2
Evaporites

This chapter gives a review of evaporites, including the development process, and a brief discussion of evaporites in Brazil.

Evaporite is the name given to sedimentary rocks that deposit as a result of an intense evaporation process from seas and lakes. Such an evaporation process leaves behind precipitated minerals that, over a period of millions of years, slowly become compacted beds overlain by younger formations. The evaporite rocks can be composed of precipitants such as gypsum ($CaSO_4$), anhydrite ($CaSO_4$), and halite (NaCl, commonly known as “table salt”), along with many other saline minerals. Salt rock bodies from the pre-salt evaporite sequence are commonly composed of halite, a salt that has negligible porosity along with a permeability of less than 1 µD (Costa et al., 2010) and makes up 78 percent of the total dissolved solids. These bodies may also consist of potassium-based minerals like carnallite and sylvanite, or magnesium-based minerals such as tachyhydrite and bischofite.

In the evaporation process, saline water (i.e., *brine*), water molecules vaporize while the salt minerals precipitate. The first to precipitate is calcium carbonate $CaCO_3$, whose solubility is extremely low and represents a small portion of less than 1% of the dissolved solids. Soon afterward occurs the precipitation of anhydrite $CaSO_4$, with halite as the third to precipitate (Botelho, 2008). Hence, the most abundant mineral is not necessarily the first to precipitate. These various types of salt compositions substantially influence the salt rock’s mechanical behavior, which will be discussed later in chapter 3.

Figure 2-1: Photos of most common evaporitic rocks. Top: Tachyhydrite. Upper left: Carnallite. Upper right: Halite. Lower Left: Calcite. Bottom right: Anhydrite (www.webmineral.com; www.jisanta.com).

Salt Mineral	Salt Compound
Sodium Salts	halite (“Table salt”, $NaCl$)
Potassium Salts	carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$,), silvite ($KCl$), Polyhalite
Magnesium salts	Tachyhydrite ($CaCl_2 \cdot MgCl2 \cdot H2O$), bischofite
Sulphates	gypsum ($CaSO_4$), anhydrite ($CaSO_4$)
Sylvanite	silvite + halite

Table 2-1: Common salts found in offshore drilling.

The greatest distinction of salt rock from all other rock types is its mechanical behavior when subjected to an applied load over a period of time. Its large time-dependent deformation, commonly known as *creep*, can be explained by its crystalline structure. In contrast to this ductile property found in salt, other existing rock types tend to present a brittle nature under the same loading conditions. In other words, most rock types are able to sustain extreme loads, but once their maximum strength is reached, cracking and fissuring occur leading to material failure. Rock salt, however, possesses a viscoelastic and viscoplastic behavior, meaning that after the elastic region in its stress-strain curve it behaves as a viscous fluid and may even “flow” under high pressure when there is a small difference in the principal stresses (Goodman, 1993). Creep is strongly influenced by deviatoric stress and temperature.

Salt rock is a very important rock in the eyes of engineers. Crystalline rocks such as salt are known for their low porosity and interlocked texture, and are generally identified as competent and strong rock types. This material behavior is dependent on the intra- and intercrystalline fissures as well as on the nature and freshness of the crystals themselves (Goodman, 1993). Salt rock is of great use for the storage of nuclear and radioactive wastes, impeding these contaminants to leak and come in contact with groundwater, thus ensuring safety for nearby municipalities. Repositories for radioactive waste disposal exist in the US and in Europe (Yang, 2000). Such repositories originate from formation of massive domes deep underground called *salt domes*. These domes are formed by the uneven uplift of salt formations, driven by its lower density in comparison to the overlaying rocks (See Figure 2-2). This ascension process of salt rock is known as *diapirism***.** As a result of this process, folds develop by the induced lateral pressures of the adjacent beds, as illustrated in Figure 2-3. Anticlines are folds that arch upwards; a downward arch is referred to as a syncline.

