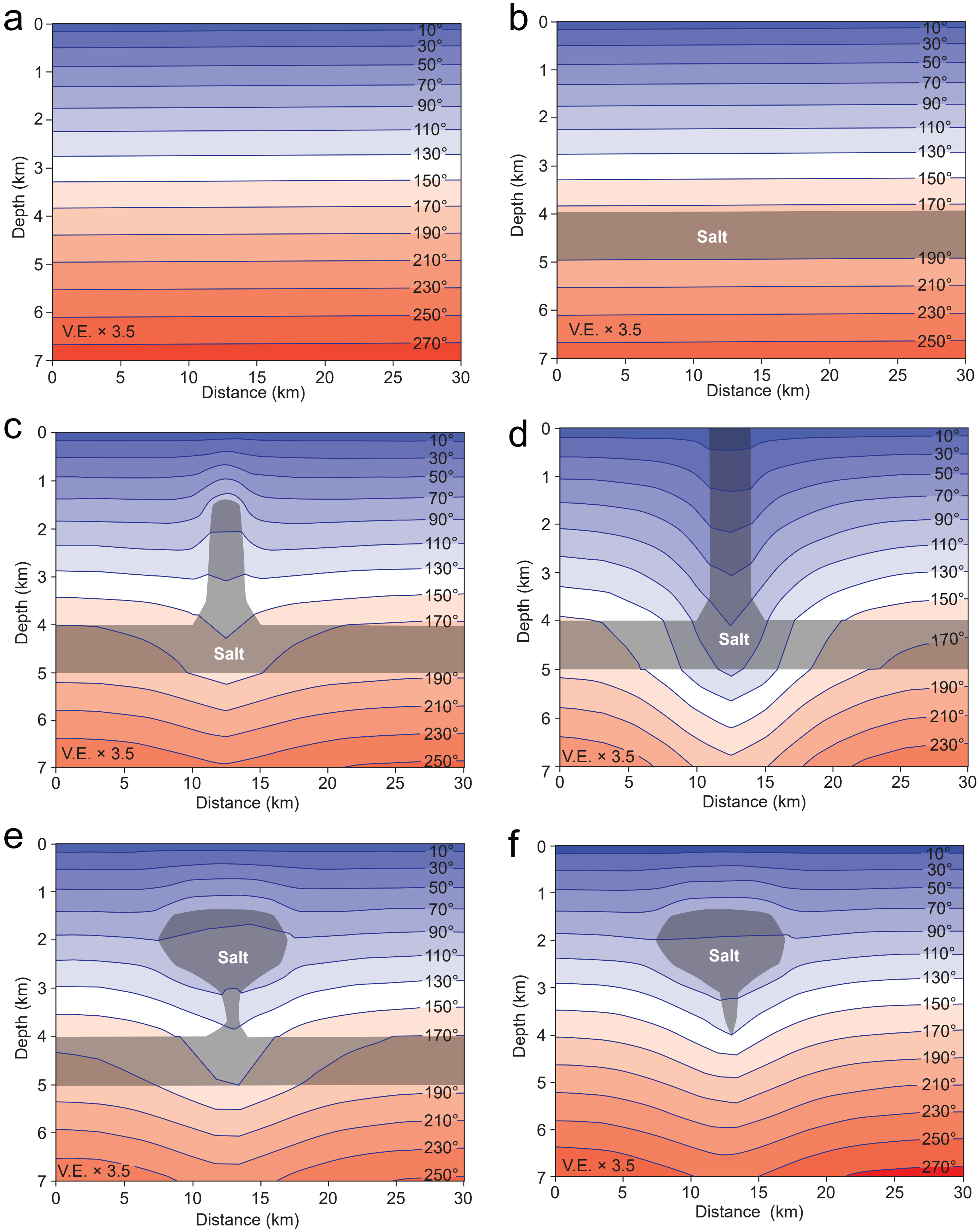
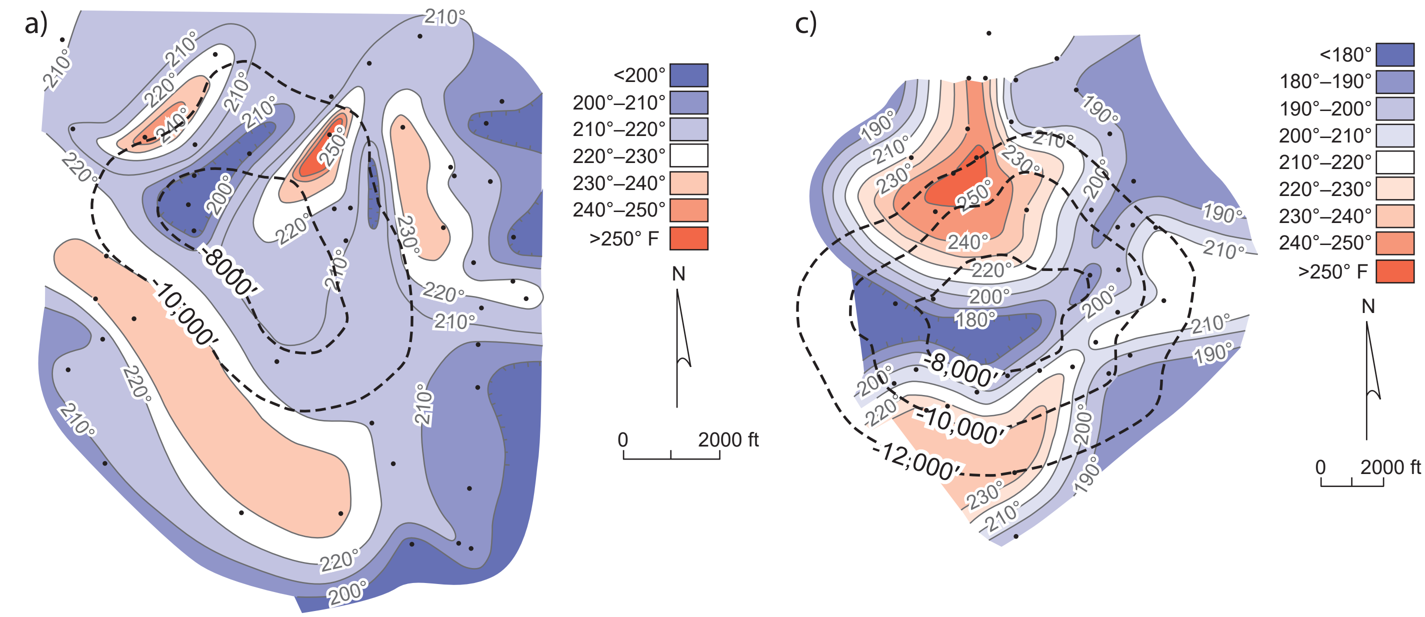