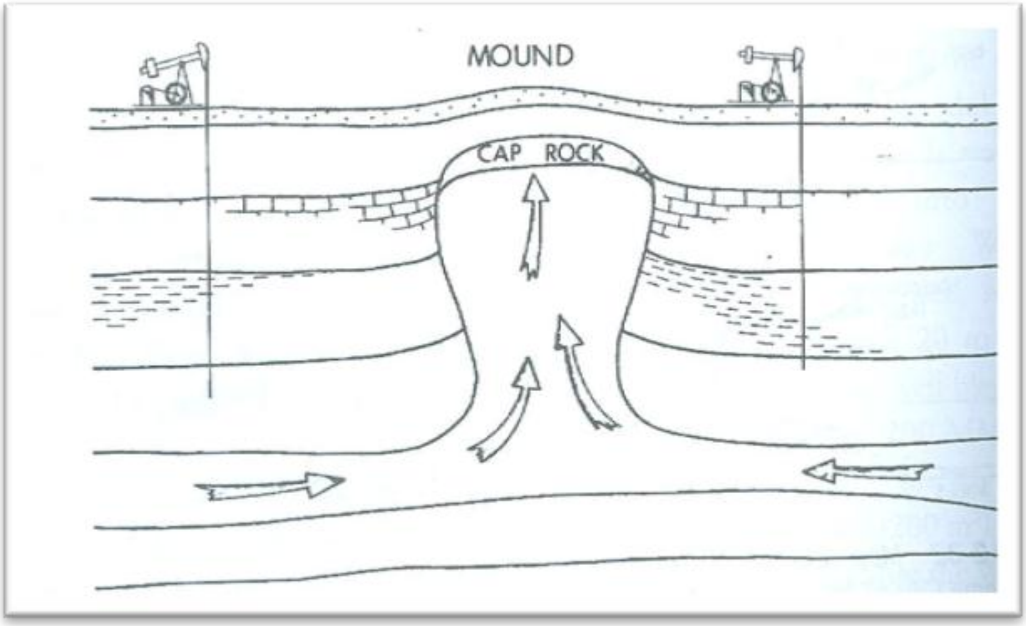

Figure 2-2: Cross Section of a salt dome (Hyne, 2001).

Diapirs may also involve faults. According to Goodman (1993), minor faults have offsets as small as millimeters while major faults can have displacements of kilometers due to repeated movements over geologic time. Faults can be regarded as active if they are prone to move further. If the mechanical properties of a fault are greater than or comparable to those of the surrounding intact material, the fault is claimed to be healed. Faults coexisting with diapirs may permit the trapping of oil and gas.

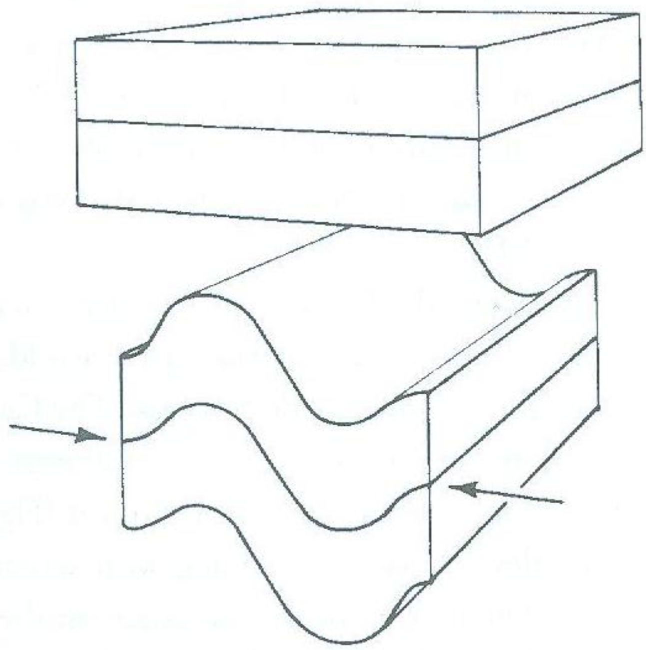

Figure 2-3: Lateral pressures form anticlines and synclines (Hyne, 2001).

Billo (1983) states that “Entrapping hydrocarbons requires the availability of nearly mature rocks, porous and permeable reservoir rocks, and impermeable caprocks, and a suitable structure on the reservoir to form a closure.”

In addition to salt domes, evaporite basins also have been proven to provide exceptional oil storage. With their bowl-shaped form, these basins easily impeded the sweeping out of organic matter and sea organisms during their geologic formation (Hyne, 2001).

2.1 Evaporites in Brazil

The five principal basins in Brazil are Sergipe-Alagoas, Campos, Santos, Espírito Santo and Pelotas (Chang et al., 1992). Brazil’s coast was once connected to the western coast of Africa building up the Gondwana, but due to tectonic activity in the Mesozoic era it began drifting away and developing the pre-salt basins. This continental separation created rifts deep in the South Atlantic which led to the development of the five basins as well as to major offshore oil accumulations (1992). In the state of Sergipe exists rock salts representative of those found in the Campos and Santos Basins (Cella, 2002; Poiate et al., 2006), currently the two most significant and potential oil reservoirs in Brazil.

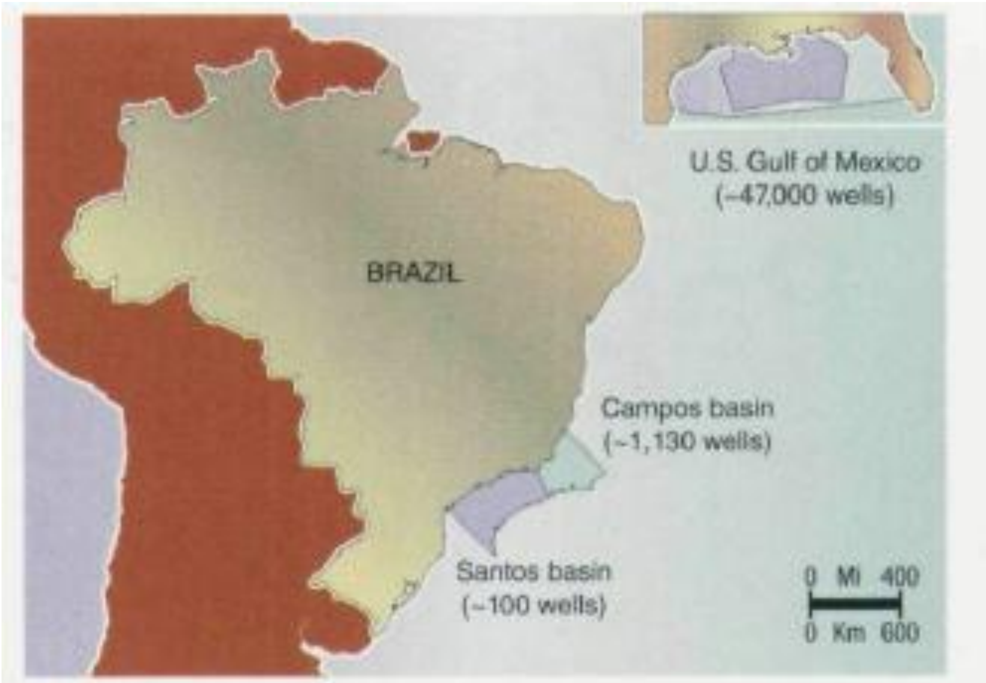

Figure 2-4: Santos and Campos Basin (Rosenfeld and Hood, 2006).

2.1.1
Sergipe

The Taquari-Vassouras underground potash mine in Sergipe is a source for collecting accessible samples of different salt types for laboratory testing. Predictions of salt rock behavior for the pre-salt may be made from sampling at this location; this area is ideal because of similarity and accessibility. Taquari-Vassouras is rich in minerals and ores such as sylvanite and carnallite along with magnesium salts such as tachyhydrite. Figure 2-5 displays a general stratigraphy of the mine. At its base is found a bed of cryptocrystalline limestone, which indicates the beginning of the evaporite deposition.

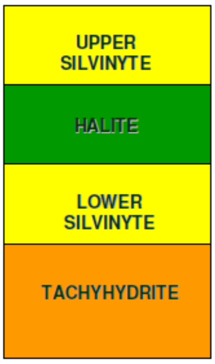

Figure 2-5: Typical stratigraphy of the potash reserve state of Sergipe, Brazil (Costa et al., 2010).

2.1.2
Campos and Santos Basins

Off the coast of the southeastern part of Brazil lies both the Campos and Santos Basins, both of which show high geothermal gradients, extraordinarily thick evaporite layers and evidence of tectonically-induced salt movement (Poiate et al., 2006). The stratigraphy of the Campos Basin consists mostly of halite (NaCl) while having occurrences of anhydrite ($CaSO_4$), gypsum (dehydration of gypsum, $CaSO_4H_2O$, originally deposited) and carnallite. The most important salt types in the pre-salt area are halite, carnallite and tachyhydrite. Studies made by Costa et al. (2010) have shown through triaxial lab experiments that tachyhydrite can develop creep strain rates up to one hundred times higher than halite. The challenge is drilling through roughly 2000 m thick of salt rock.

Because of its crystalline structure (see Figure 2-6), salt rock exhibits time-dependent straining when subjected to a constant shear load. This is due to slipping between the crystal planes; a type of straining known as creep. There are many factors that influence salt creep: the thickness of the salt formation, formation temperature, mineralogical composition, impurities, water content, and the extent to which differential stresses are applied to the salt body (Costa et al., 2005). Salt rock also has the ability to creep to very large strain values without fracturing because it is self-healing (Goodman, 1993).

Figure 2-6: Left: Amorphous structures. Right: Crystalline structures (Dowling, 1999).