Figure 16: Effect of salt bodies of varying geometries on steady-stage temperature distributions. Salt bodies are encased in shale and have axisymmetric geometry. a) shows an example with no salt present. Temperatures above salt are typically elevated, temperatures below salt are depressed, and temperatures adjacent to salt are dependent on salt geometry. (Mello et al.,1995).



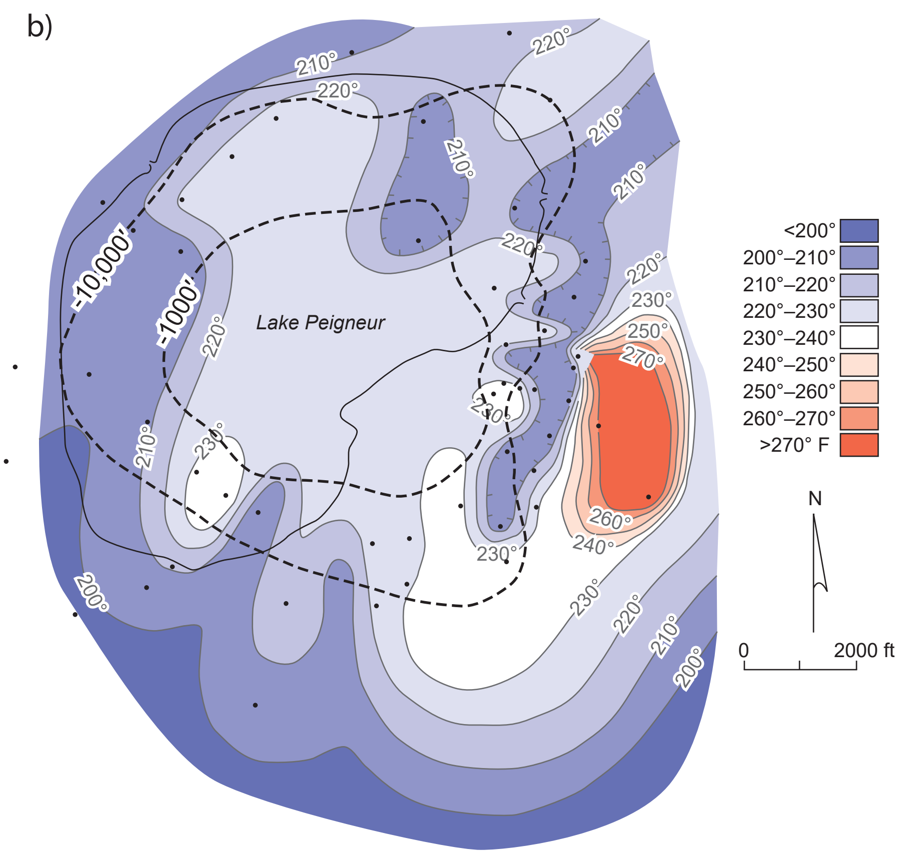


Figure 17: isotherm maps showing temperature distributions above Louisiana (US Gulf Coast) salt diapirs. Temperatures shown are in degrees Fahrenheit. Dashed lines indicate contours of the depth of the top salt surface (in ft). a) temperature distribution at the 10,000 ft level at the Plum Bob salt dome. b) temperature distribution at the 10,000 ft level at the Jefferson Island salt dome. c) temperature distribution at the 10,000 ft level at the Bayou des Allemands salt dome. In general temperatures increase over the diapirs. However, there is significant second-order variability in temperatures, the origins of which remain unclear and merit further research (Kumar, 1989 - colours modified).

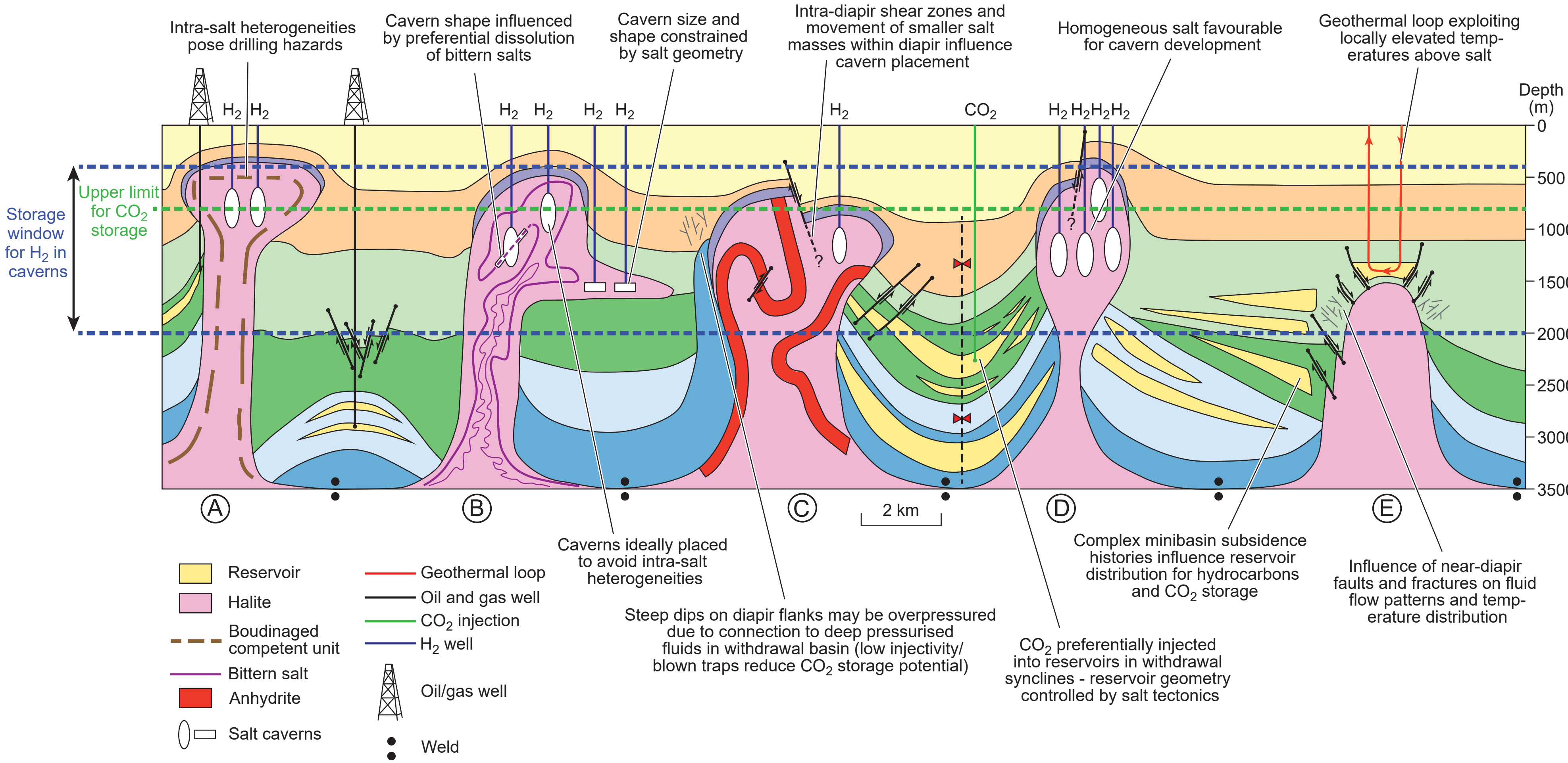


Figure 18: Conceptual model illustrating the role of salt tectonics on the effective deployment of a range of energy transition technologies (energy storage in salt caverns, CO2 storage, geothermal energy, oil and gas exploration). Note the influence of a wide range of salt diapir geometries and intra-salt heterogeneities. Diapir A is upward flaring and contains a boudinaged interval; Diapir B shows a salt sheet or wing developed and a complex configuration of 'slippery' and soluble bittern salts; Diapir C is a wide and faulted diapir with contorted anhydrite; Diapir D shows a teardrop geometry and is composed of relatively homogeneous halite; and Diapir E is deep-seated. The geometries and statal relationships in sediments surrounding the diapirs also vary significantly due to salt tectonic processes. Ultimately, each salt basin and each salt diapir is unique and understanding of salt tectonic processes is required to successfully deploy energy transition technologies.